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SPECIAL REPORT FOR GROUP A2
(Power Transformers)

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INTRODUCTION

Transformers are critical assets in T&D systems. In the competitive increasing market, these transformers are subjected to larger average loading and more frequent overloading in combination with some reduction of maintenance program. The result of these changing operating conditions is that more thermal stresses are imposed on the transformers affecting its reliability and lifetime.
Age of important transformer population has now or will exceed soon 25-30 years, namely the term, which has been traditionally assumed as transformer life span. Apparently the global task of the electric power industry will be to manage the serviceability of a huge aged transformer population in order to get the most out of the asset. One way to accomplish this is to promote the most appropriate on-site actions to ensure the longest possible service life.

The 2004 **Preferential Subjects** under which the 19 papers are grouped are as follows :
1. Thermal Performance of Power Transformers (7 papers);
2. On site operations (12 papers).

Keywords : Transformer, insulation system, thermal ageing, hot spot, modelling, testing, on-site operations, life, repair, drying, diagnostic tests , life extension.

1 PREFERENTIAL SUBJECT 1 : THERMAL PERFORMANCE OF TRANSFORMERS

1.1 Introduction

Together with the need to optimise the thermal design by the manufacturers, more and more importance is attached to the proper understanding of the thermal performance of the transformers. New thermal aging models are investigated by research labs, improved hot spot modelling techniques are developed and become more and more common practice. The use of detailed temperature measurements by means of optical fibers or infrared thermography becomes popular during temperature rise tests. The users also specify also overload regimes and like to test the behaviour of the transformer in these conditions. Finally, a big concern is issued for the capability of the thermal performance of older in service units.
IEEE released an update of the thermal loading guide in 1999. In 2001 IEC started a maintenance group MT2 to revise the very popular Loading Guide 354 now 60076-7. This WG encountered heavy discussions on thermal ageing criteria, new insulation materials and modelling techniques. A new IEC WG was erected on high temperature insulation materials releasing a Technical Specification document IEC 60076-14 in 2004.

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Due to the changed in operating conditions of transformers, as well as the developments in designing and testing transformers and the concerns in the Standard Committees, it was decided to set up the Cigre WG A2-24. One aim is to bring a state of the art review of the thermal performance of power transformers. The WG has 22 members from 17 countries and met 3 times (Merida Mexico 2003, Brussels Belgium 2003, Nurnberg Germany 2004).

- The first task is to establish a state of arts in the field of thermal ageing of power transformers. The ageing of the insulation materials is function of temperature, moisture, oxygen and acidity. This work in close collaboration with Cigre SC D1 will support the ageing criteria discussed in the revision of the IEC Loading Guide.
- The second task is to deal with loading and overloading of power transformers. The computational methods as well as experimental verification of temperatures and overload capability need to be investigated. The idea is to provide guidelines for appropriate applications of the new IEC document as well as to edit recommendation for areas not covered by IEC standards; for example, gas turbine operation.
- The third task is to consider practical applications for in service transformers, including determination of overload capability, reliability and economics, which is important for decision making.

1.2 Thermal ageing of insulation systems

Cigre D1 has done recently a tremendous work on the interaction between different ageing mechanisms on the insulation system. The combined effect of oxidation, water, acidity and temperature is investigated for both cellulose and thermally upgraded insulation. In collaboration with the WG A2-24, the results were discussed and will be presented during the A2 session.
Paper A2-103 discusses a hybrid insulation system and their use in power transformers especially in refurbishment. The average winding temperature or hotspot is typically 30 K higher than in conventional insulation systems allowing the designer to reduce the dimensions of the transformer or overload the transformer without accelerated ageing.

<u>Question 1</u> : Do manufacturers or users have experience that the transformer with a high temperature design has an improved lifetime and reduced maintenance ? How do the liquid or other thermally lower rated insulation behave ?

