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Thermal analysis of oil cooled transformer

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Summary

Thermal design of oil cooled power transformers poses a complicated interdisciplinary fluid flow and thermal problem. Traditional design relies on empirical formulae and past experiences. However this necessitates use of a high safety factor and may lead to failures in new designs.

Today methods like finite element and finite difference are avaliable for detailed 2D and 3D analysis. However these require a lot of time and money investment and are not suitable for use for routine design purposes. This paper takes a middle approach of using network method based on empirical formulae and iterative procedures, combined with underrelaxation for convergence, to tackle the problem.

Gaussian elimination has been used to solve resulting system of equations. factors such as change of oil properties with temperature from duct to duct, pressure drop due to friction, bends, gravity etc. are considered. Disc, helical nad crossover type of windings are included. Observations such as reversal of oil flow in some ducts have been verified using one time CFD analysis.

A computer program has been developed to predict top oil temperature rise, average oil temperature rise, average winding temperature rise and hot spots in the windings. ONAN, ONAF & OFAF types of cooling of transformers have been considered. It has been possible to predict the various temperatures within a reasonable accuracy using the program. The methodology used and the results are presented in the paper.

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A2-102

REQUIREMENTS FOR OPERATION OF TRANSFORMERS BEYOND NAMEPLATE RATING – AUSTRALIAN AND NEW ZEALAND EXPERIENCE

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SUMMARY:

Planning based on cyclic loading of transformers beyond nameplate rating, in Australia and New Zealand, has enabled deferment of augmentation on both transmission and distribution networks providing economic benefits. Although planning has been based on deterministic N-1 planning criteria; more recently probabilistic planning has been used.

Failure of an overloaded transformer is most likely to cause serious system constraints and result in load shedding, thus a high level of confidence of satisfactory operation at such loads is vital. In view of this, specifications for new transformers now include the overload requirements generally up to 1.3 or 1.5 p.u in line with the loading guide and require components to have similar ratings. Requirements typically include supporting tender information, design reviews, factory overload tests and fibre optic temperature probes. For the existing ageing population of transformers, assessment of their capability is usually made through design reviews, condition assessment, refurbishment and on-site testing.
Design reviews are performed to ensure that there is a clear understanding between designer and purchaser and that all aspects of the design duly considered to meet the overload requirements including temperature rise of components not covered by standards. Fibre optic hot spot temperature probes, now widely used in Australia, have provided valuable information during factory tests since they were first introduced in 1988. Difficulties encountered have been overcome and long-term durability confirmed through recent measurements on the first transformers fitted with these probes.

Factory overload tests have been significant in proving transformers at their extreme loading conditions and in providing additional information for assessment during service. A total of 10 separate defects including loops around magnetic shunts, winding inlet ducts blocked and tank hotspots, have been detected during these tests. On-site tests have been performed to prove overload capability to 1.3 and even 1.5 p.u on older transformers and this has involved full temperature rise shutdowns. Measurements of temperature by resistance using superposition method during field tests compared well with traditional shut down results. Transformers have been subjected to sustained cyclic overloads of 1.3 p.u. and 1.5 p.u on several occasions with the only adverse effects being oil leaks and a temporary increase in hydrocarbon gases. The monitoring of furanic compounds has provided an effective means of detecting overheating in-service transformers. On-line monitoring equipment has also been used to provide adaptive thermal modelling of in-service transformers.

KEY WORDS: Transformer – Overload –Test- Fibre optic- Temperature- Hotspot

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A2-103

POWER TRANSFORMER REFURBISHMENT: THE BENEFITS OF HYBRID INSULATION

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In recent years, many changes have taken place in the utility industry concerning asset utilisation, loading, maintenance and equipment application in general. Load profiles have increased while manufacturers, under constant and increasing cost pressures have fine-tuned their design techniques. Although technology in the form of modern computers and sophisticated software has improved transformer reliability while reducing overall cost, the resultant transformers are also very lean by older standards, with minimal, if any reserve above the actual nameplate rated capacity. Eventually, this may affect how customers specify equipment and design their power circuits.

Furthermore, optimisation of modern electrical power systems with higher utilisation of existing assets has frequently resulted in reduced maintenance programs by utilities. Overall system reliability and transformer life have subsequently declined in many cases as a consequence of these changes. To complicate this difficult situation, the availability of funds for capital investment has also declined on an international scale, for various regional reasons, often making repair and refurbishment a necessity.

All of these factors have combined to favour the application of less conventional techniques in power transformer refurbishment, such as taking advantage of hybrid insulation technology. This "Hybrid" concept allows much greater flexibility when repairing failed transformers and it also brings the advantage of giving more value to the repaired unit by increasing its capacity and reliability. This technique of enhancing the thermal limits of the equipment, essentially eliminates the thermal restrictions associated with cellulose insulation, provides an economical solution for optimising the use of power transformers, increases operating reliability and may reduce fluid and equipment maintenance.

