# A2 - 00

## SPECIAL REPORT FOR SC A2

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**Special Reporters**

## 1. Scope of Study Committee A2: Power Transformers and Reactors

The technical field of activity of Study Committee A2 is:

- Power transformers, including industrial, dc converter, and phase-shifting transformers for distribution, transmission, and renewable energy applications,
- Reactors, including shunt, series, saturated, and smoothing,
- Transformer components including bushings, tap changers and accessories.

Within its technical field of activity, Study Committee A2 addresses topics throughout the asset management life-cycle phases; from conception; through research, design, production, deployment, operation, and end-of-life. At all stages, technical, safety, economic, environmental, and social aspects are addressed as well as interactions with, and integration into, the evolving power system and the environment. All aspects of performance, specification, testing, and the application of testing techniques are within scope, with a specific focus on the impact of changing interactions and demands due to evolution of the power system. Life cycle assessment techniques, risk management techniques, education and training are also important aspects.

Within this framework additional specific areas of attention include:

- Theory principles and concepts, functionality, technology development, design, performance and application of materials, efficiency,
- Manufacturing, quality assurance, application guidance, planning, routing and location, construction, installation, erection, installation,
- Reliability, availability, dependability, maintainability and maintenance, service, condition monitoring, diagnostics, restoration, repair, loading, upgrading, uprating,
- Refurbishment, re-use/re-deployment, deterioration, dismantling, disposal.

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## 2. Group discussion meeting 2021 Virtual Centennial Session

The Group Discussion Meeting during the Virtual Centennial Session will take place from **12h00 until 16h00 on August 24th´and 25th, 2021**. Further detailed instructions on the session will be communicated through the CIGRE website.

**Proposed contributions need to be uploaded on the session Registration Platform by the authors no later than July 31st, 2021. All intended contributors should first finalise their registrations before they can propose a contribution.**

Contributions will be reviewed by the Special Reporter and the Study Committee Chairman based on their relevance to the Preferential Subjects and the questions prepared by the Special Reporters below. Only accepted contributions will be presented at the session. it is not possible to guarantee acceptance of any contribution.

## 3. PS1: Transformer technologies to enable integration of distributed renewable energy resources

### 3.1 Papers for Preferential Subject No 1

A total of twelve papers have been submitted to this Preferential Subject, according to the following sub-topics:

PS1-1: Application, specification, design, and construction
(8 papers: A2-101, A2-102, A-103, A2-105, A2-106, A2-108, A2-109, A2-112).
PS1-2: Effect of harmonics, including inter-harmonics and supra-harmonics
(1 paper: A2-104).
PS1-3: Effect of extreme operating environments, especially offshore and subsea
(3 papers: A2-107, A-110, A2-111).

**A2- 101 (United States)** – Distributed Energy Resources (DERs): Impact of Reverse Power Flow on Transformer.

This works describes the rapid growth in generation using distributed renewable energy sources in the recent years, and the prospects for a growth of 2378 GW, with a major contribution from wind (539 GW) and PV (403 GW). Also described are some of the different business models adopted for the integration of distributed renewable energy sources into the network. This paper investigated 4 different power flow scenarios and their impact on the operation of the transformer., especially the effect to the core. It was found that operation with reverse active and reactive flow is the most difficult condition, and that this may be associated with up to 15% over-excitation of the core. The study concludes on the need for new designs and specifications to withstand the effects of reverse power flow as well the increased level of harmonics in the distribution grid.

**A2-102 (Sweden)** – Active power control with 400/130 kV transformers. Experience from two recent projects.

This case study gives a detailed historical account of the development of the transmission network in Sweden and the use of booster transformers to control the power flow. Formed on previous experience, it explains how booster transformers can be used to facilitate the integration of distributed renewable energy resources, and it also addresses important aspects in the challenges of coping with different new sources of energy. The paper highlights the importance of utilizing the right winding arrangement for the booster, as well as ensuring the flexibility to handle the evolutions of the network, both in the transmission system and with constantly changing energy infeed from production at lower voltage levels.

**A2-103 (Sweden)** – Dynamic thermal behaviour of wind power transformers.

This paper described how publicly available weather data has been used in combination with novel transformer thermal models to reduce windfarm transformer footprint and increase efficiency compared to current practice and standards, in consideration of an optimal thermal aging of the transformer insulation material. A reduction in size of up to 30% can be obtained as an additional benefit for offshore wind power, where compact transformer design drives cost.,

**A2-104 (Great Britain)** – Solar Farm Transformer Condition Monitoring and Automated Anomaly Detection Using Micro-Synchrophasors.

This case study presents the development of solar farms (PV) in Great Britain and addresses emerging reliability problems of an increasing number of transformers and other component failures. For this case study, a micro-synchrophasors based monitoring program for a selected number of solar farms has been installed for the gathering of online data to support a condition-based monitoring system. Advanced and intelligent data handling tools, like Automatic Fault Detection and Diagnostic (AFDD) and outlier analysis, made possible the processing of the large amount of data coming from 6 utility-scale solar farms installations with a view to detect anomalies which would
not be viable with industry standard SCADA data, thus reducing operating costs, avoiding outages, and extending operating life was made possible.

**A2-105 (Germany)** – Smart dynamic shunt compensation – inductive and capacitive reactive power based on common transformer technology.

This paper explains that the integration of renewable energy resources, which will in particular require extensive use of high voltage cables, will require additional reactive compensation, suggesting increased use of shunt reactors. The authors briefly describe existing technologies for magnetically controllable shunt reactors and, in more details, a new and simpler technology. Test results on a small prototype of a magnetically controlled shunt reactor ("full variable shunt reactor") and the conceptual design for a 130 MVAR, 400 kV shunt reactor are then presented. The advantages, requirements and possible new applications of the magnetically controllable shunt reactor concept over the variable shunt reactor concept are described.

