D1 - 00

SPECIAL REPORT FOR SC D1
(Materials and Emerging Test Techniques)

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Special Reporters

1. General

The aim of Study Committee D1 is to facilitate and promote the progress of engineering and the international exchange of information and knowledge in the field of materials and emerging test techniques. The committee contributes to this information and knowledge by synthesizing state-of-the-art practices and by developing recommendations.

These activities include follow up and evaluation of new developments 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.

2. Group Discussion Meeting

SC D1 invited for the Group Discussion Meeting contributions within three preferential subjects (PS), as follows:

Preferential Subject No 1: HVDC Insulation Systems
- Measurement methods for validating electrical field simulations
- New diagnostics for maintenance
- Experience and requirements for new test procedures and standards

Preferential Subject No 2: Materials and Ageing
- New stresses, e.g. from power electronics
- Higher stress operating environment, e.g. compact applications
- Materials with lower environmental footprint

Preferential Subject No 3: Testing, Monitoring and Diagnostics
- Experience and added value from online monitoring systems

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– Reliability of equipment and systems for testing, monitoring and diagnostics
– Advanced condition assessment

In total, 40 papers have been accepted of which 7 papers cover Preferential Subject No 1, 10 papers cover Preferential Subject No 2, and 23 papers cover Preferential Subject No. 3. In the following parts of this report, each of the preferential subjects is discussed separately.

Additionally, two papers of Young Members were proposed and finally selected for giving a short presentation. The will be integrated in our General Group Discussion Meeting.

Information concerning the Group Discussion Meeting and Poster Session

The **Group Discussion Meeting** shall address questions of general interest related to the topic of the preferential subjects, and thus will focus on the questions raised by the Special Reporters. It is not intended that individual papers will be presented and discussed in the Group Discussion Meeting. Delegates who wish to make contributions in the Group Discussion Meeting are required to send their contribution to the Special Reporters (franck@eeh.ee.ethz.ch, Lars.Lundgaard@sintef.no, and simon.j.sutton@gmail.com) with a copy to the Chairman (pietsch@highvolt.de) and the Secretary (johannes.seiler@siemens.com) of SC D1, not later than July, 29th. For Session details see http://cigre.org/Events/Session/Session-2018 (right column DOCUMENTS).

Contributors are required to meet with the Group Chairman and Special Reporters the day before the Discussion Meeting, i.e. on Tuesday, 28 August, 2018, 9h00 - 12h30, Room 237, for the organisation and finalisation of their contribution. Main Intention is to coordinate the format / layout, order of the presentations and time schedule of all accepted presentations.

Selected and approved CIGRE papers will be presented by the authors in the D1 **Poster Session,** which will take place on Tuesday, 28 August 2018, 14h30 - 18h00, Hall Ternes. Authors or their representatives are requested to participate in the Poster Session. Chairman of the Poster Session is Joe Tusek, Joe.Tusek@ampcontrolgroup.com. Please contact him to coordinate your poster presentation.

Preferential Subject No.1, HVDC Insulation Systems

Overview of submitted papers and discussion questions

The papers are slightly reorganized to fit better into the preferential subjects.

Paper D1-101 presents experiences in dielectric testing of a HVDC GIS. Gas-insulated HVDC systems are still under development and first pilot systems are installed in the grid. This paper describes the experiences of qualification tests on a 320 kV HVDC GIS. These tests cover dielectric tests, insulation system tests and long-term performance tests. Included were also the DC cable terminations. Another focus is the discussion of dimension rules & guidelines for such a technology.

Charge phenomena in or on epoxy systems for HVDC GIS spacers are addressed in three papers (Paper D1-102, Paper 103 and Paper 104). Two of the papers compare experimental and simulated results from HVDC GIS spacers, whereas the other examines the space charge characteristics in model filled-epoxy sample geometries. Across the papers a wide range of parameters have been varied; gas, humidity, surface coating, filler material, temperature etc. and the response of the materials recorded over periods to up eight days. Paper D1-103 also addresses the development of a new particle trap.