1.3 Modelling of thermal performance of transformers

Many manufacturers have investigated intensively in the accurate modelling of the thermal performance of a transformer. Detailed models based on physical laws of thermodynamics and hydraulics have been used such as in papers A2-101, A2-105 and A2-107 and the authors report detailed temperature profiles. The models presented show to have an improved accuracy of 3 K and have been benchmarked against other models and tests.

<u>Question 2 :</u> Is there a general agreement what physical models (both heat transfer and hydraulic friction) are now to be used for the detailed models in transformers in order to obtain the required accuracy ? Can the required accuracy be obtained by considering each winding independent of another and of the external cooling mode such as ON, OD and OF ? Before accepting these models in design and design reviews, how many transformers need to be benchmarked ? Can the models be used for all type of transformers such as small transformers to for example >500 MVA transformers ?

Two papers also use detailed finite element analysis codes solving the Navier Stokes equations and energy equation for a detailed flow analysis in winding. These CFD simulations clearly show the detailed velocity and temperature profiles inside windings.
Most of the models show a steady state temperature calculation. However, in practice, the critical loading will mostly be transient resulting in fluctuating temperatures in the insulation system.

<u>Question 3 :</u> How can the finite element codes be useful in designing or reviewing a transformer. How are these code models benchmarked versus experiments ? What are the developments in transient thermal modelling for transformers ? Do they cover specific areas of thermal stresses with the relevant temperature accuracy ?

Paper A2-104 highlights the impact of transformer shielding in order to reduce the tank losses. The extra losses will also lead to a higher temperature inside the transformer.

<u>Question 4</u> : Extra losses in metal components such as tank, clamping, cover and its temperature rise need to be modelled. Do they need to be modelled accurate in order to guarantee a reliable transformer. What about the thermal design of other components such as bushings, leads, tap changer in high load or overload conditions ?

1.4 Testing of transformers

The accurate testing of the thermal performance in a temperature rise factory test is as crucial as the modelling. The method of top oil measurement and average winding measurement are standardized. Hot spot values and location in winding or other components cannot be found by these methods.
The temperature rise test is limited to a steady state situation at rated load.

<u>Question 5</u> : Should the specification or the standards also address :
- how to measure the value and location of hot spot ?
- how to specify the transient behaviour of a transformer and its overload capability ?

For new transformers, standardized temperature rise tests can be performed and when more information is needed, accurate modelling and detailed testing is possible in order to verify the compliance. Most of the transformers are however in service. Paper A2-106 explains in detail a successful in situ temperature rise test on a 420 kV transformer and showed a good accuracy in comparison with factory tests.

<u>Question 6</u> : Can the results of a temperature rise deviate during the life time of a transformer ? Is the in situ temperature rise test the only way to verify the thermal performance at rated load or overload to evaluate a in service transformer ?

Paper A2-102 explains the Australian and New Zealand practice and massive experience when dealing with transformers beyond nameplate rating. It stresses the importance of clear specification by utility transformer engineers, design reviews, the success of detailed measurements with optical fibers and factory overload tests. The paper discussed an on site temperature test showing the limited thermal performance of an OFAF transformer.
Finally, as discussed in the papers, many efforts and research are done by both manufacturers and users to have an accurate thermal design, temperature rise test and use of transformers for high loads. These efforts are required to get a reliable transformer in the network and reduce the possible risk of failure and the ageing rate.

<u>Question 7</u> : What are the practices of users regarding the specification and testing of transformers for loads beyond name plate ? Do users have experience that transformer failures or very short life time have been the result of a continuous overload or a short peak overload ? Was the cause a wrong design, wrong assessment of the integrity or extremely high loading ?

2 PREFERENTIAL SUBJECT 2 : ON SITE OPERATIONS

2.1 The many faces of transformer life

The life of a transformer may be introduced as the change of its condition with time under the impact of thermal, electric, chemical, electromagnetic and electrodynamics stresses, as well as under the impact of various contamination and aging processes. The withstand strength of the transformer will naturally decrease over its life due to various ageing processes (normal ageing), but may deteriorate faster than normal under the influence of contaminants or destructive processes.

