7. LIST OF PAPERS AND ABSTRACTS

LIST OF PAPERS

I. NUMERICAL MODELLING

II. TRANSFORMER LIFE MANAGEMENT

I. NUMERICAL MODELLING

Chairmen: Z Cheng, Ž. Štih

Thursday, 17 May, 9.15 a.m.

1. **(Invited) Zhiguang Cheng** (R & D Center, Tianwei Group Co., LTD, CHINA)**, Norio Takahashi** (Dept. of E.E., Okayama University, JAPAN)**, Behzad Forghani** (Infolytica Corporation, CANADA)**, Xiaoyan Wang** (R & D Center, Tianwei Group Co., LTD, CHINA)

ENGINEERING-ORIENTED BENCHMARKING AND APPLICATION-BASED MAGNETIC MATERIAL MODELING IN TRANSFORMER RESEARCH

The paper highlights the engineering-oriented benchmarking and application-based magnetic material modeling, as two important events in transformer research, reviews the newly extended progress in TEAM (Testing Electromagnetic Analysis Methods) Problem 21 Family, and presents the related benchmarking results.

2. **Oszkár Bíró** (Graz University of Technology)**, Ulrike Baumgartner** (Siemens Transformers Austria)**, Gergely Koczka** (Graz University of Technology)**, Gerald Leber** (Siemens Transformers Austria)**, Bernhard Wagner** (Siemens Transformers Austria)

FINITE ELEMENT METHOD FOR NONLINEAR EDDY CURRENT PROBLEMS IN POWER TRANSFORMERS

An efficient finite element method to take account of the nonlinearity of the magnetic materials when analyzing three dimensional eddy current problems is presented in this paper. The problem is formulated in terms of vector and scalar potentials approximated by edge and node based finite element basis functions. The application of Galerkin techniques leads to a large, nonlinear system of ordinary differential equations in the time domain.

The excitations are assumed to be time-periodic and the steady state periodic solution is of interest only. This is represented in the frequency domain as a Fourier series for each finite element degree of freedom and a finite number of harmonics is to be determined, i.e. a harmonic balance method is applied. Due to the nonlinearity, all harmonics are coupled to each other, so the size of the equation system is the number of harmonics times the number of degrees of freedom.

The harmonics would be decoupled if the problem were linear, therefore, a special nonlinear iteration technique, the fixed-point method is used to linearize the equations by selecting a time-independent permeability distribution, the so called fixed-point permeability in each nonlinear iteration step. This leads to uncoupled harmonics within these steps resulting in two advantages. One is that each harmonic is obtained by solving a system of algebraic equations with only as many unknowns as there are finite element degrees of freedom. A second benefit is that these systems are independent of each other and can be solved in parallel. The appropriate selection of the fixed point permeability accelerates the convergence of the nonlinear iteration.

The method is applied to the analysis of a large power transformer. The solution of the electromagnetic field allows the computation of various losses like eddy current losses in the massive conducting parts (tank, clamping plates, tie bars, etc.) as well as the specific losses in the laminated parts (core, tank shielding, etc.). The effect of the presence of higher harmonics on these losses is investigated.

3. **Slawomir Wiak, Henryk Welfle, Pawel Drzymala** (Technical University of Lodz)

MAGNETIC FIELD AND POWER LOSSES COMPUTATION OF SCREEN IN HV POWER TRANSFORMER

The paper presents the computer (discrete) model of the tank structure of the high power transformer. The model is created as 3D geometry of the core, windings and tank as well. Presented in the literature [2], [3] results of electromagnetic fields distributions and losses in the tank by means of computations with assumptions made for simplified designs, especially geometry, are not satisfactory even for rough estimation. The paper presents the methodology of the model creation for the full geometry of the transformer. The electromagnetic field analysis leads to the identification of the points with high dense losses in the structure. The field and losses distribution computation is essential for further research leading to the design of magnetic or electromagnetic screens. For screens designing procedure it is very important to define the screens positions on the tank, then consequently the structure, and reducing the total losses in the whole transformer structure.

4. **Robert Sitar** (Končar - Electrical Engineering Institute)**, Žarko Janić** (Končar - Power Transformers)

IMPACT OF ELECTROMAGNETIC SHIELDS ON LOCAL OVERHEATING IN TRANSFORMER TANK

The paper describes different influences of magnetic and electromagnetic shielding on stray flux distribution in power transformers. The application of electromagnetic shields on the reduction of high temperature spots in transformer tank is studied in detail by using a 3D model for a coupled electromagnetic-thermal calculation.

The analysis of transformer models with various shapes and dimensions of electromagnetic shields show which factors are the most important for reduction of temperature hot spots in the tank. Proposed shielding solution should reduce the total stray loss and maximum temperature value. It is shown that the reduction of these values is not always achieved by shielding most of the area endangered by the stray flux from the high current leads. The choice of the shield must take into account the surrounding component material properties and transformer lead arrangement.

5. **Franjo Kelemen, Kosjenka Capuder, Leonardo Štrac** (Končar Power Transformers Ltd.)

SKIN – EFFECT LOSSES IN DIFFERENT LOADING CONDITIONS OF A POWER TRANSFORMER

The subject of the analysis is a 300 MVA auto-connected power transformer in different loading conditions with regard to the load losses. During the electrical design time, some operating points of the transformer were analyzed in more detail using 2D electromagnetic field finite element method (FEM) software. The models included 2D magnetic stray field calculation and covered a range of transformer loading cases that covered some that are more difficult to solve with traditional analytic methods based on the static magnetic field calculations. This is due to the presence of a phase shift between the currents through the windings. The results of the static magnetic Rabins' method field calculation and the FEM method are compared and the best practice method is defined and determined accordingly.

6. Ivan Šulc, Zvonimir Valković (KONČAR – Electrical engineering Institute)

FLUX DISTRIBUTION INSIDE THE TRANSFORMER CORE IN SHORT CIRCUIT

This paper shows results of experimental research on a scaled two winding single phase transformer model and FEM calculation of stray flux inside the core in short circuit test connection (load loss test). For the measurement purpose core was divided into 7 “packages” continuously along core’s cross section. Around each package 4 turns were wounded for flux distribution measurement. Stray flux distribution was observed in three positions along limb and yoke.