**A2-106 (Japan) –** Effects of thyristor type step voltage regulator (TVR) application on various voltage changes caused by reverse power flow, distributed power supply and renewable energy.

This paper describes the effect of change in energy production to a larger amount of renewable energy sources, introducing fluctuation in power production, changing energy flow and imbalance in the distribution network. The paper analyses the use of more advanced voltage controller for the distribution network than the traditional mechanical tap-changer used to control the voltage on transformers. The authors introduce a fast-acting thyristor type step voltage regulator (TVR), which can adjust faster and will not experience the same wear and tear compared to mechanical tap changers when many daily operations are required. At the same time a more optimal voltage scheme can be obtained, for the benefit of the operator of the network.

**A2-107 (Spain)** – Enhanced cooling of dry-type transformers for wind applications.

This case study presents a newly developed concept for a liquid cooled dry-type transformer. The authors suggest that this technology might be beneficial for wind-turbine applications over existing dry-type transformers and liquid-immersed transformers. A prototype has been constructed for the purpose of verifying the concept when subjected to the simulated conditions of the severe environment of a nacelle or turbine tower. The liquid cooled dry-type transformer allow the losses to be transferred more efficiently from the core, reducing the size and weight similar to conventional oil cooling, offering at the same time enhanced fire protection, a performance similar to high flame point insulating liquid that has been the preferred solution for wind turbines in the recent years.

**A2-108 (China)** – Study on key technology and demonstration application of UHV AC controlled shunt reactor.

This paper describes the challenges of integrating renewable energy sources in remote areas via long-distance AC transmission lines, including the need for reactive compensation for line optimization and voltage imbalance. The possibilities around Controlled Shunt Reactors (CSR) for the compensation and the importance of dynamic reactive compensation suggest that a CSR connected directly to the line, through a high impedance transformer is the best method for overcoming these challenges. The CSR is controlled by a multistage switch controller circuit, giving steady state regulation and fast dynamic response from the magnetic control of the iron core. The paper addresses in addition the challenges in the design and construction of a prototype of the transformer, shunt reactor switchgear, auxiliary circuit, thyristor circuit as well the complete system in a combined test.

**A2-109 (Slovenia)** – System for on-line evaluation of power transformer dynamic thermal loading capability.

This paper describes a dynamic rating concept for real-time forecast of operational limits of transformers that has been implemented in one Slovenian TSO control scheme in order to improve the flexibility and the reliability in the network. A case study is performed on a 300 MVA transformer on the 400kV grid, for verification purpose. The dynamic rating system (DRS) uses ambient conditions such as temperature, wind speed (real-time and forecast) as input parameters to predict the load/overload capacity of the transformer based on an advanced thermal model. The calculated values from the thermal model have been verified with the case study and showed an acceptable margin with the measured values. The thermal model prediction will be useful in emergency loading situation as well as for making maximum use of short time overproduction of renewable power.

**A2-110 (Finland)** – Thermal design aspects of subsea transformers.

This case study highlights important aspects for submerged transformer and shunt reactors used in offshore applications such as windfarm and oil & gas platforms. The paper describes the consideration taken in the design of a 12 MVA prototype unit at 132 kV with a passive cooling circuit directly submerged in water. According IEC 60072-2 it would be treated as ONAN, however the real ambient conditions and properties should allow for higher oil temperatures due to the better of water compared to air. The prototype has been load tested for 4000 hours in real submerged conditions for the verification of the concept and it is claimed to have potential for applications up to 145 kV class and 200 MVA.

**A2-111 (Great Britain)** – Influence of harsh operation conditions present on offshore platforms to the design of power transformers and shunt reactors.

This work describes the considerations and efforts one needs to go through to determine the right transformer and shunt reactor design for an offshore substation due to the severe conditions, restricted accessibility and high reliability requirements. The paper also addresses other important aspects such as: installation, post energization, transportation, maintenance, and the use of more advanced finite element analysis to optimize the transformer and shunt reactor design. Details are given on the selection criteria for the right electrical, mechanical, thermal and insulation design to meet the requirements of offshore transmission systems and to help achieving both a lighter offshore platform and cost savings.

**A2-112 (South Africa)** – Eskom’s approach on the technical specification for the transformers to be used in the BESS environment.

This paper describes some of the challenges for the integration of battery energy storage solutions in the distribution grid at 11 and 22 kV, with an expected capacity in South Africa up to 1000 MW. Due to the inverter-based system, phenomena such as DC biased voltages and harmonics put additional stresses on the transformer and the loading, with frequent switching and unbalanced load, is quite different from the conventional distribution application. All these considerations make the normal distribution transformer unsuited and need to be brought into the speciation's and the design review. Therefore, an interdisciplinary team was put together within the utility for solving the task of creating an updated specification for transformers that could cope with the new environment of a battery system. For example, Buchholz relays, over pressure devices as know from power transformers have been prescribed, as well have ester-based of insulating liquid have been chosen for better transformer safety and environmental considerations.

**3.2 Discussion for Preferential Subject No 1**

New transformer technologies have always been relevant, and the transformer technology has developed over the years, with optimized new solutions like vacuum interrupters for tap changers. With the ingress of distributed and renewable power to the grid at all voltages, the transformation of the power grid has become even more visible and will require that the transformer industry comes up with strong, reliable solutions, but also flexible solutions to meet the challenges in the future.

The subject for this Preferential Subject, "Transformer technologies to enable integration of distributed renewable energy resources" is part of the answer. The challenges of integrating an ever-increasing amount to renewable energy and the predominance of inverts used in renewable production stresses the importance of advanced control scheme to keep the power system stable.

