GENERAL REPORT FOR SC A2

(Transformers)

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SESSION OPENING

Claude Rajotte, SC A2 Chairman, opened the session at 08:45 with approximately 300 delegates attending. He welcomed attendees and explained the CIGRE Paris session organisation with special reports, questions and contributions.

He also presented the SC A2 organisation, activities and active working groups.

He ended his remarks by presenting the technical committee award to Mr. Carlos Dupont from Brazil. Mr. Gilson Bastos received the award on behalf of Mr. Dupont.

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PREFERENTIAL SUBJECT 1: ADVANCES IN TRANSFORMER DIAGNOSTIC AND MONITORING

A total of 16 papers have been submitted, according the sub-topics:

- Innovative practices for data interpretation and condition assessment: prognostic, case studies and success stories
- Diagnostic, monitoring, maintenance and operation information for strategic management of a transformer fleet
- Specification, integration, and management of monitoring systems to ensure effective utilization of data

PS1 - Keynote presentation by Mr. Patrick Picher (CA)

Mr. Picher presented a keynote on the advances in transformer diagnostics and monitoring. He reviewed the diagnostics approaches being presently investigated by A2 experts (FRA, ageing markers and partial discharge measurement). He also discussed on condition monitoring as part of a complete asset management strategy. He concluded his keynote with a discussion on health index developments.

The Special Reporter Mr. Gilson Bastos formulated the following questions to structure the contributions from delegates.

Question 1.1: What are the practices to combine maintenance and diagnostic data from different sources in order to define an overall health condition of transformers? How can diagnostic and monitoring data be combined?

Question 1.2: What is the existing practical experience with the use of different proposed methods to locate PD through UHF measurements? Is there any generally agreed best method?

Question 1.3: What are the strategies considered by users in implementing single or multi-gas analyzers for generator and transmission transformers? Is the use of multi-gas analyzers recommended for all transmission transformers or only critical units?

Question 1.4: What is preferable in a monitoring system: few key reliable parameters or a large amount of parameters with complex software to provide information to the users? What is the experience of users with the use of a reliable and integrated system in substations which can receive information from different sources (suppliers)?

Question 1.5: In paper A2-109 (figures 9 and 10), methanol shows a linear increase for decreasing DP in high DP value region, and a following decrease for low DP values. Is this behavior observed in other laboratories and field experiments? What are the advantages of using methanol comparing to the use of 2-FAL?

Question 1.6: What are the user's experiences with applying RCM and FMEA to the condition evaluation and intelligent diagnostic of transformers?

Question 1.7: How to determine when it is time to retire an old transformer? Which are the measures to extend old transformer life and influencing factors in transformer life? What are the influencing factors on dielectric properties?

Question 1.8: Which criteria are recommended for objective FRA results interpretation? What kind of faults could be identified by FRA based on the analysis of changes of winding natural frequencies?

Question 1.1

A contribution from Germany reports a method based on multi-agent artificial neural network modelling to integrate monitoring and diagnostics information.

A contribution from France reports on a system for prioritization of replacement and maintenance using two different indices: The Asset Health Index and The Asset Maintenance Index. Data may come from different sources and visual inspection is an integral part of the assessment and guidelines for interpretation has been implemented in the system to ensure a better objectivity for interpretation. It is claimed that the indices for general ageing and maintenance cannot be the same because an asset with a major issue that can be repaired on site at a reasonable cost would have a bad maintenance index result but could have a good general asset health index value. This approach has been applied successfully on more than 25 000 power transformers.

A contribution from Brazil reports the development of a software application that can integrate various sources of information i.e. maintenance records, operational data and diagnostics test results in a aim to optimize maintenance costs, extend useful life of asset and protect corporate image.

A contribution from South Africa reports on the development of a Plant Health Index (PHI) aggregating the available diagnostics information using a weighted sum model. The output is used in a risk matrix to improve operational reliability, to optimize the allocation of resources and to reduce the financial burden of costly failures.

Question 1.2

A contribution from South Korea explains a PD localization method based on Finite-Difference-Time Domain (FDTD) simulation. Measurements are compared using the root-mean-square-error (RMSE) method to a reference time-difference table. Experimental test on a 3 MVA transformer has shown that the proposed methodology is 40% more accurate than a more standard triangulation method.

