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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:

<u>Preferential Subject No 1</u>: Compact Insulation Systems (AC and DC)

- High field strength phenomena
- Field grading
- Ageing and long term performance

Preferential Subject No 2: New Materials

- Nanocomposites
- Eco-friendly materials

<u>Preferential Subject No 3</u>: Non-standardized Stresses and Emerging Test Techniques

- Offshore and subsea application (high pressure, corrosion, etc.)
- Advanced diagnostic techniques
- Impact of non-standardized stresses on materials

In total, 32 papers have been accepted of which 13 papers cover Preferential Subject No 1, 8 papers cover Preferential Subject No 2, and 11 papers cover Preferential Subject No. 3. In the following parts of this report each of the preferential subjects is discussed separately.

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 (stanislaw.gubanski@chalmers.se and uwe.schichler@tugraz.at) with a copy to the Chairman (josef.kindersberger@tum.de) and the Secretary (johannes.seiler@tum.de) of SC D1, not later than July, 29th. For Session details see http://www.cigre.org/Events/Session/Session-2016 (right column DOCUMENTS).

Contributors are required to meet with the Group Chairman and Special Reporters the day before the Discussion Meeting, i.e. on Monday, 22 August, 2016, 9h00 - 12h30, Room 362, for the organisation and finalisation of their contribution.

Selected and approved papers will be presented by the authors in the D1 **Poster Session** which will take place on Monday, 22 August, 2016, 14h30 - 18h00, Hall Maillot. Authors or their representatives are requested to participate in the Poster Session.

3. Preferential Subject No 1 – Compact Insulation Systems (AC and DC)

Overview of submitted papers and discussion questions

The submitted papers cover a range of aspects related to applications and testing of various insulation systems, with main focus on HVDC technology.

<u>*Papers D1-101* to *D1-103* and <u>*D1-108*</u> deal with the dielectric performance of compact gasinsulated systems (GIS) at AC and DC voltage.</u>

<u>Paper D1-101</u> presents an experimental validation scheme for a model to simulate DC electrical field distribution in HVDC gas-insulated systems. It is based on the measurement of electrical currents in the solid and gaseous insulation, measurement of surface potential distribution of epoxy insulators, and determination of flashover voltage of insulators at HVDC stress. The time scale of the capacitive-resistive surface potential transition predicted by the model is in good agreement with the measured temporal evolution of the surface potential.

<u>*Paper D1-102*</u> discusses the dielectric characterization of solid material and SF₆ in regard to DC GIS. The dependency of solid material conductivities on temperature and electric field stress is identified. Gas conduction phenomena have been measured. Different approaches for the DC field modelling of an insulation system are introduced and applied in case of polarity reversal and superimposed impulse testing. A test program including a long-term test based on CIGRE TB 496 with slight modifications was applied to a 320 kV DC GIS.

<u>Paper D1-103</u> reports on various characteristics of GIS insulation systems and the withstand voltage performance evaluation method for insulating spacers as important factors in insulation design and testing on residual DC voltage. The resistive characteristic of insulators and the behaviour of metallic particles under DC voltage are presented. A test method is

introduced for evaluation of the insulating spacer DC withstand voltage performance of a three phase encapsulated 550 kV GIS.

<u>*Paper D1-108*</u> discusses the effects of conductor surface treatment and dielectric coating of conductors on the dielectric performance of GIS. Thin single-layer coatings (e.g. epoxy) and multi-layer coatings consisting of Al_2O_3 and PTFE are investigated to reduce the high electric field from micro scale roughness of electrode surface and the maximum electric field at the solid-gas interface. An increase of about 10% was detected for the LI breakdown voltage (negative polarity) by decreasing the surface roughness from 10 µm to 1 µm. Further test results show an improved LI breakdown characteristic (> 30%) for coated conductors.

Question 1 – Compact gas-insulated HVDC systems are under development and DC electric field simulations including capacitive-resistive field transition are mandatory.