Development of hybrid insulation technology for liquid-immersed power transformers has evolved over a number of years and originated during the mid 1980's as a solution for packing more power into a given space. The current situation in the power industry together with global economic and environmental circumstances, have led to a renewed interest in this technology. Furthermore, it has expanded to include variations such as semi-hybrid and mixed insulation systems. Standards development has tracked and underscored this renewed interest. Beginning with the early development of an IEEE standard, the standards community in reflecting the industry needs, has now completed an IEC document with publication expected in 2004.

Keywords: Hybrid Insulation – Semi-hybrid Insulation – Mixed Insulation – Maintenance – Refurbishment – Reliability – High-temperature Insulation - Cellulose –

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Aramid – Mineral Oil

A2-104

ESTIMATION AND MINIMIZATION TECHNIQUES OF TRANSFORMER TANK LOSSES

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There is no doubt that transformers are classified among the most important building blocks of any electric power system network. Enhancing the overall performance of a particular transformer would, thus, positively reflect on the quality of its network. In a competitively increasing global market economy, loss minimization may be regarded as the most crucial aspect on which current design efforts are focussed. While rough estimation of the bulk transformer losses resulting from ohmic and core losses is straight forward, evaluation of other losses resulting from stray flux in transformer copper and iron, both active and non-active, parts is known to be more complicated. Until recently many companies have relied mainly on empirical calculations, either derived experimentally from older designs or from papers dating from as far back as the early part of the century, to determine the stray losses on power transformers. For the majority of standard designs empirical relations have served as good gauges of eddy induced loss but for designs of special transformers or units with very tight specification tolerances the same relations have often proved to be inadequate. More specifically, it can be stated that in general the proper evaluation of stray and/or tank losses requires more sophisticated analytical and computational capabilities including electromagnetic field calculation. The purpose of this paper is to present a detailed study of transformer tank losses. It is known that these losses result from eddy currents induced by stray flux. Consequently, tank losses are affected by several factors such as; core magnetic loading, tank wall shapes and thicknesses, clearance between tank walls and transformer active parts, in addition to tank material magnetic and electric properties. While previous studies mainly focussed on relatively large power transformers, this paper focusses on the stray loss investigation for ratings below 100 MVA in part of comprehensive efforts aiming at maximizing efficiency of such transformers. Using finite-element analysis the aforementioned aspects have been investigated in order to deduce optimum tank configurations. Moreover, effectiveness of tank shield sheets on the overall tank losses have also been investigated. Details of the proposed study are given in the paper.

Keywords:- Tank losses - Electromagnetic field analysis - Shielding

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A2-105

THERMAL PERFORMANCE OF POWER TRANSFORMERS : THERMAL CALCULATION TOOLS FOCUSED ON NEW OPERATING REQUIREMENTS

by

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SUMMARY

The issues of thermal performance control are different for substation transformers and generator step-up transformers. For the system, the issue is to optimise the use in order to post-postponed the purchase and the installation of new transformers. Therefore the decision of reinforcement takes into account two types of factors : failure risk and climatic uncertainties. To ensure the continuity of service with respect to system equipment limitations, the operating rules are mainly based on the definition of two types of overload : long-time emergency overloads and short-time emergency overloads. For the generator step-up transformers at nuclear power stations, the issue is the ageing and the reliability of a great number of identical units, operating at loads close to their rated value, and supplied over a short period.

In recent years, the manufacturers have improved their thermal design control and have had some opportunities to compare the life durations, as estimated theoretically, with the field observations. The accurate knowledge of the temperatures reached particularly by the hottest spot within the windings enables the manufacturers to improve the design, taking into account the assigned life duration of the insulations. This was reached through a better understanding of the loss generation and heat dissipation, and appropriated thermal software development. This understanding has been supplemented by the knowledge of some new high-temperature insulation materials, but the high cost of which is still limiting general use.

The evolutions of the electricity market and the growing pressure on the transmission costs have led to new needs for technical and economic optimisation. To make network access and exchanges easier, the system operator has to use its installation at the highest capacity and if necessary introduce new equipment such as phase-shifting transformers. The possible solutions are :

- increasing the load and overload levels by accepting a reduction in life expectancy
- searching for design margins,
- modifying some design features.

For the nuclear power company, the needs are :

- extending the life time of the first-generation equipment from 30 years to at least 40 years and if necessary by modifying the cooling system
- testing the thermal performances of new designs, which are no longer of the design purchased before.

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With their increased know-how, the manufacturers are able to contribute to the mastering of these evolutions. The design tools and their validations have been improved. Thus new computing tools have been developed, which are based either on simple analytical methods or using thermal modelling. Several examples applied to some parts of the windings illustrate some attainable information, which contributes to the mastering of the thermal performance of the whole transformer as well as the assessment of hotspots and their locations. One example of application of these tools, to new design qualification, is particularly presented, which includes some values of direct temperature measurements.

