D1

SPECIAL REPORT FOR SC D1
MATERIALS AND EMERGING TEST TECHNIQUES

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Special Reporters

Simon Sutton (Chair) and Gordon Wilson (Secretary)

Introduction

Study Committee D1 aims to facilitate and promote the progress of engineering, and international exchange of information and knowledge in the field of materials and emerging test techniques. In this role we provide specialist knowledge and support to many of the other Study Committees, as well as responding to requests from Standards bodies, e.g. IEC, for recommendations for new and revised tests.

The activities of SC D1 include evaluation of new developments and assessing performance within:

- New and existing materials for electrotechnology
- Diagnostic techniques and related knowledge rules
- Emerging test techniques which may be expected to have a significant impact on power systems in the medium to long-term

In 2024 CIGRE published its latest Strategic Plan covering the period to 2030. This plan expands CIGRE's scope to consider the End-to End generation to consumption of electricity: this reflects CIGRE's desire to support the energy transition. SC D1's scope will correspondingly broaden to incorporate these new topics.

The CIGRE Week

During the CIGRE week there are many opportunities to participate in the activities of SC D1, including the tutorial, a joint workshop, the poster session and Group Discussion Meeting (GDM). The poster session is your opportunity to meet the authors of the Session papers and discuss their work. The GDM is where the questions posed in this Special Report are discussed; anyone is free to contribute, and we encourage you to do so.

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For the 2024 Session, papers were invited on the following three Preferential Subjects (PS) which are aligned to SC D1's activities:

PS1: Testing, monitoring and diagnostics

- Testing and condition monitoring for reliability in conventional high voltage systems and power electronics applications.
- Assessment of diagnostics for equipment in remote or inaccessible locations.
- PD measurement under DC, rectifier, and impulse stress.

PS2: Materials for electrotechnical purposes and modelling

- Ageing of materials under electrical, mechanical or thermal stresses and ageing markers.
- Modelling materials and field simulations for AC and DC applications.
- Assessment of compatibility of aged and new materials resulting from refurbishment or life extending activities.

PS3: Materials to enable the energy transition

- Alternative electrotechnical materials or manufacturing processes which reduce environmental footprint.
- Materials and systems for energy storage; batteries, charging devices, capacitors etc.
- Materials to enable a hydrogen economy

The removal of National Quotas for the 2024 Paris Session led to an increase in papers for all Study Committees. Following a rigorous review process supported by 50 peer reviewers from around the globe, 65 papers have been accepted this year. These papers come from 20 countries; a good reflection on the international nature of CIGRE. The breakdown of submissions is as follows: 35 for Preferential Subject 1, 24 papers cover Preferential Subject 2, and 6 papers are aligned with Preferential Subject 3.

This year we had four proposed papers from the Next Generation Network (NGN); the best two have been accepted to present in the Group Discussion Meeting (GDM): these are papers 11856 and 11861.

Information about participating at the SC D1 Activities at the Paris Session

Guidelines for the GDM Contributions and Poster Sessions, as well as templates must be strictly observed and are posted on the CIGRE website Session page.

D1 Group Discussion Meeting and Preview Meeting

You are invited to participate in discussing this Special Report at the SC D1 session held Tuesday 27th August, in the Bleue Room from 08:45 to 18:00.

The reporters have compiled up to 24 questions, these are not specifically aimed at the papers' authors, but are synthesised from common issues and trends identified in across the papers. This provides the opportunity for a broader response and participation in the discussion session. We encourage you to share your views or experiences *in response to the specific questions* in this report.

Procedure for contributions.

1. Contributors should **upload your contribution** on the registrations **portal** – "Contributions to Group Discussion Meetings" section - using your existing account and own credentials **before 10ᵗʰ August 2024, 18.00 CET** for a prior screening and a good organization of the Group Discussion Meeting. Important points;
   - 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 start of June.
2. Special Reporters will review the prepared contributions (Power point presentation with max 3 slides and a written word file with max 1000 words per contribution). A guide for contributors as well as templates and sample pages will be available on the Paris session 2024 webpage.
   - No commercial names are to be included in presentation or the written summary.
   - Any recommendations or changes to the contributions will be provided by the Special reporters directly on the Registration platform between **10ᵗʰ of August and 16ᵗʰ of August 2024**. Contributors are encouraged to visit their account on the registrations portal to see the result of this review.
3. All contributors with accepted/finalised contributions will be contacted by the Special reporters of SC D1 by email between **10ᵗʰ of August and 16ᵗʰ of August 2024**, to finalize the presentation and receive the instructions regarding the session.
   - Important **note:** All contributions should be uploaded prior to the Conference in Paris.
4. It is expected that the questions relevant to the three 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.

There might be the opportunity for spontaneous contributions during the session, which will only be verbal with no slides. Attendees who provide a spontaneous contribution, are encouraged to summarise their contribution as a short written response for the Proceedings. This text is required to be forwarded within two weeks after the SC D1 Session by **Tuesday September 10ᵗʰ 2024** to be considered in the proceedings. The written summaries shall be sent to SC D1 Secretary.