- New installation and concepts stress the importance that the industry embraces the changes and calls for a strong collaboration between the end user and the supplier, as addressed in A2-111, for an optimized transformer rating based on the cable limitation as well in A2-103, where the wind measurements are used to utilize the transformer better and allowing a smaller transformer. So, a need for more customized products is clear, as described in A2-112, with transformers for BESS applications. However, for cost and complexity constraints, there is also a need for more standardized solutions, this also comes with the globalization and trends from wind turbine industry with an interest to deliver more standardized products across the global market.
- Case studies to cope with the different environment in remote places are discussed in A2-110 for submerged transformers, and for long sea transportation in A2-111 where either advanced design tools or real test set-up can be used for the verification of the transformer, This is also described in A2-107, where a dry-type transformer for wind turbine applications has been proposed, with a prototype installation.
- Measurement and diagnostic tools have become more advanced and the computing power has increased over the years. The effective combination of reliable measurements and advanced signal processing can both increase the capacity in the grid at critical times as described in A2-104 and be used for fault prediction and assessment of the health of the system, analysing the system behaviour, in combination with artificial intelligence as described in A2-109.
- To cope with the challenges of a changing power system, measures to ensure a stable operation, which traditionally have been supplied by large rotating machines, have over time been replaced by advanced power electronics in inverters, SVC's and STATCOM's. However fast controllers for shunt reactors as described in A2-105, can also be utilized for this support, and a prototype is described in A2-108.
- The challenges of using thyristor-controlled transformer in the distribution network for controlling the reverse power flow are discussed in A2-101, as well the recent experience with this type of control scheme in A2-106.
- Changes in the direction of power flow not only require the development of new solutions, but also impact the installed transformer base at both the distribution and transmission level as

described in A2-101 and A2-102 along with the importance of ensuring that the power systems of the future are designed accordingly..

And last but not least, the recurrence on this preferential subject will remain pertinent because there will always be new technology solutions that will arise to answer a continuously evolving context. A single session is not sufficient, so future sessions to the topic of this preferential subject will be required in view of addressing the increasing size of the wind turbines and the transformers becoming sub-transmission, the increasing need for HVDC transformers for interconnection and the additional supporting services in the future, e.g., hydrogen production and energy storage facilities.

### 3.3 Question for Preferential Subject No 1

Question 1.1: Due to the problems associated with the integration of renewables, what changes are required in the transformers specifications to ensure that they will perform satisfactorily?

Question 1.2: What type of tests should be done to verify that the special requirements are met for transformers in renewable applications? When testing is not possible, to what extent can/should advance simulation tools be relied upon as a substitute?

Question 1.3: What are the best strategies to combine data collection with analytical tools in order to observe and optimize the operation of transformers in renewable energy applications? What is the most critical data to be collected to ensure that the necessary knowledge can be captured over time?

Question 1.4: Could the solutions presently considered to address the problem of integration of renewables carry other important issues in the future? Ex: Could the principle of DC saturation for compensation create more harmonics or noise issues?

Question 1.5: Could/Should there be a strategy so that the solution to renewable integration problems is coordinated effectively between the Transmission and Distribution transformers at the system level?

## 4. PS2: Advances in Dielectric Design and Testing

### 4.1 Papers for Preferential Subject No 2

A total of 8 papers has been submitted to this Preferential Subject, according to the following sub-topics:

PS2-1: Specification of dielectric design requirements, especially for new and unusual applications
(1 Paper: A2-208).
PS2-2: New and advanced dielectric design concepts and techniques
(3 Papers: A2-201, A2-203 and A2-204).
PS2-3: Challenges in dielectric testing and how to overcome them
(4 Papers: A2-201, A2-205, A2-206 and A2-207).

Note that the preferential subject and sub-topics relate to three current CIGRE Working Groups:

- A2/D1.51 Improvement to Partial Discharge Measurements for Factory and Site Acceptance Tests of Power Transformers
- A2/C4.52 High-frequency transformer and reactor models for network studies
- A2.63 Transformer impulse testing

**A2-201 (France)** – Simulations and tests based on dielectric studies to improve the power transformers technical specifications and their performances

This paper presents the improvements that were made within EDF to enhance the power transformers technical specifications to increase their reliability in service.

Two experiences related to dielectric design issues that have been addressed by tests in the manufacturer's laboratories and by EDF's simulations are presented.

- The first experience is related to the GSU transformers used by EDF in their Nuclear Power Plants. In the past these transformers were equipped with screens to reduce the capacitive coupling between the windings of different voltage and prevent that the fast-front overvoltages were transferred to the LV bus-bar duct or to the generator. The new GSU transformers are designed without earthed dielectric shield, so the manufacturer shall demonstrate by calculation and tests the compliance of maximum transferred voltage coefficient from HV to LV specified by EDF. Simulations and test are discussed and described.
- The second experience is related to the transformer dielectric behaviour in service conditions compared to the Factory Acceptance Tests (FAT) defined in the IEC 60076-3. The influence of the neutral grounding configuration on the voltage distribution in the winding and the consequences of the dielectric stresses in the winding solid insulation are analysed in the case of a transformer that had a dielectric failure in service, close to the HV neutral, as consequence of a lightning strike. The failure conditions are simulated and compared with the FAT and the conclusion is that the dielectric stresses in service conditions are not well covered by the FAT.

**A2-203 (Russian Federation)** – Resonant overvoltages inside power transformers windings and the measures improving their ability to withstand high-frequency stresses

This work discusses the issues of computational and experimental verification of the transformers' ability to withstand the dielectric stresses consequence of high-frequency transient overvoltages.
To ensure the ability of transformers to withstand the stresses it is necessary to evaluate the voltages affecting their inter-turn and inter-disc insulation. The application and the accuracy of combined usage of simulations results and available measurements are discussed.
In the first part of the paper the influence of transformer winding type and their constructive details on resonant overvoltages are analysed. Then is noted that these high-frequency oscillating voltages are not covered by the classical IEC dielectric tests (SI, LI and LIC) and new tests methods are proposed for the experimental validation of internal insulations capability to withstand high-frequency stresses.
Finally, different approaches to evaluating stresses on the insulation of transformer windings are analysed:

- Estimation of voltages on the longitudinal insulation of windings by fitting measured spatial voltage distributions
- Estimation of voltages on the longitudinal insulation using values measured in available points of a winding
- Estimation of voltages on the longitudinal insulation of windings with white-box models, improved by measurements in available points

The three cases are validated using the measurements on a 630 kVA, 10/0.4 kV, dry-type transformer.