- What are the dominant phenomena and factors of influence for electric field distribution in DC systems under operating conditions? How can the simulated field distribution be verified and how close are the simulated field distributions to the real ones? Which test procedures are considered suitable to verify the long-term performance of compact gasinsulated HVDC systems?
- Which advanced technologies are available to optimize the dielectric performance of gasinsulated HVDC systems?

<u>*Papers D1-104* to *D1-106*</u> consider materials for insulation of HVDC cables. Material properties and ageing stability are in focus.

<u>Paper D1-104</u> discusses applicability of small scale specimens (compression moulded plaques and model cables) for assessing conductivity of insulation materials for HVDC cable applications. The contribution emphasizes the role of careful preparation of the test objects as well as of the measurement procedure for obtaining meaningful results in the process of cable development and quality control. It is also demonstrated that test objects with moulded semiconducting electrodes often exhibit higher, but within the same order of magnitude, conductivity level as compared to ones measured in contact electrode arrangements. The authors indicate a need for developing a standard test procedure for measurements of field dependent conductivity in materials for HVDC cable insulation, also including description of specimen preparation procedure.

<u>Paper D1-105</u> presents results of investigations on long-term stability of a new unfilled XLPE material, approved for use in 525 kV HVDC cables. It is characterized by a lower degree of crosslinking as compared to presently used standard counterpart. Thermo-oxidative tests of samples prepared from both the materials were performed on dumbbells (cut from compression moulded plaques) and on cable cores at 135 °C for up to 1 year. The investigations revealed that despite of the lower crosslinking degree, the new material exhibits a satisfactory stability of its mechanical characteristics. Also a similar change of DC conductivity of both the materials was observed during the ageing, i.e. it significantly decreased at the initial ageing stage and then stabilized.

<u>Paper D1-106</u> also reports on the impact of a combined thermo-electrical ageing of XLPE material (standard grade qualified for up to 320 kV HVDC cable) on its dielectric characteristics, such as dissipation factor, bulk conductivity and space charge accumulation. According to the authors, regardless of the aging conditions the performed investigations did not show any significant evolution of dissipation factor and electric conductivity of the investigated material. At the same time, the distribution of space charge within the tested samples exhibited changed, modifying this way the internal distribution of electrical field in the tested

objects. This field modification, represented as a field enhancement factor, is suggested to be considered as an aging marker.

Question 2 – Papers *D1-105* and *D-106*, present different conclusions regarding variation of electrical conductivity of HVDC cable insulating materials during thermo-oxidative ageing tests. One factor responsible for this effect could perhaps be linked to the form of used test objects. Another one could be related to the duration of the measurement itself (the charging currents hardly stabilize even during very long measurements – see *Paper D1-104*).

- Is it desired to initiate joint efforts for developing a standard test procedure for measurements of conductivity in materials for HVDC cable insulation, as proposed in *Paper D1-104*?
- What is the relevance of thermo-oxidative aging for evaluating material performance in HVDC cable insulation, as the operating conditions of such cables involve environment free of access to oxygen and humidity as well as limits diffusion of crosslinking byproducts?

<u>Paper D1-107</u> presents investigations on evaluation of zinc oxide (ZnO) microvaristor based stress grading varnish and tape for stator windings of large electrical machines. In the investigations comparisons were made to the behaviour and properties of traditional tape and varnish based on silicon carbide (SiC). It is shown that dissipation factor of ZnO materials is lower and the partial discharge inception voltage as well as the breakdown voltage after 1000 hours of electrical aging are higher in experimental bars containing the new type of stress control system than in bars with SiC field grading. Also the test aiming at assessing the applicability of the new materials for applications at high altitudes (reduced atmospheric pressure) provided positive results.

Question 3 – Materials based on ZnO microvaristors have been over recent years used in design of field control elements in various types of high and medium voltage components (cable terminations and joints, bushings, spacers, etc.).

- What is the experience of users of various equipment containing ZnO microvaristor based stress control elements as regards their performance under long-term exposure in service environments? Are there any negative experiences as compared to SiC based elements?
- What are the general requirements for field grading materials, in particular for high operating field stress?

