21, rue d'Artois, F-75008 Paris
http://www.cigre.org

12-204

Session 2000

Enhanced Diagnosis of Power Transformers using On- and Off-line Methods: Results, Examples and Future Trends

S. Tenbohlen*, D. Uhde, J. Poittevin
ALSTOM T&D,

H. Borsi, P. Werle
Schering-Institute of High-Voltage Technique and France Engineering, University of Hannover,
Germany

U. Sundermann
RWE Energie AG,
Germany

H. Matthes
PreussenElektra Netz GmbH u. Co. KG,
Germany

Abstract - Both, on- and off-line measurements have been performed through the last years on several large power transformers. This paper describes the most recent developments of sensor technology, such as an electronic Buchholz Relay, an OLTC monitoring based on the power consumption of the motor drive and on-line PD-measurement. The presentation of results gained from the combination of on- and off-line methods shows, that they are powerful tools to take decisions on the operation of the transformers. Even more it allows to define concepts for efficient assessment of the transformers condition.

Keywords: Power Transformer, Monitoring, Lifetime Assessment, Buchholzgas sensor, OLTC, PD-Measurement, Frequency Response Analysis, Thermal control

1. INTRODUCTION

Transformer outages have a considerable economic impact on the operation of an electrical network. Therefore it is the aim to ensure an accurate assessment of the transformer condition. Techniques that allow diagnosing the integrity through non-intrusive tests can be used to optimise the maintenance effort and to ensure maximum availability and reliability. With the increasing average age of the transformer population there is an increasing need to know the internal condition. For this purpose on- and off-line methods and systems have been developed in recent years. On-line monitoring can be used continuously during the operation of transformers and offers in that way a possibility to record different relevant stresses which can affect the lifetime. The automatic evaluation of these data allows the early detection of an oncoming fault. In comparison to this, off-line methods require disconnecting the transformer from the power network and are mainly used during scheduled inspections or when the transformer is already suspicious.

2. NEW SENSOR TECHNOLOGIES FOR ON-LINE MONITORING

Transformer outage rate statistics indicate on-load tap changer, bushings and winding insulation as the most frequent causes of long duration outages [1, 2]. Therefore the installation of a comprehensive monitoring system to warn in case of an oncoming fault is advisable for strategically important power transformers.

A multitude of different measurable variables can be collected for on-line monitoring. However, it is very rarely useful to use all the available information. So the sensor technology must be adjusted to the specific requirements of a particular transformer or transformer bank, depending on their age and condition [3,4]. This demands a very high degree of modularity and flexibility for the hard- and software of the monitoring system.

To fulfil this requirement Alstom designed and developed the on-line monitoring system MS2000 in co-operation with some utilities. Because of its modularity, the system can easily be adapted to the customers needs and the requirements of the monitored transformer. It is possible to propose a personalised set of sensors and functionalities. The customer may prefer to have a wide range of condition indicators or to concentrate on specific ones. Another main advantage is that the integration of all kinds of future sensors is possible without any problems. Retrofitting a transformer which is currently in operation should be achieved without requiring long wiring, and in the shortest time possible. This is realised by the use of field bus technology, which reduces significantly the expenditures for wiring and installation, and allows furthermore the monitoring of several trans-

* Rheinstr.73, D-41061 Mönchengladbach,
Stefan.Tenbohlen@tde.alstom.com

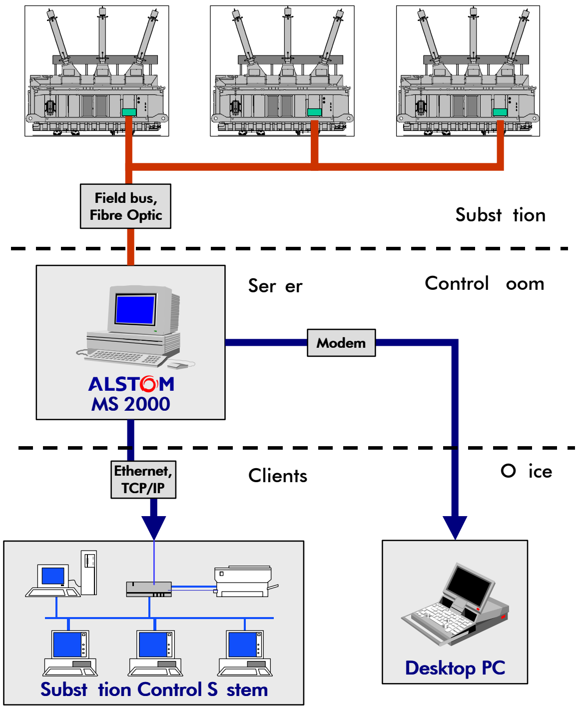

Fig. 1: Architecture of monitoring system MS2000

formers in a substation by only one monitoring system **(Fig. 1)**. The superiority of the field bus technology for the retrofitting of on-line monitoring systems is proven by several on-site installations.