Results have shown that an appreciable amount of stray flux appears inside the core even in the central packages. Flux distribution changes both in limb and yoke when power supply is changed from inner to outer winding.

Comparison has shown that experimental results, representing flux density, correlate quite good with the results from FEM calculation.

7. Franjo Kelemen (Končar Power Transformers Ltd.)**, Goran Plišić** (Končar Power Transformers Ltd.)**, Sead Berberović** (Faculty of Electrical Engineering and Computing)

ESTIMATION OF STRAY LOSSES IN POWER TRANSFORMERS USING 3D FEM AND STATISTICS

Total losses of a power transformer are subdivided in several distinctive parts. The I2R losses are easy to calculate and can be precise to a level of measurement repeatability and tolerances of the guaranteed material properties. The additional losses inside the windings can be calculated almost with the same precision using analytic methods. The third part of the load losses that consists of stray losses is the smallest and the most difficult to estimate. However, stray losses estimation is very important in the design phase of a power transformer. Not only because the guaranteed design parameters have to be satisfied, but also the utmost care has to be taken that local losses density across the power transformer does not exceed levels that are permissible in the long term loading conditions of a transformer. The additional losses estimation process presented in this paper models the additional losses level in a transformer as a unit.

8. Zoran Andjelic (ABB CHCRC, Switzerland)**, Jan Anger** (ABB SETFO, Sweden)

COMPUTATION OF THE FORCES ACTING ON THREE-PHASE TRANSFORMER WINDINGS

Present work covers the results of the force computation for 250 MVA three-phase generator transformers. The goal was to get the information about the distribution of the stray electromagnetic fields around the windings, composed of the fields produced by the excitation currents in the windings and the fields due to the core magnetization.

The comparison of the calculated forces and force densities is discussed for different excitation cases.

9. Branimir Ćućić (Končar - Distribution and Special Transformers Inc.)

MAGNETIC FIELD COMPUTATION OF A LOADED TRANSFORMER

A simple numerical method based on integral approach was described to compute the stray magnetic field in the surrounding region of a loaded distribution transformer. The model for magnetic field computation was made of transformer windings and low voltage conductors. Windings were modeled by rectangular and round blocks with uniform amper-turn distribution throughout the winding cross section. Low voltage conductors were modeled as series of

straight current-carrying wire segments. The computed and measured results of magnetic induction are in good agreement.

10. **Ralf Wittmaack** (Siemens E T TR EU PN EN4)

CFD SIMULATIONS OF OIL IMMERSED AND DRY TYPE TRANSFORMERS

At Siemens the in-house CFD code UniFlow is employed to investigate fluid flow and heat transfer in oil immersed and dry type transformers as well as transformer components like windings, cores, tank walls, and radiators. We outline its physical models and numerical solution methods.

As an oil transformer application of the method, the simulation of oil flow and heat transfer in 5 windings of a prototype transformer with ONAN/ONAF cooling mode is described. It corresponds to a heat run test with the total losses.

Furthermore, we outline an application to an AFWF cast resin transformer prototype operated at ships in an enclosure. The ventilator driven air flow is cooled by sea water. In addition to the LV and HV windings the core is simulated. Here also the heat radiation makes a significant contribution to the heat transfer.

11. **Hugo M. R. Campelo** (EFACEC Energia, S.A.)**, Carlos M. Fonte** (FEUP University of Porto)**, Ricardo C. Lopes** (EFACEC Energia, S.A.)**, Madalena M. Dias** (FEUP University of Porto)**, José Carlos B. Lopes** (FEUP University of Porto)

NETWORK MODELLING APPLIED TO CORE POWER TRANSFORMERS AND VALIDATION WITH CFD SIMULATIONS

Parametric studies, based on Computational Fluid Dynamics (CFD) simulations, have been made to evaluate the influence of geometrical configuration and operating conditions on the friction factor and heat transfer coefficients. New correlations for the friction factor and heat transfer coefficients have been developed for better description of flow and temperature distribution.

A computational tool coupling the Thermal-Hydraulic Network Models (THNMs) concept with CFD calibration has been developed – named FluCORE. This tool estimates the steady-state temperatures under natural (ON) and forced (OD) cooling regimes with comparable results to CFD simulations. FluCORE is a lumped parameter model and has been found to be an industrializable and versatile decision helper, capable of being adjusted to different operating conditions and design configurations while reducing considerably the computational time and effort of simulation when compared to CFD simulations.

12. **Nebojsa Gavrilov, Ivica Roketinec** (Končar Power Transformers Ltd.)

ANALYSIS OF OIL FLOW INSIDE OF WINDING SEGMENT WITH OPENFOAM®

This article presents use of publicly available open source software for the purpose of CFD analysis of oil flow inside of windings. It will be presented that this kind of software can give equally good results as commercial one does. For the purpose of comparison, the model form article presented at CIGRE is used [1]. In addition to comparison of the results some additional simulation is done, to investigate behavior of oil flow in low oil flow areas.

13. **Andrew Goode** (Alstom Grid – Research & Technology (UK))

MODELLING TRANSFORMER TEMPERATURES - A RAPID DESIGN METHOD

A method is described for predicting temperature distributions on transformer tanks, based on electromagnetic loss intensities calculated at the design stage. These predictions can show if there is a need to mitigate high temperatures by designing in measures such as wall shunts. The method is quick to use and avoids the complexity of producing time-consuming computational-fluid-dynamics simulations. It incorporates convective heat transfer calculations and fluid property models specific to the conditions found within transformer tanks. It arrives at the temperature distribution by calculating the pattern of values of heat transfer coefficient over the surfaces of the transformer.

Comparing results with measurements on manufactured transformers, the method shows good agreement and any difference is on the side of caution. On this basis, the method is an improvement on earlier heuristics and on calculations relying on uniform heat transfer coefficients.

14. **Wilerson Calil, Vinicius Rubio, Jorge Inhasz** (ABB Ltda)

DEVELOPMENT OF A PROGRAM FOR THE DETERMINATION OF THE TEMPERATURE AT TRANSFORMERS COPPER BUS BARS BY CALCULATING THEIR DIMENSIONLESS NUMBERS

The present technical study aims to demonstrate how to make the determination of the temperature at Transformers Copper Bus Bars by calculating their dimensionless numbers its will explain about the development of a thermal software that represents a viable and cost-effective to dimensioning the transformers Bus Bars due the temperature rise generate by the current. In this environment, the program is basically a virtual lab where is only necessary the cost of specialized engineering analysis and the critical time analysis.