Paper A2-209 discusses four major factors regarding transformer deterioration in various manners : 1) Thermal factor, namely, deterioration of DP and mechanical strength of paper with time including possible bubbles evolution from moistened paper due to sharp rise of temperature during overloading; 2) Electrical deterioration of insulation dielectric strength under repeated effect of lighting and switching surges and in some cases under electrostatic discharges; 3) Mechanical deterioration under impact of through fault currents and frequent in-rush currents; 4) Environmental factors, which affect basically tank and sealing gaskets.

Paper A2-201 reports power transformer failure associated with corrosive sulfur in oil. Early studies have shown that non-corrosive sulfur could become corrosive at some elevated temperature while contaminated oil could cause degradation of contacts and winding coil deteriorations. The paper underscores also dangerous effect of dissolved in oil metals especially the copper.

Paper A2-204 highlights critical impact of moisture and oxygen on acceleration of insulation decomposition. Hence on-line drying and degassing processes are considered as effective operations to extend the life.

Paper A2-206 suggests key factors for some transformer components and their maintenance techniques. Oil oxidation and contamination is reported to be a subject of primary concern.

Paper A2-212 states that typical defective condition of aged transformers involves contamination of insulation with carbon and metal particles, and absorption of oil by-products.

***Question 8 :* Can problems related to the reliability of aged transformers and relevant failure statistics be reported by the experts ? Which operations would be technically and economically justified to maintain a reliable service ? What are the criteria to select the candidates for life extension and those to determine the relevant required operations ?**

2.2 Updating the overview of diagnostic methods

The SCA2 Colloquium in Merida (2003) highlighted substantial progress in diagnostic techniques particularly in interpretation of test data and evaluation of thermal, electrical and mechanical transformer properties. Several papers continue the discussion on the efficiency of these methods.

Partial Discharge (PD) measurements : 28 counties contributed to the CIGRE survey reporting successful experiences of PD measurements for diagnostic, monitoring and quality assurance purposes. Achieved sensitivity of electrical PD detection (about 50 pC with appropriate HV low noise source) shows a new opportunity particularly in the quality control of in-field repair.

Paper A2-209 considers PD measurement as a preferential tool to assess insulation electrical deterioration including the detection of possible electrostatic phenomenon.

Papers A1-203 and 210 highlight PD tests as the most effective way to guaranty the quality of major repair.

Fluid as diagnostic media : Paper A2-201 highlights fluid as a powerful diagnostic media emphasizing that transformer oil retains about 70% of the diagnostic information available for transformers. In-depth analysis and new analytical techniques, especially analysis of dissolved sulfur and dissolved metals are recommended as a complementary diagnostic tool.

Insulation life assessment : Analysis of furanic compounds especially Furfural (2FAL) and relevant interpretation of Degree of Polymerization (DP) of paper as well as direct measurement of DP of samples remain the fundamental technique to assess residual life in term of reduction of PD and deterioration on mechanical properties of paper.

Report A2-212 mentions that DP measurement is adopted as a major method for insulation life assessment and for the determination of loss of life during drying out. However the latest CIGRE findings reported to A2 Colloquium in Merida have shown that diagnostic accessibility of aged transformer is still rather limited. The difference in insulation temperature is responsible for the nonuniform decomposition of the paper oil insulation. Amount of heated insulation that is subjected to an accelerated ageing process is sometimes less than 4 % of the total insulation mass. There is also a questionable interpretation of DP value in hot spot areas through DP of samples taken from accessible outside members (e,g. leads). For a given level of paper degradation, the furanic content could be different for different types of paper. Thermally upgraded paper showed very low furanic production, while non-upgraded Kraft paper showed the highest content.

Novel diagnostic methods : Thanks to the evolution of techniques based on Frequency and Time Domain Spectroscopy new more precise tools are becoming available.