2.1. Electronic Buchholz Relay

The Buchholz-Relay, which has been in use for many decades as a protection tool for oil filled-transformers, is based on a mechanical device consisting of two swimmers installed in a chamber normally filled with the oil of the transformer. In case of faults in the transformer undissolved failure gases come up into the chamber and replace the oil. If the gas amount exceeds a defined quantity for example 100 up to 200 ml one of the swimmers moves downwards and an alarm or a switching signal is activated. In some cases a diagnosis of the failure can be carried out by analysing the gases collected in Buchholz-Relay and by an additional dissolved gas–analysis (DGA).
One of the main disadvantages of the conventional Buchholz-Relay is its integral measuring characteristic. It can only show, how much gas had come into the chamber since the last emptying. If an alarm is signalised it is difficult to know, if the gases were generated by a large fault or caused by a small error emerged during a long time period since the last emptying. Then the result is an erroneous alarm and misinterpretation in many cases. Furthermore the history of the gas-development, which is important for a diagnosis of the fault, is unknown. Beside electrical breakdown there are a few reasons for gas generation:

- Degassing of saturated oil,
- Drawing of air because of underpressure in front of operating oil pumps,
- Behind the oil pumps degassing by cavitation,
- Strong mechanical vibrations can cause bubbling in saturated oil,
- Sudden temperature changes in small oil volumes,
- Sudden decrease of ambient pressure,
- Blocked air dryers can cause underpressure inside the tank, which leads to bubbling.

A computer aided monitoring using the Buchholz-Relay is difficult, because of its poor sensitivity. The Buchholz-Relay in its actual form is thus only a protection device and can not be used as a diagnosis tool. Fail-alarm and fail-interpretation is possible. To reduce the possibility of erroneous alarms the small amounts of gases which develop during a long time period and are not an indication of a large failure should be emptied out of the chamber. Only in this case a signal from the Buchholz-Relay indicates a large failure and the signal can be used as protection signal.
In the following a new developed sensor is introduced in which the functions of the Buchholz-Relay are extended [5]. An incorrect alarm can be suppressed because the gas-rate can be detected, which may be used for diagnostic purposes.
The sensor consists of a cylindrical capacitor which usually can be installed on the top of the Buchholz-Relay above the degassing valve. It has a volume of 10 up to 25 ml and is normally filled with the transformer oil. Small amounts of gases entering the chamber of the Buchholz-Relay ascend into the sensor and replace the oil. The capacitance of the sensor changes adequately by the gas. The change of the capacitance is thereby a measure for the gas-amount. After measuring the gas volume, the gases are transferred into a gas collector, where they can be stored and analysed. The time of the gas-detection and the amount of the measured gases are stored in a memory. Additionally different parameters such as temperature, pressure or the load-condition can be stored. Beside this if the oil level decreases because of e.g. a leakage an alarm is activated. If the sensor is connected to a monitoring system these functionalities can be taken over by the central control unit.
The sensor was installed for about two years on a 200 MVA, 110 kV/220 kV transformer in a substation. On this transformer the Buchholz-Relay generated signals irregularly and therefore the transformer was failure suspicious. The reason for the gas generation was unknown [6].
With the help of the installed sensor it became obvious, that the gases were generated continuously with an amount of about 6-9 ml per month in winter time and about 1 ml per month in summer time. This finding was in accordance with the experiences of the utility, that the Buchholz-signals appeared mainly during winter time. Thus it could be concluded, that the gases were not originated from a large fault in the transformer. An analysis of the collected gases showed, that the main component of the gases was air (containing oxygen and nitrogen). Further investigations allowed the assumption that in wintertime during ambient pressure changes gases are dissolved in the oil in the region of the flat ex-

pansion vessel mounted on the top of the transformer. By temperature changes the gases come into the pipes between the expansion vessel and the transformer vessel and can go out of solution. This effect had been supported by vibrations of the pipes thus the generated undissolved gases come into the Buchholz-Relay or respectively into the new sensor. After repairing the pipes and increasing the oil volume in the expansion vessel this failure was no longer detected.

A further example, which also demonstrates the efficiency as well as the diagnosis possibilities of an electronic Buchholz-Relay, is described in the following where the gassing behaviour of a 250 MVA transformer with horizontal bushings could be clarified. The sensor was installed on the Buchholz-Relay for the separated oil volume of the 220 kV bushings. **Fig. 2** shows the gas appearance during three weeks in summer after strong increases of oil or ambient temperature. Each gassing consists of the small amount of about 4 ml. Cold oil has a lower gas absorption capability as warm oil, which leads in the small oil volume inside the bushing to gas generation at sudden temperature changes. Because of the small rate of gas generation it could be concluded that this is not a critical condition of the transformer.