This program allows to be done a large number of tests with different types of Bus Bars and different positions of this Bus Bars with the main objective of loss and temperature reduction, material and final cost of the equipment it can also be used to avoid a possible re-work, non-acceptance or disapproval in heating tests, improving the overall performance of the equipment.

To find the temperature at the Bus Bar was necessary to calculate the losses at the Bus Bars and the dimensionless numbers of Prandtl which is the ratio of momentum diffusivity (kinematic viscosity) to thermal diffusivity, Grashof which is a dimensionless number in fluid dynamics and heat transfer which approximates the ratio of the buoyancy to viscous force acting on a fluid, Rayleigh which is associated with buoyancy driven flow (also known as free convection or natural convection) and is the product of the Grashof number and the Prandtl number also and finally Nusselt which is the ratio of convective to conductive heat transfer across (normal to) the boundary. The conductive component is measured under the same conditions as the heat convection but with a (hypothetically) stagnant (or motionless) fluid. All dimensionless numbers were considered for natural convection.

To do this calculation an analytical program using Visual Basic at MSExcel was created. To find this temperature some variables are dependent. In that case, this variables need to be fixed after the first temperature found at copper Bus Bars. Some iterations must be done using the program starting from this first temperature to find the correct final temperature.

After this procedure is possible to determinate the temperature considering the paper layer of the copper Bus Bars when it exists.

The measured results show the reliability of the proposed model by calculating the dimensionless numbers for the determination of the temperature at Transformers copper Bus Bars.

15. **Miljenko Hrkac** (ABB S.p.A., Italy)**, Grzegorz Kmita** (ABB Sp. z o.o. Corporate Research,Poland)**, Michal Kozupa** (ABB Sp. z o.o. Corporate Research,Poland)**, Robert Platek** (ABB Sp. z o.o. Corporate Research,Poland)**, Robert Sekula** (ABB Sp. z o.o. Corporate Research,Poland)**, Roberto Zannol** (ABB S.p.A., Italy)

VIBROACOUSTIC BEHAVIOR OF A SMALL POWER TRANSFORMER

Results of advanced measurement techniques of sound radiation and structure vibration on a 40 MVA transformer are presented in this paper together with electromagnetic-structural and structural-acoustic numerical simulations. Two novel and unique measurement methods in power products industry are used: Laser Doppler Vibrometry (LDV), based on velocity, contactless multipoint vibration measurements and Acoustic Camera (AC), which utilize beamforming technique in noise source identification. Vibration results are used for tuning and fitting the numerical model in terms of excitation forces and consequently obey the magneto-structural analysis.

This comprehensive analysis provides detailed information about frequency, directivity and largest amplitude areas of the noise source, while the ordinary tests performed according to international standards requirements can only give an overall and aggregated information of the transformer noise performance.

II. TRANSFORMER LIFE MANAGEMENT

Chairmen: M. Krüger, A. Mikulecky

Thursday, 17 May, 3:00 p.m.

1. **(Invited) Michael Krüger, Maik Koch, Alexander Kraetge** (OMICRON Energy, Klaus, Austria)

NEW EXPERIENCE IN THE TRANSFORMER DIAGNOSTIC

With advancing age of power transformers, a regular check of the operative condition becomes more and more important. The Dissolved Gas Analysis (DGA) is a proven and meaningful method such that if increased proportions of H2 and hydrocarbon gases are found in the oil, the fault must be located as soon as possible. In order to find out the reason for high gas rates, further tests have to be performed. Common methods are: winding resistance measurement (static), On-Load Tap Changer (OLTC) test (dynamic resistance test), turns ratio and excitation current measurement, measurement of the leakage reactance and of the frequency response of stray losses (FRSL), the measurement of the transfer function (FRA), capacitance and dissipation factor measurement, the measurement of Partial Discharges (PD) and dielectric response measurement with PDC and FDS.

2. **Erich Steindl** (Maschinenfabrik Reinhausen GmbH, Germany)

RISK MANAGEMENT & TRANSFORMER MONITORING

Recent changes on the energy market in South East Europe lead to new requirements in the Transformer Substation equipment. The period of use is rising especially for Transformers and the stress to the equipment, for example throughout temporarily overloads, is increasing as well.

Hence, there is a demand for intelligent and user-friendly devices that are capable of remote control, monitoring, collecting and sending important measurement parameters around the transformer to the control room.

This paper will inform you about possibilities to support users to conquer the current challenges in the energy market such as possibilities to increase Power Quality and reliability of regulated Power Transformers in order to stay a competitive partner in today's and tomorrow energy market.

3. **Marek Andrzejewski, Przemysław Wronek, Wiesław Gil** (MIKRONIKA)

THE INTELLIGENT POWER TRANSFORMER COOLING CONTROL

The upgrading of power transformer cooling gives an opportunity to achieve significant improvement of its safety and economical efficiency. The results are gained by the application of intelligent multi-criteria cooling control, adaptable to various cooling constructions. The thermal model implementation in the control algorithms not only allows to operate according to the winding temperature but also to gain the additional functionality such as the calculation of transformer ageing factor and load prediction in emergency situations. The implementation of the PN-EN 61850 communication standard enables integration of the intelligent cooling controller into the station automation system. Thanks to this approach the cooling controller becomes a source of valuable information for the other station systems and devices. Practical solutions presented in this article have been applied in a number of units in Poland.

4. **Gusztáv Csépes** (MAVIR Ltd.)**, Bálint Németh** (Ovit Ltd.)**, Balázs Mészáros** (MAVIR Ltd.)**, István Kispál** (Diagnostics Ltd.)

QUASI-INTELLIGENT OFF- AND ON-LINE TRANSFORMER MONITORING – HUNGARIAN EXPERIENCES WITH TraMoniS SYSTEM

Utility companies are operating equipments which are now coming to their estimated life time. However it may be economically good to operate the equipment beyond this time if the risks of failures and power outages can be minimised. The fully interactive intelligent electricity network requires sophisticated control and communication systems, enhancing reliability and minimising risks of major disruptions. To achieve these goals monitoring systems are needed. Over the past few years many transformer monitoring techniques and systems have been developed offering a variety of advantages for the transformer operator and asset manager. Regarding varieties of the monitoring systems for the customer it is very difficult to choose which type of monitoring is most appropriate, depending on the importance and health of the transformer. The next step of the evolution is an efficient electricity supply, low costs, satisfactory quality and security of supply, etc., in short the smart grid.