**A2-204 (China)** – Electric Field Analysis for Valve-side Lead-out Insulation Structure of UHVDC Converter Transformer

The paper analyses, based on experiences gained in a lot of UHVDC projects, four typical insulation structures of valve side lead-out, which suffers severe stresses from both AC and DC voltages.
These insulation structures are the cause of most insulation failures, either in factory tests or in operation, of converter transformers.
The four structures analysed, all located in a multi-layer cylinder, are:

- Semi-cover
- Full-cover
- Double ring electrode
- Ω shape-cover

The finite element method is used by the authors to calculate AC and DC electric fields to find out critical points and to make safety assessment.
Principles and measures for improving field distribution are concluded:

- For AC insulation, the pressboard cylinders and moulded covers are necessary to divide radial oil gaps, especially the first oil gap.
- For DC insulation, the important principle is to avoid high field stress in oil at the mound cover ends and keep long and broad axial oil channels along both sides of the electrode to release DC field stress gradually and smoothly.

The conclusion is that the "Ω shape-cover" may be a proper solution for both AC and DC insulation.

**A2-205 (Republic of Korea)** – Partial Discharge Localization Algorithm for Power Transformer Using UHF Signals

In this work a more accurate, faster and practical method for partial discharges localization which can be used in transformers on site based in an Advanced Triangulation Method is presented. The proposed method is highly effective when there is no detailed knowledge of the internal structure of the transformer. The proposed method establishes a signal attenuation ratio map and measures a difference in arrival time between sensors for the PD position estimation. As validation of the developed method, the sources of defects were estimated for transformers with partial discharge problems in the field and the technique developed proved to be effective through visual inspection of the active parts of the transformers after the measurements.
The current method has been developed as an estimation technique for the location of partial discharge defect sources in transformers through portable equipment. In the future, more efficient monitoring diagnosis will be applied by using the method developed in on-line transformer monitoring diagnosis system.

**A2-206 (United States of America)** – Advances of Dielectric frequency response testing for HV OIP bushings

This work describes how to improve the classic tan Δ test to detect incipient faults in the condenser body of Oil Impregnated Paper (OIP) bushings.
As reported by CIGRE TB 755 between 5 to 50% of transformer failures are related to bushings, some of the events deriving into power outages, catastrophic failure, environmental and property damage. More than 50% of those failures are associated with OIP bushings.
The paper analyses the improvements in diagnostics of OIP bushings by comparing the following approaches:

- C1 capacitance and tan Δ at 50/60 Hz
- C1 capacitance and tan Δ at 50/60 Hz with Individual Temperature Correction (ITC)
- Narrow Band Dielectric Frequency Response (NB DFR) between 1 to 500 Hz
- Narrow Band Dielectric Frequency Response (NB DFR) between 1 to 500 Hz with ITC
- Wide Band Dielectric Frequency Response (WB DFR) between 0.005 to 1000 Hz

The conclusions of the authors are that assessment of OIP bushings based only on C1 and tan Δ at 50/60 Hz might be misleading when the dielectric response is unknown, is imperative the revision of technical references and implementation of the analysis of ITC for tan Δ at 50/60 Hz and NB DFR, it is paramount to use a frequency range at least between 1 to 500Hz for advanced diagnostics, and WB DFR test has proven to be the most inclusive test, which provides information of moisture and contamination in solid insulation as well as conductivity of oil.

**A2-207 (United States of America) –** Simulation and Measurements of Special Termination Lightning Impulse Test on Power Transformers

This paper analyses the differences in voltage distribution inside transformers windings under standard and special termination lightning impulse test (LI and STLI respectively). Based on recent reported cases about transformers that successfully passed all factory dielectric tests (FAT) but failed at site under impulse conditions, follows the question if the existing factory dielectric tests really reflect the actual operating conditions of transformers in service at site principally in the terminal connections.

Two 345 kV designs, a 245 MVA GSU transformer and a 450 MVA autotransformer, were analysed under both LI and STLI test connections. In LI all the non-impulse terminals are grounded whereas at STLI they are connected to ground via their surge arresters.
The calculations for the GSU transformer, with all non-impulsed terminals open, are compared with RSO (Recurrent Surge Oscillograph) low voltage measurements to validate the calculation tool. Then the transformers are calculated for LI and STLI (with the surge arrester connected in all non-impulsed terminals) and the results in both conditions are compared.
Conclusions are that under STLI conditions, higher magnitude voltages as compared to LI can occur and at unforeseen locations in critical insulation major gaps like HV-LV and phase to phase, where the design based on only LI can prove to be insufficient. For minor insulations inside the windings both conditions do not differ very much, or LI remains as the worst case.
The authors propose, as a practical design rule in case of testing under STLI conditions, designing the major and minor insulations one BIL step higher.