Group of <u>*Papers D1-109* to *D1-113* and <u>*Paper D1-311*</u> discuss aspects related to outdoor insulation and mainly concentrate on testing, selection and performance of composite insulators.</u>

<u>*Papers D1-109*</u> and <u>*D1-110*</u> compare tracking and erosion performance of silicone materials and composite insulators for line and station AC & DC applications.

In <u>Paper D1-109</u> results of DC inclined-plane "material test" are compared to results of DC "insulator tests", the latter involving tracking wheel test, 1000 h salt for test and 5000 h multistress test. The general feature of all the tests is that the intensity of discharges developing on surfaces of material specimens and insulators is stronger than during equivalent AC tests. There is also a strong influence of test voltage polarity, opposite for the two types of tests. The authors propose considering these effects while evaluating various insulator designs and indicated that based on the experiences of the reported work, some new test procedure have been introduced to relevant Chinese standard.

<u>Paper D1-110</u> discusses on the other hand the consequences of performing laboratory 5000 h multiple stress test with direct spraying (IEC/TR 62730) on station insulators of larger

diameters and compares the outcome to the good service record of the same insulators under natural conditions. Reference is made to a specially designed 5000 h test of insulators with different trunk diameters (22 mm and 136 mm), in which the latter performed much worth due to uneven salt fog distribution, e.g. exhibiting heavy erosion. As similar results were obtained in other laboratories too, the authors propose to reconsider the application of the test procedure with direct spraying, especially for insulators of large diameters. Paper D1-110 brings also up a discussion on tracking and erosion testing of composite insulators for DC application, which so far lacks a standard. It is suggested that modified 1000 h or 5000 h multiple stresses tests, without direct spraying and reduced test voltage to 70% of respective r.m.s. AC voltage might be feasible alternatives.

Question 4 – CIGRE WG D1.27 has adopted the Chinese DL/T 810 specification and used them in a Round Robin Test for DC Inclined Plane and DC 1000 h tests, results of which are documented in CIGRE TB 611. The DC 1000 h test appeared quite useful and in line with good service experience. A possibility of material ranking in DC Inclined Plane Test was also indicated, however the latter had shown large scatter of the results and lack of reproducibility in different laboratories.

• What measures and more detailed procedures can be developed in order to reduce the scatter in test results of both the tests in order to fulfil requirements for standardization (repeatability, reproducibility, representativity and cost effectiveness)?

<u>Paper D1-113</u> refers to a need of increasing the reliability of 400 kV transmission network in the Gulf region trough improvement of outdoor insulation performance in this extremely harsh environment combined of desert, marine and industrial pollution. To address this aim the contribution presents preliminary results of pollution severity and insulator tests in selected lines as well as in the newly established Al-Fadhili pilot pollution test station. The present focus is on the performance of RTV coated ceramic cap&pin (porcelain and glass) insulators of different shed designs and involves evaluation of changes of their surface hydrophobicity as well as efficiency of fitting galvanization.

Question 5 – The tradition of testing insulators in field stations has become less popular because of the required long test periods for obtaining meaningful results and thus also the involved costs.

• What type of additional information can still be expected from field station testing as compared to the well-established laboratory tracking and erosion test procedures?

<u>Paper D1-111</u> analyses the conditions at which bird streamers may cause flashovers on strings of glass cap&pin insulators in HVDC transmission lines. In South Africa the bird streamer initiated flashovers contribute to as much as 38% of HVAC line faults. However the probability of such events in HVDC lines still require verification. A special test program has therefore been established, involving laboratory simulations, both in South Africa and the US, on bird streamers occurring in the space between pylons, insulators and energized conductors. Results of the laboratory tests are reported in the paper and show that the minimum length for causing the bird streamer flashover is approximately 2.8 m. However, also the volume and the distance of the streamer from insulator string are important factors in determining the probability of a flashover.

Question 6 – The effect of bird streamers on flashover events in HVAC lines have been broadly reported in literature.

• Is there more information available from other parts of the world on bird streamer initiated flashovers in HVDC lines?