Paper A2–207 reports results of intensive studies about the sweep Frequency Response Analysis method (FRA) and PDC (Polarization and Depolarization Current). The paper validates the FRA as a sensitive and an efficient tool for the evaluation of possible displacements and deformations of the windings.

Paper A2-209 confirms that FRA is an effective method of diagnosis, which allows to detect even slight changes within the windings.
New WG A2-26 “Mechanical condition assessment of transformer windings ” will develop relevant guidance and FRA standardization.

On-line monitoring :
Paper A2-204 insists on advantage of moisture sensor, which measures oil relative saturation (RS). It is significant that RS directly correlates with dielectric breakdown of oil. Authors suggest that the RS sensor can be more effective than a water measurement by Karl Fisher titration and more convenient than PDC and FDS.
Paper A2-202 reports experience with automated on-line monitoring of 8 individual gases. Authors emphasize that besides traditional diagnostic purpose the automated DGA monitoring allows to identify a transformer "personality" on certain operation condition and a better understanding using dynamic behaviour of gases versus load and temperature. The example of a failed GSU transformer shows a 20 day evolution starting from a thermal fault, then to high-energy discharges, finally to a fault that involves the degradation of cellulose.
Clear benefit could be derived from condition-based expert systems elaborated on the basis of important parameters controlled by on-line sensors. Paper A2-206 presents a monitoring system allowing thermal model, moisture model, dissolved gas model and vibration model. Validation on the model is shown on normal condition, overloading and failures.
Paper A2-209 presents on-line PD monitoring system for important transformers.

<u>Question 9 :</u>* Considering all economic and technical issues, may off-line and periodical in–service sampling be replaced by on-line techniques ? Does it exist obstacles to switch from a periodical testing (sampling) to a condition based maintenance (CBM) with on-line sensors ? What is the experience of condition assessment of winding insulation by means of the analysis of furans and acids versus the extraction method (direct extraction or by-products analysis e.g. from vacuum condensate during transformer treatment) ? What are the minimum set of on line monitoring techniques required to allow CBM ?

2.3 Repair on site

Recently complete repair of large transformers have been reported including replacement of winding and insulation parts.
Papers A2-203, 209, 210 present experience with major repair of large power transformers and associated problems.
A2-210 states that since 1992 successful in-field repair was carried out on about 96 transformers rated 30-440 MVA and 115-765 kV and appropriate quality has been confirmed with reliable post-repair service during more then 425 transformer-years.

Diagnostic procedures to assess and locate damages in the active part prior to repair : A2-203 emphasizes that advanced diagnostic methods are important for the reliable and economic decision process. Analysis of pre-failure operation condition and failure recorder data, as well as comprehensive test program are necessary to determine the scope of repair and the relevant tools and on site facilities.

Design review : Experience has shown that in many instances some old transformer designs are not adequate to modern requirements. Hence modification of design is most welcome especially in case of post-failure repair in order to reduce future risks (A2-203). The tear-down expertise of a failed unit can give valuable information about the failure modes of a transformer family (design weak points).

Insulation preservation : The preservation of insulation from moisture, dust and other contaminants is one of the most important first repair steps. Preservation is, in many respects, much more efficient than the post drying out because subsequent drying process takes much more time than a preventive operation.
A2-209 and 203 suggest special housing to protect insulation from dust and moisture as well as maintaining a low relative humidity by means of a ventilation with dry air, under a positive pressure.

Preservation and quality assurance of delivering windings and insulation : A2-203 suggests delivering windings and associated insulation in blocks after preliminarily drying out and impregnation with oil. Factory measurements of winding resistance; voltage ratio (with auxiliary test core); measurements of leakage magnetic flux and applied voltage between parallel conductors are used for quality control.

Processing : Processing includes a wide range of operation from removing residual oil out of active part and especially out of the core (A2-209), preliminarily cleaning to remove all debris, particles (A2-203), etc .... up to final filling with oil and bubbles removing. A well-controlled drying process is essential for successful repair of large active part on site as well as fully impregnation with oil and final winding compression.