A contribution from France reports that the UHF measurement using a UHF antenna is best suited to trigger acoustic PD localization measurement because of its inherent immunity to outside noise, the tank acting as a Faraday cage. For outside noise, three UHF sensors can be installed outside in the test bay to localize sources of corona discharge. This methodology is especially useful for testing HVDC transformers (for DC applied voltage and Polarity reversal test).

A contribution from Germany explains the advantages of using UHF measurement compared to standard IEC 60270 practices, i.e. a better external noise immunity and partial discharge localisation. Difficulties persist for calibration and sensitivity depending on the localisation of the antenna in a more central location compared to the bottom or the side of the tank.

Question 1.3

A contribution from France reports that multi-gas sensors allowing Duval triangle diagnostics should be used on more strategic units (HVDC and 400 kV autotransformers). A combination with PD monitoring can help identify the source of the dissolved gasses. For implementation on a larger scale, the use of single-gas monitors can be used as a flagging system to identify incipient faults before the Buchholz relay operates.

A contribution from South Africa reports that all 139 GSU units (and auxiliary transformers in the same substations) in ESKOM are considered strategic and are therefore equipped with multi-gas monitors.

Question 1.4

A contribution from South Africa reports that all DGA data for generator transformers are collected in a central database and algorithms are used to make the diagnosis allowing the detection of incipient faults. Some failures happen without any prior symptoms; however this is not in the majority of cases. The utility is pursuing the integration of other diagnostics information, e.g. electrical tests, to obtain a more general condition assessment of the active part, components and accessories.

A contribution from Brazil reports on a centralized system used to collect and interpret diagnostics data as well as contextual and operational information to assess the failure modes in the various components. As example, a monitoring system were able to capture an incipient fault on the corona ring of a HVDC transformer bushing, thus preventing a major failure.

Question 1.5

A contribution from Sweden reports the results of laboratory investigations of methanol generation and stability over time. It has been found that oil itself can generate a small amount of methanol and the methanol is not stable with time, the reason being unknown at this stage (perhaps esterification). It is concluded that the major advantage of using methanol over 2-FAL is the fact that it is sensitive to thermally upgraded paper ageing, however, the many influencing factors would make its field application very challenging as those factors are generally unknown.

A contribution from France concludes from laboratory investigations that under inert gas blanket (close to sealed design), MeOH is well correlated with DPv (TUP included) and detected at an earlier stage than 2-FAL compound. Under air blanket (closer to free breathing transformers), MeOH is also detected, but generation is uneven versus DPv decreasing. Deeper investigations are necessary to better understand the influencing factors.

A contribution from France reports that the main advantages to use methanol instead of 2-FAL are the applicability for TUP ageing detection and the presence of methanol at an earlier stage of degradation allowing a monitoring of the degradation throughout the entire lifetime. Influencing factors like temperature and ratio of materials still need to be investigated further for field applications.

Question 1.6

A contribution from United-States indicates that the preferred methodology for creating a transformer health index integrates the Reliability Centered Maintenance (RCM) and Failure Mode and Effects Analysis (FMEA) approaches. The contribution illustrates the drawback of conventional health index approaches based on the weighted sum of condition parameters as this method can mask a major issue in the transformer.

A contribution from Brazil reports the positive experience regarding the use of RCM and FMEA for transformer asset management. The utility reports positive feedbacks on the reduction of unplanned outages due to failures, the identification of the most appropriate maintenance actions to increase transformers availability and the overall system reliability.

Question 1.7

A contribution from France reports that the cooling system upgrade is an interesting solution for decreasing the operating temperature and the ageing rate, and thereby increasing the lifetime, for transformer in good service conditions. The upgrade of coolers/radiators can be easily implemented on-site, with or without the need to drain the oil depending on the complexity of the work required.

A contribution from France reported ageing experiments on pressboard samples in mineral oil and natural/synthetic ester oils in a aim to assess the dielectric performance (under AC and LI stresses). It was concluded that even if a small but noticeable decrease of dielectric performance can be detected, the main contribution to the dielectric performance degradation of aged transformers is most probably due to aged oil and not aged pressboard.

A contribution from Japan reports the TEPCO’s approach for distribution transformer replacement based an expected lifetime of 75 years that can be adjusted based on the specific condition of the units using a health index aggregation model. The result of the analysis prompted TEPCO to increase the replacement number from 40 units to 50 units, representing 1.3% of the overall fleet, which is consistent with the utility’s capital and human resources.