The papers comparing simulation results with experimental data (Paper D1-102 and Paper D1.103) have examined the spacers at different resolutions but in both cases, non-axially symmetric charge distributions were observed which the simulation not predicted. Additionally, neither model accurately reproduced the measured surface voltage or charge density under all circumstances; if the model matched the experiments for one set of conditions; it failed to match under different conditions. Both papers performed experiments to derive the parameters needed for the model.

Question 1

How can HVDC GIS spacer models be improved to reflect better experimental results and ultimately be relied upon to avoid costly full-scale testing?

Paper D1-106 describes a test using composite DC and LI voltages to investigate if negative synergetic effects could occur that question testing with singular stresses. Tests were done in an oil-paper insulation under uniform field. These questions are of a generic nature and of large interest for the end user, not only for HVDC. Examples of synergetic effects can for example be space charge effects or inception of discharges with an extinction voltage above expected service stress. These questions are relevant for all types of high voltage apparatus.

Question 2

- Are todays FAT test regimes (factory acceptance test) using singular stresses like AC, SI and LI sufficient to cope for synergetic effects that could emerge during energized condition on any type of electrical apparatus?
- Can service conditions as e.g. ageing with increased water content and/or raised particle content or temperatures, introduce conditions where synergetic effects may be triggered?

Preferential Subject No.2, Materials and Ageing

Overview of submitted papers and discussion questions

For Preferential Subject 2.3, Materials with lower environmental footprint, three papers have been submitted with respect to alternative gaseous insulation systems. Two papers in this area have been withdrawn before submission of the final manuscript.
Paper D1-105 discusses in a first part toxicity and EHS related questions with respect to alternative gas mixtures. Results from toxicity studies in animal tests on new and aged gas samples are reported and potential consequences for applications are discussed. In a second part, electrical tests (LI withstand, PD inception), short-circuit making and internal arc fault tests, as well as compatibility tests are presented for HFO1234zeE. Overall, the authors conclude that HFO1234zeE in combination with vacuum interrupters would be the preferred solution for medium voltage switchgear.

Paper D1-201 discusses questions arising from the application of a Fluoronitrile/CO_2/O_2 mixture in High-Voltage equipment: vapor pressure curve, low temperature cycling including condensation, arc extinction in circuit breakers and related decomposition products, toxicity and EHS, humidity and by-product adsorption. Overall, the authors conclude that a Fluoronitrile/CO_2/O_2 mixture is a viable solution for high voltage equipment.

Paper D1-202 discusses questions arising from an application of Fluoroketone mixtures with CO_2/N_2 and O_2 in gas-insulated switchgear. In a first part, the authors present results from studies on gas decomposition under partial discharge activity and after arcing. In a second part, monitoring results from the first year of operation of a 170 kV GIS in Switzerland with this gas mixture presented. Overall, the authors conclude that based on the laboratory investigations and the monitoring analysis, equipment filled with a Fluoroketone/CO_2/O_2 gas mixture can be safely operated over the entire expected lifetime.

In the moment, users and manufacturers are intensely discussing the development and use of SF_6 free solutions. To date, SF_6 free switchgear is available at medium voltages based on gaseous, fluid, and solid insulation concepts (mostly in combination with vacuum circuit breakers) and in high voltage based on alternative gas (mixtures). First user experience is gathered in prototype installations, but research and development is continuing. Whereas the last years have been devoted to the identification of suitable alternative gases, the current discussion evolves around questions arising from the application, mainly EHS issues. From the information presented, it is not possible to form an unbiased opinion as either not all information are given or because too different experiments are given by different authors that hinder a direct comparison. Most striking example is the fact that in two of the manuscripts presented here, toxicological studies in the same institute (with the same authors, yet in collaboration with different co-authors) report on lethal concentrations of pure Fluoronitrile that differ by a factor of 62 (>100’000 ppm and ≈1600 ppm). Cigre SC D1 has started working group D1.67 with the task to make at least the electrical characteristics of the novel mixtures comparable and thus meaningful. For no other parameter of interest this has been proposed, and the community is requested to start the discussion about this (interruption performance and arcing related ideas should be discussed in A3 community, questions of operation and handling in B3).