Transformer - Overload - Ageing - Modelling - Specification - Design - Optic fibre

A2-106

TEMPERATURE MEASUREMENT OF PRIMARY WINDINGS OF TRANSFORMERS IN THE HYDRO-ELECTRIC POWER PLANT "DJERDAP 1" RATED 380 MVA, 2×15,75 kV/420 kV, d5/d5/YN, OFWF, UNDER LOAD AFTER 30 YEARS OPERATION

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Although the temperature rise test had been done immediately after manufacturing in the factory in laboratory conditions, using the short-circuit method, it occurred as necessary to check the values of both losses and temperature rise of windings for all four transformers after 30 years operation. The purpose has been to obtain relevant data for re-designing the cooling system in order to revitalize the transformers of the plant and to increase their rated power by 10 %.

The applied temperature rise test under direct load means that the transformer operates in normal conditions, with approximately rated power. The crucial difficulty of this method is the minimization of the time needed to decrease the load from full rating down to zero, to disconnect the transformer from the mains, to ground the windings and to connect them to the prepared measuring circuitry. This is very complicated work as each transformer is connected to two 190 MVA generators.

The transformers in the plant "Djerdap 1" have two primary LV windings, in delta connection, which is not possible to disconnect. The average temperature rises of primary windings are assessed by measuring the d.c. resistance increment using a measuring circuit where two windings are producing equal and opposite magnetic fluxes, which results in very fast establishing of the measuring d.c. current. The characteristics of the measurement made is the fact that both LV windings are steadily in galvanic connection both during the measurements and during the operation on the mains, which enables the measurers to form the circuitry for measurement very quickly after the transformer is disconnected. The advantages of the method are: use of cheap and conventional instrumentation, energy saving compared to the short - circuit test method and normal operation of the transformer except two disconnections lasting about one hour when trained measuring staff is engaged.

The complete measuring procedure is presented – electric wiring, realized before the transformer was connected to the mains, as well as the heat-run process, including measurement and calculation before and after the thermal steady state has been reached. The complete test was carried out on October 2002. At this time, all necessary conditions were fulfilled – quick load reduction, prompt grounding and immediate start of resistance measuring.

The following items are further treated: measuring results of individual losses in no-load and short-circuit tests when the source of energy was one of two generators connected to the transformer, as well as the power carried out by two heat exchanger systems by the calorimetric method. In this way, all power losses are determined including the heat losses transferred via transformer tank surface under two extreme weather conditions - first, at a cold and rainy autumnal day, and second, at a hot summer day.

Keywords: Power - Plant, Hydro - electric, Transformer, Revitalization, Testing - *in - situ*, Temperature - Rise, Direct - Loading, Loss, Calorimetry, No - Load, Short - Circuit.

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A2-107

NEW DEVELOPMENTS IN TRANSFORMER COOLING CALCULATIONS

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Thermal aspects affect transformer design. Therefore precise temperature calculations ensure good quality and long life expectancy of transformers. Since cellulose insulation is mainly used until yet and the ageing rate of paper-oil insulation strongly depends on its temperature it is important to know more about temperatures inside the solid insulation system. The windings hottest spot temperature is also a limiting factor for transformer operation. A large variety of winding types and cooling duct arrangements used in power transformers are considered referring to the problem of temperature calculation. Measurements were carried out which take into account all relevant influence parameters.
The temperature gradient between conductor and oil consists of a gradient inside the solid winding insulation and a gradient inside the boundary layer at the winding surface. The gradient inside the solid insulation depends on the thickness of the enamel, paper insulation and oil pockets between conductor and paper wrapping. The temperature gradients inside those elements of the insulation can be calculated precisely. The heat transfer at the winding surface is determined by the cooling conditions. Two general approaches are in use: The forced convective cooling (OD) and the natural convective cooling (ON). For both cooling modes general approaches are discussed. For the case of natural convective cooling a correlation between the convective heat transfer coefficient (HTC) α and the Nusselt number using a modified Rayleigh number is presented. The characteristic of the HTC at the winding surface were evaluated using heat run test results of various ON- and OD-cooled winding types.
Further temperature rise experiments with an ON-cooled disc winding operated with variable heat flux densities were performed in order to investigate the influence of the heat flux density on the cooling efficiency of the boundary layer. It is shown that there exists a strong dependency between the HTC and the heat flux density. All parameters of the general approaches are calculated for windings of different geometries but of the same winding and cooling type.
Another important thermal design aspect is the longitudinal temperature gradient inside ON-cooled windings which results from a balance of the natural convective oil driving forces accelerating the oil flow and hydraulic resistances in the oil circuit slowing down the oil flow. Longitudinal temperature gradients measured in heat run tests with variable hydraulic resistances inside the winding were evaluated. The results show that a direct measurement of the relevant tank top oil temperature is difficult because it represents a mix of different oil flow temperatures.
Experimental results are discussed and the applicability for winding design practice is emphasized. Experience with heat run tests show that the calculation accuracy is in the range between 3-5 K. This seems to be sufficient compared to uncertainties coming from manufacturing and measurement tolerances.