A contribution from Sweden reports that life extension can be made by controlling the paper ageing factors i.e. temperature (cooling system maintenance and upgrade), oil reclaiming, insulation drying and keeping the oxygen out (using nitrogen blanket or rubber bag). Other items also includes parameters that utilities consider important for the safe and reliable transformer service operation, so a good condition assessment is mandatory to allow any kind of life extension.

A contribution from Poland reports that the decision for refurbishment involves an assessment of technical condition of transformer solid insulation and magnitude of no-load loss. As technical life of the On-Load Tap Changer (OLTC) and bushings may be shorter than that of transformer solid insulation, cost of their replacement is taken into account. The contribution reports that paper ageing can induce a reduction of clamping pressure which can be more problematic for regions with higher seismic probability. An assessment of these parameters has been carried out on a 400 kV, 250 MVA transformer.

Question 1.8

A contribution from Russia reports that the FRA interpretation should be based on the deep understanding of windings natural frequencies. The typical frequency response measurement (end-to-end) is characterized by several resonant frequencies; among them are some of the winding natural frequencies. Natural frequencies of individual windings can be emphasised using open and short circuit measurements and the analysis of real part of the input admittance.

A contribution from the United-States reports the many influencing factors than need to be addressed before any objective interpretation can be made. The objective interpretation is the scope of the active CIGRE WG A2.53. An example of a bad measurement (grounding problem) shows that it can be interpreted as a false positive if the influencing factor is not well considered in the assessment.

A contribution from France reports FRA case studies showing the importance of experience in ‘reading the responses’ for the correct interpretation. The slight discrepancies in frequency response can be due to several influencing factors, including to the measurement setup itself. The failure modes impacts on the measured frequency response will also depends on the design of the transformer, windings configuration and internal connections, making the interpretation even more challenging. To achieve an objective interpretation, research collaboration between manufacturers, utilities and service providers will be mandatory in order to share the collective experience in interpretation and transformer modelling.

Discussion

Several spontaneous contributions were raised from the floor regarding cybersecurity, case studies for partial discharge measurements, the impact of maintenance on oil ageing, the use of big data for creating a transformer health index, how to set limits for gas-in-oil monitors, FRA interpretation and the influencing factors for ageing markers interpretation.

Summary of PS1 contributions

- Health index is a very important tool for utilities to manage their fleet and help decisions, however some cautions shall be taken in the parameters used.
- Condition assessment depends on data from different sources.
- UHF measurement is a good option to PD localisation despite some difficulties due to antenna calibrations and sensitivity.
- Methanol is becoming a reality and no more a promise as a transformers insulation aging marker.
- Life extension is achieved by controlling temperature, humidity and oxygen content in oil.
- FRA interpretation is useful for fault detection but it is influenced by many factors. WG A2.53 will put a light on this subject.

PREFERENTIAL SUBJECT 2: EHV/UHV AND EHVDC/UHVDC TRANSFORMERS AND THEIR COMPONENTS

A total of 10 papers have been submitted, regarding the following sub-topics:

- Specification, design, material, manufacturing, testing requirements and facilities
- Transportation constraints, installation and commissioning, reliability, operation and maintenance
- Shunt reactors

PS2 - Keynote presentation by Mr. B N De Bhowmick (IN)

Mr. De Bhowmick presented a keynote on the challenges for EHV & UHV transformers and reactors in the Indian Grid. He presented an overview of the Indian grid and the growing needs for EHV and UHV transformers and reactors. The specifications were adjusted and utilities and manufacturers are in regular interaction to cope with the growing needs and the new technologies.

The Special Reporter Mr. Krause formulated the following questions to structure the contributions from delegates.

Question 2-1: The technical collaboration of manufacturers with their customers has obvious benefits. From experience, what are the issues related to manufacturer-user common technical projects, in a view of confidentiality (i.e. leakage of intellectual property of design and application), and delay due to additional time spent for the conception/design/procurement phase? What are the limits of such co-operations, not least respective to the EHV/UHV range?

Question 2-2: With regard to parameters verification that are not included in the standard factory acceptance test – Is there a need for new/more standardized test procedures specifically related to EHV/UHV transformers, to better cover these parameters? What are the economic aspects and consequences of additional testing?

Question 2-3: With the currently available limited experience of equipment in the 1000-1200 kV system voltage range, what are the possible improvements regarding the test specifications of UHV transformers and shunt reactors? What can be derived and stated to the question whether the established requirements and insulation levels in the standards are satisfactorily providing the required reliability for one hand, without concurrently demanding excessively high values, which in turn has negative impact from an economic perspective?