The main objective of the future research is to develop an intelligent transformer condition monitoring system. This paper is summarise the conclusions of the Hungarian on-line and off-line transformer diagnostics techniques and show some interesting functions of this quasi-intelligent expert system which translates the information into appropriate actions to achieving the goals of the user.

5. **Rajko Gardijan, Alen Keller** (Končar - Electrical Engineering Institute)

TRANSFORMER BUSHING – A PART OF MEASUREMENT SYSTEM

Power transformer is one of the most important and most expensive components in the electric power system (EPS) and requires, from its production and throughout lifetime, continuous monitoring and checks of the availability in the power system. All the measurements and tests on the transformer which manufacturers attempt, in order to determine the quality of their products, are carried out through the connection of different types of bushings, and these measurements and tests are conducted in accordance with requirements of applicable standards. Also, the owner of the transformer during the exploitation phase wishes and needs to know the status and availability of transformers for future work. The only available points of the transformer inside are the bushings. The technical practice from the early beginnings of the transformers are periodic off-line measurements. Following that practice and experience, the need arose for continuous supervision of transformer operation (on-line). In the 90's the first simple systems for the transformer on-line monitoring appeared. Today, it is an established fact that the modern systems for on-line monitoring of transformers provide a complete insight in the transformer state including alarms in the case of critical states. It is realistic to expect in the future that these same systems, apart from providing diagnostics and giving alarms, will be authorized to switch off transformers in the case of necessity with high degree of confidence. An important role in on-line monitoring, as a part of measurement system, has a transformer bushing. For the purpose of both off-line and on-line measurements, manufacturers of the bushings are equipping them with the measuring tap. Unfortunately, despite intentions to standardize the components of the power system, this is not the case with the measuring tap, and the intention of this paper is to draw attention to these problems and to try to find a solution.

6. **Jialu Cheng, Peter Werelius, Matz Ohlen** (Megger Sweden)

DIELECTRIC FREQUENCY MODELING – TRANSFORMER INSULATION MODEL IMPROVEMENTS INCLUDING CONTAMINATION EFFECTS

Dielectric Frequency Response, DFR (also known as Frequency Domain Spectroscopy, FDS), is proven as an excellent tool for understanding insulation properties e.g. moisture content in cellulose insulation and temperature dependence of the insulation system.

Fundamental to DFR analysis is the modeling of the insulation system. The common model used is often described as an XY-model where X and Y represent the amount of oil and paper in the insulation system. The model is a significant simplification of an actual transformer oil-paper insulation system but experience has shown that the analysis and results are quite accurate in most cases.

However for some transformers, the dielectric response does not have the expected shape for oil-paper insulation as described by the XY-model. In those cases, the analysis becomes more difficult and sometimes almost impossible. An example is “frequency hump” phenomena sometimes observed in DFR measurements.

Another issue is whether a known ”true” geometry for the transformer should be used when modeling the insulation or if the modeling program should be allowed to use X and Y as matching parameters which in many cases gives a modeled geometry that differs from “true/ expected” values.

In an ongoing project, the XY-model is compared to FEM analysis of the insulation system. With an extended FEM model it is possible to investigate phenomena and parameters not described in the standard XY-model. In this paper, two limitations of the model are presented and discussed; 1) The effect of gaps between winding turns, creating a non-continuous capacitor plate, and 2) The effect of leakage currents on the cellulose surfaces. Both effects have been modeled with FEM and results are compared with the XY-model. For the surface current effect simulations have been complemented with measurements on an actual XY-cell where a “plain” cellulose surface is compared with a cellulose surface covered with a conductive layer. Measurement results on the special test cell are well in line with results from the FEM-analysis.

7. **Maciej Jaroszewski** (Wrocław University of Technology, Poland)**, Mariusz Pietruszewicz** (EnergiaPro S.A., Poland)

LONG-TERM STUDY OF CHANGES OF PHYSICO-CHEMICAL PARAMETERS OF TRANSFORMER OILS

The average age of transformers in service is increasing and approaching the end of design life. Hence there is an increasing need to assess the condition of transformers. The utilities currently use a number of diagnostic techniques to assess the insulation condition of aged transformers. Among them physic-chemical analysis of transformer oil are frequently used.

The article presents the results of many years of routine laboratory testing of oil transformers operated in the EnergiaPro energy company. Oil testing included measurements of total acidity, water content, breakdown voltage, resistivity, tgδ.

8. **Heinz Peter Berg, Nicole Fritze** (Bundesamt für Strahlenschutz, Salzgitter, Germany)

TRANSFORMER FIRES IN NUCLEAR POWER PLANTS – STATISTICS AND PRECAUTIONARY MEASURES

Because of the high failure frequency and the resultant reliability and safety implications in particular of transformers at nuclear power plants in recent years, an in-depth assessment has been necessary. In particular main transformers are considered as critical equipment regarding the potential of fires because of the large quantity of oil in contact with high voltage elements. Experience has shown an increasing number of explosions and fires worldwide of all types of transformers worldwide. Therefore, these phenomena have been investigated in more detail using the information provided by the OECD FIRE database. 13.3 % of all fires and, thus, the most frequent fire source in the OECD database are transformer fires, mainly fires of high voltage oil-filled transformers. Some examples of transformer fires at nuclear power plants are provided. Moreover, possible diagnostic measures to avoid such events and enhance the reliability which are currently discussed in the German Reactor Safety Commission are shortly described.

