A2 - 00

SPECIAL REPORT FOR STUDY COMMITTEE A2
(Power Transformers and Reactors)

Special Reporters
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1. General

The technical field of activity of Study Committee A2 is:

- Power transformers, including industrial, dc converter, and phase-shifting transformers
- 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

2. Group Discussion Meeting in Paris Session 2018

The Group Discussion Meeting during the Paris Session in 2018 will take place from 8h45 until 18h00 on Thursday 30 August. It will be held in the Bleu Amphitheatre in the Palais de Congres. It will be open to all registered delegates.

Anyone wishing to present a prepared contribution must attend the contributor's meeting the previous day, i.e. Wednesday 29 August 2018. The venue for the meeting will be advised at the Paris Session. Their contribution will be reviewed by the Special Reporter and the Study Committee Chairman. If accepted, it will then be presented the following day. It is not possible to guarantee acceptance of any contribution, even if submitted in advance.

3. PS2 – Thermal Characteristics of Power Transformers

3.1 Papers for Preferential Subject No 1

A total of 17 papers have been submitted to this Preferential Subject, according to the following sub-topics:

PS1-1 Steady Thermal Modelling and Testing (6 papers)
PS1-2 Dynamic Thermal Modelling and Testing (7 papers)
PS1-3 Thermal Impact (either Steady or Dynamic) of using Alternative Materials (4 papers)

A2-101 (Portugal) – Dynamic Thermal Modelling (and Testing)
This work describes the development of a dynamic thermal hydraulic network model for core-type transformer windings that describes in more detail the physics of the thermal behaviour while compared to the lumped modelling approach proposed in the IEC 60076-7 loading guide. A first architecture of this model has been developed and validated using dynamic computational fluid dynamics simulations. At this stage, it has been found that the dynamic variations in the fluid domain are much faster than in the solid domain so the time constant in the fluid can be neglected and the steady state situation is assumed for each time step (pseudo steady state approach).

A2-102 (Portugal) – Steady Thermal Modelling and Testing
This work describes the development and experimental validation of a global thermal hydraulic management platform that models all the elements of the thermal loop, i.e. the active part, the pipes, the radiators and the pump. In this platform all the performance of the different components of the thermal loop are coupled and solved together, eliminating decoupling assumptions and enabling a more realistic overview of the performance of the whole transformer. A comparison with a 40MVA ODAF cooled transformer from a mobile substation has shown that the platform (and its underlying algorithms) can predict the overall temperatures and the oil flow rate with deviations lower that 3˚C and 6% respectively. A three-phase 15MVA full-scale experimental transformer has been built and will be further used to extend the validation of this platform in a more comprehensive set of operating scenarios.

A2-103 (Belgium) – Steady Thermal Modelling and Testing
Describes the development of an improved thermal network model using better friction and heat transfer correlations extracted using parametric sets of CFD simulations. This improved thermal network model in steady state is compared against the first network model developed in the 1980s by Oliver. Significant improvements are observed namely for ONAN regimes. The improved model is validated using laboratory measurements on 11 transformers rated between 21MVA and 500MVA and a significant gain in accuracy is demonstrated.

A2-104 (Slovenia) – Dynamic Thermal (Modelling and) Testing
Describes a case study newly 400kV transmission transformer recently commissioned. The accuracy of its traditional WTI has been compared against direct hot-spot measurements obtained with optical fibres. A comparison of data collected during one-year of operation shows that the WTI overestimates the real hot-spot temperature evidencing potential optimized operation strategies through improved Dynamic Thermal Models or through on-line monitoring of hot-spot temperatures.

A2-105 (Sweden) – Steady Thermal Modelling (and Testing)
This work discusses the performance of three thermal modelling methodologies having different intrinsic levels of complexity – 2D CFD, 3D CFD and THN. The methodologies are compared using the two top passes of a LV of a 160 MVA core-type power transformer under ON cooling conditions and in steady-state. The authors conclude that 2D CFD, if properly rescaled, can compare well with 3D CFD and shall be used to validate a certain design while the fast and less accurate THN can be used in early stages to choose the best design among multiple alternatives.

A2-106 (Great Britain) – Steady Thermal Modelling and Testing
Observations made in several scrapped transformers seem to indicate significantly overheated discs in unexpected regions of the windings (in the bottom ducts of the passes rather than in the top ducts where the oil temperature is expectably hotter). A comprehensive numerical and experimental work (using optical velocity measurements) has been carried out in a controlled scale model of a winding showing that stagnant and reversed flows can both occur in the top and in the bottom ducts of each pass. This provides a useful background to explain the observations in real transformers and educates the community about the need for a proper thermal design of the windings.

A2-107 (Croatia) – Steady Thermal Modelling and Testing
This work describes a numerical methodology useful to predict the temperatures in the tank walls. Being able to measure the stray losses induced in the tank walls is a crucial parameter for accurate predictions, hence the authors explain a method of measuring local stray losses in steel parts using the initial slope of a time-temperature curve. The scalability and high-accuracy of this numerical methodology has been assessed in a mock-up and in a real 280MVA power transformer using IR imaging.

A2-108 (France) – Steady Thermal Modelling and Testing
This work focus on the temperatures of the magnetic core for what the authors propose a two-step numerical methodology. First the core has been electromagnetically modelled and afterwards the losses obtained in the first step have been used in a thermal simulation to obtain the temperatures in the surface of the core. Authors have demonstrated by simulation that there could be a gradient as high as 25˚C between the surface of the magnetic core at the cooling duct surface, where the temperature probes are more practically inserted, and the centre of a core slice of the magnetic circuit. This methodology has been compared against measurements obtained from the core of a real 680MVA power transformer under over-excitation no-load tests at 1.1pu maximum. The accuracy is reasonable with the authors claiming the need for standardising temperature rise tests in the magnetic core (currently absent from the applicable standards).