The Special Reporters, D1 Chairman and D1 Secretary will meet with the contributors at the Palais des Congrès on Monday 26th August, to discuss their proposals and to allocate the period for their presentation. This meeting will take place in the room within the Poster Session area. Anyone wanting to make a last minute presentation submission should also attend this meeting; priority will be given to those who have submitted their contributions in advance.

To all those attending the GDM, please ask questions and make comments: this is meant to be an interactive session.

Poster Session

It is expected that authors present their papers at the D1 Poster Session, which will be in Halle Ternes is on Monday 26th August 14:00-18:00. The e-posters will be shown on video screens (no paper posters accepted). A draft copy of the poster must be uploaded to the ConfTool platform by Wednesday 31st July for review by the poster session convener. The final version, incorporating any requested changes, must be uploaded by Friday 16th August 2024.

The Poster Convener will upload the files in advance for the Palais des Congrès. Authors will not have the possibility to upload their own files. If the author(s) cannot attend the Poster Session, they, or the relevant National Committee, are requested to send a substitute. Details will be issued on the CIGRE homepage.

Because of the increased number of papers this year, the poster session will be split into two 2-hour sessions:

1. Session #1 = PS1
2. Session #2 = PS2 and PS3

D1 Tutorial

This year's D1 tutorial will cover elements from the Working Group D1.70, "Functional Properties of modern insulating liquids". This group has produced two Technical Brochures:

1. TB856, "Dielectric performance of insulating liquids for transformers"
2. TB927, "New laboratory methodologies for investigating of insulating liquids. Further developments in key functional properties"

The tutorial entitled, "Functional properties of insulating liquids for transformers: laboratory methodologies and dielectric performance" will be presented by Ivanka Atanasova-Hoehlein and Lars Lundgaard on Thursday 29th August between 10:40 and 12:30.

Joint Workshop

A joint workshop on, "Driving T&D substations and equipment towards ZERO emissions" will be held on Monday 26th August in the afternoon (14:00 to 18:00). Speakers from SCs A2, A3, B3 and D1 will all participate in this workshop.

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D1-PS1: Testing, Monitoring and Diagnostics

Paper No. 10166 promotes the use of improved acoustic sensors to optimize the partial diagnostics of gas-insulated switchgear. This method is often used for commissioning tests and is particularly useful for detecting free moving particles in switchgear. In the presented study, differential dual-resonance AE sensor based on PMN-PT single crystal were designed and compared. The use of this piezoelectric materials enables AE sensors with higher sensitivity compared to conventional sensors.

Paper No. 10249 reports a method for sensitive gas leakage measurement of dynamic seals in GIS in conjunction with mechanical endurance tests, by use of differential pressure in volume-reduced gas compartments, in comparison to the common Helium vacuum method.

Paper No. 10295 presents laboratory and on-site test results on UHF PD measurement in GIS (SF6 and C4-FN mixture) and power transformers, applying measurement in frequency domain, in comparison to conventional PD measurement.

Paper No. 10395 describes the design of partial discharge sensors and the system integration for continuous monitoring. The ability to estimate the probability of failure and remaining useful lifetime of high and medium voltage equipment allows to successfully introduce condition-based and predictive maintenance strategies. This makes the use of PD monitoring systems in MV grids more economically effective. Practical examples underline this thesis.

Paper No. 10396 presents a monitoring technique for overhead lines and the attendant algorithms for evaluating the presence of ice sleeve and conductor temperature. The proposed algorithm allows the identification of anomalies associated with an increase in the weight of the conductors, such as in the case of the formation of ice sleeves and has demonstrated the effectiveness in accurately tracking tension values in diverse operational conditions.

Paper No. 10415 provide insights for enhancing the performance of partial discharge (PD) monitoring systems using HFCT in the presence of challenges with varying current loads. A method to compensate for sensitivity losses due to saturation without introducing any air gaps is presented. Real PD cases from switchgear and cable in a 22ºkV distribution network are shown.

Paper No. 10483 promotes the importance of separating low and high molecular weight acids in addition to the conventional total acid number (TAN) measurement. Detailed procedures

for determining the acid types based on chromatography were introduced. In addition, the effects of low molecular weight acids on dielectric frequency response (DFR) measurements of pressboard insulation were investigated and a procedure to compensate the estimation of water content in pressboard was proposed.

Paper No. 10484 reports diagnostic results of bushings using Dielectric Frequency Response (DFR) to identify deteriorating bushings in early stages. Diagnostic testing is performed on both oil-impregnated-paper (OIP) bushings and resin-impregnated-paper (RIP) dry-type high-voltage bushings. Case studies demonstrate sensitivity of DFR to a significant moisture contamination issue.

Paper No. 10496 is related to the topic of atmospheric correction, particularly at DC and SI voltage. New test results and an analysis of already published data are presented and compared with the current correction according to IEC 60060-1. It is concluded that the IEC correction does not always fit into the test results and needs some revision.