Post-repair tests :

A2-203 emphasizes the fact that on-site repair needs intensive quality assurance program. Post-repair tests, including power frequency induced test at 110% with PD-measurement and lighting impulse test, are reported.

A2-210, 211 suggest basically a long-duration (1 hour) test with measurement of PD up to 150% of rated voltage, 24 hours tests at rated voltage with PD monitoring, and test at 115% of rated voltage. Lighting and switching impulse tests are not performed due to their high costs and the limited availability of testing equipment.

Sensitivity of short duration tests to insulation contamination is limited. Correspondingly post-repair HV tests, especially of reduced magnitudes might not contribute substantially in insulation condition verification. A long duration test with PD measurement could be the most effective procedure. A2-203 shows an example with improper drying identification by means of PD-pattern.

<u>Question 10 :</u> ***Which technical obstacles prevent from a wide extension of complete in-field repair of large power transformers and shunt reactors ? Can experts report problems to determine a proper scope of repair ? What is the difference between factory tests of a new transformer and a transformer repaired on-site ? Which kind of HV tests and which stress levels should be specified to guaranty the quality of repair ? To what extent have experts considered mobile HV test equipment necessary ?***

2.4 Drying out techniques

Drying out procedure is a critical operation among all the on-site repair activities. Papers A2-203,204,208,209,210, and 212 report adopted practices and considerations in drying out techniques.

The difference between dry-out of new and service aged insulation : New insulation is typically non-impregnated with oil and has a fairly uniform distribution of moisture across the thickness. Oil in the insulation is a drying rate limiting factor. Accordingly, the process of moisture absorption and drying in non-impregnated cellulose is much faster than in oil-impregnated cellulose where only a diffusion mechanism is acting. Service aged transformer is typically characterized by non-uniform distribution of moisture with accumulation of water within thin insulation structures. Furthermore aged transformer may contain water produced by aging decomposition, which is also distributed non-uniformly, being migrating under effect of temperature gradient. The insulation of service-aged transformer is also contaminated with particles and oil ageing products. Accordingly the conductor insulation could be more sensitive to an accelerated decomposition during the thermal treatment than other winding parts.

Difference in levels of moisture contamination : One can discern several categories of transformers to be subjected to drying out :

- transformers that were exposed to atmospheric air for several days, e.g. repair without dismantling the active part (A2-203);
- transformers affected with a free water entrance into the main tank (A2-208);
- service aged transformers which have been operated with free-breathing preservation system for a long period. According to A2-205 over 20% of power transformers rated over 20MVA may have moisture contamination on the level of 2.2% ;
- drying out after windings and insulation replacement (A2-209, 210).

Methods of drying out : Basically three methods have been experienced for on-site drying of large power transformers :

- on–line continuous circulation of hot oil and removing moisture out of oil by means of degassing, absorption with molecular sieves or filtering (A2-204, 205);
- off-line Heat-vacuum drying by means of cycles-mode heating insulation with hot oil by means of circulation of oil within transformer or oil-spray technique and subsequent high vacuum drying (A2-209, 210,212); A2-212 reports modification of this method suggesting instead of the conventional transformer oil a special cleaning fluid;
- off-line Heat-vacuum drying by means of heating windings directly with and without oil by Low Frequency pulsation current (A2-205) or by DC current (A2-208) combined with hot oil heating by means of oil spraying or circulation.

A2-205 suggests a ranking of drying methods in term of time and drying velocity.

LFH and DC current drying without oil : A2-205 reports positive experience with drying of over 40 transformers utilizing the Low Frequency Heating (LFH) process. The process considers combined heating with hot oil and internal winding losses by means of LF current including steps of heating. It starts with a steadily increased temperature from 70-80C (early stage of drying to limit aging effect), then to 80-95C (intermediate level) and finally up to 90-115C when oil is drained and only when the LFH heating is active. The DC current heating technique (A2-208) considers similar steps with increasing the average winding temperature up to 80-90C and may be up to 100-105C at the final stage of drying. According to authors, the technique using the winding conductors as a heat source allows to remove efficiently ageing water, acids and other by-products.