Question 2-4: The demand and use of alternative liquids different to mineral oil is growing, and the application in 400 kV systems is currently the UHV-level of such liquids. What are the technical limits regarding their application in 800 kV or 1000/1100 kV systems, and in DC (rectifier) transformers? How different from mineral oil is the dielectric and thermal behaviour in real transformer insulation systems? What measures are recommended or necessary to overcome the somewhat higher oxygen/air (oxidation) reactivity of natural esters specifically with regard to (unplanned) repair work, transportation, commissioning and maintenance of large transformer units?

Question 2-5: It appears that many users are not requiring Short Circuit Testing because of costs and delays. What are the best practices to allow good SC capability at best costs? The short-circuit testing of "mock-up" transformer models provides several benefits, in particular in the case of large EHV/UHV units. What is the assessment of the validity (model versus full transformer testing and/or versus forces/stress calculation and design review only)? How is the "mock-up" expenditure for design and testing (cost, time) rated?

Question 2-6: In the current standards, the insulation properties are verified for power frequency, lightning (full-wave, chopped), switching impulse, DC and polarity reversal if applicable. To what extent is the high-frequency (high dv/dt) performance of oil/paper insulation systems explored experimentally (small-scale up to EHV/UHV-scale), fully understood and reported in literature? What is known regarding the long-term behaviour of transformer insulation stressed with high frequency voltages over decades in service, and to what extent is the robustness sufficiently verified at the factory acceptance test?

<u>Question 2.1</u>

A contribution from Italia reports that the development of UHV bushings (1100 kV) has been carried out with the collaboration from the customer for determining the acceleration at the flange due to seismic events. The detailed FEM simulations was carried out with the details of the tank and bushing design to make sure the specification was adequate. The time spent for this exchange of information and collaborative work ensure a better product at the end but also put pressure on the remaining time schedule for development, fabrication and test.

A contribution from France reports that the technical collaboration between manufacturer and user is beneficial; however, the level of details required by the utility should be clearly defined at the tender stage, so the suppliers can estimate their own cost and time to prepare the documents. This practice prevents potential delay in delivering the unit. Confidentiality agreement should be made when applicable and good methods to maintain the confidentiality of the transmitted information should be implemented.

A contribution from Japan reports that the technical collaboration between utilities, manufacturers and others is promoted in Japan through the Electric Technology Research Association (ETRA) organisation since 1933. Similarly to CIGRE, ETRA coordinates several working groups regarding various important topics of common interest for the stakeholders and the deliverables are technical brochures. For example, a technical brochure was issued in 2013 regarding a survey of quality control practices for disassembly, transport and site installation of power transformers.

Question 2.2

A contribution from Japan reports the required special tests that should be carried out on site after site-assembly. These tests verify the integrity of the transformer active-part re-assembled on site after being transported in parts due to size and weight constraints.

Question 2.3

A contribution from Japan details the special requirement for a longer insulation test for a special transformer designed with 1.2 MV (dc) insulation between the primary and the secondary. The special test is required to let sufficient time (5 hours instead of 1) for the dc field to build up in the main insulation.

A contribution from England reports the successful technology transfer for the production of 800 kV HVDC transformers. The key aspects regarding design concept, people management, communication, process and training are presented.

Question 2.4

A contribution from Germany describes the 2 main dielectric performance differences between ester fluids and mineral oil: a) different streamer propagation behavior visible in non-uniform configuration and long insulating distance and b) higher permittivity of the ester liquid thus reducing the absolute stress in the liquid insulation.

Another contribution from Germany details the differences in dielectric (electrical withstand reduced in non-uniform configuration) and thermal (higher viscosity, higher thermal conductivity, higher pour point) performance of ester oils compared to mineral oil. Some design suggestions are made regarding the use of vacuum type tap-changer allowing sharing the use of the main tank oil for the OLTC, thus simplifying the overall sealed design (using expandable radiators, rubber bag or Nitrogen blanket) and reducing the size, which can be an issue for UHV transformers.

Question 2.5

A contribution from India reports that in recent years short circuit test requirement/similarity requirement has increased in India. Mock-up test is a new concept that still needs to be further explored by manufacturers and utilities. Another alternative proposal is to extrapolate the IEC standard safety margin of similar tested transformer. Evaluation of suppliers and the build-up of confidence level can be explored to waive off the test or to opt for reduced model test.