Paper No. 10497 promotes diagnostic of on-load tap-changer based on vibroacoustic measurements. The proposed method aims to predict steps in the switching sequence of a tap-changer from events detected in the vibroacoustic signals and could be used for monitoring the change in timing of a switching step due to mechanical wear.

Paper No. 10513 reports a large number of laboratory stray gassing tests using the method defined in IEC60296 by considering various influencing factors. The results indicated that the investigated stray gassing phenomenon is mainly due to oxidation of the uninhibited oils. More importantly, a mitigation procedure was proposed and trialed in some in-service transformers.

Paper No. 10556 describes the phenomenon of early failure in power equipment despite successfully passed factory acceptance and commissioning tests and the data analytics. The paper describes data analytical methods as in the IEC/IEEE 62539 standard: Guide for the statistical analysis of electrical insulation breakdown data and improvements that may be considered for the upcoming revision.

Paper No. 10651 describes a the pilot project involving a new pseudo-passive PD measurement technology at a 220 kV GIS substation is described. The system provides wide area coverage with a small number of battery powered sensors.

Paper No. 10655 addresses development of a protocol for cyclic corrosion testing of HV disconnectors under continuous current which replicates real in-service conditions i.e. a combination of stress factors. Testing was performed on a complete disconnector or on a laboratory-scale sample representative of a complete assembly.

Paper No. 10754 promotes a GIS universal voltage divider (RCR-divider). Ageing processes at DC voltages, the impact of AC voltage stress, and impulse voltage stress on used insulation material are presented in different test scenarios with significantly higher test voltages and temperatures to determine ageing processes and to determine the design limits.

Paper No. 10811 reports a newly developed online DGA (Dissolved Gas Analysis) monitor based on TDLAS (tunable diode laser absorption spectroscopy) method. Descriptions of the TDLAS principle, monitor construction, calibration and data processing are provided in detail.

Paper No. 10825 illustrates the seasonal effects on the measured ageing markers in transformer oils, with a focus on methanol. A procedure to compensate the effects of seasonal temperature and time lag was proposed based on some literature data and assumptions.

Paper No. 10827 promotes mobile X-ray diagnostic complex for high-voltage equipment. The paper presents the main technical features of this unit for digital scanning radiography for the purpose of monitoring the HVE in operation. The results of testing on high-voltage equipment of voltage classes up to 500 kV, low-oil and gas-insulated circuit-breakers, as well as outdoor terminations are presented.

Paper No. 10854 reports two case studies, one 500 kV shunt reactor and one 500 kV power transformer that show an increasing trend of hydrogen in relatively short time span (month/s). Post-mortem investigations attempted to link the gas generations with partial discharge (PD) activities inside the equipment.

Paper No. 11032 introduces a new method to measure dissolved gases in liquids using PD-HID (pulsed discharge helium ionisation detector). It also demonstrates the potential to measure water content and SF6 in liquids using the same method.

Paper No. 11053 introduces a new sensor (using an XLPS block instead of aluminum to couple with a PVDF sensor) and a measurement system that can determine the space-charge distribution in XLPE HVDC cables under real operating conditions in full-size cables.

Paper No. 11055 presents the basic measurement principle of the Q(t) method, discusses its advantages, and provides application cases, introducing a novel method for insulation diagnostics.

Paper No. 11095 provides a systematic review of DGA (Dissolved Gas Analysis) interpretation methods for on-load tap-changers (OLTCs). A machine-learning (ML) based DGA interpretation model for vacuum type OLTCs was proposed and applied successfully in a utility's OLTC DGA database.

Paper No. 11115 introduces an online sensor, through measuring oil temperature and relative humidity to estimate AC breakdown voltages of the oil, for OLTC applications. Installation advice was also provided, and uncertainties of the estimation were quantified.

Paper No. 11139 introduces a study on optical PD measurement in GIS and transformers, based on improved industrial light sensors, while in the case of GIS SF6, a C4-FN/O2/CO2 mixture and synthetic air were used. In case of particular defects of low PD magnitude, a better measuring sensitivity was found, compared to conventional or UHF PD measurement.

Paper No. 11319 describes deficiencies in IEC 62217 which failed to detect flaws in composite insulators only revealed later during laboratory analysis. The paper proposes the use of Dynamic Mechanical Analysis to measure Tan δ and Tg as a new quality assessment method of the composite rod.

Paper No. 11326 provides a comprehensive introduction to the DGA technique and some critical reviews on the application of this technique in transformer condition assessment based on the author's extensive experience.

Paper No. 11379 reports a study on PD measurement of the two defect types "protrusion" and "free moving metallic particle" in GIS, comparing SF6, C4-FN gas mixtures and CO2, and using conventional and UHF PD measurement. In conclusion, common PD measurement methods can also be applied in the alternative gases with similar PRPD patterns in the case of the particles, while the patterns were different in the case of protrusions.

Paper No. 11442 investigates the dielectric strength of elastomers partially embedded in silicone rubber or oil, considering the properties of both rubber and oil. It provides insights into the influence of conductivity and strongly recommends accounting for these effects.