<u>Paper D1-112</u> presents a continuation of investigations conducted in Germany on the performance of composite insulators in hybrid AC/DC lines. The first report related to this work was extensively discussed during the 2014 CIGRE Session and evoke various opinions on at that time proposed application of DC design principle if the DC field component on insulator is larger than 10%. The additionally performed investigations on the effect of hybrid AC/DC electric field stresses involved flashover tests and wheel tests and revealed that the application of classical AC design criteria for the AC circuit insulators and DC design criteria for DC circuit insulators are enough. No significant and particularly no negative changes in both the flashover voltage levels as well as erosion severity were found, which makes unnecessary modifications of the existing test procedures. It is thus concluded that the earlier established criterion on the applicability of DC design principle if the DC component exceeds 10%, can be modified and a new threshold of 50% is proposed.

Question 7 – Findings of this extensive research program will provide valuable guidelines and recommendations for designers of future HVDC hybrid lines. The German Commission for Electrical, Electronic and Information Technologies (of DIN and VDE) has recently created a draft for dimensioning of AC/DC systems, including principles for selecting insulators for the hybrid tower configurations based on the findings presented in Paper D1-112. It will be published soon and seems to be the first standard of this type.

• Are there any other attempts known that regulate the dimensioning of hybrid AC/DC systems?

<u>Paper D1-311</u> reports on the development of test facility and procedure for evaluating fatigue strength of composite station post insulators. The variable load under service conditions is represented in the developed test by cycled cantilever swinging of an insulator. The contribution also describes a model accounting for deterioration of the fatigue insulator strength under such conditions. The presented results indicate that the applied cantilever testing procedure has a strong impact on the mechanical strength composite station post insulators, as the variable cantilever load may damage the insulator at lower bending force than the static strength and in some cases even lower than declared by manufacturers maximum design cantilever load (MDCL) or specified cantilever load (SCL) levels.

Question 8 – Fatigue testing of composite insulators provides important information of their long-term mechanical durability.

• Is there an agreement among insulator community that such test should be introduced in addition to the static tests into relevant standards and if so should a new working group be established (in cooperation with SCs B2 and B3) addressing this issue?

4. Preferential Subject No 2 – New Materials

Overview of submitted papers and discussion questions

The submitted papers cover a range of aspects related to applications of new material solutions in high voltage technology.

A group of papers (*Papers D1-201, D1-202* and *D1-208*) concentrate on the behaviour and experiences arising from the use of natural and synthetic ester liquids as an insulation medium.

<u>*Paper D1-201*</u> presents a comparison of electrical, thermal and ageing properties of a synthetic ester liquid, a mineral oil and a new type of hydrocarbon oil, the latter being a new development within the gas to liquid (GTL) conversion technology. Cons and pros as regards

the considered properties and applicability of the "new" liquids are discussed, indicating the possible different application areas for the ester and GTL hydrocarbon liquids.

<u>Paper D1-202</u> indicates that despite the very long and positive experiences of an Italian power company arising from the used of mineral oils, the newly imposed regulation on environmental protection force adoption of vegetable based esters into the insulation systems of large power transformers. For facilitating this requirement, a research program has been initiated and the obtained results indicate that natural esters may be applicable as alternative insulation and cooling media, though a number of design and operating conditions need to be reconsidered.

Also <u>Paper D1-208</u> provides results of comparative investigations on natural and synthetic ester insulating liquids by means of a new method for testing their oxidation stability, the property often considered as limiting for applications in open breathing transformers. The method relies on using a headspace vial with defined amount of air and the tested liquid with inserted piece of copper strip, subjected to elevated temperature for a defined period of time. It is combined with high pressure liquid chromatography based method for determining content of additives (inhibitors and passivators) in the tested liquids. Based on analyses performed by means of various methods, limits for important in-service parameters are proposed.

Question 9 – Discussions on applicability of new types of insulating liquids in high voltage technology have been ongoing within SCs A2 and D1 since long.

- Which types of activities are still needed within SC D1 regarding the development of recommendations and guidelines for successfully meeting the environmental and technical challenges related to the replacement of mineral oils in power transformers by ester liquids?
- What can be the advantage of using GTL hydrocarbon oil in terms of their environmental impact?