Question 3

Which test methods make results for different gas mixtures intercomparable and thus meaningful?

- Practical insulation performance in real equipment (devices, electrode configurations, surface characteristics, voltage stress, external parameters, …)
- Aging of alternative gas mixtures under partial discharge with relevance for electrical strength but also EHS (devices, electrode configurations (single/multiple emitter), stress indicator (Partial discharge level in pC, cumulative charge), duration, …)

Up to now, users have requested “one (and only one) solution with similar performance than SF_6” with respect to size, ambient conditions, toxicity levels, cost, … but with low (to no) global warming impact. It becomes evident that this can only be fulfilled for a very limited number of applications. Manufacturers have so far apparently chosen different optimization criteria and it is time to start the discussion in the community about the overall optimization and possible compromises.

Question 4

- In which direction should a design optimization strategy be directed and what are parameters (operating temperature, size) for which users do not require the current level of SF_6 equipment for most of their equipment?
- What do experts suggest to do as confidence-building measures so that the community increasingly reduces the use of SF6 equipment?
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The addition of nano-particles to materials to modify properties is the subject of two papers:

Paper D1-204 and Paper D1-205 cover solid and liquid systems respectively. The breakdown properties under AC and DC conditions, as well as, dielectric spectroscopy measurements on epoxy filled with either hexagonal boron nitride (80-90 nm) or carbon nanospheres (80-180 nm) is reported in Paper D1-204. The results build on work reported in CIGRE Technical Brochure 661 and are further being addressed by WG D1.73. The results show an 8% and 5% improvement in the real permittivity (at 50 Hz) for the boron nitride and carbon-filled systems respectively compared to the pure epoxy. Likewise, significant improvements are seen in the resistivity of the materials compared the pure resin. Some of the breakdown data show considerable scatter, which although often be ascribed to poor dispersion of the filler, the authors have used a novel rheometry method to monitor and determine the optimum processing conditions. No significant change in the AC or DC breakdown results were observed within the statistical errors associated with the data.

Question 5

Modification of bulk properties using nano-fillers holds great promise.
What further steps in processing or characterization are needed to advance these materials from the laboratory into service?

Papers D1-208 and Paper D1-306 both addresses development of criteria for high temperature insulation systems for transformers, like those we have for machines. Oil-paper insulation is used as the base-case. High-temperature insulation systems for transformers could allow for more compact designs and would also reduce needs for cooling under e.g. hot tropical climate. The new ester liquids and thermally upgraded paper could in principle allow for this, provided good test methods are developed. It is suggested to use a test cell developed for testing cellulose in mineral oil, and basically introduce an evaluation method based on Arrhenius relations. For cellulose ageing rates changes with time towards the final stage where ageing stops when the cellulose has reached the more stable microcrystalline condition at the so-called level-off DP-stage. Standards for qualification of high-temperature insulation systems would allow for shifts in transformer designs and use. One would need a thorough verification of these to be sure that any risks are avoided.

Question 6

- Is there experience with ageing models for cellulose introducing time dependent ageing rates? How is this time dependence considered in the proposed scheme for establishing a thermal index concept?

Use of Arrhenius relations is based on only one single ageing mechanism. In cellulose acid-catalyzed hydrolysis is dominating.

- Are there other mechanisms like e.g. water absorption and equilibrium that could influence the ageing rates in a composite solid-liquid system?

Paper D1-107, Paper D1-205 and Paper D1-324 addresses quality of transformer liquids, either traditional liquids or liquids with added nanoparticles. Paper D1-206 discusses quality of glues for lamination of cellulose for clamping systems in transformers. Partial discharges measurement is one diagnostic method used in two of the papers. Qualification of insulation materials is important both for manufacturers of apparatus and for the end users. Quality of materials will often determine the defect tolerance and life expectancy of the apparatus within which they are used.