**A2-208 (Austria)** – Verification of Withstand Capability for Very Fast Transients of a 200 MVA, 500 kV GSU-Transformer by Modelling and Testing

This contribution is an excellent summary of the state of the art of design, modelling and testing of transformers subjected to VFTO (Very Fast Transient Overvoltages).Transformers connected to GIS (Gas Insulated Substations) are subjected to VFTO with very variate wave shapes, with a time rise in the range of 5 to 20 ns and a peak value between 1.5 to 2.5 p.u. that are not covered by the classical high frequency tests specified in the standards (Full wave and chopped wave lightning impulses and switching impulse). There is also a lack of knowledge in the industry about the withstand of insulating materials (oil and paper) to these types of overvoltages. This work describes in detail the transformer modelling, design procedures and tests to guarantee the capability to withstand VFTO of a 200 MVA, 500 kV, GSU-transformer connected to a GIS.
The VFTO have frequencies up to 5 MHz and as a consequence a turn-by-turn modelling of transformer windings is used to determine the voltage distribution and possible internal resonances inside the windings needed as an input to analyse the withstand of the insulating materials to these VFTO. Also, the different approaches published for the withstand of insulating materials to VFTO are presented and the discrepancies between them are discussed.
Finally, a special factory acceptance test is described, according to customer's specification, to try to probe the withstand capability of the transformer by applying a SF6 chopping device creating an extremely high steepness during chopping.

### 4.2 Discussion for Preferential Subject No 1

Dielectric specification, design and testing are one of the most critical, controversial, and challenging aspects to obtain transformers that will operate in service for many years without problems, and their state of the art must be reviewed permanently.
First, the technical specifications must clearly reflect the service conditions of the transformer regarding permanent and transient conditions that can affect the dielectric design to avoid problems in the tests and in the field (A2-201).
Then, suitable models of the transformers must be used during the design stage to be sure that the transformer will withstand all the dielectric tests and service requirements. For that more and more sophisticated and detailed models are needed that must be validated as far as possible with tests on models or real transformers (A2-201, A2-203, A2-204, A2-207, A2-208). There is also a lack of knowledge in the industry about the withstand of insulating materials, oil and paper, to VFTO (A2-208).
During FAT there are many challenges to solve. There are not tests in the standards that can probe the ability of the transformers to withstand VFTO (A2-208) and the conditions of transformer terminal connections during dielectric FAT (SI, LI, LIC) are not representatives of terminal connections in service (A2-201, A2-207).
Finally, in service, off-line testing and on-line monitoring, are fundamental to evaluate the condition of insulation of transformers and bushings by means of PD measurements (A2-205) and Wide Band Dielectric Frequency Response of bushings (A2-206).

### 4.3 Question for Preferential Subject No 2

Question 2.1: Which tests can be included in the standards to probe the ability of transformers to withstand VFTO?

Question 2.2: What is known about the ability of insulating materials, oil and paper, to withstand VFTO?

Question 2.3: What is the state of the art regarding high-frequency transformers modelling using white-box models?

Question 2.4: Which tests can be included in the standards to better represent the transformers' terminals connections in service conditions?

Question 2.5: Which are the most effective methods for PD localization?

Question 2.6: What is the state of the art regarding insulation integrity monitoring of OIP bushings using Narrow Band and Wide Band Dielectric Frequency Response of bushings?

## 5. PS3: Improved Reliability for Transformers

### 5.1 Papers for Preferential Subject No 3

A total of 23 papers have been submitted to this Preferential Subject, according to the following sub-topics:

PS3-1: Use of new materials (e. g. natural ester)
(5 papers: A2-301, A2-304, A2-305, A2.306, A2-316)
PS3-2: Specification and Life Extension
(8 papers: A2-303, A2-307, A2-302, A2-317, A2-323, A2-322, A2-315, A2-320)
PS3-3: Condition monitoring and Asset management methodologies
(8 papers: A2-309, A2-310, A2-311, A2-313, A2-319, A2-321, A2-312, A2-318)
PS3-4: Impact of low frequency currents
(2 papers: A2-308, A2-314)

**A2-301 (Brazil) -** Ten years of experience with natural ester in 245 kV: shunt reactor of Vilhena substation

This detailed case study describes the specification, design, construction, installation, and operation of a 245kV class shunt reactor immersed in natural ester. After dielectric testing filled with mineral oil the liquid was replaced by natural ester and tested again. The authors state that for shunt reactors with 245 kV voltage class the design criteria of windings, oil flow channels, etc., can be the same used for designs with insulating mineral oil.
The operational experience with the shunt reactor during more than ten years has been successful. Samples of natural ester were collected at regular intervals for physical-chemical and gas chromatography tests. Also presented in this paper are the details of a corrective maintenance performed to eliminate a small leakage of the insulating oil.
The testimony, analyses, data and conclusions presented in this paper, brings relevant information to the Brazilian electricity market by proving and consolidating the benefits of the use of natural ester in high voltage transmission equipment, the development of new safe, environmentally friendly products, with superior technology and durability, with increased quality and with application of a renewable resource.

**A2-302 (Algeria) -** Investigation on the operating conditions of MV/LV transformers and recommendations to improve their reliability

The paper presents a case study for assessment of a fleet of 26 MV / LV transformers. Incidents analysis carried out throughout a seven year period revealed that the predominant causes of failures were overloads, internal failures, lightning, and LV short-circuits. The purpose of this investigation is to identify the factors that cause these damages and failures to formulate recommendations and to set up an action plan to address them. On the basis of the results of electrical and dielectric tests the authors note that all transformers reveal dielectric losses which exceed the normative limits. These are explained by the degradation of insulation used in the transformers (paper, cardboard and oil). In order to reduce damage rates, actions are recommended in order to improve the reliability of transformers and ensure better functioning of the distribution network.

**A2-303 (Canada) -** Continuous improvement of transformer specifications at a large utility

The paper describes how a large power utility (Hydro Quebec) has made continuous improvements to their transformer specification to optimise transformer reliability, safety, compatibility, maintainability, safety, quality and cost. The specific areas to the improvements in specification are discussed: transformer tanks, transformer compatibility, winding solid insulation, bushings, tap changers, cooling system, online monitoring, design reviews and testing program. Future improvements to their specification are also discussed.