A2-109 (Spain) – Dynamic Measurements Windings
This work discusses the use of different instruments and techniques to measure the top oil temperature and the hot-spot temperature. The top oil temperature measured with thermocouples and OTIs are compared and discussed. The hot-spot temperature measured directly with the optical fibres is compared with the hot-spot temperature indirectly measured using WTIs. Based on data obtained in a real autotransformer, the authors conclude that the indirect hot-spot measurements obtained with the WTIs can be quite erroneous (if based on 'default' dynamic parameters and if not previously calibrated with direct hot-spot measurements).

A2-110 (Canada) – Dynamic Thermal Modelling and Testing
This work summarises the extended overload tests and related pass-fail criteria specified by a major Canadian utility for assessing the thermal performance of new transformers. Direct

winding temperature measurements using fibre optic probes are specified and an agreement must be reached at the design review on the number and exact position of the probes. Transformer manufacturer must explain any difference exceeding 3 K between calculated and measured values. The winding temperature indicator is adjusted based on the highest value and cooling control is based on the indirect measurement from the digital winding temperature indicator. Fibre-optic measurements while the transformer is in service allowed highlighting transformer thermal behaviour and the authors have demonstrated that the temperature rise is significantly increased on transformers in ON regime at low ambient temperature. The authors conclude that further research is encouraged in this area.

A2-111 (Austria) – Thermal Impact (either Steady or Dynamic) of using Alternative Materials
This work focus on the temperatures of the windings during cold start-ups of a 15MVA ON cooled single-phase autotransformer immersed in a synthetic ester. The tests were conducted in a large climatic test chamber with controlled external air temperatures. Two cold start-ups have been performed on the autotransformer: one very smooth start with 40% load at -50°C air temperature, and a second, quicker start with 100% load at -40°C air temperature. At -50°C, even though the radiator were inactive, no temperature overshoot was observed because the losses at 40% load were low and the heat exchange through the tank walls was sufficient to stabilize the system. However, the test at full load at -40°C caused the radiators to be inactive for about 14.5 hours and an overshoot of about 20°C has been observed in the hotspot of both windings. This means that while the radiators are inactive, the heat exchange is only made through the transformer tank surface and, depending on the load profile and radiator arrangements, these start-ups may cause an overshoot over the normal steady state temperature and over critical temperatures.

A2-112 (Netherlands) – Dynamic Thermal Modelling and Testing
The IEC 60076-7 loading guide proposes empirical models that can be used to predict the steady and unsteady temperatures of the transformer in multiple operating conditions. Those empirical models are typically implemented in the WTIs and depend on some parameters (called exponents). This work addresses the process of estimating those exponents using temperature measurements of the oil and of the windings. For that purpose, the author discusses the uncertainties associated with temperature measurements in real transformers, describes how the uncertainties accumulate and propagate up to the final estimation of the exponents. At the end it is concluded that it is better to use the default values suggested in the loading guide rather than extracting customized values for the exponents in a case-by-case basis (during the temperature rise test of the transformers).

A2-113 (Japan) – Steady and Dynamic Thermal Modelling and Testing
This work describes the development of ultra-compact 3-phase, 500kV, 1500MVA power transformers in Japan by two different manufacturers. The original design has been reengineered to be assembled on-site which means that the coil transportation mass had to be reduced from 75 tonnes to 45 tonnes. This target allows for the use of relatively inexpensive trailers, short-time transportation with milder travelling regulation with no need for road surveys or reinforcement. This technological breakthrough has been achieved by reducing the cross-sectional area of the conductors and by increasing the conventional currents. For validation purposes, two full scale transformer models have been built wherein the maximum and average winding temperatures have been measured. The transformers have been tested from 1pu up to 1.35pu revealing good agreement against the design values and against existing the standard loading guides, hence validating the technological approach conducted.

A2-114 (United States) – Thermal Impact (either Steady or Dynamic) of using Alternative Materials
This work reviews the gassing patterns of the current materials used in cable insulation and evaluated the performance of other types of insulation materials and design of the cable insulation. Various materials and insulation builds were manufactured and both the individual insulation materials as well as the complete cable assemblies were tested. Tests on the insulation materials included an evaluation of gas evolution vs temperature. Tests on the complete cable assemblies included temperature rise, dielectric behaviour, processing parameters and temperature profile of the insulation. From the work that was done, it appears that an improved insulation system for a lower voltage application would be a 100% low density aramid paper papers and allow the current in the cables approach 200% of the conventional system. For higher voltage systems, a duplex system using a combination of aramid paper and TUP insulation can be used. This would allow the current to on the duplex system to run at approximately 150% of the conventional system.

A2-115 (France) – Thermal Impact (either Steady or Dynamic) of using Alternative Materials
This work is divided in three parts. In the first part, the authors confirm (through laboratory scale ageing experiments) that the natural ester has a positive impact in the cellulose lifetime while compared with mineral oil immersed samples. Thus, the authors proceed with a comparative calculation of high-temperature design variants for an 80MVA and for a 515MVA transformer. The comparison shows that with the whole insulation made of materials with a thermal class higher than 155°C results in very compact transformers but at relatively high costs (18% increase over conventional design cost). Although a semi-hybrid insulation with TUP in the windings, pressboard in the solid materials that are not in direct contact with copper and natural ester can result in a competitive solution (only 2% over the conventional design cost). In the second part the authors describe a case of increasing the overload capability of a 70MVA power transformer up to 100MVA for the same time-period. In the third part the authors suggest potential improvements in the transformers thermal performance using speed controllable fans and pumps.