9. **Subhash Kumar Joshi, Hari Om Gupta, Pramod Agarwal, Ganesh Kumbhar** (IIT Roorkee, India)

FIELD INVESTIGATIONS INTO HARMONICS POLLUTION AFFECTING TRANSFORMERS

Field investigations on harmonics caused by loads are essential to have a quantitative visualization and formation of premise of research. Field investigations have been carried out covering spectrum of loads and voltage levels right from generation to consumers, as at present. Investigations have revealed that low tension consumers form cluster of non-linear loads and are major contributors of current harmonics. Traction loads are another major category of harmonic pollutant. Industrial consumers do provide reactive compensation which helps to filter out current harmonics partially. However, in absence of any regulatory measure consumers keep polluting current harmonics into the system and also bear with the consequential disturbances. Voltage harmonics are significant only at leaf ends of distribution distribution system, where source impedance, seen by the harmonics generated by the load, is high. Tranasformer is the first major equipment in power system to intercept the harmonics. These harmonics caused accelerated ageing of transformers and even objectionable rise of temperature of cover-plate and turets.

10. **Antun Mikulecky** (Končar - Electrical Engineering Institute)

TRANSFORMER BUSHINGS – FAILURE CASE STUDIES

Relationship between bushing failure and transformer failure is discussed and, in regard of that, two bushing failure types are recognized: incipient bushing failure that does not result in transformer damage and terminal bushing failure having transformer failure as a consequence. It can be seen, that without applying the diagnostics, all bushing failures are terminal. Thirteen bushing failures have been analyzed regarding their cause, failure mechanism and consequences. In that sense, the ability and limitation of off line and on line diagnostics are discussed and some improvements are proposed. Some switchyard properties in the aspect of fire protection are indicated and, especially, the possible influence of rigid tubular connections on bushing failures. Beside mentioned design, service, condition diagnostics and other properties of all three condenser types of bushings are described in the paper.

11. **Rejhana Džaka** (Podružnica "Elektrodistribucija", Sarajevo)**, Alma Šupić** (JP EP BiH Sektor za distribuciju, BiH, Sarajevo)

TRANSFORMER STATIONS 10 (20) / 0,4 kV AND ENVIRONMENT

The paper referred to the national legislation in the field of environmental protection that are "Elektrodistribucija", Sarajevo obliged to apply, and it is primarily the Environmental Protection Act. Rulebooks, technical recomendation and other regulations prescribed by the level of Public Enterprise Elektroprivreda Bosne i Hercegovine" in the field of environmental protection are also mentioned in this paper. The application is required during the design, execution and supervision of works, exploatation and maintenance of power plants, because the "Elektrodistribucija", Sarajevo is one of the five distribution parts within the Public Enterprise.

12. **Kenneth Elkinson, Tony McGrail, Gregory Topjian** (Doble Engineering Co.)

TRANSFORMERS: THE BACKBONE OF OUR SOCIETY

This paper explains how critical transformers are in our everyday lives, even when most of society does not know they exist. Both online and offline testing of transformers is discussed, and how these results relate to factory testing. When marrying these test results with real time data, it becomes clear that a vast amount of data is available, and needs to be analyzed. To do this, the asset manager needs to have the proper tools in place to analyze the data, as well as plans in place to act when a problem is found through datamining.

13. **Simon Blake** (Durham University)**, Philip Taylor** (Durham University)**, Mary Black** (Northern Powergrid)**, David Miller** (Northern Powergrid)

USING CONDITION DATA AND FAULT CONSEQUENCE TO INFORM ASSET REPLACEMENT PROGRAMMES

Asset replacement is often the largest category of capital expenditure for a power utility, and it must therefore be allocated effectively. Prioritizing competing replacement projects can be done based on asset age alone, but this is unlikely to be the most effective policy. This paper develops a composite methodology based on expected fault rates which incorporates asset age, location and utilization history, then condition data, and finally the consequences of a fault for each asset. Each additional refinement to the methodology has implications for the year in which each asset should be replaced, and thus for the relative priority of replacing different assets. The methodology as a whole is illustrated by a case study based on a sample from a population of over 400 extra high voltage power transformers belonging to Northern Powergrid, a distribution network operator located in the North of England.

14. **Mircea Aciu** (SC ELECTROPUTERE SA , Craiova, Romania)**, Viorel Mandache** (SC ELECTROPUTERE SA , Craiova, Romania)**, Ion Budan** (SC ELECTROPUTERE SA , Craiova, Romania)**, Ancuta-Mihaela Aciu** (ICMET-Craiova , Craiova, Romania)**, Vladimir Pantic** (VIMAP d.o.o., Belgrade, Serbia)**, Dejan Pantic** (VIMAP d.o.o., Belgrade, Serbia)

APLICATION OF ABSORBER-BASED ON-LINE TECHNOLOGY FOR REVITALISING THE SOLID INSULATION IN POWER TRANSFORMERS IN ROMÂNIA

Power transformer working life is generally determined by the life of paper-oil insulation system. An overview of the age structure for the transformers in operation shows that most of them are over 20–30 years old and they are closing to the end of their estimated life. On-site chemical

treatment includes the use of natural and synthetic adsorbents, leading to the removal of the derivative products of oil and paper, which cannot be achieved by other treatment methods. On-site and on-line revitalization technology does not require putting the transformer out of operation, it decreases the labour costs and removes the expenses for transportation and re-mounting. The revitalization costs are usually lower than those for oil replacement. Saving is significantly (several times) higher when on-line revitalization limits the losses caused by interrupting the power generation and transmission.

15. Gusztáv Csépes (MAVIR Ltd.)**, Ivan Kudela** (EKOFLUID s.r.o.)**, Zsolt Laczkó** (Ovit Ltd.)**, Balázs Mészáros** (MAVIR Ltd.)**, István Kispál** (Diagnostics Ltd.)

ON-SITE TRANSFORMER OIL RECLAIMING (HUNGARIAN AND SLOVAKIAN EXPERIENCES)

Today the insulation in HV power transformers is still being made from oil/paper therefore the management of this kind of insulation will be inevitable in the next forty years or so. In transformer management, important factors are budget planning and the pressures to postpone costs for replacement investments. The transformers were designed for a 30 years lifetime therefore the owners are concerned when to replace them and how risk increases with age. The life expectancy of a transformer depends on operational and environmental data, but also on design aspects and manufacturing processes. The expected life time is influenced by the utility maintenance concept and the practical way that possible repair and maintenance operations are carried out for each unit. Insulating oil and Kraft paper have long been used as the basic insulating materials in power transformers. It well known that life of the transformer is exclusively determined by the life of the paper which ages by thermal degradation. The ageing rate depends – among other things - on operating temperature, moisture, oxygen and acidity levels within the oil, and also the type of paper. Kraft paper aging is accelerated when the acid is present in the oils.