Paper No. 11665 presents simulations and test experiences on 320 kV cable system with new temporary overvoltage (TOV) waveforms. Non-standardized waveforms like very slow front TOV, very slow front chopped TOV, zero crossing damped TOV are possible in HVDC systems. The tests presented in the paper were conducted in accordance with CIGRE TB 852: Recommendations for testing DC extruded cable systems for power transmission at a rated voltage up to and including 800 kV.

Paper No. 11695 reports measurements of methanol and ethanol, as solid insulation ageing markers, in oil samples collected from about 100 in-service transformers with varying service lifetime.

Paper No. 11723 proposes a new method to monitor power transformer oil-pump wear based on oil samples analysed using Particle Size-Independent Method ICP (PSIM-ICP). This method has advantages compared to the currently applied ASTM D 7151. Comparative results are presented.

Paper No. 11820 describes three case studies of HV and EHV transformers with high insulation power factor results. In each case the results of additional diagnostic testing and oil analysis used to support the root cause analysis are discussed.

Paper No. 11825 introduces a promising method that uses Convolutional Neural Networks (CNNs) based image processing technique to identify the tarnish levels of copper strips after standard corrosive Sulphur tests.

Paper No. 11856 reports lightning impulse breakdown voltages and acceleration voltages of various transformer liquids at three gap distances under both positive and negative polarities. The liquids tested include inhibited and uninhibited mineral oil, natural and synthetic esters, GTL (gas-to-liquid) and biodegradable hydrocarbon liquid.

Discussions of PS1

Testing, monitoring and diagnostics are essential to determine and evaluate the technical performance and condition of power distribution and transmission systems. The prediction of reliable system operation is important for its optimization in terms of economics and under ecological aspects. The submitted papers give an insight into the current progress in the respective technical fields.

Dissolved Gas Analysis (DGA) remains a hot topic for liquid-immersed high voltage equipment, e.g. power transformers, and hence attracted many contributions on this topic. On one hand, this is due to the proven advantages of this technique for indicating the health status of the equipment and users continue the efforts to know more. On the other hand, this is due

to the active developments and applications of new liquids in the past decades, and hence established knowledge on measurement techniques and interpretation methods needs to be validated for the new liquids. Stray gassing is still a challenge to be addressed due to the wider range of materials and additives used in the equipment and the variety of potential reaction mechanisms involved. The current approach is more empirical; based on laboratory tests or field experience. Should there be more theoretical or modelling approaches taking advantage of the advanced molecular level simulations? For data quality, there always seems to be room for improvement. JWG D1/A2.77 will include round-robin test results of partition coefficients and Ostwald's constants for DGA applications in various types of liquid. It will also provide a template for data collection including, but not limited to, DGA. Meanwhile JWG A2/D1.67 will focus on guidelines for online DGA monitoring. For data interpretation, in addition to the conventional analytical methods, Machine Learning (ML) based methods are increasingly considered and have shown some successful cases. However, such methods require a large database with high quality data, in particular the accuracy of data labelling. Expertise is often required for data labelling, which is a subjective process and may not be readily available for all users, certainly not to the same level of expertise. Data labelling based on post-mortem analysis is much more reliable, which is however limited to replaced/retired transformers.

Furan and carbon oxides have been long used as the chemical markers in liquids to indicate paper degradation processes in transformers. Since paper degradation determines the thermal lifetime of transformers, there are always motivations to seek for addition chemical markers. Methanol and/or ethanol were proposed as new markers in early 2000s. A series of laboratory studies showed clear correlations between methanol and DP reduction in particular at early stage of ageing. However, issues like stability of the markers and generations from liquids themselves were also reported. An IEC technical report 63025 on determination of methanol and ethanol in insulating liquids was published in 2021. Some utilities worldwide have conducted methanol measurements. Experiences obtained from field practice, e.g. population analysis and successful cases are critical for influencing the future of this chemical marker. Also in early 2000s, low molecular weight acids (LMA) were identified as both by-product and catalyst for paper degradations. In contrast to the conventional total acid measurement, separation of LMA tends to reveal more useful information towards paper degradation. There was an initial attempt to establish an international standard for measuring LMA but it determined that the state of the art was insufficient at the time and more research was required. Ester liquids have been increasingly used in transformers. Degradation of ester liquids produces a high amount of acids through oxidation and hydrolysis processes. However, a large part of these acids are high molecular weight acids (HMA) rather than LMA. This shows the necessity to further separate acid measurements in liquids and potentially provides another motivation to re-consider standardization of the method.