A2-116 (Serbia) – Dynamic Thermal Modelling and Testing
This work is subdivided in two parts. In the first part a 112MVA power transformer ODWF cooled has acted as the case study for a comprehensive numerical assessment using a detailed THNM. The numerical assessment involved modelling the performance of the case study transformer under steady state conditions with ambient temperatures ranging from 40˚C to -40˚C with mineral oil and with natural ester. The results of the simulations show that operation at the very low ambient temperatures (-30˚C and -40˚C) with natural ester can be critical namely for ON cooling modes. For these conditions the detailed THNM did not show converged results. The second part complements the first and describes a catastrophic failure of a generator step-up transformer with oil-to-water heat exchanger after its switching on and loading with the rated load at very low ambient temperature. In this start-up the temperature of the water (1˚C) was higher than the oil (-6˚C). Using the same detailed THNM steady-state tool together with the IEC Loading Models for the dynamic predictions, the authors were able to explain how the water initialize its crystallization inside the tubes, thus broke the tubes of the oil-to-water heat exchanger and finally caused the failure. This failure emphasizes the needed procedures for cold start-up in conditions of very low ambient temperatures.

A2-117 (Spain) – Thermal Impact (either Steady or Dynamic) of using Alternative Materials
In this work three identical single-phase units of a 200 MVA/420 kV conventional shell-type design have been successfully tested using mineral oil, natural ester and synthetic ester. The tests were conducted following factory testing procedures according to the relevant international

standards. The original cooling equipment used with mineral oil was not changed for the other units. The main criteria for the thermal comparison was to maintain the temperature values with esters as similar as possible to the temperatures measured with mineral oil. All the three transformers were tested in ODAF and ONAN cooling conditions. The results show that for ODAF the temperatures are similar for the same power rating (200MVA) while in ONAN there is a need of downrating from 120MVA in mineral oil to 86MVA with synthetic ester and to 77MVA with natural ester. At the end the results are qualitatively compared against CFD simulations.

3.2 Discussion for Preferential Subject No 1

The thermal characteristics of power transformers have always been relevant. The first published work on the subject dates back two centuries ago in 1895 by W.L.R. Emmet entitled "Transformer Heat Transfer and Loading". Early power transformers were dry-type and termed 'air-blast transformers'. In that work, after tests in the Niagara Falls Power Station, Emmet concluded that an air blast was necessary to avoid excessive temperatures. In 2018, and from this selection of papers, it seems clear that the power transformers nowadays are radically different being now mostly liquid-immersed and core-type.

This historical note means that the thermal characteristics of power transformers is a preferential subject that ought to be revisited from time to time. The recurrence is pertinent:

- Because the transformers are being designed increasingly more compact (progressive lower ratios of kilograms of copper/MVA and kilograms of oil/MVA). The increased current densities and decreasing distances certainly pose challenges that need to be addressed. First example is in the paper A2-113 where the mass of a large coil has been reduced 44% to optimize its transport and a 1500MVA full scale transformer model has been built. Second example is in the paper A2-114 where the compactness of the cables was tested with success. A hybrid insulation in low voltage cables can increase. Third example is in the paper A2-102 where an extremely compact mobile substation demanded the use of a more complex, global and accurate thermal hydraulic network platform. Fourth (indirect) example is in the paper A2-107 where a novel method has been devised for estimating the induced losses and temperatures in the tank walls and should be increasingly useful for high impedances and compact designs.
- Because of the changing topology of the networks and the consequent changing conditions wherein power transformers are operated. One example is in the paper A2-108 where the authors conduct an extensive numerical and experimental work on the temperatures of the magnetic core to assess the impact of the new European Grid Codes on transformers. Due to widespread intermittent generation sources more volatility is expected, and these grid codes will extend the permissible voltage fluctuations for longer time periods.
- Because the economy underlying the operation of power transformers is also changing. The 'smarter' grids are driving the interest in monitoring the transformers in real-time which in turn drives the need to update/improve the existing loading guide models implemented in most of the monitoring systems nowadays. The papers A2-104 and A2-110 address precisely the lack of accuracy of the existing loading guide models for low ambient temperatures and for ON conditions. Both papers are reinforced by the paper A2-116 where the authors show a complex and advanced THN that does not converge at low ambient temperatures due to increased viscosities. Interestingly the paper A2-112 discusses the accumulation of uncertainties involved in the process of

improving the existing loading guide models and A2-101 describes an alternative approach to the loading guide models based on dynamic thermal hydraulic networks.

- Because of the introduction of alternative high temperature insulation materials and liquids (such as esters). In paper A2-115 the authors confirm in laboratory reveal that the combination of TUP in the windings, with pressboard in other parts and natural ester as the main fluid can be a good compromise between improved performance and competitive costs. In paper A2-117 the authors demonstrated the successful use of natural and synthetic esters in a 420kV shell-type power transformer (namely for OD conditions). In turn, in paper A2-111 the authors discovered that at very low ambient temperatures the synthetic ester can block the circulation in the radiators causing significant overshoots in the internal temperatures of the transformer.
- Because of the widespread availability of optical fibres that challenge that the conventional cooling control strategies. In paper A2-109 the authors conclude through extensive testing with optical fibres that the indirect hot-spot measurements obtained with the Winding Thermal Images can be quite erroneous, which is indeed a reinforcement that the standard loading guide models implemented in these devices need to be further researched and improved as other papers suggest (namely A2-104 and A2-110).
- Because of the routine and progressively more frequent usage of numerical methods that unlock explanations for 'older' and 'practical' observations. This is the case in the paper A2-106 where important reversed flows in unobvious ducts of the top pass of a disc-type winding have been observed first through CFD simulations and then validated through optical velocimetry measurements. This seems to explain practical observations of overheated ducts in that regions in multiple transformers taken out-of-service over the years. On the other hand, the paper A2-116 also comprises an interesting example of how a complex numerical modelling (such as THN) was used to explain the cause of a catastrophic failure occurred during the cold start-up of an ODWF cooled power transformer in Serbia.
- Because the product development cycles keep being optimized with more complex and accurate thermal tools. This is well illustrated in paper A2-105 where the authors compare different thermal modelling approaches to assess the adequate level of complexity (and effort) needed in each stage of the development cycle of a transformer. In turn paper A2-103 well illustrates the need and the pursue of increasingly better and improved thermal models, in this specific case through the combined use of CFD and THN techniques.