Question 7

- What are the functional requirements for a dielectric material for transformers?
- Do the present standards address these requirements, and do the standards give a basis for differentiating qualities between the various materials?
- Will PD measurement reveal defects like PD producing particles and voids in glue in laminations?

Paper D1-207 describes an investigation of PD inception, AC an LI withstand voltages in a semi-uniform field with covered electrodes, and compares results with much referred curves from Moser (Weidman). The test set-up was designed with wedges in high field locations, where discharges may occur due to field enhancement originating from permittivity mismatch. The Moser curves originate from PD inception experiments under AC, but are also used as a basis for design for other voltage shapes via so-called conversion factor (design insulation level) resulting in the well-known voltage versus time curves that is the basis for insulation coordination and test levels for AC, LI and SI. While liquid breakdown tests for positive LI in rod-plane gaps differentiates between various liquids, there are fewer studies in gaps with more uniform field and with covered electrodes.

Question 8

- What are the experiences with dielectric performance of different transformer insulation liquids in geometries with fields with high utilization factors?
- Are there experiences with insulation systems with covered electrodes?
- Are the design insulation level factors universally accepted?
- Should voltage time curves and test voltage relations developed for mineral oil systems be used also for alternative insulation systems?
- Do manufacturers adjust designs depending on the insulating liquid used?

Preferential Subject No.3, Testing, Monitoring and Diagnostics

Overview of submitted papers and discussion questions

PD measurements and PD diagnosis in and on GIS are still an important tool to check the dielectric performance of the GIS. They can be helpful to detect defects before the may lead to a failure. This well-known measurement technique is discussed in detail under various viewpoints in four papers. Presented are also different measurement methods, but the focus lies on the Ultra High Frequency (UHF) method.

Paper D1-302 exemplifies an interesting idea: The measurement of the PD activity during the application of oscillating lightning or switching impulses (OLI and OSI) by means of the UHF method. Testing of important GIS stations within the grid with OLI or OSI impulses during commissioning or after maintenance is common practice since two decades. New is the combination with the sensitive UHF PD measurement method. As PD activity in a GIS depends strongly on the applied voltage wave shape, OLI and OSI impulses are able to detect especially protrusions on high voltage conductors and on insulators. Shown are examples of successful applications of this method (OLI / OSI with UHF PD measurement) in finding critical defects in GIS. This method is common practice for some years in China, and is described in this paper.

Paper D1-303 describes a development of a wireless PD measurement system, which enables a direct contact with 22.9 kV life-line Gas Switchgears. Its principle and the successful application within the grid are presented.

Paper D1-304 summarises the return of experience in the application of on-site PD tests with the UHF-method. Discussed is the applicability of the CIGRE UHF PD sensitivity check and the right positioning and amount of UHF sensors within a large GIS. As a conclusion, the paper recommends a careful application of the UHF sensors to achieve higher sensitivity to detect critical defects with low PD amplitudes, like protrusion on HV parts and particles on insulators. Main reason is the complex signal propagation within the GIS, especially when the enclosure diameter changes often along the signal propagation path.

Paper D1-305 describes also the return on experiences on the uses of GIS PD monitoring systems, based on the UHF method. Concentrations lies more on a detailed description and critical view of the right application of the UGF technique itself. Discussed are inner hardware technology, the right choose of frequency bands and noise rejection methods. Presented and analysed in detail is the so-called "band scanning technique" to improve the application and sensitivity of the UHF method for GIS PD monitoring applications.

Question9

There seem to be still some open questions in the right application of the on-line UHF PD monitoring method. Is this a general observation?

The transformer populations in many countries has grown old. Often half of the units installed has reached 30 years age or more. However, recent studies (TB 642) show that the failure rates still are manageable (< 1%). To allow for postponing of reinvestments monitoring strategies are exploited to reduce risks. Much data is generated, and statistical and analytical methods are used to extract important features from these databases. Periodic inspection and measurement are well established. Paper D1-307 and Paper D1-308 show results from chemical analysis for DGA and furanic compounds.