Oil reclamation is effective in removing acid compounds from oils. Knowledge of the general behaviour of an impregnated insulation system and its ageing is the key to understanding the possibilities for improving service conditions for cellulose (e.g. water content, oxygen and acid content) and to slow down the ageing rate of the cellulose. Oil Regeneration Treatment restores oil quality properties, thereby extending the serviceable life of the mineral oil and the reliable life of the transformer. Guides exist for condition diagnostic of oil-paper insulation and maintenance. Reclaiming will slow the aging rate of the oil, thereby extending the life of paper insulation.

Looking at the Hungarian and Slovakian experiences this paper would like to show long-term effectiveness of oil regeneration techniques considering the life extension of the cellulose in a transformer.

III. MATERIALS, COMPONENTS AND NEW TECHNOLOGIES

Chairmen: R. P. Marek, I. Sitar

Friday, 18 May, 8:30 a.m.

1. **(Invited) Richard P. Marek** (DuPont, Energy Solutions)

DIELECTRIC COMPARISONS OF DIFFERENT TYPES OF ARAMID INSULATION

This paper summarizes the results of a number of very different test programs designed to characterize the dielectric performance of three families of aramid paper products. The first part of the testing includes a range of papers that seem well suited to layer type liquid-immersed transformer winding applications. The rapid rise breakdown testing includes multiple thicknesses of the three aramid families that vary in density and surface texture. Wire wrap insulation is the focus of the second part of the testing examined. The results include several different types of test programs, ranging from single flat sheet to multiple flat sheets to actual wire wrapped with multiple thicknesses of the sample insulation. In this series, both rapid rise and impulse breakdown testing is reported. Where possible, statistical analysis was used to make comparisons.

2. **Faruk Erenler** (Enpay Transformer Components)**, Selim Yürekten** (Enpay Transformer Components)**, Gerfrid Newesely** (Senior Consultant)

COMPATIBILITY TEST OF PRESSBOARD WITH TRANSFORMER OIL

The compatibility of transformer oil with pressboard which is produced according to the IEC 60641-3-1 TYPE B.3.1A and used as insulation in HVAC and HVDC transformers is very important. In order to understand how much the oil is affected from the pressboard and pressboard from the oil, contamination tests should be carried out.

These compatibility tests provide indications about the behaviour of pressboard and oil during the life of the transformer in service. There are several standards for testing of relationship between pressboard and transformer oil, which have been carried out. It was interesting, that some of these tests showed unexpected results. Pressboard obviously absorbed some materials from the oil that normally would have negative effect to criterions like IFT (Interfacial Tension) and DDF (Dielectric Dissipation Factor).

One target of this investigation was to find some of these substances and to describe their behaviour.

3. **Petar Gabrić** (Končar - Electrical Engineering Institute)**, Maja Glavinić** (Končar - Electrical Engineering Institute)**, Antun Mikulecky** (Končar - Electrical Engineering Institute)**, Vladimir Podobnik** (Končar Power Transformers, A joint venture of Siemens and Končar)

RESEARCH OF TRANSFORMER MAIN INSULATION DESIGN RULES

Kappeler research performed more than 50 years ago is widely used for HV transformers insulation design. Even though the original experiment was done for oil ducts width from 0.5 to 6 mm, the results have been extrapolated to ducts up to 100 and more mm without detailed publication that would confirm the validity of this extrapolation.

This paper presents the experiment that aims to expand Kappeler research to oil duct width up to 30 mm. Model setup also allows creepage and barriers effect testing up to 30 mm.

4. **T. Judendorfer** (Graz University of Technology, Graz, Austria)**, R. Woschitz** (Graz University of Technology, Graz, Austria)**, M.Muhr** (Graz University of Technology, Graz, Austria)**, W. Exner** (WEIDMANN Electrical Technology AG, Rapperswil, Switzerland)**, S. Jaufer** (WEIDMANN Electrical Technology AG, Rapperswil, Switzerland)

ELECTRICAL CONDUCTIVITY OF PRESSBOARD AND THE INFLUENCE OF MOISTURE CONTENT

The electrical conductivity σ is an important parameter for material condition evaluation at AC applications and is responsible for electrical field distribution in DC equipment. With a focus on HVDC equipment design, the influence of moisture content in oil-impregnated pressboard is determined in this preliminary investigation. The electrical conductivity of pressboard samples, which have been wetted artificially in the laboratory, is investigated within this work. Moisture contents between <0,3% and 5,5% could be achieved artificially through increasing pressboard moisture content levels in a climate chamber. The electrical conductivity was determined by voltage-current measurements at 20°C in the style of IEC 60093 with measurement times up to and longer than 24 hours. For these investigations, the pressboard samples with a thickness of 1 mm have been placed in an (mineral) oil-filled test vessel and stressed by a DC field with E = 3 kV/mm.

It could be demonstrated that the moisture content of pressboard has a strong influence onto the electrical conductivity: An increase of electrical conductivity by a factor of around 10 for each percentage point of moisture increase up to moisture levels of around 3,5% was observed. At higher moisture contents (>5%), other mechanisms seem to govern the electrical current and the conductivity respectively, which is also discussed within the work.

5. **Bittner Markus** (Hochschule Osnabrück)**, Buckow Eckart** (Hochschule Osnabrück)**, Havekost Michael** (Hochschule Osnabrück)**, Kroeger Martin** (Hochschule Osnabrück)**, Szewczyk Radoslaw** (DuPont)

PARTIAL DISCHARGE PERFORMANCE OF SOLID INSULATION IN LIQUID-IMMERSED INSULATION SYSTEMS

This paper describes laboratory testing performed at the University of Applied Sciences Osnabrück and focused on investigating the partial discharge (PD) performance of various insulating papers and boards. Conventional cellulose-based and aramid materials have been tested. New test methodology was used: non-contacting electrodes to avoid the oil wedge effect at corners of traditional IEC electrodes.

The testing performed proved that oil strength is critical for the strength of entire liquid-immersed insulation systems, and breakdown in oil occurs before any PD activity could be observed in solid materials. PD inception level could not be reached in any of the tested materials (cellulose or aramid).This would mean that these materials are equally applicable in liquid-immersed insulation systems of power transformers with respect to partial discharge performance.