And last but not the least, the recurrence on this preferential subject will remain pertinent because there will be always new technology solutions that arise to answer continuously evolving contexts. A single session is not sufficient and perhaps the three most relevant unaddressed sub-topics are the thermal challenges associated with the design and operation of the new HDVC power converter transformers, the thermal challenges associated with special transformer applications such as wind farms or the thermal challenges associated with large dry-type power transformers.

3.3 Questions for Preferential Subject No 1

Question 1.1: CIGRE WG A2.38 has recently identified the state of the art of steady thermal modelling techniques (used both by manufacturers and utilities): as being Computational Fluid Dynamics and Thermal Hydraulic Network Models. What are the main parameters affecting the precision and accuracy of this modelling techniques? Being these techniques dependent on complex 'recipes', and due to its current widespread use, would it be useful to have clear standard guidelines on the use of these techniques to guarantee comparable and quality outputs? What are the main advantages of these techniques, which are the known limitations and when are they needed? Are there any other numerical techniques already in use or with potential of becoming usable?

Question 1.2: The numbers of optical fibers to be installed has been recently reviewed in CIGRE WGA2.38 and translated into the most recent version of IEC 60076—7 Loading Guide. The new guidelines recommend the number of sensors dependent on the leakage flux/phase. But besides the number the installation procedures are quite important to guarantee the correct measurement. What are the best installation procedures? What is the acceptable deviation between thermal predictions and measurements? What are the typical total uncertainties associated with optical fiber measurements and with the average winding temperature determination through resistances? Do you foresee these deviations and uncertainties to be used as a parameter for qualifying manufacturers? What is the percentage of new power transformers that have temperature rise tests and from those transformers tested how many have optical fibers installed? Are the heat run tests representative of the on-site performance? Do you usually repeat on-site the same short-circuit and no-load tests conducted in the HV Laboratory?

Question 1.3: The existence of reversed flows in the bottom horizontal ducts of the top pass of a winding have been recently reported in a few papers and its existence is herein reinforced by measurements in a scale model of a winding. This seems to be depend both on the design of the windings and on the flow characteristics. Thus, one pertinent question is what is properly designed winding and what is the average and maximum oil velocity permissible inside the windings? Are there any other ‘practical’ observations of overheating in core or shell type transformers that still need to be better supported by modelling?

Question 1.4: There is an increased interest on the dynamic thermal models available in the loading guides. Namely because they enable the calculation of instant overloads capabilities. What are the main advantages and limitations of these loading guide models? Do you have experience with other dynamic modelling approaches? Would you consider feasible designing a power transformer for a dynamic load profile instead of systematically designing it for a peak load value? What are the variables that need to be measured, and with what frequency, to enable an optimized thermal management of a transformer? (Moisture? Flow rate in each internal hydraulic circuit? Temperatures in the magnetic core and in the leads?)

Question 1.5: The thermal transients associated with cold startups involving oil at low ambient temperatures and involving esters at low temperatures seem to be relevant because they cannot be easily captured through modelling and because its consequences maybe catastrophic. Are there any other relevant thermal transients worth addressing?

Question 1.6: From a thermal perspective, what are the most critical components and the most demanding power transformer applications? What shall be the maximum permissible temperature limits for tank wall surfaces and for leads?

4. PS2 – Advances in Diagnostics and Modelling

4.1 Papers for Preferential Subject No 2

A total of 15 papers have been submitted, according to the sub-topics:

PS2-1 Experience with different methods of measuring partial discharge at the factory an at site
PS2-2 Interpretation and modeling of winding frequency response results
PS2-3 High frequency transformer modelling for power transformers, including comparison with measurement

Paper A2-201 (Korea) presents a UHF Partial Discharge (PD) monitoring system emphasizing the importance of PD condition monitoring to prevent failure of the insulation system. The UHF method is shown to have more advantages to conventional PD detection methods as it is less influenced by ambient noise and other environmental limitations. The monitoring system can measure the partial discharge based on the operation voltage of the transformer and determine the type and location when a partial discharge occurs. In addition to that, functions for online and portable PD measurement were integrated to enhance measurement flexibility. The system configuration and the methods used to detect and localize the PD is described in detail. To evaluate its performance, the results of two applications in a factory test (225 kV, 150 MVA and 500 kV, 750MVA transformers) and two on site (13.8 kV, 1.5MVA and 800 kV transformers) are discussed and presented good results.

Paper A2-202 (Iran) investigates the effects of ungrounded conductive objects near power transformers on Induced Voltage Partial Discharge (IVPD) measurements. It is well known these kinds of measurements can be affected by several factors such as grounding of conductive objects, corona on the high voltage electrode, etc. As one of the challenges of IVPD test is to analyse the PD patterns and identify causes if the standard limit is exceeded, the investigation of possible effects of ungrounded objects near the transformer being tested is very important. Under this context, the paper presents some experimental results of IVPD test during factory test of a transformer considering two case studies. The conclusion was that these effects can lead to incorrect IVPD measurement results.

Paper A2-203 (Sweden) presents a bushing life management pilot project of equipment in operation in the Swedish National Grid. The motivation was that condition assessment have not traditionally been performed on bushing and some substation failures have occurred with faults probably originating in these components. The investigation strategy was to consider a number of transformers and reactors selected according to age and type of bushing. One group considered transformers commissioned in the 1970s with a bushing, referred to as Type 1. The other group were 400 kV transformers and reactors, commissioned in the 1980s, with an improved design of bushing, referred to as Type 2. Different diagnostic methods were used as part of the condition assessment. The conclusion was that application, not just age and design, may be decisive when prioritizing bushing life management although no correlation with system operation could be found in this study.