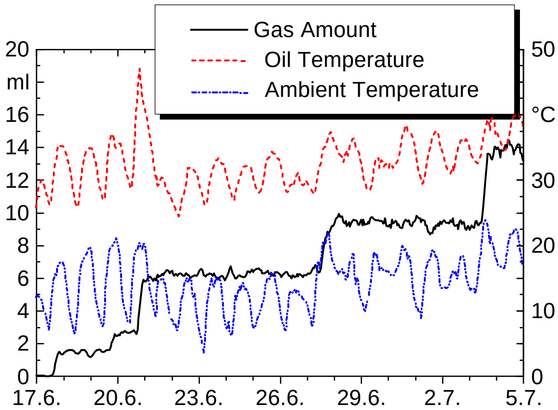

Fig. 2: Gassing behaviour of oil volume of a 220kV bushing

The new feature of this sensor to connect temporal resolution of gas generation with operational data such as temperature and load conditions requires in future additional work to evaluate fingerprints of abnormal conditions.

2.2. Mechanical Condition Assessment of OLTC

Due to the fact that serious damage to the transformer can be expected in the event of a failure of the On Load Tap Changer (OLTC), its condition is strategic to the reliability of the transformer. It is therefore important to monitor this mechanically and electrically highly stressed element on-line.

There are a few methods to perform an on-line monitoring of the OLTC, e.g. the measurement of the temperature differential between the main tank and the tap-changer compartment to detect cooking contacts. To evaluate the mechanical condition between the maintenance intervals of the tap changer, the measurement of the active power consumption of the motor drive during an operation is implemented in the Alstom monitoring system MS2000. Compared to other approaches this method is more simple and reliable, while maintaining all important information [7].

The active power is recorded by means of an Aaron measuring circuit with a sample rate of 20 ms. **Fig. 3** illustrates the characteristic curve for the operation of diverter switch, selector and pre-selector contacts. During the first 300 ms of the switching process a power peak occurs due to the starting current. The intention is to draw conclusions regarding the mechanical state of the OLTC from the position and the amplitude of the following power peaks, which form a typical signature of a specific tap changing. The entire signal consists of three parts dependent on the components which have a part in the specific operation. The loading of the springs for the diverter switch is part of the active power up to the final load switching at 4500 ms. During this period the opening of selector and pre-selector contacts, the revolution and the closing of the contacts take place. All these events are represented by typical peaks in the curvature of active power.

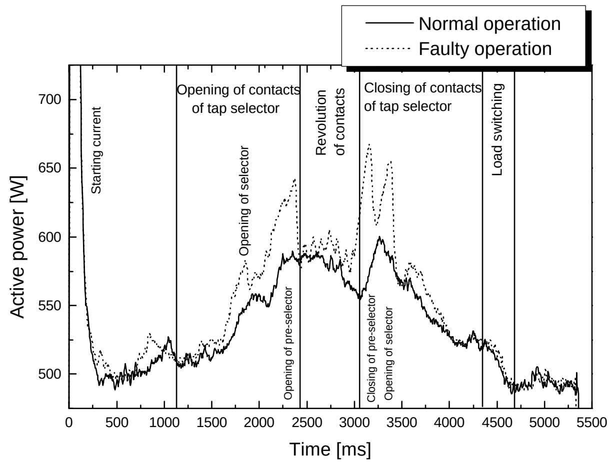

Fig. 3: Active power of motor drive of OLTC

Additionally an operation with simulated problems, is shown in **Fig. 3**. These faults were generated by adhesive tapes, which were fixed on the metallic surface of the selector and pre-selector contacts to simulated mechanical resistances while moving the contacts. The incorrect operation can be recognised by the higher amplitude of the corresponding power peaks. For the application of this method to the on-line monitoring the complete switching operation is divided in 8 sections. In the event that the maximum peak within one section exceeds an alarm level the monitoring system will trigger a warning. In the case of retrofitting the alarm levels are ascertained according to the recorded fingerprints for each tap switching after a few weeks in service.

The load current of the transformer is also stored during a tap changer switching with a sampling rate of 20ms. The difference of load current before and after tap switching is also a valuable information about the correctness of the switching operation. Furthermore in case of a failure during tap changing the knowledge of load currents is of a great importance for the identification of the causes.