A2-201

INTEGRATED PROGRAMME OF DIAGNOSTICS, DECONTAMINATION AND DETOXIFICATION OF FLEETS OF TRANSFORMERS IMMERSED IN OIL

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Management of oil insulated transformers and equipment in electrical energy Generation, Transmission, Distribution and Use represents, for Utilities and Users, a new technologic challenge of remarkable complexity. This situation may be specially critic in the case of equipment service breakdown with the subsequent direct damages (loss of assets), indirect (loss of production or service interruption) and environmental in the case of leakage of dangerous substances.
In order to assist to the maintenance management of such equipment fleets, this paper describes a maintenance and protection system integrated into three steps:

- Predictive maintenance and transformer diagnosis by oil analysis and PCB inventory;
- Decontamination treatments of the oil in order to restore the properties deteriorated by ageing and extend its end of life;
- Dehalogenation and detoxification of oil and transformer should the oil is contaminated by polychlorobiphenyls (PCBs).

On some occasions, standardized analytical techniques for transformer condition monitoring have demonstrated not being enough for a proper diagnostic, thus new techniques, specially dissolved sulphur and metals are strongly recommended. Moreover, oil analysis laboratories must take into consideration the uncertainty of the measurements, in order to perform trend analyses to estimate the risk of failure associated with the evaluated transformer condition.
Once the diagnosis evidences oil contamination or ageing, reclamation is a suitable technique to restore oil properties; however, depending upon the contaminants present in the oil, it has been shown that the use of the well known fuller’s earths is not enough for such purposes. Evidences of such behavior and a solution for this problem are described in the paper.
Finally, environmental concerns have posed an additional strength on PCB contaminated transformer management. This paper discuses the problems associated to the use of sodium based decontamination technologies and describes a new one which overcomes all these difficulties, as it uses an intrinsically safe solid reagent which allows to perform the decontamination process at moderate temperatures. An additional advantage of this technology is that allows for the decontamination and reclamation of the oil in just one step, thus minimizing the stoppage time of the transformer. Analytical results after the treatment are reported in the paper.

A2-202

TRANSFORMER CONDITION ASSESSMENT EXPERIENCES USING AUTOMATED ON-LINE DISSOLVED GAS ANALYSIS

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SUMMARY

Automated on-line monitoring of individual dissolved gases is now a reality. Although it has been a long time coming, 24 x 7 Green-Yellow-Red condition assessment's time has come, logically starting at power plants where "non-redundant" GSU transformers are vital in delivering the power plant's product. Critical system-tie autotransformers and phase-angle-regulators are close behind. The 50 years experience with laboratory dissolved gas analysis (DGA) tends to be considered a baseline, however the dynamic behavior of dissolved gases requires continuity & trending unlikely to be captured through periodic manual sampling. Automated on-line DGA brings opportunities for new experiences, learning, & knowledge vital to take full advantage of the information the gases can provide to understand what is happening inside a transformer. Examples are presented showing dynamic loading and other effects. Special attention is given to on-line DGA data from an operating GSU transformer that failed 3 weeks after the application of recent & recently-proposed diagnostic methods would have provided three confirming indicators of a serious problem, whereas existing industry DGA guidelines did not.

Two examples show transformers operating with high levels of ethylene, methane and ethane plus traces of acetylene clearly associated with loading events. Even when the source of accumulated "hot-metal" gases has been identified, there is still concern that high levels will obscure gas increases due to a new or worsening problem. These experiences show that continuous trending provided by on-line DGA can detect PPM increments in spite of accumulated high levels. This is unlikely to be possible through intermittent DGA sampling due to variables in sampling, testing, and specific transformer conditions at time of sampling.

On-line DGA data in a third case captured the dynamic behavior of all fault gases, plus carbon dioxide and oxygen, during a 25 day period ending with complete failure of an operating power plant main transformer. Rapidly rising carbon monoxide and carbon dioxide along with decreasing oxygen clearly showed a pattern of cellulose degradation early in the 25-day period although levels reached would not be considered serious by existing industry guides. Application of ethylene, methane and acetylene trace amounts (each less than 10 PPM) to Duval Triangle Method indicated intermittent AC voltage breakdowns very similar to what sudden increases to levels 500 to 1000 PPM indicated 30 hours before failure. Incremental CO2/CO ratios (proposed by published experimental data) indicated cellulose degradation temperatures as high as 240 C 20 days before the failure. Hydrogen produced by the early intermittent AC voltage breakdowns probably rose rapidly as bubbles and escaped.

A2-203

ON-SITE REPAIR, REFURBISHMENT AND HIGH VOLTAGE TESTS OF LARGE POWER TRANSFORMERS IN THE TRANSMISSION GRID

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Large power transformers at critical nodes in the transnational transmission grid are strategically important components. Their reliability is essential for the safe and stable operation of the whole power infrastructure. In Switzerland and in other countries of central Europe, the majority of the power transformers connecting the 400 kV and 220 kV transmission systems were installed in the 60's and 70's, i.e. they are more than 30 years old. Deregulation and the fast growing energy markets have led to a significant change in the seasonal and and/or daily loading patterns of these service aged units. In particular cases, such load patterns with peaks near or above the name plate loading capability may cause significant thermal stress in the active part of a transformer and, as a consequence, increases the risk of in-service failures with a forced outage.