<u>Paper D1-203</u> presents results of molecular simulations for insulating paper modified by addition of Al_2O_3 nanoparticles. The simulations indicate that the binding energy between the cellulose base and the filler increases with the lattice dimension of the latter. Experiments are also reported and show the positive impact of adding nanoparticles to the insulating paper on its dielectric permittivity (lower level) and on variation of tensile strength during a thermal ageing.

<u>Paper D1-207</u> reports on a development of new and cost effective technology, based on electrostatic absorption, for improving thermal conductivity and filler dispersion in insulating composites based on polymethylmethacrylate (PMMA) and boron nitride (BN) particles. The latter were prepared in different forms: as platelets, a mixture of platelet agglomerate and platelets, spherical agglomerates and low-density agglomerates. Particle distributions in the composites were characterized by means of scanning electron microscope (SEM) observations and experiments involved determining their thermal conductivity and electric breakdown strength. It was found that orientation of BN particles determined both the parameters.

Question 10 – Numerous evidences are presented that indicate possibilities to improve properties of traditionally used insulating materials by using nano-fillers or by introducing new technologies for better control of filler dispersion and distribution in composites.

• Are there examples of practical applications of these developments and if so what is their impact on the design criteria of insulation systems?

<u>*Papers D1-204* to *D1-206* report on eco-friendly materials with respect to alternative insulating gases and recyclable thermoplastic insulation material.</u>

<u>*Paper D1-204*</u> reports on the basic characteristics of a fluoronitrile/CO₂ mixture, which can be – for temperatures higher than -30 °C – an alternative to SF₆ in high voltage technology. Test results confirm the performance of the applied eco-friendly gas mixture from environmental, health and safety, material compatibility and stability, and gas tightness point of view.

<u>*Paper D1-205*</u> shows a comparison of alternative gases to SF_6 and proposes a procedure to evaluate the main candidates for medium voltage switchgear application. It is mentioned that all the investigated potential fluorinated candidates can be used as dielectric medium. The toxicity and quantity of by-products after breaking are very high and therefore breaking in these gases should be avoided in order to ensure human safety.

<u>Paper D1-206</u> discusses the performance of thermoplastic insulation material for low voltage switchgear application. Laboratory tests and simulations on moulded case circuit breakers and current transformers confirmed the applicability of the thermoplastic insulation material (aliphatic-polyamides). The investigated material is expected to increase the recyclability of switchgear components.

Question 11 – Eco-friendly insulating materials like alternative gases and thermoplastic insulation materials are under investigation and pilot projects are already in service.

• What are the characteristics of eco-friendly insulating materials (e.g. alternative gases, solid materials) and what is the return of experience from pilot installations?

5. Preferential Subject No 3 – Non-standardised Stresses and Emerging Test Techniques

Overview of submitted papers and discussion questions

<u>Papers D1-301 to D1-305</u> focus on development of new procedures and tools for diagnosis and testing of the insulation system of power transformers.

<u>Paper D1-301</u> reports on attempts to automate the evaluation of the results of frequency response analyses (FRA) on power transformer winding. As there are many influences on the practically obtained FRA spectra, including the type of instruments used, the configuration of the test circuit as well as the test cable arrangements, the goal of the presented work is to reduce the involvement of individual operators on the interpretation of the results. The authors claim that the FRA spectra can be parametrised using a developed by them Frequency Localising Basic Functions (FLBF) algorithms for using it in an informative fault identification system and propose including it relevant standards.

<u>Paper D1-302</u> presents a device for on-line monitoring of moisture content in the solid part of insulation system of power transformers. In contrast to the presently used devices, it measures changes of electric capacitance of a sensing capacitor with a piece of pressboard as the dielectric layer between its electrodes. The contribution reports on results of laboratory tests of the developed device.

<u>Paper D1-303</u> demonstrates capability of the absorption spectrophotometry in ultravioletvisible (UV-VIS) range to evaluate the content of 2-furfuraldehyde (2-FAL) in mineral transformer oil. The adopted test methodology is described and the presented results of analyses are calibrated against results obtained by means of the commonly used highresolution liquid chromatography (HPLC) method.