Paper A2-204 (Germany) presents the basic research necessary to allow the transition from vibroacoustic offline to online monitoring of tap-changers and variable reactors. Online monitoring is considered very important for the diagnostic and asset management of these equipment due to its exposure to considerable mechanical stress created by the vibration of the reactor. In this context, the paper presents the first results of long-term measurement on a variable shunt reactor and different assessment procedures for the online analysis of on-load tap-changers. Regarding the online vibroacoustic monitoring of tap changers, two methods are described. The paper also presents the analysis of the operating noise of a variable shunt reactor. Two vibroacoustic measurements were carried out on a variable reactor as a starting point for the analysis of the operation condition of the equipment. The evaluation showed that the current database available was not sufficiently comprehensive to be able to generate precise models. The conclusion of the analysis is that vibroacoustic evaluation presents a great potential to improve the quality for monitoring and functional analysis.

Paper A2-205 (Switzerland) proposed a PD localization procedure based on the analysis of the frequency spectra and the time-domain signals generated by a partial discharge (PD) source in the insulation system of transformers. This approach is considered more reliable to localize internal PD source due to its oscillating characteristic that presents attenuation on its way to the measuring system. The proposed PD localization is based on information about PD impulse propagation and PD signal coupling between transformer windings which are measured simultaneously at all bushings. To achieve that, a set of real PD data in time-and frequency-domain is compared with the "characteristic time-domain signal" and the "characteristic time-domain signal" of the transformer under test. The advantages and limits of the method are discussed using practical examples considering different PD locations in the transformers. In the conclusion, the authors point out that although the proposed PD localization procedure delivers good results, its efficiency could be improved with the simulation model for the PD propagation inside a transformer. The development of a high frequency transformer model suitable for this application is an attractive topic for future work.

Paper A2-206 (United States) Asset management in the power grid of the 21st Century requires smart techniques and algorithms compatible with the very fast-growing quantities of available data be it from new sensors that spread over a large range of applications such as DGA, oil quality, mechanical vibrations, bushing condition, etc. or from digitalized data that in the past used to be stored in paper format. Maintenance and operations engineer require fast and reliable engineering models and tools to be able to assess power transformers conditions on a fleet wide basis to optimize maintenance resources and postpone investments as much as possible. Artificial intelligence techniques have been around for some time since the inception of computers in the early fifties with the so called Expert Systems which were fundamentally human-experts rule base systems applicable to many diagnostics issues. With the increase in size of the power systems and the encounter between IT (information technology) and OT (operations technology) in the era of internet of things (IoT), mobile devices and digitalization of almost everything, the need for the development and application of new algorithms became positively required. Machine Learning, by definition, constitute a set of algorithms that learn from data, extracting hidden structures and finding interesting correlations that would otherwise be very difficult to find with old-fashioned numerical methods given not only the complexity but also the size of the datasets ("Big Data").

Paper A2-207 (Jordan) presents an experimental procedure of PD and/or fault localization considering FRA measurement results together with the analysis of the behavior of a high frequency model of the transformer under investigation. For this application, the FRA should provide a current transfer function. to be considered the finger print of the transformer. If any deviation from this transfer function occurs in the future, a model of the frequency response of a general component of the transformer (core and winding) is carried out based on the FRA measurements of this operational condition. The model is made of a certain number of cells and each cell contains a section of the winding. The main objective of this modeling is to obtain a correlation between the changes in the internal parts (cells of the model) and their reflections on the response. These changes may indicate PD sources as the admittance of the winding will have changed when compared with the "finger print" of the transformer.

Paper A2-208 (India) presents Power Grid experience in the application of a novel approach for bushing fault diagnosis. Their motivation was a significant number of random failure of OIP bushing at an early stage of operation. Although Dissipation factor (Tan δ) test at 50 Hz has been used by Power Grid for condition assessment of bushing since last two decades, to avoid such random failure, supplementary diagnostic tests were introduced and have proved to be effective for better diagnosis of bushing as well as in reduction in random failure. Three types of diagnostics techniques were performed: FDS and variable frequency dissipation factor; Capacitance and Tan δ test in variable temperature; and bushing DGA. The paper presents some examples where the application of these techniques prevented a catastrophic failure as the bushings could be taken out of service at the initial fault stage. It was pointed out that most of the problems involved reactor bushing. It is suspected that reactor switching, and /or other types of overvoltage sources may have contributed to high dielectric stress to the bushing which combined with other factors such as poor manufacturing/moisture etc. led to the failures. In the conclusion, the authors discuss their experience with the diagnostic techniques considered in their investigation, enlightening the main particularities of each of them

Paper A2-209 (Russia) presents an approach to FRA interpretation with the aim of assessing the mechanical and electrical condition of windings of power transformers and reactors. The method is based on the analysis of winding natural frequency deviations due to internal short-circuits faults by means of graphical representation of patterns of these deviations. It is shown through examples that different patterns of natural frequency deviations are related to different types of internal short-circuits. To visualize these patterns, the authors proposes to consider the first three natural frequency deviations to plot a triangle and determine its centroid (center of mass). The fault location according to the proposed method was in good agreement with results of experimental studies performed on a real scale physical model of continuous disc-type winding. Similar results have also been obtained by the application of white box models in EMTP-type software. So far, this type of model has usually been applied for the analysis of impulse transients along the windings. It is in the scope of the current CIGRE JWG A2/C4.52 to identify best practices of white box model parameter calculations to improve its applicability in different types of evaluations

Paper A2-110 (France) presents a generic methodology for the development of high frequency transformer model based on 2D magnetostatics and electrostatic finite -element calculations. The models are usable for any transformer winding and core technology and can be automatically exported to the EMTP-RV software. The main input data are the geometrical characteristics of the transformer project provided by the manufacturer. The model is very useful not only for the computation of transients at the transformer terminals but also for the distribution of the voltage along the windings. It could also be applied in other studies requiring a frequency dependent transformer model, such as diagnostics using FRA. Simulation results were compared with measurements considering a mock-up of a single-phase power transformer and a real power transformer. Although most results were quite satisfactory, further investigation is required to understand some differences found in the analysis.