Partial discharge (PD) measurement techniques intend to enable the detection of imperfections in gas-, liquid- and solid-insulated systems. While conventional and ultra-high frequency (UHF) PD measurement techniques, applied to SF6 gas-insulated systems, are state of the art since tens of years, alternative techniques provide advantages in specific cases. Optical PD measurement may enable a better detection of some types of defects, particularly under high electrical disturbance, and may also be a solution under DC voltage. Narrow-band UHF measurements contribute to a better signal-to-noise ratio. New insulating gases are progressively applied to gas-insulated systems, particularly natural-origin gases and its mixtures with new fluorinated gases, while its influence on the partial discharge properties and the detectability of defects is still under investigation in the community, and also in

CIGRE WG D1.78. On the other hand, technical guidance is required when applying PD measurement techniques. The new Technical Brochure TB 933, prepared by WG D1.66, gives comprehensive knowledge on state-of-the-art UHF PD monitoring systems for gas-insulated systems.

PS1 Questions

PS1-Q1: Machine Learning (ML) based methods have been increasingly used in data mining and model training for asset condition assessment. As an example, partial discharge measurement data can enable identification of defects. One critical step of the process is expert judgement and labelling of the data, which is still required. Can this be only local experience or generalised nationally and internationally? Any good practice or guidance on expert labelling? Any comments on the perspective of further and wider utilisations of ML based methods?

PS1-Q2: Dissolved Gas Analysis (DGA) is well recognised as a powerful diagnostic method for liquid-immersed high voltage equipment. Data quality remains a technical challenge for fully utilising the merit of the technique. Is this due to lack of guidance from standards or implementation difficulties in practice? After decades of DGA practice, how can data quality be further improved? In addition, large effects were paid for identifying the 'fault' type using various interpretation methods, how about the value of historical records e.g. the trend analysis and etc? How early DGA can give an indication of 'fault' development?

PS1-Q3: Although, DGA is a well recognised diagnostic method for liquid-immersed high voltage equipment, such as transformers, has any progress been made in understanding DGA data from either Self-Contained Oil-Filled (SCOF) or High Pressure Fluid-Filled (HPFF) cable systems?

PS1-Q4: In terms of using methanol and/or ethanol as additional paper ageing markers, what are the field experience of measuring methanol/ethanol? Any case studies showing the benefit of these measurements for assessing transformer health conditions? Have there been enough evidence/results to help utilities to justify the continuation or termination of such measurements?

PS1-Q5: Total Acid Number (TAN) has been widely used as a degradation/oxidation indicator of mineral oils. Should the TAN/Acidity measurement be considered the further classifications into low and high molecular weight acids? Would transformer asset managers see the benefits of such measurements? Are the measurement techniques readily available for the liquid testing laboratories? Is the state of the art ready for standardisation? Would classification of acids bring more clarity to the understanding of the condition of esters in particular?

PS1-Q6: Different partial discharge (PD) measurement techniques are common or under investigation, and trends towards more ecofriendly gases than SF6 can be stated. Beside the submitted papers, are there any further examples how the application of new techniques or new gases impacts PD measurement in the laboratory or on site?

PS1-Q7: In many cases, human experts are still required to interpret partial discharge diagnostic results, especially when it comes to assessing the potential risk to the operation. In addition, these monitoring systems are expensive, but are increasingly being used also for distribution networks. Are there new systems for evaluating PD measurements? Can the cost-

effectiveness of such monitoring systems be confirmed by the experience of operators? Direct calibration of most PD measurement systems (acoustic, UHF, VHF) is not possible. What new approaches are there to compensate for this apparent disadvantage?

PS1-Q8: With the increasing number of HVDC interconnectors and integration of renewable energies using HVDC connections, is there any progress in the automated acquisition and interpretation of PD measurement data under DC voltage conditions?

PS1-Q9: Space charge measurements are possible in the laboratory on full sized HVDC cables. Is there a need to perform these measurements in the field? Is continuous online monitoring practical or desirable? What are the barriers to adoption and what would we learn from such long-term monitoring?

PS1-Q10: With the integration of renewable energies over long distances, HVDC connections are increasingly being used. This also leads to other, new types of dielectric stresses in the HVDC connection, but also in the connected HVAC system. For example, stresses occur due to special voltage wave forms (TOV) and overvoltages. Is there an additional need to define and standardize new voltage wave forms? Has the influence of the new voltage wave forms on the service life of the individual components or insulating materials been sufficiently clarified? Is the necessary high voltage testing technology even available and can it suitably map the necessary requirements?

PS1-Q11: The test with superposition of different types of voltages, such as DC and SI/LI, is now required in some international standards. This does not only apply to cables. The test circuits may differ and, in some cases, influence the results. To what extent can the type of voltage superposition influence the test result (depending on the insulation material)? Can the test parameters of the voltages be freely selected? What examples and requirements are there for the type of voltage? Does standardization need to take action here?

D1-PS2: Materials for Electrotechnical Technical Purposes and Modelling

Paper No. 10130 reports a study on different equations of state of SF6. To derive precise information on SF6 gas quantity and leakage, and as a base towards SF6 alternatives, a best fit towards the real conditions is required. A comparison of several equations of state between each other and with experimental data is given, and a recommended virial expansion model, based on a truncated Beattie-Bridgeman formulation, is derived.