**A2-304 (Germany) -** Power Transformers using Esters next generation – ready to cope with all grid operation challenges

A detailed case study about the specification, design, and construction of a 420kV class transformer immersed in natural ester is presented. Due to a strong focus by the utility on green issues, much emphasis is placed upon sustainability in their engineering decisions. The paper describes how an improved design has been developed with better performance, especially at low temperatures, based on earlier experience. Key problem the authors are addressing is the black-start of ester filled transformers at temperatures less than -10 °C. The viscosity of an ester becomes very high at low temperatures, and will freeze at -20 °C. Consequently, preheating was advised if restarting at low ambient temperature, which as an extra operation is undesirable for a utility which is trying to re-establish power. Therefore, a lot of emphasis was put on understanding the performance of an ester filled unit under these conditions. A cold start test of a 15 MVA transformer at -25 °C was done to investigate the behaviour of NE at pour point condition. Almost the whole NE was solidified completely before load switch on. The result was used in order to verify and ensure the capability to operate the transformer in emergency mode if ambient temperature dropped below the specified minimum temperature -25 °C and transformer was out of operation beforehand for at least 48 h. The authors describe that they are using a natural ester fluid which has a pour point of -30 °C to cope with low temperature black-start, and they block the OLTC from operating at temperatures below -12 °C. Using natural ester filled transmission transformers is considered a technical success by this utility, and will in no doubt be of interest to other transmission utilities.

**A2-305 (France) -** Compatibility tests between solid and liquid materials for reliable transformers

The paper describes the need for compatibility between different transformer materials, and how this can be checked by testing. The authors give an overview about how different materials are selected. Compatibility between solid and liquid insulation in a transformer is a key factor to keep a good dielectric withstand as well as avoid premature ageing. In particular, a material could generate gases which is undesirable as it interferes with dissolved gas analysis of transformers. They don't believe that existing material test techniques IEC 60793-2 and ASTM D3455 are enough to validate a transformer material. So, a relevant and comprehensive official test method should be developed in the future to assess the compatibility of liquid insulation with transformer materials.

**A2-306 (India) -** Reliability evaluation of ester oil filled on-load tap changers through critical tests

A detailed case study is presented on the use of natural ester in on-load tap changers, demonstrating its suitability. This paper details the capability evaluation through critical experiments conducted on ester oil filled OLTCs. The test chosen was the service duty test as per IEC 60214-1. Many properties and health parameters of the OLTC test samples were monitored before, during & after the critical service duty test of 50000 operations to ensure the adequacy of the performance. Based on the evaluation, the paper concludes that the field performance of over 300 OLTC's is providing positive affirmation in Indian utilities about the adequacy of ester oil based non vacuum OLTCs. The tests conducted indicate a suitability of ester oil based non vacuum OLTCs for use in transformers up to 400 kV system voltage.

**A2-307 (France) -** Improving the reliability of key power transformers (GSU for nuclear plants) through specifications

The paper describes how a large utility (EDF) has made improvements to their transformer specification to enhance the reliability of generator step-up transformers. The specific improvements are discussed in great detail and are related to thermal performance, mechanical dynamic performance, and materials specification and maintenance aspects. Improvements were based on lessons learnt both during operation, design reviews and factory acceptance testing. Improvement in thermal performance that are discussed are the hotspot location with in-house developed EDF tools for assessing thermal characteristics; the accuracy of fibre optics implementation and accuracy of measurements; the location of ambient sensors; and an example characterising transformer temperature rise for specific service conditions. Mechanical performance improvements are focussed on dynamic behaviour during short circuit tests. Prevention of oil leaks are also addressed through detailed specification of the gasket design.

**A2-308 (USA) -** GIC magnetic and thermal assessment of a large fleet of power transformers – a case study

The paper provides a detailed case study in four parts on the impact of a benchmark geomagnetic disturbance (GMD) event on a fleet of 500kV transmission and generator step-up power transformers. The first part looks at system modelling and geomagnetically induced currents (GIC) flow studies when the power system is exposed to the benchmark GMD event; the second part provides an assessment of the magnitude of susceptibility of transformers to the benchmark GMD scenario. The third and fourth parts looks at the magnetic assessment and thermal assessment of transformers on the fleet, respectively.

**A2- 309 (Brazil)** - Health index and hierarchizing scale methodologies for prioritizing on-line monitoring

The paper discusses the outcomes of research carried out in Brazil to help utilities manage their transformer and reactor fleets. Two multi-criteria methodologies supported by experimental software, were developed for prioritising sensor and online monitoring systems applications in power transformers and reactors. The developed health index (HI) methodologies evaluates the equipment condition, and the hierarchisation scale (HS) methodology associates the equipment's health index results with the impacts that a possible failure on the asset under analysis will have on the transmission company's objectives. The HS methodology has integrated a risk matrix that has been used in the process of risk assessment to associate the HI with an impact index, prioritising the potential applications of online monitoring systems. The software was based on the estimation of the HI and the HS scale which is used to prioritise and recommend the appropriate online monitoring system.

**A2-310 (Brazil) -** Improving transformer reliability through operation, maintenance, repair and asset management for extended life

The paper discusses the asset management strategy of Electronorte, a Brazillian generation and transmission utility. The DianE system developed by the Electric Energy Research Center, is also discussed as an asset management application, which integrates known techniques of analysis into a single system that aids decision making on operational and maintenance needs. The capital investment decision making process is demonstrated with a case study of 3 x 200MVA, 500kV autotransformers with 30 years of operations, to maintain the reliability of the electric system.

**A2-311 (Norway) -** Transformer management by learning from condition, failure and scrapping data collected nationwide

The paper describes ongoing work in Norway to improve the nationwide collection of relevant transformer data through collaboration between transformer owners, the Norwegian group for power and industry transformers, the transmission system operator and research institutes. The preliminary analysis of available data is presented and the use of the collected data for improving transformer management is also discussed. A method designed to use statistics for assessing the aging condition, probability of failure, and remaining lifetime of a transformer is detailed. The method assesses the individual condition of transformers by analysing and comparing operational data to statistical data, which enables the method to learn from the actual transformer failures, scrapping investigations and condition statistics. The use of the method and its potential for improving long term management of a transformer fleet and supporting replacement decisions is demonstrated with an example of a hypothetical transformer.