A recent explosion of a high voltage bushing caused an outage of two 400 MVA transformer groups connecting the European 400 kV grid with the 220 kV Swiss grid. When such a serious failure occurs inside a large power transformer of strategic importance, remedial actions must be introduced within a short delay. In particular, the owner of the transformer must select, based upon economical and operational considerations, one of the following options:

- Replacement of damaged unit with a new transformer or with a spare unit
- Repair of damaged unit in the manufacturer's workshop
- Repair of damaged unit on site.

To support this decision process it is essential that advanced on-site diagnostic tools are readily available to assess and localise the damage in the active part of the transformer. Considering damage type, transportation costs and outage time it was decided in this particalar case to repair the damaged transformers on site.

This paper describes the failure incident, decision process and the on-site repair actions on a 400 MVA transformer group in a 400-kV/220-kV substation with particular attention to the on-site diagnostic and high voltage testing procedures.

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New Concepts for Prevention of Ageing by means of On-line Degassing and Drying and Hermetically Sealing of Power Transformers

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The moisture and oxygen content of the insulation system has a decisive impact on the ageing rate of power transformers. Oxygen together with a water content of 2% in the paper insulation can raise the rate of ageing by a factor of 20. Thus for ensuring a long operating life it is necessary to control both oxygen and humidity content of the insulation system.
Description, results and uncertainties of different on- and off-line methods, e.g. Karl Fischer titration, FDS, PDC, capacitive probe, to determine these values are presented in this paper. The results determined with the KF method are strongly influenced by the acidity of the oil. The comparison of measurements with FDS and PDC method reveals that the accuracy of both dielectric methods has to be improved by new reference data especially for aged insulation material. All parameters such as degree of gas saturation, moisture and oxygen content can be determined on-line by a measuring device which is directly connected to the transformer oil. The on-line measurements offer the advantages of continuous supervision and the abolishment of errors due to incorrect sampling and analysing.
Where a high level of oil humidity is diagnosed drying can, firstly, be an appropriate measure to ensure reliable operation in the short term by raising the breakdown strength of the oil, which had been lessened by the humidity. Secondly drying can extend the service life of the transformer by reducing the ageing process. The described drying systems applied semi-continuously represent together with the improved measurement and control methods suitable tools for these purposes. In the paper successful drying process of aged transformers are depicted. The history of DGA samples shows the positive impact on the humidity and fault gas levels of this type of oil treatment. After finishing the oil treatment the deterioration processes are strongly reduced which can clearly be seen by the amount of water separated from the active part and the positive development of oxygen content.
A priori the accumulation of moisture and oxygen can be prevented by hermetically sealing of the active part which was performed for the first time for higher ratings with a power transformer of 80 MVA/110kV. In order to enable an alteration in the oil volume without conventional conservator an expansion radiator was developed. By using a special welding procedure the radiator is capable of taking over both the cooling function and the function of the expansion without an accompanying loss in mechanical stability. Besides the abandonment of the conventional conservator this new type of design offers the advantage of a reduced ageing speed of the oil-paper insulation system due to the hermetically sealing and savings of maintenance costs, because there is no longer a need for the inspection or exchange of the silica gel filled air breathers. The experience gathered with several hermetically sealed transformer and the data acquired by a monitoring system hereby prove the advantages of this new sealing concept for power transformers.

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A2-205

PRACTICAL EXPERIENCE WITH THE DRYING OF POWER TRANSFORMERS IN THE FIELD, APPLYING THE LFH** TECHNOLOGY

**(LFH = LOW FREQUENCY HEATING)

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Summary

Drying of a utilised power transformer is an object that has been worked on for many years. The main problem is to achieve an optimal drying of an aged power transformer without the displacement to a workshop, as this operation is very cost intensive and sometimes no longer possible. There is a wide range of possibilities known on the market. A new possibility is now offered with the so-called Low Frequency Heating System. This system and the process have developed over the time and are used in different countries. Over 40 power transformers with a power of up to 400 MVA were dried successfully on site. Long term measuring has been shown that much better drying effects could be achieved than with other known processes.

The latest development is the combination of the LFH process with other known processes such as the hot oil spray process. With such a combination the needed drying time could be again reduced and the achievable moisture values were considerably lower and are below 1% H_2O, coming into the range of the original values in the production. Thus the ageing velocity of the insulation material could be reduced massively and subsequently the lifetime prolonged.

Keywords:

Transformer, Drying, Onsite, Vacuum, Low-Frequency-Heating, Oil spray

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A2-206
EXPERIENCES IN MANAGING TRANSFORMERS THROUGH MAINTENANCE OPERATIONS AND MONITORING SYSTEMS

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1. INTRODUCTION

Nowadays, the population of transformers within the transmission and distribution systems worldwide is aging. Utilities are concerned, and it is necessary to manage the remaining life of the units in operation and assess the impact of a predictable increasing failure rates in the next future as the transformer population approach their end of life [1].

Maintenance operations are focused in techniques allowing to get information to diagnose the state of the transformer, which combined with an established policy allow to handle the transformer life.