Paper No. 10138 is related to the topic of liquefaction of C4-FN/CO2/O2 gas mixtures, which is an important aspect to derive correct gas pressure and mixture coordination, particularly in low temperature applications. Respective tests have been conducted to determine thermodynamic equations, in dependence on gas mixture and gas pressure.

Paper No. 10250 examines the development of electrical trees and partial discharge characteristics in epoxy resin at various temperatures under combined AC/DC voltage, providing a theoretical and experimental basis for assessing the aging of solid insulating materials under combined voltage.

Paper No. 10251 highlights the importance of surface treatment of silica and ATH, common fillers in silicone rubber for high voltage outdoor insulation. It proposes dielectric spectroscopy as a method to characterize these treatments, which are not easily detected by

methods suggested in CIGRE Brochure 595 "Fingerprinting of Polymeric Material for Outdoor Use".

Paper No. 10252 reviews the literature on developing eco-friendly epoxy resins used for insulation in high voltage technology, discussing possibilities for recycling conventional epoxy resins and optimizing EP resins for recycling.

Paper No. 10253 investigates the insulation characteristics of epoxy resin under composite voltage with multiple harmonics, demonstrating that this voltage causes more severe deterioration in epoxy resin materials than AC voltage. It highlights the importance of considering voltage waveform in the aging behavior of insulating materials.

Paper No. 10254 reports water absorption in samples of silicone rubber over time based on weight gain. The adsorption coefficient, desorption coefficient and diffusion coefficient of silicone rubber were shown to conform to the Langmuir model.

Paper No. 10297 presents experimental results for resin-impregnated paper samples under negative HVDC voltage, including short-term and long-term aging tests. Results indicate higher moisture susceptibility than expected, affecting the lifetime of RIP material, and highlight the significance of leakage current as a precursor to breakdown.

Paper No. 10298 reports accelerated thermal ageing tests of kraft paper in various transformer liquids under three temperatures. The liquids tested include a mineral oil, a synthetic ester and two biodegradable hydrocarbon liquids. Correlation of retained tensile strength with 2-FAL and methanol concentrations were discussed.

Paper No. 10299 introduces test results on the dielectric performance of liquid nitrogen, which is e.g. used in superconducting fault current limiters. Particularly superimposed voltage tests (LI + DC) were conducted and found to be of high relevance for the dimensioning of superconducting equipment for DC applications.

Paper No. 10487 introduces a novel method to evaluate the compatibility of dielectric lubricating fluids in cable joint interfaces. It addresses the swelling of silicone rubber due to fluid absorption, which can cause dielectric failure. The method allows measurement of dielectric strength at interfaces under controlled pressure and temperature conditions for aging purposes.

Paper No. 10824 models the aging process of insulation materials for low voltage cables based on EVA copolymer, considering different processes, including aging inhibited by antioxidant additives and oxidative destruction and structuring of high-molecular weight chains when antioxidants are consumed. It presents both theoretical and experimental lifetime predictions.

Paper No. 10826 investigates the effects of fine details of sample preparation on DP (degree of polymerization) measurement. Two factors including paper grinding methods and solvents were considered.

Paper No. 10855 reports the FEM modelling results of PD signal propagation in instrument transformer. Three individual defects at different locations of the oil/paper insulation system are considered and the resulting PD.

Paper No. 10856 reports the thermal class of thermally upgraded paper in natural ester liquid based on extremely long ageing tests following IEEE C57.100-2011 procedure. The effects of two reference lifetimes, 180,000 hours and 135,000 hours on the determination of thermal class of the candidate system were discussed.

Paper No. 10857 compares the thermal ageing performances of hybrid (aramid/cellulose) paper and thermally upgraded cellulose paper when immersed in mineral oil and natural ester, respectively. IEEE C57.100-2011 test procedure was followed. The ranking of various insulation combinations was provided based on different end-of-life criteria.

Paper No. 10893 discusses the cause of silver corrosion and how it is different from copper corrosion. Experiments at various temperatures were conducted and suggestions to improve the test standard were made. Trials to remove elemental sulphur, a cause of silver corrosion, in both mineral oil and synthetic ester were completed.

Paper No. 11016 reports the gas generation characteristics of transformer liquids under laboratory simulated thermal faults using a tube-heating method. Four transformer liquids including inhibited and uninhibited mineral oils, natural and synthetic ester liquids and three temperature levels including 275 °C, 550 °C and 800 °C were considered.

Paper No. 11054 reports the electrical insulation performance of insulating spacers using functionally graded materials (ε-FGM) in natural-origin gas GIS. Compared to the conventional type of uniform-permittivity spacer, the ε-FGM spacer exhibited a 19 % LI-FOV increase at 0.5 MPa-abs and 27 % at 0.6 MPa-abs. The results confirm the ε-FGM spacer has sufficient insulation performance even in dry air owing to its electric field control effect.

Paper No. 11138 presents the similarities and differences between the UHF PRPD pattern and the conventional PRPD pattern for the use at cable terminations and to compare them. Three different artificial imperfections were used to generate reproducible partial discharges. In particular, the PDIV and PDEV, the frequency distribution, the phase position and the intensity of the discharges were investigated and analysed.