6. **Edward Casserly** (Ergon Refining, Inc., United States)**, Jimmy Rasco** (Ergon Refining, Inc., United States)**, Kris Patrick** (Ergon Refining, Inc., United States)**, Nils Herlenius** (Ergon Europe MEA, Inc., Belgium)

CORROSIVE SULFUR-FREE NAPHTHENIC TRANSFORMER OIL THROUGH MODERN-DAY SEVERE HYDROPROCESSING A REFINER'S EXPERIENCE

Naphthenic mineral oils, refined from naphthenic crude oil, are mixtures of naphthenic, paraffinic and aromatic hydrocarbons. They have been used as electrical insulating oils for well over a century. In the beginning, and for most of the 20th century, the petroleum refining industry was

limited in its technology to separation techniques such as solvent extraction, adsorbents or acid treating to remove detrimental molecules (olefins, polycyclic aromatics and polar compounds) from crude oil. Distillation is first used to separate crude oil into discreet petroleum distillates that have varying properties and are useful for differing applications. Solvent extraction and adsorbents physically remove the unwanted molecules from these petroleum distillates. Acid treatment uses strong acids to react with the reactive molecules and then remove them from the purified petroleum distillate. These refining processes tend to be more costly to operate, be less environmentally sound, have lower yields and produce lower quality products. In the last half of the 20th century, refining processing technology has progressed tremendously. Severe hydroprocessing uses metal catalysts, high pressure hydrogen gas and temperature to remove and/or convert the detrimental molecules (olefins, polycyclic aromatics and polar compounds). This refining process tends to be more cost effective, be more environmentally sound, have higher yields and produce a higher quality product. This has been true for petroleum refining in general, not just for refining of naphthenic mineral oils for transformer oil applications.

Severe hydroprocessing of naphthenic oils was introduced in the late 1980's and today most naphthenic mineral oils for electrical applications are manufactured by this state-of-the-art process. It produces a higher quality, more oxidatively stable oil for electrical and other applications. In addition, severe hydroprocessing has proven extremely effective at removing all the corrosive sulfur that comes from the crude oil. Instances of failures of shunt reactors and transformers due to corrosive sulfur and the formation of copper sulfide have not occurred in electrical insulating oils manufactured via severe hydroprocessing without the addition of dibenzyl disulfide (DBDS).

7. **Dijana Vrsaljko, Veronika Haramija, Božena Musulin, Anđela Hađži-Skerlev** (KONČAR-Electrical Engineering Institut)

COMPATIBILITY OF SOLID MATERIALS USED IN TRANSFORMERS WITH MINERAL TRANSFORMER OIL

Insulation system failures are the most common transformer faults causing major and expensive problems in energetic systems. The insulation materials and components have to be carefully chosen during the manufacture to ensure fault prevention and correct and reliable operation of the transformer.

In this paper, compatibility test results of solid materials used in transformers with mineral transformer oil are presented. The aim is to contribute to better understanding of the interactions between solid materials and mineral insulation oil and to emphasize the importance of qualification and compatibility tests during the selection of materials for the use in electrical equipment. The focus of the paper is on transformer oil characteristics and specific degradation products soluble in the oil, determined by different chemical techniques.

8. **Per Wiklund, Anna Biverstål** (Nynas AB)

MONITORED SIMULATED AGING OF INSULATING OIL AND PAPER

Insulating oils (transformer oils) of the types inhibited and uninhibited have been exposed to monitored simulated aging in modified versions of the IEC 61125C oxidation stability test. In this test the outlet gasses from air-bubbled oil is allowed to dissolve in pure water. Through the addition of a pH-electrode into the tube containing the water, it was shown to be possible to follow the development of volatile acidity in real time. This procedure enables the precise determination of oxidation induction time and in combination with traditional titration gives information of acid strength of the formed types of organic acids.

In a further development of the procedure also cellulosic paper was added to the material test. This approach revealed initial absorption of volatile acidity and later formation of formic acid from cellulose.

9. Anđela Hadži-Skerlev, Veronika Haramija, Dijana Vrsaljko, Božena Musulin (Končar- Electrical Engineering Institute)

CARBON MONOXIDE AND CARBON DIOXIDE IN CLOSED-TYPE POWER TRANSFORMERS

Gases carbon monoxide (CO) and carbon dioxide (CO2) are formed in transformers in larger quantities as a product of degradation of cellulose, than by oxidation of oil.

In transformers with closed-type breathing system, without any indication of failure or fault, it was observed that the concentrations of CO are higher than the typical values according to IEC 60599 and CO2/CO ratios lower than 3 frequently have been found.

This paper presents results of laboratory investigation of some influence parameters on formation gases CO and CO2.

The typical values for CO as well scheme concerning their ratios need to be revised in standard IEC 60599. The criteria need to be established separately for closed type transformers.

10. Ivanka Radić, Ivan Sitar, Branka Jakopović, Ana Majcen (KONČAR D&ST d.d.)

SYNTHETIC ESTERS IN POWER AND SPECIAL TRANSFORMERS

This paper describes the use of synthetic ester insulating fluids in power and special transformers. It points out the differences of the ester oil properties compared to mineral oil and other fluids used for transformer insulation.

Because of its high importance in transformer design, a compatibility of commonly used materials with this type of oil is described and the influence of various materials on synthetic ester oil neutralization value is shown.

Due to the differences of the properties such as relative permittivity, viscosity and thermal conductivity (compared to mineral oil), an impact of synthetic ester oil on transformer dielectric and cooling design, as well as the manufacturing process is also described.

Finally, the examples of power and special transformers filled with synthetic ester oil are given.

11. Cristiano Greggio (ABB S.p.A.)**, Andreas Gustafsson** (ABB AB)**, Miljenko Hrkac** (ABB S.p.A.)**, Jurjen Kranenborg** (ABB AB)**, Roberto Zannol** (ABB S.p.A.)

BIOTEMP® TRANSFORMERS IN THE MODERN SUBSTATION

This paper presents some of the advantages and critical aspects related to the use of BIOTEMP® as a dielectric and cooling medium in transformers. Investigations on natural esters as an alternative to mineral oil started in the early 90's and already in 1996 the first small distribution transformers were manufactured and installed. Since that time, many transformers designed for mineral oil have also been retrofitted with natural esters. Nowadays this technology is known and gaining ground in larger units. Raising the current and voltage limits poses a number of problems to the designers and to the developers, since the cooling performance and the dielectric withstand of these fluids are quite different compared to mineral oil. A real case of thermal modeling is presented in this document and the calculated temperature rise values are compared to measurements on a real unit.