Paper A2-111 (Poland) presents a contribution to the interpretation of the low frequency resonance (LF) in FRA analysis of transformer windings. The focus is the evaluation of some factors that may influence the position of the first parallel resonance, especially changes in the capacitance in the non-tested winding. Examples of industrial measurements, experiments performed on real units and model verification were presented. It was shown that, especially in the case of low voltage and tertiary windings, this resonance does not depend only on the winding tested but on the entire construction of the transformer. Significant first resonance shifts were observed in the experimental measurement on industrial and laboratory transformers with additional capacitances were connected in the windings which remained opened during the test. The same behavior was verified by modeling an air insulated laboratory transformer and changing the values of the capacitance of the opposite side winding. Regarding failure diagnosis, the result of the experiments on transformers where controlled deformations were introduced into the windings was that these deformations did not cause changes in the first resonance.

Paper A2- 212 (Netherlands) presents a possible approach to obtain baseline reference of the frequency response of a power transformer via a modelling method. The initial model was the same one applied to check the transient behavior of the design, based on geometrical design data of the equipment. Then damping in the winding was added and an inductor to represent the core behavior. The comparison between SFRA measurements and calculations results presented good agreement up to 20 Hz. Above that frequency, the model requires further refinement. The paper also presents the comparison of simulations with and without hypothetical deviations included. One of the deviation considered led to a very subtle difference in the signals which illustrates that SFRA interpretation remains a challenging task. The investigation showed that the modeling approach could serve for additional support for SFRA result interpretation.

Paper A2-213 (on behalf of JWG A2/C4.52 – High-Frequency Transformer and Reactor Models for Transient Studies) presents the work done so far by the JWG, whose main objective is to facilitate the use of more advanced transformer models in system studies by the transformer end users. The JWG performed extensive measurements on two three-phase transformers in 2015; a 1-ph unit and a 3-ph unit. for validation of alternative transformer models. The relevant model categories are the white-box model which includes a detailed description of the windings; the black-box model which is a terminal equivalent; and the grey-box model which attempts to fit an assumed topological model to measured terminal data, including simplified models to terminal data, including simplified models. The paper presents comparisons between time domain voltage responses obtained by measurement and by simulation with the white box and black box models for selected voltage excitations. Regarding the white box models, the results demonstrate a very good agreement in the prediction of the maximum voltages values that appears in the measured points inside the transformers but a poor agreement in the temporal wave shapes which are dependent on the natural (resonance) frequencies of the transformer. As future work, the WG needs to explain the causes of these differences and try to improve the white-box tools to obtain a better agreement between calculated results and measured values. The paper also presents a discussion about grey box modelling and a proposal of model interfacing with transient simulation program.

Paper A2-214 (Germany) proposes a detailed high frequency (HF) transformer model which can be used for FRA interpretation to study the characteristics of different mechanical faults without performing destructives tests. The parameters of the model are calculated automatically using finite element method (FEM). One advantage of this approach is the possibility to obtain the FRA traces evaluating the circuit models which presents some drawbacks concerning the frequency dependency of the parameters. As the FEM is more flexible compared to analytical methods, it is possible to calculate the frequency-dependent parameters of the windings in detail which was considered in the model. To validate the HF FEM model with measurements, simulation and measurement results were compared for three experimental models. The analysis was done considering the healthy state condition of the windings and the presence of axial displacement. The results showed an agreement between measurements and simulations which shows a good performance of the proposed HF model. Further electrical and mechanical fault implementation will be considered in future steps to generalize the application of the HF model for FRA studies.

<u>Paper A2-215 (Great Britain)</u> discusses transformer failures due to internal resonances initiated by switching transients. It is pointed out that these failures may occur even when transformers have passed dielectric tests in the factory. The paper presents some examples of transformer failure investigations where a special FRA test was applied. This test had an arrangement that made it possible to measure the transfer voltages at accessible internal points of the windings. The results showed significant resonance at frequencies in the range of switching impulse. This condition may pose potential problems for transformers at all voltage levels, especially smaller ones connected to new installations with frequent switching such as on wind farms. In the conclusion, the paper suggests a further study and review of current practices for a better evaluation of this phenomenon. One proposal could be a review in the standard dielectric tests, in particular switching impulse rest, with the inclusion of special measurements to investigate the susceptibility of transformer design to internal resonance.

4.2 Discussion for Preferential Subject No 2

It is well known that Partial Discharge (PD) measurement is an important detection method of incipient failures. Different measurement approaches are discussed by some papers. A2-201 highlights the advantages of UHF partial discharge compared to conventional PD detection methods. The evaluation of the electrical signals in time and frequency domain in a PD localization procedure is presented in A2-205. It also suggests, as future work, the application of transformer high frequency model as a support to PD localization. Another important aspect is the influence of ungrounded conductive objects in the accuracy of the Induced Voltage Partial Discharge measurements. A2-202 presents some information on this topic.

The importance of self-learning vibroacoustic monitoring of reactor tap changers for a variable shunt reactor is described in A2-204. It also shows the potential for condition analysis of the active part of reactors and transformers.

Bushing condition assessment is another critical issue, dealt with by two papers. A2-203 presents a survey of the status of 400 kV shunt reactors bushing in the Swedish national grid and A2-208 presents the experience in bushing fault diagnosis in Power Grid, India.