A contribution from France summarizes the pros and cons of full short-circuit tests compared to tests on half of a transformer (one leg) or a mock-up (one leg with reduced height). The mock-up must be carefully designed to make sure the mechanical stresses are at least the same as those on the real transformer. Experience shows that the cost of a mock-up test (manufacturing and testing) can be up to 40% of the cost of the full transformer.

Question 2.6

A contribution from Brazil reports that the effect of high frequency repetitive impulses, the effect of very high rate of rise transients and the effect of dielectric age-related degradation are not well covered in the literature. As detailed in a 525 kV reactor example, the collaboration between utility and manufacturers is required to improve the dielectric performance because the standard dielectric tests do not always adequately represent the real internal stress due to network interactions during switching. Site measurements can be provided to the manufacturer upfront to validate the dielectric design performance.

Discussion

Spontaneous contributions were raised regarding the polarity reversal test and the need for standard revision, the performance of ester oil and the related standard development requiring more experience in HV.

Summary of PS2 contributions

Collaboration Manufacturer-User

- ETRA (Association) produces brochures regarding quality, safety, environment and reliability.
- Collaboration issues = confidentiality, cost, time.

Parameters not included in standards

- On-site test (results) is compared with factory acceptance test. Experience up to 500 kV / 1000 MVA.

UHV Test specification

- HVDC Transformer (ITER project): depending on oil resistivity, 1-hour DC test is not sufficient to achieve steady state condition. Extension to 5 hours test is successful.
- 800 kV DC: Transfer of technology, challenges, and way to overcome.

Alternative liquids for EHV/UHV

- Example natural ester
    - Oxidation, trans-esterification / sealing, avoid air exposure
    - Viscosity and cooling performance, oil filling, resting time, cold start procedure
    - Dielectric strength different from mineral oil
    - Material compatibility
- Breakdown behaviour of ester liquids
    - Faster streamer propagation, longer stopping length
    - Lower withstand voltage for non-uniform field configurations – geometry dependent

Short-circuit verification with «mock-up»

- Not practiced
    - Limitations: time, confidentiality, no standards, model is waste, no experience
    - Evaluation uncertain
    - Review safety margins, derive confidence factor about experience, software, manufacturing
- Experience positive

  - Radial buckling, spiralling, tilting 100 %
  - Representativeness: stress level for mock-up 120%
  - Total costs up to 40 % of actual transformer, derive margin from stressing mock-up until failure

HF (high dv/dt) insulation performance

- Dielectric failures, unknown cause
  - Assessment of equipment reliability is a challenge
  - Not covered by standards: repetitive impulses on insulation, high rate of rise, degradation

PREFERENTIAL SUBJECT 3: TRANSFORMER WINDINGS

A total of 11 papers have been submitted, according the following sub-topics.

- Five papers discuss mainly design aspects (3x thermal, 1x dielectric, 1x short-circuit)
- Four papers focus on testing (1x impulse, 1x stray gassing, 1x lifetime, 1x short-circuit)
- Two papers highlight life extension aspects (component replacement, moisture ingress/drying)

PS3 - Keynote presentation by Mr. Peter Werle (DE)

Mr. Werle presented a keynote regarding transformer windings, the most important component of transformers that is also mostly determining the transformer useful life. He reviewed the conductor and insulation materials, design and simulation aspects and presented an outlook of the potential future developments.

The Special Reporter Mr. Ploetner formulated the following questions to structure the contributions from delegates.

Question 3-1: During last decade, 3D computer simulations enabled significant refinement in the quantification of transformer phenomena in mechanics, dielectrics, magnetics and more recently, the thermal area. More precise design tools were developed. Is there the expectation that this will lead to a reduction in design related failures during final acceptance testing and in service? Are there already signs indicating this in recent failure statistics? Are there other observations in this respect (shrinking unit dimensions…)?

Question 3-2: The degree of network meshing / interconnection is expected to increase with consequences for the available short-circuit power and the number of events. With reference to chapter 7 of paper A2-304, what is the expectation for the short-circuit performance of power transformers in service under harsher conditions? Will it be justified and supportive for the network reliability to perform more short-circuit lab testing or will improved designs and manufacturing techniques due to more advanced tools and manufacturer experience account for the more severe service conditions?

Question 3-3: While dry-type transformer technology for higher voltage classes and power rating is technically possible, questions about the economics and efficiency are risen here. What are the ratio figures between dry-type and liquid-filled technology in prime cost, running cost, efficiency, space requirement (with OLTC), maintenance cost, lifetime? Will dry-type technology remain a niche product in the upper voltage classes/rating or evolve to be more frequently in use?