<u>Paper D1-304</u> presents, through case studies, Brazilian experiences with application of the dissolved gas analysis (DGA) for predictive monitoring of on-load-tap-changers (OLTC). The

referred cases concern OLTC without direct contact of their oil with the oil in transformer tank and the presented results confirm that application of already established criteria (CIGRE TB 443) is sufficiently reliable to carry the assessment tasks.

Question 12 – Diagnostic techniques for evaluating condition of impregnated insulation system continuously improve.

• What are the main trends in this development – increase in precision of determined parameters, automation of measurements and interpretation schemes or generality of the obtained information (overview picture)?

<u>Paper D1-305</u> reports on extensive studies undertaken by laboratories in Brazil and the US that aim at evaluating procedure described in IEEE Std. C57.100 determining "Test Procedure for Thermal Evaluation of Insulation Systems for Liquid-immersed Distribution and Power Transformers". The intention of the standard is to permit the evaluation of a new insulation system based on reference to a known one. The contribution concentrates on characterizing the reference "industry proven system", including thermally upgraded kraft paper, cellulosic pressboard and mineral oil, not precisely defined in the standard and may thus be represented by products obtained from different manufacturers.

Question 13 – Existing standards for thermal evaluation of insulation systems focus on mechanical or electrical parameters which can significantly be influenced by the type of insulating liquid.

• Is it realistic to expect that known insulation materials may be assigned to another thermal class when used with natural esters?

<u>Papers D1-306 and D1-307</u> deal with partial discharge (PD) measurement and PD pattern recognition under DC voltage.

<u>*Paper D1-306*</u> reports on DC PD pattern recognition and PD location for gas-insulated equipment. Artificial defects can by identified by modified chaotic analysis of PD (CAPD). PD location based on directional sensors and considering the signal polarity seems to be an effective way. The discrete wavelet transform is used for de-noising of PD signals.

<u>*Paper D1-307*</u> shows the DC ripple influence on PD patterns, which are generated on the basis of differences in PD time occurrence (Δt) and amplitudes (ΔQ) between consecutive pulses. Laboratory test results show the influence of the ripple voltage to PD occurrence. A 3D PD clustering software based on the analysis of the pulse wave shape is applied for diagnostics.

Question 14 – PD measurement and diagnostics at DC voltage is important for the asset management of DC equipment.

• What are the procedures for PD testing of DC equipment and what is the physical background for acceptance criteria? Which techniques are available for noise suppression and PD diagnostics at DC voltage?

A group of papers <u>(*Papers D1-308* to *D1-310*)</u> deals with insulation characteristic under lightning impulse (LI) and the front time error of large ultra high voltage (UHV) impulse dividers. Based on experiments new k-factor functions are proposed.

<u>Paper D1-308</u> shows a review of dielectric strength with distorted lightning impulses. The evaluation of parameters from distorted LI with the standardized single k-factor procedure (IEC 60060-1: 2010 and IEEE Std. 4, 2013) is discussed in detail. Experimental work has shown different values of k-factor for air gaps and a generalized function of the k-factor is proposed.

<u>Paper D1-309</u> reports on the LI test and the long-duration AC PD test as the basis for the insulation design of a HV insulation system. The insulation characteristics for non-standard LI waveforms, superimposed voltages of LI and AC or DC voltages, and trapezoidal waveform are investigated for GIS and transformer insulation from a practical perspective. Based on experimental data a new k-factor function has been developed and proposed for UHV equipment.

<u>*Paper D1-310*</u> discusses the front time (T₁) error correction of large impulse ultra high voltage (UHV) dividers with the deconvolution method, which restores the recorded waveforms with the measured impulse response of the divider. Experimental results from a 2400 kV damped capacitor impulse voltage divider show the effectively use of the proposed deconvolution method.

Question 15 – The evaluation of distorted lightning impulses is still under discussion and a challenge for testing of UHV equipment.

• Is there a need of new k-factor functions for the evaluation of impulse waveform parameters? How can the LI testing of UHV equipment be improved?