2.3. On-line Partial Discharge Measurement

In the last few years extensive investigations on partial discharge (PD) measurements at high voltage devices have been made, leading to improvement in measurement and sensor technology and also to various kinds of algorithms for PD-evaluation. On-line PD measurements on transformers can be performed using various methods, thus beside acoustic measurements electric PD detection methods are used. Acoustic measurements use special sensors often based on the Piezo electric effect for measuring the compressional waves in a frequency range between 50 kHz and 350 kHz. Using this technique in some cases a location of the PD source is possible, but due to the high damping owing to the insulation, conductors, magnetic circuit and the vessel of the transformer the sensitivity of this technique is quite small. Nevertheless a PD location is possible within a radius of about 20 cm [8]. Therefore in an unfavorable case in which a PD source is located at the edge of a coil opposite to the neighbouring coil even the phase of the transformer in which the PD appeared can not be detected. Furthermore usually a lot of sensors are necessary thus increasing the efforts concerning the measurement equipment as well as the evaluation and the processing of the collected data. Also the determination of the energy of the discharge can not be performed precisely, because calibration measurements are almost impossible. For these reasons electric PD measurements are more preferable, because they allow the determination of the apparent charges and in some cases also a PD location is possible. Electric PD measurements can be divided into narrow-band and wide-band measurements. Narrow-band measurements are characterised by a centre frequency and its bandwidth between 9 and 30 kHz whereas wide-band measurements have a bandwidth between 100 and 400 kHz according to the proposal for the revision of the international standard IEC 60270 [9]. Narrow-band techniques enable due to the selection of a suitable centre frequency a noise suppression, but often it is necessary to choose a centre frequency of a few MHz for an adequate noise suppression. This must not be in accordance to the IEC 60270 where the centre frequency is limited to 1 MHz, except the frequency spectrum of the partial discharge is almost constant up to the chosen centre frequency. Otherwise a measurement in the high frequency range exclusively allows only a statement about the existence of partial discharges but not about their apparent charge, thus the comparison of high frequency components only is of less accuracy. Furthermore a PD location as well as a characterisation concerning the type of the PD based on the evaluation of so called φ-q-n patterns or t-q-n patterns is difficult and can in general only be performed with expert knowledge.
Therefore a broadband PD detection is preferable for on-line PD measurements, thus investigations have shown that a bandwidth of about 10 MHz is suitable in order to enable a location of PD sources using pattern recognition methods [10, 11]. This bandwidth is in accordance with the revision of the IEC 60270 and defined as ultra-wide-band measurement, which represents a practical technique especially for the PD location.
Using ultra-wide-band techniques the PD signals can be decoupled with Rogowski coils mounted at the bottom of the bushings, capacitive dividers or measurement taps, which are usually integrated in the bushings. The measurement setup on site is shown in **Fig. 4** where the decoupled signal is low pass filtered and amplified before it is recorded by a digitizer and processed.

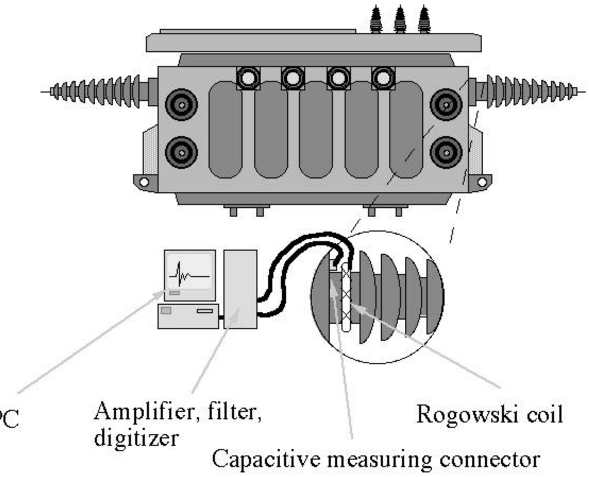

Fig. 4: Measurement setup

During broadband measurements on site various noise signals influence the measurements, thus it is necessary to suppress them by different filtering techniques. First the continuous sinusoidal noises are suppressed using an adaptive digital filter. In **Fig. 5** a measurement on a transformer in operation is shown before (a) and after (b) the suppression of sinusoidal noises. In this case the measurements on a 200 MVA transformer have been recorded using a frequency range between 20 kHz and 10 MHz.

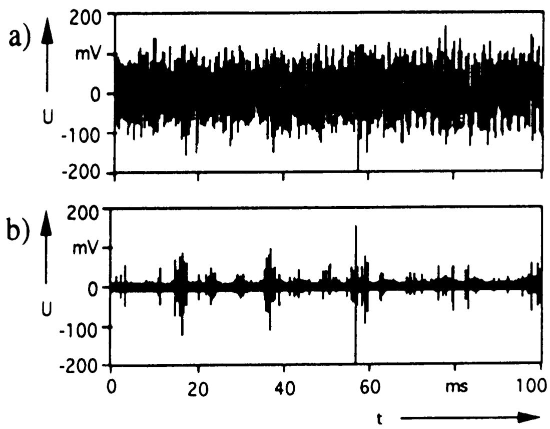

Fig. 5: Suppression of sinusoidal noises

Afterwards it is necessary to suppress periodical pulse shaped noises caused by e.g. thyristor drives which can be efficiently done with adaptive correlation algorithms or frequency rejection filters. The residual signal only contains PD signals and stochastically impulse shaped noises caused by e. g. corona. Because these signals are quite similar it is difficult to separate them. Therefore directional coupling techniques are suitable, because they determine the energy flux of the signals, thus a distinction between signals from inside and outside the transformer is possible [12].