Question 3-4: With reference to paper A2-306, is there DGA experience available due to sparking between floating electrodes – located in close vicinity and directly exposed to oil (bare metal parts – no cellulose involved)? Can the ratio acetylene / hydrogen indicate the involvement of cellulose and therewith provide information on the criticality of the discharge? Is it possible to say, a slow increase in acetylene with no or very little hydrogen generation is non-critical for the transformer service?

Question 3-5: Is the larger water content in ester liquid of any dielectric risk, specifically in service conditions with potential for unintended air/moisture ingress? What are the differences in this respect between mineral oil and ester designs?

Question 3-6: Paper degradation in ester liquid designs is mainly a function of temperature because the moisture content in paper remains small due to the liquids characteristics. To what extent is paper ageing slowed down compared with mineral oil designs (same temperature profile), where paper moisture is higher and increasing with time? How does the slowed down paper degradation relate to a longer lifetime of the entire transformer? Are there already practical examples verifying the increased lifetime of ester designs? What about other factors averting an increased transformer lifetime (oxidation, unintended moisture ingress)?

Question 3-7: In respect to findings outlined in paper A2-311, is there a need to reconsider the wave shape requirements for LI testing of transformers and modify / extend the testing requirements? Would this be a subject for a new CIGRE WG?

<u>Question 3.1</u>

A contribution from France reports the experience with 3D electromagnetic modelling to assess the structural parts and tank heating due to windings leakage flux and high current in bus bars at the proximity of the tank. The very complex problem needs experimental data for validation and improvement of simulations. The application enables optimized solutions in respect of losses and unit dimensions.

A contribution from Japan reports 3D electromagnetic and subsequent thermal modelling of a shell-form transformer to assess the increase of temperature on core and metallic structural parts during GIC events. It has been demonstrated that the use of non-magnetic stainless steel for the core metallic structure support limits the overheating to a safe level. Winding currents under GIC are determined with a circuit network. The parameters are derived by 3D electromagnetic simulation of the exact winding configuration. Core and tank are magnetized with closed loop currents. Losses in windings are estimated from the results and evaluated. Conclusion: Properly designed shell-type windings have sufficient withstand capability against GIC.

A contribution from France describes the benefit of 3D modelling for shell-type and 2D (validated with 3D) for core-type thermal analysis. The better understanding of the thermal behavior allowed the better localization of the hot-spot temperature (validated with point measurements using fiber-optic) which often is located just after the blocking washer where the oil flow is minimum. This example shows the importance of considering not only the loss factor (*Q*) but also the cooling factor (*S*) which, in this specific case, was dominant.

<u>Question 3.2</u>

A contribution from Netherlands reports that 23% of the short-circuit tests carried out on 300 transformers (rated 25 MVA and above) in the last 20 years were not successfully passed. There is a tendency for improvement, as the average fails reduced from 30% in the mid-nineties to about 20% recently. The explanation seems to reside in the very complex nature of the stresses and forces during a short-circuit event. The electromagnetic field is often estimated using a 2D axisymmetric calculation, but the real winding is a 3D object, with inhomogeneity like transpositions, pitch, etc. The accessories behaviour is also out of the reach of modelling, e.g. oil spills and damage to bushing flange. The dynamic nature of short-circuit and the various mechanical builds make it even more challenging to estimate the real mechanical stress in the various components.

A contribution from France discusses the complexity of transformer short-circuit withstand capability and the remaining risk level in respect to possible verification methods. The complexity is exemplarily demonstrated by a 3D electromagnetic simulation showing the different axial and radial mechanical stress during short-circuit in the plan perpendicular to the core and in the window under the core. This example demonstrates the importance of considering the 3D effects to ensure a better estimation of the stresses that can lead to failures in service.

A contribution from France informs on the intentions for the ongoing IEC 60076-5 (Short-Circuit withstand) standard revision. In the revised standard, more details will be given for the three withstand evidence methods ‘full testing’, ‘mock-up testing’ and ‘calculation’. Information on the remaining risk level is key topic here. A further new section will inform on handling heavily stressed transformers such as arc furnace units, specifically in respect to fatigue stresses.