Paper No. 11317 develops a low-cost method to create a superhydrophobic surface with improved mechanical stability and durability, enhancing flashover performance and providing an effective method to improve the performance and reliability of HV SiR insulators.

Paper No. 11495 investigates the degassing process of methane (CH4) from crosslinked polyethylene (XLPE) in insulated cables. It includes experiments to analyze the degassing mechanism, development and verification of mathematical models, and applications. It discusses the benefits of a degassing simulator and Human Machine Interface for real-time CH4 concentration monitoring in XLPE cables, considering potential industrial use.

Paper No. 11533 models charge transport in XLPE based on bipolar charge transport, offering an overview of models based on molecular dynamics and density functional theory, and simulating various scenarios.

Discussion of PS2

Developments of new insulating materials and their applications in high voltage equipment have progressed well in the past decades. A much wider range of liquid materials (inhibited and uninhibited mineral oils, natural and synthetic esters, gas-to-liquids, biodegradable

hydrocarbons etc.) and solid materials (non-thermally upgraded paper, thermally upgraded paper, aramid paper, hybrid paper etc.) are available for transformer applications. There is a high demand for characterising these materials and their combinations. WG D1.70 summarised the functional properties of modern transformer liquids and will give a D1 tutorial in Paris. WG D1/A2.80 will look into the functional properties of solid insulating materials used in transformers while WG A2/D1.71 will focus on modern insulating liquid qualifications for OLTC, bushing and other accessories.

It is important to understand the long-term ageing performance of a candidate insulation system before being adopted into the equipment, which attracted many contributions in PS2. WG D1.76 is also working on this topic including round-robin tests of ageing experiments, DP (Degree of Polymerisation) measurements and kinetics studies. DP and TS (Tensile Strength) have been widely used to indicate the mechanical strength of paper insulation. Certain criteria e.g. DP of 200 and retained TS of about 30% are commonly used to indicate the end-of-life of the paper insulation. However, questions are raised to their suitability or validity for new combinations of liquid-solid insulation systems. Is DP measurement suitable for hybrid paper (aramid/cellulose sandwiched paper)? When considering different types of paper insulation, the same retained percentage of TS may mean very different absolute TS. It is the absolute TS reflecting the withstand ability of the paper to withstand mechanical force that could appear in a transformer, so should absolute TS rather than retained percentage of TS be used when considering various material combinations? WG D1.65 is going to publish a technical brochure including mechanical properties of insulating materials used in transformers while WG D1/A2.70 will focus on dynamic behaviour.

Comprehensive investigations on more eco-friendly insulating gases than SF6 led already to the application of different technologies in respective equipment. Despite some years of experience in the field, the particular knowledge on specific aspects like ageing mechanisms or thermodynamic properties is still increasing, and the submitted papers contribute to get a fuller picture.

PS2 Questions

PS2-Q1: Due to the increased options of solid-liquid combined insulation systems for applications in high voltage equipment e.g. power transformers, how is the performance of new combined insulation system assessed? Should all the tests developed for a conventional option be repeated for any new candidate system or should there be a tiered approach to test the candidate systems? Is there any systematic guidance on this?

PS2-Q2: DP (Degree of Polymerisation) and TS (Tensile Strength) are widely used to indicate the mechanical strength of transformer paper insulation particularly in laboratory ageing assessments. What is the validity of DP measurements for new type of paper e.g. aramid/cellulose hybrid paper? Is DP of 200 the true end-of-life criterion? Should retained percentage or absolute TS be used as the end-of-life criterion? Any potential improvements for the TS test method for reducing the scattering of results and/or sample size requirement?

PS2-Q3: Is corrosive sulphur in transformers still an issue for utilities given that it has been out of the spotlight for a while? How did people choose to manage the risk?

PS2-Q4: Biodegradable hydrocarbon liquid has emerged as a new candidate insulating liquid in the past years. Are there more systematic assessments of this type of liquid? Any field experience of using this type of liquid in high voltage equipment?

PS2-Q5: Gas-insulated systems using alternatives to SF6 are installed in the grid, and some years of service were already gained. This year, only one paper was submitted concerning the lab and field experience with respective insulation systems, related to ageing, potential change of gas and material properties over time, in dependence on the conditions under test and service. Feedback in terms of field or lab experience supports the improvement of respective insulation systems. Is there any further news?

PS2-Q6: The use of inverters in renewable power generation is increasing the harmonic content of the system voltage. What studies exist to show the influence of harmonics on material ageing? How will this impact existing equipment life or design of future equipment? Can any failures be attributed to harmonic content?

PS2-Q7: What gaps exist in our understanding of material properties to better model HVDC insulation, composites and components under static or dynamic conditions?

PS2-Q8: Only one paper was received by SC D1 on nano-materials this year. What other recent advanced have been made towards applying nano-materials and composites in real-world applications?