This paper will deal with policies and experiences referring these maintenance operations, giving information about how to manage and improve the condition assessment of transformers (RED ELECTRICA's policy) and practical examples about how to get direct information from the transformers (UNION FENOSA DISTRIBUCION's transformer monitoring system).

KEYWORDS: Transformer life managing, Transformer monitoring system, Transformer diagnostic techniques

A2-207

APPLICATION OF MODERN TECHNIQUES FOR THE CONDITION ASSESSMENT OF POWER TRANSFORMERS

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1. Abstract
The outstanding technical and economical importance of power transformers in the electrical transmission and distribution networks does not need to be discussed. The continuous awareness of the evolution of the conditions of the insulation system and of the internal mechanical sturdiness is of great value for the system operator as it allows to optimise the lifecycle management of the machine as well as the scheduling of the maintenance operations. Power transformers are designed to withstand dielectric stresses linked with the operating voltage and overvoltages as calculated in the insulation coordination process, thermal stresses linked with their loading guide and electrodynamical stresses linked with external short-circuits. Internal displacements or damages may be generated during the transportation of the machines if the internal mechanical structure of the windings and core are not correctly tight together. When a transformer has undergone abnormal stresses, it is necessary to check its response to the stresses and consequently its conditions, to be aware of its residual ability to withstand further abnormal forces. The Sweep Frequency Response Analysis method (SFRA) has been found to be adequate for the evaluation of possible displacements and deformation of the windings as well as for the pointing out of short circuits between coils. The SFRA method is based on the assumption that any mechanical deformation may be associated with a change in the capacitive-inductive equivalent circuit and therefore detectable through a transfer function. In essence, the method consists in applying on one end of machine winding a low voltage sinusoidal signal made of a sweep of frequencies covering a range between 10Hz and 2MHz and measuring on the other end of the winding the corresponding response in terms of amplitude ratio with respect to the input signal. The experience has shown that in the evaluation of the test results, the behaviour in three different ranges of frequencies must be considered:

- Frequency < 10 kHz: in this range phenomena linked with the transformer core and magnetic circuits are evidenced: the analysis in this range must take into consideration the residual magnetisation which can slightly modify the obtained response from one test to the other. In this range coil faults, winding interruptions, magnetic circuits problems are brought to light;
- Frequency in the range 5 kHz to 500 kHz: in this range phenomena linked with radial relative geometrical movements between windings are evidenced;

- Frequency > 200 kHz: in this range axial deformations of each single winding are evidenced.

The experience gained through the extended application of SFRA both in the field and in the laboratory with different types of defects allowed the validation of some of the most important general rules for the interpretation of the SFRA waveshapes and the two cases analysed in the paper confirm these rules. The information gained with SFRA are very effective; however, the confirmation of the results must always be looked for with other traditional methods for a sounder condition assessment. The sensitivity of SFRA has been confirmed as very high and the repeatability of the results is such as to allow to visualize also minor defects. The SFRA method is based on a comparison analysis: the availability of a reference path for a given type of construction could also allow to point out construction differences over production lots of machines of the same design. In order to minimize the necessity of an expert interpretation, it is important to set up threshold values to evaluate quantitatively the criticity of deviations in the SFRA waveshapes. At present, on the base of the experience gained, the authors have observed that variations higher that 5 dB in specific ranges of frequency, indicate the presence of critical defects in the machine. In such occurrence, further checks, using other more conventional dedicated methods, should be used to confirm the diagnosis and point out the location and the importance of the defect before proceeding to the eventual untanking of the machine.

The level of humidity in the paper-oil insulation system may cause a premature ageing and, in presence of abrupt variation of the temperature, formation of bubbles leading to potential internal discharges in the machine. The Polarization and Depolarization Current (PDC) method has been deeply investigated and analyzed on machines in service and in the workshop and has appeared to be effective in pointing out defects in this respect. The working principle of the PDC method is based on the following effect: when a step-like DC charging voltage U_c is suddenly switched to the sample, previously uncharged, there is a motion of charges, due to the interaction of the electrical field with the free and the different kinds of bound charge within the dielectric. This so-called polarisation current $i_{pol}(t)$ is a pulse-like current at time=0, then decreases during the polarisation time T_c down to a certain value related to the insulation intrinsic conductivity. The polarisation current can be stopped when it becomes stable or very low. If the sample is then suddenly short-circuited, a discharging current $i_{depol}(t)$ (depolarisation current) jumps to a negative value that gradually decreases down to zero. If T_c is large $i_{depol}(t)$ becomes directly proportional to the dielectric response function. At the light of the experience illustrated in the paper, the PDC method has been found an interesting complement to the classical chemical, physical and instrumental checks on power transformers: its capability of evaluating the level of humidity in the paper and pressboards is an outstanding advantage with respect to the mere oil analysis, which shows the eventuality of false-positive results (i.e. situations in which the quantity of water in the oil seem acceptable, while the real moisture in the insulation is excessive for a reliable operation of the machine). Its extensive application to a wide variety of cases would allow to increase the knowledge on which all the interpretation are based.