Question 3.3

No contribution was received to this question. The subject ‘liquid-filled versus dry-type transformer’ is nevertheless considered important for the power transformer industry because the possible power rating at the newly introduced higher voltage classes up to 145 kV for dry-type units offers an alternative for a segment so far exclusively covered by liquid-filled technology. In order to select the better option for a specific application, sufficient information including such asked in the question should be available and easily accessible for the purchaser. It is therefore suggested to consider the subject in further studies.

Question 3.4

A contribution from South Korea reports experiments on a model, built to produce partial discharges in oil between floating metallic electrodes. Two different PD pattern are observed and are called ‘initial PD’ and ‘intermittent bulky discharge’. For the ‘initial PD’ (at lower voltage), the gap has never been completely closed by the arcing whereas the ‘intermittent bulky discharges’ (at higher voltage) bridges the gap repeatedly but no breakdown occurred. The DGA indicated low energy discharge, thus showing the self-healing behavior of an oil gap. Gas content was mainly C2H2 with much less H2, which usually is the most significant gas on low energy discharges. It is worth to investigate the effect for different types of insulating oil / liquid in further experiments.

A contribution from Germany explains that discharges in oil due to a floating metallic part usually lead to the creation of hydrogen, but for oil with high aromatic content, hydrogen is less present. This uncertainty in the hydrogen generation makes it impractical to use the acetylene to hydrogen ratio as a condition indicator. As an example, the contribution presents the operation of change-over selector of a tap-changer that will create floating electrodes, causing sparks and low energy arcs in the oil. A design using a spring-loaded snap contact leading to a much shorter arcing/sparking time, thus reducing the gas generation by at least 90%, is suggested.

Question 3.5

A contribution from France reports that the natural ester breakdown voltage (IEC 6056) is similar to mineral oil in relation with the relative moisture content, even if the ppm level is higher due to higher moisture solubility. Natural ester designs must be sealed due to the higher sensitivity to oxidation. Sealing of the tank can be made using expandable radiators, rubber bag or Nitrogen blanket.

A contribution from Germany reports that ester liquids can absorb much more moisture before saturation. At room temperature, mineral oil is saturated with approximately 55 ppm, comparatively to 900 ppm for natural ester and 1880 ppm for synthetic ester. The oil breakdown voltage starts to decrease significantly with the relative humidity in the liquid exceeding 40%. Since the ester oils can absorb much more water, it is concluded that such are more resistant to unintended water ingress. However, high water content can lead to rust on metallic parts and also deteriorate the oil. Therefore, all liquids used in HV shall have minimum water content.

A contribution from Germany reports again that the relative saturation, not the absolute water content, determines the dielectric breakdown performance. The limits of relative saturation are similar for mineral oil and esters. There is an important difference between esters and mineral oil regarding the diffusion coefficients between solid and liquid: Moisture diffusion in ester is 2 times quicker than in mineral oil (from thin insulation) and is a further dielectric advantage. The chemical nature of esters can make them react with high moisture content, creating free acids and alcohols which can lead to increased acidity and conductivity. This is an important argument for keeping water content low also in ester filled equipment.

<u>Question 3.6</u>

A contribution from France reports that in transformers, hydrolysis, pyrolysis and oxidation act simultaneously and cause cellulose degradation. Experimental ageing tests have shown a reduction of cellulose degradation rate in natural ester oils presumably due to the drying effect of natural esters on the paper during the ageing process, thereby reducing the hydrolysis effect.

A contribution from Japan reports comparative ageing tests using rapeseed oil (natural ester) compared to mineral oil. Based on experiments in a sealed container with a nitrogen blanket it has been found that the rapeseed oil has a slightly longer lifetime than mineral oil. With air-tight sealing the difference in lifetime is bigger. In terms of gas formation, it has been found that the CO+CO2 formation is similar to mineral oil, however, a large quantity of methane and propane was generated, which is not the case for mineral oil.

<u>Question 3.7</u>

A contribution from Russia reports that the wave shape requirements for chopped and full lightning impulse should be revisited. For chopped impulse, the standard specifies that the time to first voltage zero should be as short as possible, however, this parameter does not have a strong influence on the transient voltages affecting the inter-disc insulation. The over-swing factor after the chop would be the most critical parameter to specify and it should be lowered to ensure a representative test. Regarding full lightning impulse, the *k*-factor is used to compensate for the overshoot at the front of the impulse, however this approach does not represent correctly the stress in the oil ducts all along the winding. This topic should be the scope of a new CIGRE working group.