Paper D1-310 addresses possibilities for improving FRA analysis for verifying mechanical integrity of windings, and Paper D1-312 discusses tap changer diagnostics using resistance measurement.

Paper D1-311 discusses experiences from scrapping investigations comparing paper ageing in windings and leads. The study is accentuated by the report of CIGRE WG A2.45 on scrapping and failure investigations. Continuous monitoring is used to get early warnings for example from DGA (Paper D1-209), from load dependence on water-in-oil (Paper D1-309), from transient through fault current events (Paper D1-313). Data is used to continuously adjust risk and health indexes (Paper D1-209 and Paper D1-313).

Question 10

Diagnostic and monitoring should give an early warning of failure conditions, and offer better maintenance planning and better management of risks and reinvestments.

- What are the most frequently revealed failure conditions and failure modes?

- Do utilities regularly perform scrapping investigations to get a return of experience from service, and what can be learnt from that?
- What are the experiences with introducing continuous monitoring for fleet management?
- Are decisions made from physical interpretation schemes or are statistical methods based on big data concepts trusted?

Three papers address properties of silicone rubber under different circumstances. Two papers address hydrophobicity, one on insulators recovered from service (Paper D1-316) and one on the influence of material formulation on properties (Paper D1-210); finally, Paper D1-315 considers a method to study the silicone rubber/FRP rod interfacial resistivity.

Paper D1-210 considers the influence of filler concentration and surface treatment on both hydrophobicity retention and transfer is considered; such tests are not covered by current international standards. The data show considerable improvements in properties can be achieved with sufficient optimization. The work has been extended further to consider adding silicone oils of different viscosities and in different concentrations to the formulation in an attempt to increase the time to failure; however, the results were largely invariant.

In Paper D1-316, the hydrophobicity transfer was also measured but on service aged insulators recovered from highly polluted environments. Insulators from three locations each supplied by a different manufacturer were examined. Analysis showed two of the materials to have very similar loading levels of ATH filler, whereas the third had approximately 33% less. The sample with the lowest loading showed the fastest hydrophobicity recovery.

Question 11

- What methods are available to speed up material optimization either computationally or through alternative testing regimes/methods?
- What tests or assessment methods can be used to determine the remaining life of filled silicone rubber insulators whilst in service? How can these methods be validated or improved upon?

Paper D1-314 reports the deployment of an Asset Health Centre (AHC) for utility wide transmission asset monitoring. Standard combinations of online monitoring devices have been defined transformers which are installed on all new units (>230 kV) and have been retrofitted to older units. Trials have also been conducted on circuit breakers, substation batteries, XLPE cables and lower voltage transformers. Use is also being made of permanently installed thermal imaging cameras and PMUs. Besides the technical challenges of collecting and developing algorithms to analyze all this data, the authors highlight the cultural aspects of changing the mindset and working practices of the company. The AHC is credited with preventing three major transformer failures in just three years.

Question 12

- What other examples of utility-wide monitoring exist and how has the expense been justified?
- Are there other success stories of automated algorithms identifying developing failures?

Paper D1-315 presents and discusses a novel method to study the interface resistivity between silicone rubber housing and FRP rod material of composite insulators. As liquid permeation is one of the most common and harmful stresses for such interfaces, the authors present a four-electrode system to study the resistivity of interface samples. This resistivity measurement is suggested as a sensitive parameter to check the performance of the FRP rod-housing interface.

An alternative method for determining the pollution levels on overhead line insulator strings based on synchro-phasor measurements is discussed in Paper D1-317. The method has been used to determine the leakage current across the insulators in a 116 km 400 kV line with 306 towers. Although this method is online and avoids taking surface swabs from the insulators when the line is de-energized, it provides an average leakage current for the entire line and neglects spatial variations in contamination levels along the route. A pollution survey as part of a countrywide initiative has shown the entire route to fall under Class I conditions.