2. Keywords
Transformer diagnostics – winding displacement – frequency response – insulation ageing – polarisation effect – dielectric spectroscopy

A2-208

ON – SITE PROCESSING OF INSULATION SYSTEM OF LARGE POWER TRANSFORMERS AND HOT – SPOT COMPUTER DETERMINATION

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Summary

On – site drying process with hot oil and high vacuum applied to large power transformers is preferred in Poland. The process as well as measurement results illustrating the insulation system condition of autotransformer 500 MVA 410/245kV and generator transformer 630MVA 400 kV are presented.
Autotransformer 500 MVA was significantly poured with water during extinction of a fire after damage of on load tapchanger joined with an explosion which damaged cover of the tapchanger. Before the drying process the transformer tank was thermally insulated and the process was repeated several times. Each cycle consists of three parts – heating the insulation system by means of hot oil, quick removing the oil, and drying with high vacuum. The condition of the paper – oil insulation was monitored during the process by measurements of C_2 / C_{50} and tgδ.
After stabilising these parameters transformer was filed by fresh oil and oil treatment procedure was done with checking water content in oil. Before commissioning of the autotransformer, a prolonged no – load test, supplied by an auxiliary small power source with an arrangement reducing switching – on current was performed. Before and after the test PD and DGA were measured.
Similar on site investigations and measurements were performed on generator transformer 630 MVA 400 kV. Large volume of water entered the main tank due to failure of cooling system (ODWF). Drying of the transformer was carried out in the following stages:

- Removing water from the bottom part of the tank together with oil – water emulsion, washing the windings and the core with new oil, sealing and filling the tank with dry nitrogen.
- Washing of the windings and the core with post – processed oil by means of special oil splashing system. The process was repeated several times.
- Vacuum drying with heating of the windings.
- Filling the tank with processed oil and heating of windings up to 90 – 95°C. The process was repeated several times and finished when water content in paper samples was below limits.
- Finally, filling the tank with new oil and continuous circulating processing of the oil.

Thermal performance and overload capability of a transformer depends significantly on its hot – spot level. In the second part of the report a computer determination methodology of the temperature distribution within a coil of the transformer winding with OD cooling system and a hot – spot location is presented. An elementary heat balance method is used for calculations. A real eddy current of loss distribution along the coil is taken into account. Moreover, variations of a convection coefficient of a heat transfer from a surface of the coil to oil are discussed.

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SITE MAINTENANCE OPERATIONS ON OIL-IMMERSED TRANSFORMERS AND THE STATE OF RENEWAL FOR LOW-COST OPERATIONS IN JAPAN

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1. Summary

Our living environment and social functions are becoming increasingly sophisticated and complex, calling for high reliability of electric power supply more strongly than ever before. Accordingly, the reliability of transformers which play a major role in the maintenance of stable supply of electric power is ever increasing in importance.

It is generally said that transformers have a service life of 30 years. In order to minimize the cost of operation of the transformer throughout its life, it is important to periodically check the internal conditions of the transformer carefully, diagnose the degree of its deterioration on the basis of its performance and operating condition, and carry out proper maintenance of the transformer taking its remaining life into account.

Some causes of transformer deterioration are thermal, electrical, mechanical, and environmental stresses. Under these stresses, the transformer insulators decline in performance and component materials become degraded, causing the transformer characteristics and performance to decline. Therefore, the maintenance of oil-immersed transformers is carried out based on accurate judgments on the influence of each of the above stresses on the deterioration of the transformer and its accessories and on the process of deterioration.

On the other hand, with the aim of reducing the total cost of electric power facilities through prolongation of their life, improvement of efficiency of transformer operation, etc., standards and techniques to evaluate transformers are being established. In particular, not only the renewal of the entire transformer but also the periodical replacement of its accessories and the renewal of its internal components (the windings, iron core, etc.) for prolongation of the transformer life have been positively proposed.

This paper describes the concepts of on-site maintenance and renewal of oil-immersed transformers in Japan. In addition, this paper introduces the techniques to replace the internal components of transformers efficiently, including the on-site quality control of transformers that applies the established technique of site assembly transformer, as part of the efforts to minimize the cost of transformer operation.

A2-210

On-site Repair of a HVDC Transformer

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The Itaipu Power Plant is located in the Paraná River at the border between Brazil and Paraguay. It is the largest hydropower plant in the world today with 12600MW (plus 1400MW until 2004) of installed generation capacity. Two main transmission links connect the power plant to São Paulo and Rio de Janeiro heavy industrial load centers far more than 900km from the power plant. One HVDC 6300MW, ±600kV, 2-bipoles and another HVAC 765kV links are used for transmission purposes.

The HVDC transmission system has at the sending end a large converter station from 500kV AC to ±600kV located near Foz do Iguaçu while at the receiving end the inverter station from ±600kV to kV345kVAC is located near to São Paulo. This HVDC system has been operating since 1984 and its reliability is very critical to the stability of the whole Brazilian interconnected power system. In each converter and inverter station there is a set of 24 large single-phase converter transformers connected to the valves.