A contribution from France reported on EMTP simulations that showed that the standard 1.2/50 impulse wave shape may not represent well the real overvoltage solicitation at the transformer terminals during a significant lightning strike, especially if the neutral is not earthed. That can lead to stronger overvoltage within the windings compared to standard full wave test. Further research and collaboration between manufacturers and users is recommended and this work could be addressed within a new CIGRE working group.

<u>Discussion</u>

Several spontaneous contributions were risen from the floor regarding the different stresses caused by positive and negative impulses and the applicability of mock-ups for short-circuit tests.

Summary of contributions for PS3

Improvements by 3D simulations are visible

- Electromagnetic design (losses, tank hot spots, GIC withstand)
- Thermal winding design (fibers location setting, site analysis, cooling stage definition)

Short-circuit withstand verification

- Real size SC testing most reliable verification method
- Design verification by calculations/simulations may be reliable if the rules and manufacturing techniques are suitably validated by tests and experiments
- Design verification without experimental demonstration – also if using 3D tools – is not a reliable verification method

Liquid-filled vs. dry-type – Economics

- Need to perform overall comparison studies between dry-type vs. liquid-filled transformers for voltage classes 72 kV – 145 kV
- Target: Provide guidelines for the optimal selection

Gassing on floating electrodes

- H2 usually dominating vs C2H2 for low energy PD
- Repetitive (bulky) discharges (sparking) may result in C2H2 being dominant
- No service risk if low amount or increase rate in C2H2 only
- Example: sparking with some gassing during 'change-over selector' operation is normal

Moisture in mineral oil and in ester

- Moisture diffusion in ester much faster resulting in small RS hysteresis during temperature cycling
- Ester designs dielectrically less critical against moisture
- All HV liquids shall be kept dry because of risk for rust, hydrolysis (increase of acid number and conductivity), polymerization

Paper degradation in Ester liquids

- All lab tests prove a slowed down paper aging in esters
- Generation of CO+CO2 comparable for mineral oil and natural ester
- Natural esters show low temperature gassing of CH4 and C3H8

Reconsideration of LI testing

- k-factor approach and chopping requirements (time to zero, over-swing) as per IEC standard can lead to insufficient testing

- Service LI wave shapes can cause higher stresses in windings than during testing

- Consider a new CIGRE WG to revisit LI test requirements

CLOSING REMARKS

In his closing address to A2, Chairman Claude Rajotte presented his vision of the following trends and challenges for power transformers.

Condition assessment (transformer utilisation)

- Users and suppliers should continue and intensify the sharing of successes (case studies) and ideas to improve the condition monitoring technologies

- Improvement of off-line tests interpretation is still needed (e.g. FRA – A2 WG started, DFR, etc.)

- Importance to gain experience with the utilisation of ageing markers in conjunction with a more intensive application of post-mortems to improve the interpretation (A2 WG completed soon)

Maintenance and replacement strategies (transformer utilisation)

- Use of the best practices possible to develop and improve health indices (A2 WG completed soon)

- In the context of intensification of transformer replacements, there is a need for utilities to find ways to extend the life of transformer (A2 WG started)

- Need for having frequently revised reliability data (A2 brochure recently published – previous CIGRE transformer reliability survey was published more than 30 years ago)

- Even with all the diagnostic techniques available, it is still very difficult for transformer specialists to answer the FAQ: "Can this transformer remain safely in operation for another 10 years?"

Modelling (transformer technology)

- Importance for transformer designers to keep the basic knowledge even if they use very sophisticated software during transformer design

- More intensive application in the future of modelling to evaluate thermal and dielectric performance and intensive use of transformer HF models (A2 WG running)

- Use of modelling for tank design for an increased performance to contain oil and to prevent fire in case of transformer failure

SC A2 Chairman, who has played this role since 2010 and who is terminating his mandate, thanked all the persons who supported him during the last 6 years, in particular:

- Patrick Picher - Secretary

- François Devaux, Pierre Lorin, Stefan Tenbohlen and Yukiyasu Shirasaka - Advisory Group conveners
- Past and current Working Group conveners
- Past and current Study Committee members (regular and observer)
- Special reporters and Colloquium Chairmen for all sessions and colloquium
- Pierre Boss - Past Chairman

Mr. Rajotte drew this A2 2016 Paris Session to an end by thanking all the persons involved in the 2016 Paris session and confirming the next SC A2 event is the Colloquium being held in Krakow, Poland, in October 2017. Detailed information will be available on the SC A2 web site.

The session was closed at 17h50.