**A2-312 (Croatia) -** Fleet asset management opportunities arising from transient monitoring of power transformers and shunt reactors

The paper investigates the use of transient overvoltages to quantify the additional stress on a transformer or shunt reactor's insulation that will assist with assessing the current state of the insulation system as input to asset management. The validation of a transient monitoring system is demonstrated in a laboratory, a real case of overvoltage caused by lightning strikes in a power network is provided. The real impulses and standard test impulses are compared using the frequency domain severity factor.

**A2-313 (Sweden) -** Fleet screening of HVDC transformers

In this case study a fleet screening of converter transformers serving an HVDC link is presented. The transformers including key components such as DC-bushings, tap changers and coolers are ranked with respect to probability / economic consequences of failure and the most vulnerable units of the fleet are identified. After briefly describing the developments in HVDC transmission from 1954 onwards, the methodology adopted for fleet screening of seven HVDC transformers based on an assessment of the risk of failure is presented. The development of new HVDC-specific rules for the evaluation procedure is based on expert knowledge of HVDC transformer design. This includes knowledge of the converter transformer itself, the DC-bushings and their interconnection, tap changers and coolers. The HVDC-specific evaluation is also based on understanding of the different types of aging and degradation processes, and how they are influenced by maintenance aspects and system impacts.

**A2-314 (Austria) -** Field experience of small quasi DC bias on power transformers – a first classification of low frequency current pattern and identification of sources

The paper describes research carried out in Austria into the low frequency currents (LFC) or quasi DC in the electric power transmission network. Their research investigation was initiated in 2013 with audible noise concerns from some power transformers. During the course of the investigation they found that there was a correlation between geomagnetically induced currents, and were surprised that these currents were found in Austria. This led to the installation of a measuring system covering most of Austria where continuous measurement data is available since 2016. The paper then deals with the analysis, characterisation and classification of the LFC sources through measurement data and experimental laboratory test set-ups.

**A2-315 (Japan) -** Rationalization and high precision of transformer lifetime evaluation method

The paper describes three improved methods developed in Japan for the estimation of solid insulation ageing based on oil tests and operational data. Two of the improved models relate to improved use of results of 2-furfural and improved use of meteorological and loading data to estimate solid insulation ageing. The third improved method is quite innovative, and involves the use of fibres suspended in oil. The refractive index of the fibres is changed by ageing, and so can be used to evaluate solid insulation ageing. Furthermore, from the viewpoint of mechanical performance, the evaluation results of the residual clamping force in removed from service transformers and the expected lifetime of transformers based on them are introduced. These introduced evaluation methods are helpful in rationalization and transformer lifetime evaluation with high precision. It also considers possible effects of the loss of clamping force during transformer life.

**A2-316 (Italy) -** Large power autotransformers filled with natural ester – working parameters from the field and maintenance notes

A detailed case study presents information collected by the execution of on-site tests and by the records acquired by multiple monitoring systems, relating to the operation of an autotransformer filled with natural ester with a power of 250 MVA at 400/135 kV, KDAF cooling, built in 2016 and in regular service since 2017. Especially results of PDC, FRA and DGA measurements during the first two operating years are shown. The autotransformer is operating without particular problems with maximum load values of about 80% of the nominal load. After approximately one year of operation, there was a decrease of moisture in solids, measured with PDC method, of -12.8%. This result confirms the properties of the natural ester to retain moisture by removing it from solid insulations.

**A2-317 (Australia) -** Experiences from transformer onsite refurbishment

The paper describes the onsite refurbishment programme of a transmission system operator in Australia carried out on 16 power transformers in the period 2014 to 2019. The refurbishment scope includes bushing replacement, cooling fan replacement, leak repairs, oil filtration, tap changer maintenance, conservator bag replacement, protection overpressure relay maintenance, and pre and post refurbishment tests. Key experiences with refurbishment scope are discussed, as well as a comparison of pre and post refurbishment tasks to assess effectiveness of the tasks that were carried out

**A2-318 (Australia) -** Application of conditional probability in risk assessments to optimise transformer design, operation and maintenance practices

This paper explores the background behind common cause failures and how they are modelled in a probabilistic risk system. A study of defects and failures has been undertaken on historic transformer data to identify and quantify plant failure risk of substations operating below a redundancy level. Several options and their cost/reliability improvements are discussed. The authors note that when calculating the risk of an outage within a substation, it is simplistic to treat multiple transformers as independent entities. For instance, all the transformers may have been subjected to the same faults, or could suffer from the same reliability issues. Consequently, the risk of all the transformers in a substation may be higher than most organisations expect. The authors then discussed methods to evaluate failures of different components, and propose methods to analyse reliability.

**A2-319 (India) -** Development and implementation of intelligent condition monitoring system for transformers and reactors

Describes new information systems developed by a large utility to improve transformer and reactor life management. One tool is a dissolved gas analysis system, using data from installed dissolved gas monitors and transmitted through SCADA. A second tool is an asset health indexing system, using data from the dissolved gas analysis system and also from off-line electrical tests. They used customer feedback to guide the development, and are currently monitoring 2800 units. In the paper two case studies present the application of the developed techniques to 765 kV line reactor and a 400 kV transformer.

**A2-320 (Thailand) -** Increasing reliability tertiary voltage side of power transformers by installing relay protection

The paper presents two case studies of tertiary faults on autotransformers with causes, consequences and measures taken to improve protection and prevent recurrence. The tertiary side feeds an ungrounded system. The advantage of the ungrounded system is a low single line to ground fault current, but it cannot be detected by an overcurrent relay. The details of a new protection scheme at the tertiary side including voltage transformer, neutral overvoltage relay and overcurrent relay for fault detection are explained.