An advanced tool for transformer condition assessment is presented by paper A2-206. It describes Machine Learning (ML) algorithms as supporting tools for the automatic classification of power transformer operating condition. The main steps towards the training of the ML algorithms and how to handle the common missing data are also presented

Frequency response analysis (FRA) interpretation is still considered a complex task. Some of the papers suggest the application of transformer high frequency model as a tool to support FRA diagnostics. The frequency response of the transformer model could be used as a baseline reference for future comparison (A2-207, A2-209, A2-212, A2-214). A2-211 concentrates on the two lowest frequency resonances and highlights the little commented fact that at low frequencies the form of the responses of different windings are practically identical in form and frequency of these two resonances, despite the fact that different windings will have very different series capacitances and inductances

There are different approaches to build a high frequency transformer model. A2-213 presents the work which has been carried out so far by JWG A2/C4.52 “High frequency transformer and reactor models for network studies” and discuss White, Grey and Black Box models). One of the highlights is the comparison between simulation results, considering the application of these models, and measuring of the response of two transformers (one phase and three phase unit) to some voltage excitation. A2-210 also presents a high frequency transformer model which is compatible with EMTP.

Transformer failures due to internal resonances initiated by switching transients is discussed by A2-215. The paper presents a special SFRA test which helps the investigation of internal resonances and explain some failures. Some recommendations are presented to prevent this type of failure especially regarding wind farm small transformers.

4.3 Questions for Preferential Subject No 2

Question 2.1: Considering the state of art of PD measurement, what parameters and criteria could be used to identify anomalies in the various components of a power transformer or reactor (bushings, OLTC, windings, insulation system, etc.)? Would the possible criteria be sufficient to support some action in the field (inspection, downgrading or even replacement of equipment)?

Question 2.2: Current standards have some technical information on PDs which are not considered for type testing purposes for transformer and reactor acceptance or field intervention criteria. Would it be possible to propose additional normative recommendations for laboratory-type test purposes with PD measurement by electrical and/or acoustic methodologies? For example, could Annex C of IEC 60270 be updated with information from the latest developments (noise treatment, new powerful instruments and monitoring systems, new analytical techniques, more complete databases, and so on)?

Question 2.3: Bushing is one of the most important cause of failures during reactor and transformer operation. Also the application (Transformer or Shunt Reactor) seems to arise as influencing factor. Some surveys show that reactor bushing have higher failure rate than transformer bushing (CIGRE brochure 642). Are there any data and or investigation to confirm this behavior? Can reactor switching be one of the causes of this high rate of failure and should its dielectric impact on the bushings be better evaluated? Are there other experiences, and possibly alternative techniques, that could possibly support (or modify) the experiences and recommendations with bushings?

Question 2.4: What is the major difference between the application of Machine Learning and the so called Artificial Intelligence or even conventional statistical tools when it comes to transformer diagnostics? Can other transformer businesses such as design, testing and manufacturing benefit from the use of Machine Learning? How can transformers users benefit from the use of Machine Learning and ML related tools in their daily operations?

Question 2.5: Transformer high frequency (HF) model has typically been applied for insulation design. This type of model application is also important to study the interaction between transformer and the system transient analyses. In addition to that, some papers suggest the use of HF model to support SFRA diagnostic and PD localization. What is the potential and main challenges of this novel approach? Instead of ‘end to end’ impedance measurements, would it not be more useful in developing modelling to try to measure the whole transmission characteristics of windings?

Question 2.6: Transformer failures due to internal resonances and switching have been reported and confirmed in the literature (IEEE Guide C57.142). Is it accepted that this is a significant failure mode? In studies of interactions between transformers and the system, should the transformer model be accurate to determine resonances between the transformer and the system? Since IEC 60076-16 recognizes that "high level of transient over voltages due to switching" is a special risk for wind turbine transformers, should new switching impulse (SI) tests be recommended as a type test for these and distribution transformers, despite these being at present deemed as 'not applicable' for such voltages by IEC 60076-3? Considering the steep wave fronts of switching transients in wind farms, how should the SI wave shape parameters be chosen?

5. PS3 – Site Commissioning Tests

5.1 Papers for Preferential Subject No 3

A total of 6 papers were received and accepted against the advertised sub-topics:

- Required site commissioning tests for transformers and reactors
- Additional site commissioning tests for transformers and reactors, depending on circumstances
- Trial operation of transformers and reactors, including requirements for additional monitoring

Note that the papers relate to three current CIGRE Working Groups:

A2.54 Power Transformer Audible Sound Requirements
A2.58 Installation and Pre-Commissioning of Transformers and Shunt Reactors
A2.59 On-Site Assembly, On-Site Rebuild, and On-Site High Voltage Testing of Power Transformers

Paper A2-301 (Canada) presents the benefits of high voltage testing at site for power transformers, principally the ability to carry out full dielectric testing at site, to validate site repairs or suspect units without risking the catastrophic damage that might arise if the transformer failed on the system. A containerised system is described which can be powered from the network or a diesel generator and can provide single or three phase test supplies in various configurations and voltages using a step-up transformer, with inductive and capacitive compensation. A mobile impulse test set for up to 1800 kV BIL is also described. Three case studies are detailed: diagnostic PD testing of a large 345kV 340MVA transformer to pinpoint a dielectric fault and then full dielectric testing after an on-site repair involving replacement of windings, confirmation of an LV dielectric fault on a 345kV 880MVA GSU and retesting after field processing and LV bushing replacement, and testing of two large 400kV shell form transformers after an upgrade which involved replacing windings, bushings and tap-changer.

Paper A2-302 (Australia) discusses the emerging role of FRA as a required commissioning test. It concludes that such tests have a proven sensitivity and reliability, but counsels that they primarily detect winding deformation and cannot detect mechanically damaged support structures unless there is associated winding movement. It also comments that sometimes SAT results are 'better' than FAT reference results.

Paper A2-303 (Romania) describes their experience of additional site commissioning tests, specifically FRA and dynamic resistance measurements, applied for correct decisions regarding technical condition. It gives examples where there are differences between FAT and SAT FRA results, possibly due to different test equipment and practices and requests robust criteria for assessing the significance of such differences. It also suggests that LVI tests be made to complement FRA, despite the fact that many consider FRA tests have superceded LVI, apparently because in their experience SFRA tests are prone to interference from the substation above 300kHz. It is also stated that in Romania assets can only be kept in service beyond their 'normal/expected' life, of 24 years for transformers, if a satisfactory technical report from a certified body has been produced.