Considering the trends of the world energy demand and the evolution expected for the power grid architecture in the future, the BIOTEMP® transformer technology could answer many of the needs for a reliable, safe and sustainable power system.

12. **Roman Žičkar** (Siemens AG Energy Sector, Dresden, Germany)**, Boško Jaković** (Končar Power Transformers Ltd., Zagreb, Croatia)

FUTURE DEVELOPMENTS OF INDUSTRIAL TRANSFORMERS

The industrial transformer is the core of the industrial plant. That is why continuous communication is necessary between the manufacturer of the transformer and the designer of the industrial plant. Building of the industrial plants is based on the principles of concurrent and cross-enterprise engineering.

Open communication on a technical level enables spotting bottlenecks and problems with all elements of the industrial plant. This information serves as indicators and impulses for further development of these components, where the transformer with its complexity and sophistication takes a special place. This article provides a list of fundamental problems that stand in the way of development of electro industrial plants and large power industrial transformer.

13. **Igor Žiger, Danijel Krajtner, Zvonimir Ubrekić, Mile Brkić** (Končar – Instrument transformers Inc.)

DESIGN OF THE OPEN – CORE POWER VOLTAGE TRANSFORMER

The power voltage transformer is a specific type of product. Conceptually, it is at the same time a power transformer and an instrument transformer. Its main purpose is to supply a formidable (from an instrument transformer standpoint) amount of electrical power directly from high and extra high to low voltage, which makes the design of the transformer more complex and challenging than that of an inductive voltage transformer.

With that in mind, this paper outlines two main topics. The first is the selection of main transformer components in respect to the inductive voltage transformer it is based on, but also updating their design so that they can serve their primary function, which is power supply. The second part gives an overview of main calculations done as well as the methods used. This includes the calculation of impedance voltage and magnetizing current, as well as a basic loss analysis.

All calculations are done on an actual 100 kVA power voltage transformer for U_m=362 kV.

14. **Ana Orešković** (Končar - Electrical Engineering Institute)**, Zdenko Godec** (Končar - Electrical Engineering Institute)**, Miroslav Poljak** (Končar - Electrical Industry Inc.)**, Rajko Gardijan** (Končar - Electrical Engineering Institute)

ON-SITE ACCURACY COMPARISON OF CAPACITOR AND INDUCTIVE VOLTAGE TRANSFORMERS

In this paper an on-site accuracy comparison of capacitor and inductive voltage transformers is presented. A 400/110 kV transformer substation in Croatia has been chosen as an appropriate location for the comparison as both types of transformers (capacitor and inductive) operate there simultaneously. Each transformer type is a part of one of the two existing measuring chains for measurement of electrical energy. Their accuracy comparison is, therefore, carried out indirectly, by actually comparing the energies measured by the first and the second measuring chain and then estimating the measurement uncertainty of their difference. Without measurement uncertainty, a parameter that shows the quality of any measurement result, it is generally not possible to conclude about the accuracy of measurement or to compare measurement results mutually. In this measurement uncertainty estimation real on-site conditions in transformer substation, especially those which effect voltage transformer accuracy, have been taken into account (voltage, transformer load, frequency, temperature, etc.)

15. **Michael Ertl, Stephan Voss** (SIEMENS Transformers, Nuremberg)

LOAD NOISE INCREASE OF TRANSFORMERS BY LOAD HARMONICS

Harmonic components in the load-current have a larger impact to the increase of the load noise level of transformers than might be expected from their amplitude. The reasons are (a) the interaction of the harmonics with the large load-current at power frequency, (b) the rising sound radiation efficiency with frequency and (c) the A-weighting filter curve which suppresses sound components at lower frequencies. This paper presents a calculation scheme able to estimate the noise increase and the noise spectrum of electrical transformers for non-sinusoidal load conditions. The proposed calculation scheme is applied to three practical examples.

16. **C.J.G. Spoorenberg** (SGB - Smit Transformers Nijmegen)

STATISTICAL ANALYSIS OF TEMPERATURE RISE TEST FOR INCREASED ACCURACY ON X- AND Y- EXPONENTS

On a large number (> 50) of identical large power single-phase autotransformers ONAF temperature rise test have been performed as part of the customer specification. Part of the 24 hour test is a 125% overload for 8 hours. Based on this data one can statistically evaluate aspects as average value, standard deviation and correlation on many parameters.

Measurement tolerances have a large influence on the top oil exponent x and the winding exponent y. The calculation of x and y is determined by the ratio of two temperature differences due to a load difference, which can result in larger errors than expected.

In two transformers fibre optic (FO) sensors were installed in the common winding to measure the hot-spot, not only during steady state, but also during transient conditions. For ONAF cooling, a step increase of load takes a relatively long time before the oil flow reaches a steady state, as is described in the loading guide. The overshoot in the gradient between the hot-spot temperature and the top oil temperature is demonstrated and can influence the hot-spot gradient exponent z.

Based on the test results and a statistical simulation one can conclude that the normal tolerances in the temperature- and resistance measurements, result in a large standard deviation in the exponents x and y. Use of the exponents x and y, based on a heat run of one single transformer, should be handled with extreme care. In case of doubt, the use of the exponents given in the loading guide result in a safe margin when determining the overload capabilities of a transformer.

17. **Bhaskar R. Nandi, V. M. Varkey** (Siemens Transformer India)

NET ENERGY ANALYSIS OF POWER TRANSFORMER

Energy demand increases worldwide that lead to increase in electrical network and demand of transformer. As there are always certain percentages of loss in a transformer that extends to its life span, and there is also increase in the attention for total environmental impact of a product. Evaluating the life cycle energy of power transformer by a net energy analysis is an option that can describe the total energy get consumed by a transformer or equivalent amount of MTCO2 emission in the environment.

Net energy analysis is carried out considering the energy requirement for manufacturing power transformer loss and auxiliary loss over their lifetime. Case study is presented for 500 MVA, 400 kVA auto transformer and overall performance is evaluated.