Fig. 6 shows this technique applied for PD signals measured on a 200 MVA transformer on-line. From a comparison of the PD voltage signal U_c decoupled by the capacitive divider and the PD current component U_{Rog} decoupled by Rogowski coils (see Fig. 6 a and b) a selection between partial discharges and noise pulse is possible. Because calibration measurements have shown that pulses with voltage and current component of the same polarity are coming from outside the transformer the pulses shown in detail (see Fig. 6 c and d) must be noise pulses.

Finally from the recorded signal stream only partial discharges are left. This signals can be evaluated using various kinds of pattern recognition methods in order to find out where they have their PD origin. However, this stage has to be performed off line because a lot of different algorithms are necessary to analyse the data.

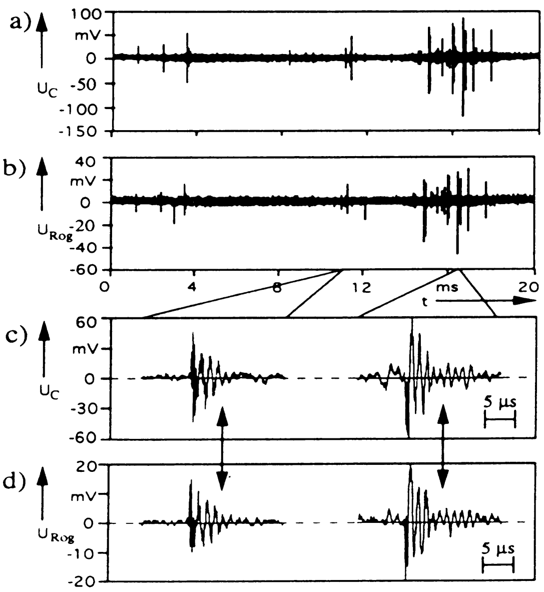

Fig. 6: Separation of PD and noise pulses

3. DIAGNOSTIC BY COMBINATION OF ON- AND OFF-LINE METHODS

The experience gained from on-line monitoring of power transformers is increasing steadily. There is nevertheless still a lack on how to integrate the information obtained by the on-line monitoring into the actions taken onto the service of the transformer. The combination of on-line monitoring and off-line diagnosis provides a powerful tool for the complete and economic assessment of the transformer condition. The supplementary information obtained by the off-line diagnostic after the detection of an abnormal condition is a worthful information to be integrated into future on-line monitoring systems.

Off-line diagnosis can use same methods like an on-line system, as this is the case for PD-measurements. Online PD-measurements do allow to detect PD, but it is difficult due to the difference in the measuring technique to determine the apparent charge of the PD. Offline diagnosis is carried out under well controlled system conditions, using enhanced measurement methods like a multi-channel PD recorder, allowing the detection and quantification of the PD.

Off-line diagnosis provides furthermore powerful tools which allow supplementary information on the transformer condition, which so far cannot be integrated in an on-line monitoring system reliably and cost effectively; among these methods are for example Frequency Response Analysis (FRA) and detailed Gas Chromatograph Analysis (DGA).

3.1. Frequency Response Analysis

The transfer function of a transformer winding is a unique characteristic for each transformer or transformer winding. A transformer winding behaves as a complex RLC network at high frequencies and its transfer function represents according to the system theory the characteristic behaviour of a linear shift invariant system. Small changes in the geometry of the winding lead to changes of the corresponding capacitances and inductances and consequently to a change in the FRA result. Different methods exist in order to determine the transfer function of a transformer winding [14, 15]:

- High Voltage Impulse (HVI)
- Low Voltage Impulse (LVI)
- Frequency Sweep Analysis (commonly called FRA)

The HVI and LVI methods are based on the same principle, a steep impulse voltage is applied to the transformer terminal and simultaneously the current in the different terminals is measured. From these two signals the transfer function can be calculated.

The transfer function between the input and output leads as well as the transfer function between different windings on the same limb can be calculated.

The HVI method uses a High Voltage impulse, as during the lightning surge factory test or can be used as an on-line measurement during switching or lightning in the network [16]. The main inconvenient of the HVI method is the poor frequency spectrum of the input signal and the sensitivity of this technique is not sufficient to detect minor changes in the winding.