Criteria to end the drying out : Several criteria can be used to assess the end of the process :

- A2-203 suggests as a main criterion rate of removed moisture less than 0.5 liters/day;
- A2-210 adopted measurement of moisture in insulation patterns (sized pressboard materials) extracted from transformer after each drying cycle. Drying is considered to be complete when moisture content of test model is below or equal to 0.5%;
- A2-208 recommends similar criterion (water content in pressboard samples 0.5-1.0mm less than 0.5%) and, moreover stabilization of dielectric parameters (tan δ, and C2/C50).

Insulation loss of life : Any temperature treatment of cellulose results in some loss of its life.

- Paper A2-212 states that conventional on-site drying out can resulting reduction of PD by 50-250 points. Obviously, presents of acids in cellulose would aggravate deterioration.
- A2-205 and 208 consider steadily increasing drying temperature as moisture reducing.
- A2-212 reports application of special additives to improve solvent properties of oil and in this way to reduce degradation rate. Accordingly authors suggest measurement of DP prior and after drying out.

<u>Question 11 :</u> ***What are the factors taken into account to select proper drying out technique ? In which cases experts do consider off-line drying obligatory ? Could any users report on some problems associated with on-site drying out ? How to guaranty absence of local insulation overheating while heating winding with conductor losses without oil ? What is adequacy of interpretation of winding temperature through winding resistance measurement considering transformer design variety, e.g. brazed joints of windings ? How to prevent from an over-drying of the hottest coils in comparison with an under-drying insulation of other cold areas ? Can efficient criteria to end the drying process be reported by the experts ? Which criteria can be suggested to make a decision about the necessity of re-clamping the winding after a drying out ?***

2.5 Life extension procedures

Most of the problems with aged transformers are of a reversible mode and can be corrected on site. It is feasible to maintain or even restore the safety margin of contaminated dielectric system, if the insulation gaps are unchanged, by means of drying, cleaning and regeneration of the oil-paper structure. It is possible to reduce the rate of further insulation deterioration by means of removing water, acids, dissolved metals and other aging by-products.

A2–201, 204, 206, 212 report about on-site procedures related to life extension, which can be performed basically without transformer de-energizing. There have been several risk factors, which make some technical and psychological obstacles to wide implementation of such in service and on-line procedures : 1) risk of failure due to possible introduction into the tank of air, bubbles, particles or other impurities; ... 2) loss of oil level; ... 3) occurrence of static electrification.

A2-206 deal with some recommendations to avoid most common problems.

A2-204 suggests a concept for the prevention of ageing by means of on-line degassing and drying and hermetically sealed power transformers.

A2-201 states that treatment of the insulating oil would allow to improve oil properties extending the oil service life up to 300 %. In order to restore physical, chemical and dielectric properties procedures are recommended to decontaminate the oil (removing polar contaminants sludge and precipitated material on the windings).

Paper A2-212 reports experience with regeneration of solid insulation by means of application of special additive to improve solubility of processing oil during complex drying out operation. Some impressive data showing a significant improvement of the insulation condition are presented.

Question 12 ***: Can experts present experience with on-line processing of HV power transformers and relevant problems ? Can experts report a successful experience with removing ageing by-products out of cellulose insulation ? How advanced are the techniques for full on-line processing ? On-line dehydration and degassing can affect the oil as the diagnostic media in terms of removing faulty gases and furans, accordingly oil reclaiming can consume some furans : do these circumstances prevent form deciding to use on-line processing techniques ?***

Life management and life extension programs involve complex maintenance procedures, which require special knowledge, experience and techniques and accordingly different providers.

Question 13 ***: How to organize and to manage the maintenance of the transformer asset from a local business point of view including out sourcing ? Who are the actors ? Does it exist any business model related to the developing market of the techniques addressed in the above questions 8 to 12 ?***