Paper D1-318 presents and discusses the first test results of tests performed at a new pilot test station for natural pollution tests, located close to the Arabian Gulf. Tested was the performance of eleven types of uncoated and coated glass & porcelain insulators, with particular focus on their material and geometrical design and shape. The harsh environmental conditions cover temperatures up to 50°C or more, high humidity (up to 100%) and large temperature variations between day and night. As the most appropriate method for site pollution severity estimation the ESDD and NSDD methods were applied and evaluated.

Question 13
When considering measurements over long distances, how many, if any, continuous local measurements are needed to supplement methods, which give spatially averaged results?

Paper D1-322 reviews the challenges of monitoring the thermal environment around and strain in long subsea cables. Insurance claims on UK offshore windfarms of about £210M over a 13 year period: 68% of these claims were associated with cable faults often caused by damage during installation. Better monitoring through distributed strain sensing (DSS) offers the opportunity to lower the risk of failure. Additionally, distributed temperature sensing (DTS) allows the cable capacity to be optimized by use of real-time thermal rating (RTTR) systems. The paper reviews the different optical principles behind these measurement techniques and corresponding pros & cons. The authors also provide some real-world examples where the operational range has been pushed to the current technological limit (~80 km) and propose a method to further extend the range.

Question 14

- How can suppliers be encouraged to invest in developing sensing systems with ranges of many hundreds of kilometers suitable for HVDC interconnectors when the potential market is of limited size?
- Are DTS or DSS systems being deployed in other areas of the power industry and what advantages are being gained?

Partial discharge (PD) measurements are routinely used during factory acceptance testing, but when applied in the field, determining an absolute discharge magnitude (in pC) is very challenging, as is determining the sensitivity of the measurement.

Paper D1-323 proposes a method to address this latter issue with PD generator cells; three cells have been designed for corona, surface and cavity discharges. These have been characterized for PD magnitude and repetition rate as a function of applied voltage. The sensitivity of a commercially available online PD detection system has been determined by injecting simulated white noise and signals from the test cells into the detector.

Question 15

What experience is there of calibrating or performing partial discharge sensitivity tests in the field?

Impulse testing with lightning impulses (LI), switching impulses (SI) and steep front impulses are applied during development, type and routine tests (e.g. transformers) to check design, insulation coordination and manufacturing processes. Three papers tackle this topic, including the measurement and analysis of lightning impulses. One paper discusses the parameters of the LI and SI testing and evaluation of impulse testing, especially on HV and EHV voltage equipment, such as transformers and GIS above 800 kV rated voltage.

Paper D1-319 discusses impulse testing of UHV equipment. The paper focuses on the k-factor function of LI voltage test, the standard lightning impulse waveform, and the standard switching impulse form. Due to test results, performed on large air gaps, large oil gaps and large SF_6 gaps, the paper proposes a new k-factor. The existing k-factor, described by $k(f)=1/(1+2.2xf^2)$, is proposed to be replaced by $k(f)=1/(1+7.5\ xf^2)$. This is practical a shift to lower frequencies. For SI impulses, the authors suggest no need of changes.

Two papers concentrate on the correct measurement technique, accuracy and calibration of such impulse tests.

Paper D1-320 presents test results with steep-front impulses. The paper discusses the circuit arrangement for the generation of the step-front impulses and the developed measurement system. Presented are the results of testing a 500 mm section of a 330 kV polymer insulator and 11 kV stator coils. Peak voltage was 850 kV with a rise time of 350 ns. The stator coils were testes with 32 kV and a rise time of 260 ns. The measurement uncertainties for the peak voltage and front time were 3 % and 5% respectively.

Paper D1-321 describes the principle, construction and performance of a reference impulse calibrator, which can be used to calibrate digital transient recorders as part of the whole measuring chain. This method is allowed as an alternative method for the comparative method according to IEC 60060-2. The presented device can generator full LI and SI impulses up to 600 V. The estimated uncertainty for the impulse peak is less than 0.05% and 0.02% for LI and SI respectively and for the time to half value less than 0.3% for both.

Question 16

Does measurement practice justify the need for a change / adjustment of the k-factor function for LI pulse voltage tests? Ultimately, it represents an average function across all insulating materials (oil, air and SF_6 gas).