For the LVI method a low voltage impulse (some hundred Volts) is applied to the winding. The steepness of the applied impulse can be adjusted in order to obtain a wide frequency band. The sample rate must be chosen to allow measurements at the highest wished frequency. The main problem using LVI is the repeatability of the test results, as they are depending on environmental noise conditions, thus it is in some cases difficult to carry out comparisons between original signatures and repeated measurements.

During discrete frequency measurements the impedance of the transformer winding is measured in function of the frequency by applying a low-voltage sinusoidal test signal with variable frequency. The signals are measured at discrete frequencies to determine amplitude and phase of the transfer function for the full frequency range. The disadvantage using the FRA is the relative long duration for each measurement compared to the LVI method. The main advantage of the FRA is the good repeatability of the test results, because this technique is less influenced by superimposed noises.

The measurements presented in this paper are carried out in the frequency range between 10 Hz and 2 MHz, with a total of 2000 discrete sample points adjusted over the frequency range.

The assessment of a transformer winding through FRA can be done by comparison to an earlier recording, by comparison of the signatures of different phases in case of a multi-phase transformer or two signatures of identical transformers.

Fig. 7 shows the amplitude of an on-site recording of a 16.5 MVA, 90kV/27.5 kV single phase transformer before and after a series of three short circuits on site. The first resonance frequency changed from 325 Hz to 285 Hz. With a slight amplitude increase. At low frequencies the main inductance is determined by the iron of the magnetic circuit. Differences in the residual flux densities during the different measurements lead to changes of the magnetic permeability of the iron core material and subsequently a change in the main inductance. This does influence the frequency response for low frequencies, but does not change the HF behaviour of the winding.

The HF results before and after the short circuit do

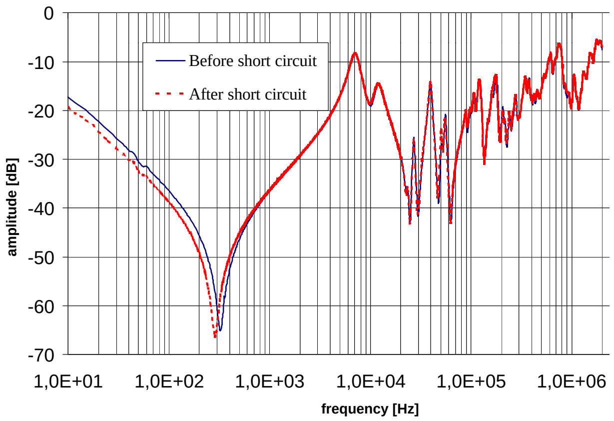

Fig. 7: FRA response before and after short circuit

match very well. The HF response is determined by the interdisc and interturn capacitances as well as the winding inductances. The transformer did successfully pass the short circuit tests. Short circuit impedance measurements before and after the short circuit confirmed the results obtained by the FRA.

3.2. Gas-in-oil detection

The on-line monitoring of dissolved gases in oil is widely used within installed systems. A number of different sensors have been developed for this purpose. The information of the rise of dissolved hydrocarbon gases in oil does normally not allow a “detailed” statement on the condition of the transformer. But it gives the trigger for an off-line diagnosis in time in order to establish a reliable diagnostic of the transformer to prevent a severe failure.

Fig. 8 illustrates a detected increase of dissolved gases using a Hydran sensor. The obtained information by the on-line monitoring must be analysed using DGA analysis in order to establish a first diagnosis of the transformer.

The increase of the on-line detection of dissolved gases triggered in this case a PD measurement. PD-measurements and their ultrasonic location allow a detailed diagnosis of the transformer insulation.

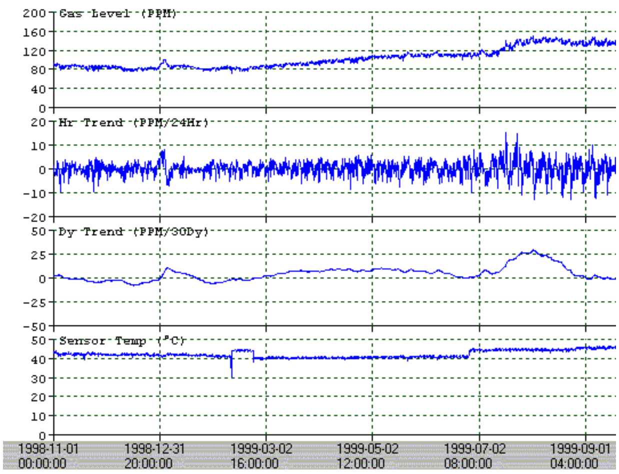

Fig. 8: Evolution of dissolved gases using a Hydran sensor

For this purpose a multi-channel Automatic Partial Discharge Recorder (APDR) has been developed [13, 17]. The APDR allows to record the signals simultaneously on up to 7 channels with a dynamic of 120 dB. The peak value, the polarity and the phase of each discharge is recorded. The obtained record can be analysed cycle by cycle for the whole duration of the test. Methods of sorting the PD’s into clusters and their characterisation can be applied. By applying this tool to the presented case the supposition could be proved that the rise of the dissolved gases was due to inception of PD in oil.