Paper A2-304 (Austria) recommends site commissioning tests for rapid recovery transformers with an installation time of less than 30 hours. Three single phase multi ratio auto-transformers with plug-in type bushings are described which can be rapidly deployed to site and installed without requiring oil processing. It is suggested that site testing can be limited to dissipation factor/insulation resistance and TTR if the transformers have been stored for a long time, or only TTR if stored for a short time. SFRA tests are recommended if the transformers have been moved.

Paper A2-305 (Korea) discusses sound measurements on power transformers to assess environmental impact. The test set-up and test execution as well as environmental factors are known to affect the sound level test of power transformers. To receive reliable test results, it is necessary to have awareness of such factors and control them properly under consideration of the selected test method. In terms of the sound pressure method, the paper is discussing the sound level uncertainty introduced by the correction for sound reflections based on absorption coefficients given in standards. Background noise handling is not discussed for the sound pressure method with reference to the difficulties involved. Instead, opportunities / limits of the sound intensity method in handling background noise is demonstrated based on 180 sound level measurements. The impact of the transformer placement is studied exemplarily by measurements and simulations. A sound level difference of 3-4 dB was found between transformer placement on the floor and on a palette.

Paper A2-306 (China) describes practices relating to the application of UHV AC site assembled transformers. In order to meet the challenges of installing large numbers of large transformers subject to varying transportation environments and conditions a site assembled single phase transformer bank of 1,050/525kV and 3,00MVA has been developed as a demonstration. Each phase is assembled from modules, including three U shaped core and frame assemblies, two complete winding assemblies and upper and lower tanks, with a maximum individual module weight of 80 tons. After the assembled transformer is tested in the factory it is disassembled into its modules which are placed in their individual transportation units filled with nitrogen or dry air and transported to site. At site the single phase units are reassembled inside a specially built field assembly building which has lifting and kerosene vapour phase drying facilities to manage the two critical quality control aspects of deviation control and drying. After assembly and processing the transformers are tested for no-load loss at 100% rated voltage and load loss at 50% rated current using a specially developed high voltage and large current test system, in addition to induced voltage tests with partial discharge to guarantee the safety and reliability of the UHV AC site assembled transformer. To date four site assembled transformers have been successfully commissioned and monitored during trial operation.

5.2 Discussion for Preferential Subject No 3

Site testing is obviously required to ensure that expensive items of large equipment such as transformers and reactors have been delivered to site without suffering transport damage and have been correctly assembled and processed, so as to assure that they are fit for service and will not present a hazard. In some jurisdictions there may be legal requirements about this.

Site tests often follow factory acceptance tests (FATs) which will provide benchmark results, but often site acceptance tests are different, either because factory test facilities are not available on site or the site environment may be different to that under which the factory tests were carried out.

Lastly, having successfully installed and commissioned transformers, these are usually monitored for some period after entering service to be sure that there are no latent defects or unusual deterioration that are only exposed by service conditions. This is sometimes described as Trial Operation, which usually lasts until the warranty period expires, when a decision has to be made about whether there is definite evidence of any incipient problem.

5.3 Questions for Preferential Subject No 3

Question 3.1: Is it accepted that according to ubiquitous health and safety regulations, utilities have a duty to demonstrate that the equipment they operate is safe and will not pose a hazard to people or the environment ? Are site acceptance tests the best way of achieving this ? Should such tests be carried out by the utility, manufacturer or third parties ? Is some standardisation or simplification of testing required for such a purpose ?

Question 3.2: Regarding the FRA test, is there consensus that the test can be performed consistently and reliably enough to detect damage incurred in transport, or is some verification of testing ability required? Are there good examples of discovered damage suffered during transit using such tests? Is it more likely that any damage arising from transport shocks will affect the core rather than the windings, and if so are there other complementary tests which should be used, e.g. excitation currents and magnetic balance, and should demagnetization be performed to remove any effects of residual magnetism? Is it agreed that if an internal inspection can be carried out safely and without major expense that this should be done, even if it could be inconclusive, particularly to assess and movement of support structures? Are LVI tests still being used, and what are the benefits over FRA?

Question 3.3: Somewhat surprisingly there were no papers on the processing of insulation during installation. Is there therefore consensus on reliable and robust methods and criteria for assessing the dryness of winding insulation before and after processing, e.g. dew point measurements, measurements of moisture in oil or indirect electrical measurements on the insulations?

Question 3.4: On-site high-voltage testing has now been introduced to verify on-site rebuild and/or diagnosis of the transformer at site. Are there any other experiences and/or suggestions of innovative and/or new on-site testing methods for verifying, diagnosing, monitoring, etc. for on-site assembly, on-site rebuild, on-site repair and others including on-site high voltage testing?

Question 3.5: Environments and conditions of transformer transportation have changed dramatically over recent years because of the increasing voltages and powers of transformers, and the changing environment of substation construction areas. For overcoming such problems and creating innovative transporting methods for transformers, are there any new experiences or suggestions, including improving space factor, downsizing, shorter lead times, improved economic aspects, etc.?

Question 3.6: The importance of the "sound level" as a transformer performance parameter has significantly increased over recent years. Many activities were started by manufacturers to improve not only the sound level design accuracy but also the sound level determination by testing. Also in focus are sound level reduction/mitigation solutions. What methods, settings and measures are recommended for accurate and reliable sound level measurements, specifically in a difficult test environment? What is the meaning of "difficult" and "reliable"? Are there any issues with the IEC/IEEE standard requirements for sound level determination? What are the challenges for site measurements and the differences to FAT? Are there case studies for handling sound level issues at site?