Early in the year 2002, an electric failure damaged one of the converter transformers installed at Foz do Iguaçu converter station. The involved unit is single-phase, two wounded limbs, rated power 314MVA 600kV. The repair requires complete replacement of the winding blocks.

The large transformers' factories in Brazil are also located near São Paulo. Road shipment, using large and heavy special trucks, is normally used for this transportation. However, to cover one way almost 1200km of road routes to factory takes more than 60days due to complexity of the transportation operations. In addition, total transportation cost may amount to more than 1000000USD on both ways site-factory-site. Transportation risks are also relevant.

This and also based on advanced application of on-site repair technology in South America, especially in Brazil, where several large transformers have been completely repaired on site in the last 12 years, has motivated Furnas, the largest Brazilian utility, to proceed to on-site repair of this large HVDC converter transformer for the first time in Brazil.

This paper presents a general view of on-site repair steps of a HVDC converter transformer combined with the corresponding manufacturing steps at factory. The following main aspects are described: setup of the site facility, hauling and transformer disassembly, untanking of the active part, active part disassembly, manufacturing steps, active part assembly, on-site drying, final processes and on-site routine and high voltage tests.

Through right high-quality application of on-site transformer repair technology, it has been possible to optimize the whole HVDC converter transformer repair process. The main achievements of the utility are: overall cost reduction, significant reduction of the mean time to repair and consequential unavailability of the transformer, elimination of transportation risks and promptness of the whole structure for future repairs.

A2-211

On-site Tests on HV Power Transformers

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On-site tests on high voltage power transformers is of increasing interest as part of transformer commissioning, as a diagnostic tool for condition assessment and as an acceptance test just after transformer repair or refurbishment.

A power transformer is one of the most important and expensive pieces of equipment in electric power systems. Economic operation of electrical energy generation, transmission and distribution is closely related to power transformers reliability and availability.

In the actual context of power system operation, on-site test on power transformers is adding value to electrical systems operation, enabling electrical utilities and users efficient diagnosis or reliable acceptance of a transformer, supporting business optimization and adding quality to transformers submitted to on-site repair or refurbishment.

Routine tests, including low voltage tests, have been carried out on site for many years. However, more recently several successful high voltage on-site tests have been reported as acceptance test of large EHV power transformers repaired on site. As a natural extension, the same on-site testing technology has also been applied in many cases as an efficient diagnostic tool for large transformers where a fault has been detected by another means. More recently, the same technology has also been used as an acceptance test for new transformers after problematic factory-station shipment.

Since 1992, on-site tests have been performed in more than 100 power transformers in South America ranging from 30MVA to 440MVA, 115kV to 765kV. Large electric power utilities and industrial plants are the main customers to this technology.

A general view and description of the test setup, test equipment as well as tests performed on site is included in the paper. A detailed description of high voltage tests, including partial discharge monitoring and measurement, is also included. Also, the application of special tests such as frequency response (FRA) is also possible and has been used in several cases. A short discussion on non-performed lightning and switching impulse tests is also presented.

The results show that on-site tests, including high voltage tests, on high voltage power transformers is fully possible and reliable. It can be selected as a proven method for diagnosis and final acceptance of new and repaired or even refurbished power transformers.

A2-212

THE REPAIR OF POWER TRANSFORMERS WITH A LONG SERVICE LIFE

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Summary. At present in Russia most power transformers for 110 kV and higher have already worked out their standardized service life of 25 years. Taking into consideration the real economic situation and the total number of transformers with a long service life, it is impossible in the nearest future to replace most of the transformers whose lifetime has been exceeded. Thus, in order to maintain the required operating security, it is very important to carry out comprehensive diagnostic inspections and to perform overhauling repairs if necessary.

This paper is devoted to the description of the results of the repairs performed according to the new technology of washing and drying of the active part of the transformer by oil spraying (oil contains detergent additives) under vacuum.

The main stages of repairs without changing of the windings are given in this paper. The preparation of oil and sorbents is one of the most important components of quality of the repairs and future reliable operation of the equipment. The oil treatment includes drying, cleaning, degassing, regeneration with the help of silica gel or other sorbents and the antioxidant additive 2,6-dytrebutil-4-metylphenol. During the last stage of the repair work, the drying of the insulation in the active part usually takes place. For transformers with a long service life, experiencing moistening and sliming of the insulation, the method of spraying oil under vacuum is used. Russian transformer oils with a high content of aromatic substances are used as the technological oil for the repairs according to the new technology. For the intensifying of oil dissolving capability, a Midel 7131 additive (based on non-halogen esters of pentaerythritol acid) and several other components are added at a certain stage. Repairs of transformers with a long service life according to the new technology improve the winding insulation characteristics, retain and enhance the mechanical strength of the paper insulation due to strengthening of hydrogen bonds in macro molecules of cellulose and improve the crystal grating. Most effective results of transformer repairs are achieved as a result of individual choice of the washing and drying mode parameters, taking into consideration the degree of sliming, moistening and destruction of the paper insulation and the nature of the contamination of the active part.

Keywords: **Transformer – Repair – Solid Insulation – Mechanical Strength.**