4. TEMPERATURE MONITORING AND CONTROLING OF COOLING UNIT

The thermal behaviour of a transformer can be represented by a one-body system [18, 19]. In stationary condition, all losses (P) are transferred to the environment via the thermal resistance (R_{th}) of the cooling equipment. For the oil temperature rise, the following applies:

$$J_{oil} - J_{air} = (P_{k,n} \cdot k^2 + P_0) \cdot R_{th} \qquad (1)$$

The variable k is the ratio of the actual load to rated load. In the case of strong fluctuations in ambient temperature or load, the thermal capacity (C_{th}) of the transformer has also to be taken into consideration. This, together with the thermal resistance, results in the thermal time constant of the transformer. The dynamic characteristic of the oil temperature (J_{oil}) can be calculated, on-line and iteratively, by means of the monitoring system in accordance with equation 2. The initial and final oil temperatures are denoted by $J_{oil,act}$ and $J_{oil,¥}$ respectively.

$$J_{oil}(t) \approx (J_{oil,\infty} - J_{oil,act}) \cdot \left(1 - e^{-\frac{t}{R_{th} \cdot C_{th}}}\right) + J_{oil,act} \qquad (2)$$

By resolving equation 1 to k, the permissible continuous load according to IEC 60354 can be calculated. The specific constants (P_0, $P_{k,n}$, R_{th}) of the transformer are determined by the specific design. The ambient temperature can be measured and the top oil temperatur should be limited to 105°C for OD-cooled transformers according to IEC 60354. In this way also the hot-spot temperature has to be controlled, because it is limited for normal cyclic loading to 120°C. It is made up of ambient temperature (J_{air}), the calculated top oil temperature, and the load-dependent temperature difference between oil and winding temperature, weighted with the hot-spot factor (h). The demand to compensate periods of high load and accelerated ageing by periods of low load and slower ageing can be met by the on-line calculation of the ageing rate and calculating the 100-day mean-value.

This thermal model was applied to a 250 MVA grid coupling transformer. The maximum possible continuous load of that transformer, with the cooling plant operating at rated load, was determined as a function of the ambient temperature and is shown in **Fig. 9**. Due to the low ambient temperature, maximum continuous load factors of up to 1.3 were reached.

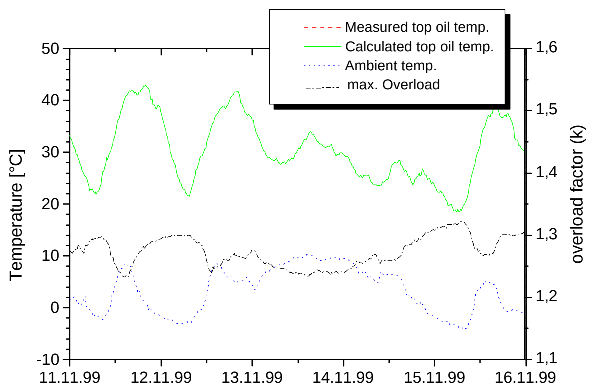

Fig 9: Calculation of oil temperature and overload capacity

The top oil temperature, calculated under consideration of the thermal time constant, corresponded with the measured top oil temperature. Minor deviation of up to 2 K will occur with strong fluctuations in ambient temperature and load. These deviations can be established by the unprecise detection of top oil temperature due to the measurement of the top oil mixture. Thus, the reliability of the model is proved so that it is possible to detect failures of the cooling system, such as failures of pumps or fans, by comparison of measured and calculated top oil temperature.

For emergency operation of the transformer the duration at a maximum load factor of 1.5 can be pre-calculated. Because of the strong variations of the oil temperature during such high load phases, it has to be borne in mind, that for the calculation of the hot-spot temperature a two-body system with a much smaller time constant as in equ.2 has to be applied [19].

This thermal model is also used for a load-dependent regulation of the cooling plant. For this purpose, the desired oil temperature is entered in the software of the monitoring system MS2000 as a control value. The thermal resistance of the cooling plant required for transferring the losses to the environment can be calculated as a function of the ambient temperature and the actual load. The monitoring system determines the number of fans to be activated corresponding to the required thermal resistance. In this way, a largely constant oil temperature is obtained; as this reduces „breathing“ of the transformer, less moisture is absorbed by the transformer oil. Compared with a conventional fan control, the use of this intelligent, load-dependent fan control offers a number of additional advantages:

- Use of life can be reduced by optimising the hot-spot temperature (life management),
- Service consumption of the transformer can be reduced, as a smaller number of fans will operate at lower ambient temperatures,
- The overload capacity of the transformer can be raised by pre-cooling of the oil before a load peak occurs,
- The selective control of fans will reduce the overall noise level of the transformer.