D1-PS3: Materials to Enable the Energy Transition

Paper No. 10755 reports on the chemical decomposition process of C4-FN in presence of water (hydrolysis) and introduces the impact of different materials and thermal cycles on this effect. An appropriate material qualification process was derived, and its results as well as full-scale tests are presented.

Paper No. 11025 addresses novel corrosion protection coatings for electrical equipment in harsh environmental conditions. By using zinc flake pigments in the epoxy coating up to 50-60% metallic zinc can be saved compared to zinc dust pigments.

Paper No. 11057 discusses advancements in lithium batteries, all-solid-state batteries, and dielectric capacitors for energy storage, detailing production processes for required nanomaterials and material choices for capacitors. It reviews these products, highlighting their potential to complement or compete in storage applications.

Paper No. 11058 introduces a systematic study on SF6 alternatives based on quantum-mechanics assisted machine learning, to predict electric strength, GWP and boiling point of already known molecules and newly generated structures, in a chemical space of several millions of substances. Several new candidates were identified, which are expected to demonstrate favorable properties and are not characterized as PFAS.

Paper No. 11644 presents calculations and experiments on the thermodynamic properties of C4-FN-containing gas mixtures. A gas model, particularly an appropriate real gas equation of state (Peng Robinson), was derived from the results, and simplified equations can be used to calculate phase diagrams, densities, and further properties of respective mixtures. Specific details are included in the paper, as a common reference.

Paper No. 11861 reports measurement results of dielectric parameters of cellulose Kraft paper impregnated in mineral oil and natural ester liquid using Frequency Domain Spectroscopy (FDS) technique. The effects of different initial water contents of the paper insulation were investigated.

Discussion of PS3

The energy transition towards reduced manmade impact on global warming is a worldwide challenge for society. On the one hand, the role of electric power systems and the requirements on its technical performance are increasing, and on the other hand the respective systems need to be more eco-friendly. Enhanced electrotechnical materials are required, and CIGRE SC D1 supports this trend in delivering particular knowledge on its properties.

More eco-friendly alternatives to the state-of-the-art insulating gas sulphur hexafluoride (SF6), which has a high global warming potential (GWP), are not only requested from the utilities, but also required by legislation in increasing parts of the world. Properties of SF6 alternatives are topics of some submitted papers. Chemistry and gas data of fluoronitrile-based gas mixtures are given. Insulating gases of reduced GWP are a compromise between GWP, electric strength and stability, and worldwide investigations are ongoing to identify potential future SF6 alternatives, based on machine learning.

Integration of renewable energies and electrifications of transport and heating are essential towards the energy transition. More power-electronics-based devices and energy storage systems will be used in future power networks. More electric vehicles will be charged by the power networks. The digitization of the future world will also see more large data centres which become heavy electricity consumers. One technical challenge faced by these applications is the thermal management of these systems as a result of increasing power density.

Direct immersion cooling using dielectric liquids has been increasingly considered in these applications due to the excellent cooling and insulating performances of the dielectric liquids. Direct immersion cooling has been widely used in high voltage power transformers for over a century. Ample experience on specification, testing and maintenance of dielectric liquids have been accumulated and hence there must be an opportunity for knowledge transfer. However, new challenges exist in these applications, e.g. liquid compatibility with other materials used in the systems, suitability of the existing standards developed for high voltage equipment, DC or high frequency electric stresses in these new applications. A collective research and development efforts on these topics are needed.

Superconducting materials and respective systems are currently solutions in specific cases only, but R&D efforts are ongoing. WG D1-69 will report soon on guidelines for test techniques of High Temperature Superconducting systems. While there was a lower number of contributions within the last years, there are continuous activities to improve the technology in terms of technical performance and cost, and to expand the application towards DC systems, as given in one submitted paper.

PS3 Questions

PS3-Q1: According to recent publications, the worldwide efforts are ongoing to identify potential new and better SF6 alternatives, particularly based on Machine Learning approaches. Some future legislation on F-gases, for example the new European F-gas regulation, can today be covered by some gases or gas mixtures only, with very limited derogations. Are there emerging any further new alternatives, fulfilling the requirements? Would industry and science be willing to work together more closely to achieve a common technical solution for the future?

PS3-Q2: In the context of liquid immersion cooling in emerging applications, what are the latest research and development activities? How are these liquids tested and following which standards? Any compatibility issues considering the wide range of solid materials used in the systems? How would users specify these liquids for their applications?

PS3-Q3: Alternatives to SF6 and natural esters have received a lot of attention in recent years due to their lower environmental footprint compared to the incumbent materials. What other materials could be replaced with more environmentally friendly alternatives in LV to EHV equipment? What thermosets could be replaced with thermoplastics? Could easier to recycle materials be substituted? Could alternative production methods or raw materials be used to reduce environmental footprint?

PS3-Q4: Are new results available to show the potential benefits of additive manufacturing for producing field graded materials or components with complex geometries? Are there examples of additive manufacturing being used to produce spare parts for existing assets?

PS3-Q5: No papers were received on superconducting materials or their application. What advances have occurred in the development of superconductivity since the last Paris Session?

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.

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