**A2-321 (India) -** An innovative solution to assess the reliability of transformers by integrated transformer health monitoring

This contribution describes an integrated transformer monitoring system, including information from DGA and temperature monitoring and also operational data. The authors investigated the behaviour of a 150 MVA 220/132 kV power transformer installed in 1976 to determine whether it should be taken out of service, or left to continue operation. They installed an integrated health monitoring system, which provided the utility with the confidence to continue usage. Based on the recorded DGA data and tap position the problem could be attributed to the tapings / selector switch of the on-line tap changer at taps with higher voltage (lower number taps). Thus, the transformer was kept in service at tap position No.16 for most of the period until system voltage permitted and alternate arrangements were made. Thus, a proactive monitoring & diagnostics approach, based on measured electrical, DGA and thermal data of the transformer, gives more insights into the transformer condition and helps in taking proactive measures to extend the life of the transformer, or reduce the operational costs by timely maintenance.

**A2-322 (Canada) -** Advancements in transformer site dry outs

The paper discusses the Low Frequency Heating method for onsite removal of moisture in the transformer cellulose insulation that will allow for life extension and improved reliability of aged transformers, and expand the possibilities for site assembly or site repair. Five case studies with different types of transformers are presented to demonstrate the effectiveness of the method,

**A2-323 (Ireland) -** Power transformer life extension rebuilds

The paper discusses transformer life management tests, tools and methodologies that were used for large aged power transformer onsite rebuilds in Ireland. The paper highlights three aspects of the methodology: transformer condition assessment and residual life assessment, site tool enabling cost effectiveness, and recommissioning tests and condition monitoring for reliable return to service. Two case studies are presented and discussed to demonstrate success achieved with the implementation of the refurbishment methodology.

**5.2 Discussion for Preferential Subject No 3**

Improving reliability by:

1. Use of new materials (e. g. natural ester)

   During the last decades new insulating liquids have arrived in the market. The drivers for this have been advantageous functional properties as biodegradability, low corrosivity, fire resistance and improved cooling performance. Transformer designers have increased their confidence level in applying transformer and OLTC design limits with natural ester liquids, similar to those used with traditional mineral oil-filled transformers (Paper A2-301, A2-304 and A2-306) and collected good operational experience (A2-316).

2. Specification and Life Extension

   Papers A2-303 and A2-307 describe how reliability is built into the transformer design through detailed specification, design review. A2-302 indicates how evaluation of operational experience with reliability analysis can highlight the necessity for review and changes to specification to improve reliability. In other approaches reliability improvement of older transformers above 30 years are addressed through onsite interventions: onsite refurbishment (A2-317, A2-323), onsite moisture removal (A-322). A2-317 and A2-323 provides two contrasting outcomes: one in which thorough assessment and planning of the technical and financially viability, and execution of a refurbishment program can yield optimal results; and the other, where less optimal results were achieved due to operational and network performance constraints, as well as workmanship issues. Paper A2-315 shows improved transformer lifetime evaluation by advanced interpretation of 2-furfural and the use of paper samples suspended in oil. A2-320 shows an extended protection scheme of tertiary windings.

3. Asset management methodologies

   Condition-based approaches to asset management where transformers are ranked according to risk, health and impact indices, with the aim of improving reliability through prioritising and optimising maintenance, operations and costs, are presented in A2-309 to A2-311, A2-313, A2-319 and A2-321. A2-312 looks at integrating the impact of the additional stresses from transient overvoltage as input to condition based approaches. A2-318 extends the condition-based risk approach to a system approach through understanding and assessing the common cause failure risk.

4. Impact of low frequency currents:

   A2-308 demonstrates a North American utility's adherence to regulatory requirements for overall system reliability, by assessing the vulnerability of the large power transformers fleet to a benchmark 1-in-100 year geomagnetic disturbance event through modelling and simulation. Also, in small countries far away from the poles GIC currents were measured (A2-314).

### 5.3 Question for Preferential Subject No 3

**Use of new materials (e. g. natural ester):**

Question 3.1: Several papers show good experiences regarding the usage of natural esters. When and in which cases will natural esters replace conventional mineral oil?

Question 3.2: Under which circumstances can mineral oil be replaced by natural esters without changing the dielectric and thermal design?

**Specification and Life Extensions:**

Question 3.3: In many parts of the world there is a significant shift underway to renewables and electric vehicles. Given that a power transformer is expected to last 50 or so years, is it necessary to take a forward view in specification to any changes in stresses on a transformer which might affect its reliability (and thus should be taken into account now)?

Question3.4: How can insulation shrinkage due to extensive drying be detected?

Question3.5: IEC 60076-7 discusses end of life criteria or paper to be around 25% of its tensile strength remaining (around DP=250). Of interest is that Japan uses a high value of DP=450. Has there been any discussion of the economic benefits of retiring a transformer earlier than DP=200? Can the clamping force be correlated to the DP value?

Question 3.6: How does aging characteristics and diagnostic data of thermally upgraded paper and Kraft paper compare?

**Asset Management Methodologies:**

Question 3.7: What is the minimum data (condition monitoring, electrical testing, system data etc.) requirements for developing a reliable health index for a transformer fleet?

Question 3.8: How can condition assessment data /health index be converted into probability of a transformer failure?

Question 3.9: Which specific rules are necessary for fleet screening and risk assessment of HVDC transformers?

**Low frequency currents:**

Question 3.10: The authors were surprised to find geomagnetically induced currents in Austria, because these low frequency currents are thought to be concentrated around areas close to the poles. This then raises the question, are national networks in countries bordering Austria also likely to be affected?

Question 3.11: What requirements must specifications contain in order to make the design of a transformer GIC compliant?