5. CONCLUSIONS

The condition assessment of power transformers by the combination of on- and off-line methods strongly reduces the risk of severe failures. So it provides a reliable electrical power supply in connection with an optimum exploitation of the active part. The most recent developments of sensor technology, such as an electronic Buchholzgas relay, an OLTC monitoring based on the power consumption of the motor drive and on-line PD-measurement have been described in this contribution. The results gained from the field application of these new sensor technologies show the early warning capability.

A comprehensive diagnosis however requires that in future results from on- and off-line measurements has to be put together by better proven evaluation methods, which have to be achieved in close collaboration between transformer manufacturer and utility.

6. REFERENCES

[1] "An International Survey on Failures of Large Power Transformers in Service" (CIGRE Working Group 12.05, Electra, No. 88, January 1983).

[2] D.F. Peelo, et al.: "A Value Based Methodology for Selecting On-line Condition Monitoring of Substation Power Equipment" (EPRI Substation Equipment Diagnostic Conference V, New Orleans, Louisiana, Feb. 17, 1997).

[3] S. Tenbohlen, F. Figel: "On-line Condition Monitoring for Power Transformers" (IEEE Power Engineering Society Winter Meeting, Singapore,Jan. 2000)

[4] U. Sundermann, S. Tenbohlen, "Der intelligente Transformator - Zustandserfassung und Diagnose von Leistungstransformatoren" (Elektrizitätswirtschaft, Jg. 97 (1998), Heft 10).

[5] H. Borsi; M. Urich, T. Leibfried "Das neue elektronische Buchholzrelais" (Elektrizitätswirtschaft, Jg. 97 (1998), Heft 13)

[6] P. Werle, V. Wasserberg, H. Borsi, E. Gockenbach "Kombinierte Verfahren zur Zustandserkennung der Isolierung von Leistungstransformatoren" ETG Tage, München, November 1999

[7] A. Krämer, et. al.: "Monitoring Methods for On-load Tap-changers. An Overview and Future Perspectives" (CIGRE Session 1996, paper12-108).

[8] H. M. Shertukde, J. G. Lackey: "Interpretation of Results obtained from Testing of Oil filled Electrical Power Transformers in Field for several Utilities in the World" (IEEE International Symposium on Electrical Insulation, Vol. 1, pp. 49-52, June 1998, Washington DC, USA)

[9] IEC 60270: "Partial Discharge Measurements"

[10] P. Werle, H. Borsi, E. Gockenbach: "Hierarchical Cluster Analysis of Broadband Measured Partial Discharges as Part of a Modular Structured Monitoring System for Transformers" (11th International Symposium on High Voltage Engineering, Vol.5, pp. 29-32, August 1999, London, UK)

[11] D. Wenzel: "Teilentladungsmessungen an Transformatoren im Netz mit Verfahren der digitalen Signalverarbeitung und Mustererkennung" (Dissertation, Universität Hannover, 1998)

[12] M. Hartje: " Erfassung von Teilentladungen an Leistungstransformatoren im Netzbetrieb" (Dissertation, Universität Hannover, 1990)

[13] C. Moreau, P. Tantin, B. Mansuy, J. Poittevin, P. Despiney: "Monitoring and operational behaviour of HV and EHV Instrument Transformers" (Cigre 1998, 12-101)

[14] P.T.M. Vaessen, E. Hanique: "A New Frequency Response Analysis Method for Power Transformers" (IEEE Transactions on Power Delivery; Vol .7 N° 1, January 1992, pp. 384 – 391)

[15] J. Bak-Jensen, B. Bak-Jensen, S.D. Mikkelsen; "Detection of Faults and Ageing Phenomena in Transformers by Transfer Function" (IEEE Transactions on Power Delivery; Vol. 10, N° 1, January 1995, pp. 308-314)

[16] T. Leibfried, K. Feser: "Off-line and On-line Monitoring of Power Transformers using the Transfer Function Method" (International Symposium on Electrical Insulation, Montreal, 1996)

[17] J. Poittevin, D. Uhde, N. Foulon, J.-P. Lucas, G. Barré: "Partial Discharge Measurements on Transformers: Fingerprint Analysis" (INSUCON/ISOTEC 1998 pp; 278 – 290)

[18] IEC 60354: "Loading guide for oil immersed power Transformers" (IEC, 1991)

[19] S. Tenbohlen, M. Schäfer, H. Matthes: "Beurteilung der Überlastbarkeit von Transformatoren mit online Monitoringsystemen" (Elektrizitätswirtschaft, Jg. 99 (2000), Heft 1-2)