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DEVELOPMENT AND APPLICATION OF NEW CONDITION ASSESSMENT METHODS FOR POWER TRANSFORMERS

by

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SUMMARY

Recent advances in the application of non-traditional methods and procedures for off-line diagnosis and on-line monitoring of new and service-aged power transformers are discussed. Advanced off-line methods are based on the main operational stresses (electrical, mechanical, thermal) and on typical failure modes: measurement of polarisation- and depolarisation currents (PDC), electrical detection of partial discharges (PD) and measurement of the transfer function (FRA). A pilot installation of an on-line monitoring system on a strategically important transformer is described. The measured data of the built-in sensors (e.g. load, temperatures, gas and moisture in oil, overvoltages) are analyzed using a model-based software approach with an adaptive threshold to define faulty conditions.

KEYWORDS

Monitoring and Diagnostics, Transformers, Insulation, Ageing, Life Management, Relaxation Currents, Partial Discharges, Frequency Response Analysis.

1. INTRODUCTION

Large power transformers belong to the most expensive and strategically important components of any power generation and transmission system. Their reliability is of key importance for the availability and profitable operation of such systems. A serious failure of a large power transformer due to insulation breakdown can generate substantial costs for repair and financial losses due to power outage. Therefore, utilities have a clear incentive to assess the actual condition of their transformers, in particular the condition of the HV insulation system, with the aim to minimise the risk of failures and to avoid forced outages of strategically important units: power station step-up transformers, large substation transformers or autotransformers in a HV transmission system.

According to an international survey of CIGRE [1], typical failure rates for large power transformers with windings for voltages up to 300-kV are in the range of 1% to 2% p.a. More recent figures from Germany [2] confirm that the statistical failure rates of transformers increase significantly with system voltage (see Table I). Although reliability considerations apply throughout the life of a transformer, the in-service failure rates of large power transformers and other HV-components alone cannot justify all the efforts made world-wide to improve condition assessment methods by introducing new diagnostic tools and monitoring systems [3],[4].

Table I: Average Failure Rates of Power Transformers based on data from 1980 - 1993, [2]

U_n	Failure Rate (p.a.)
110-kV	0.36 %
220-kV	1.54 %
380-kV	2.07 %

The real driving forces behind the efforts to develop and apply better diagnostic methods and tools for assessing the condition of large power transformers are the increasing age of the transformer population (the majority of large power transformers in Switzerland and most other countries in central Europe were installed in the 60's) and the deregulating environment in the electric power sector which requires a reduction of operating and maintenance costs. A transition from time based maintenance (TBM) to condition based maintenance (CBM) can create substantial economic benefits, provided that reliable diagnostic methods are available to assess the condition of all critical elements of a transformer: insulation, tap changer, bushings [1].

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Today, utilities are therefore challenged with the following questions: (1) how can incipient faults in strategically important units be detected at an early stage, (2) how can the lifetime of service-aged transformers be extended without loss of reliability or availability, and (3) how can we further reduce the cost for maintenance and refurbishment ?

To answer any of these questions, we need (a) more detailed information about typical failure modes in real transformer designs, (b) a better understanding of the ageing behaviour of the oil-cellulose-insulation system, (c) advanced diagnostic techniques and monitoring systems for on-site use to assess the electrical and mechanical condition of power transformers, and (d) clear rules for the interpretation of diagnostic results.

To address these needs in Switzerland a project was initiated in collaboration with utilities, technical universities and the transformer industry to investigate and explore new diagnostic methods and surveillance systems for large power transformers. This paper describes the main objectives and some results of this project: (in section 2) development and practical application of advanced off-line diagnostic procedures to assess the condition of both new and service aged power transformers, and (in section 3) development of an on-line monitoring system to keep track of the condition of a strategically important transformer which was repaired on-site after a serious fault.

2. OFF-LINE DIAGNOSTIC METHODS

Typical failure modes and the „technical lifetime" of power transformers are mainly influenced by the electrical, thermal and mechanical stresses of the insulation system during service. Due to the complexity of both, the design of the large power transformers and the multi-parameter stress situation in service with their combined effects and inter-relationships, a unique diagnostic method, however, does not exist.

2.1 Traditional Diagnostic Methods

A survey of traditional diagnostic methods and their application to transformers and to other equipment is given in [3][4][5]. In Switzerland the common diagnostic practice for assessing the condition of power transformers is mainly based on the following procedures [6][7]:

- visual inspection
- physico-chemical analysis of the oil (IEC 422)
- chromatographic oil analysis (DGA, HPLC)
- measurements of capacitance and dielectric dissipation factor (DDF) of the HV-bushings.

The analysis of dissolved gas in oil (DGA) indicates slowly developing failures and irregularities in the oil/cellulose insulation system, such as hot spots, bad contacts, arcing or partial discharges. The DGA-procedure is well established and the interpretation of results are described in IEC publications 567 (1992) and IEC 599 (1978). Despite of existing international standards and extensive use of DGA (since more than 40 years), the correct judgement of the severity of a fault and its localisation inside the transformer is often not possible. In general, „limiting values" for maximum admissible decomposition gas concentrations for a specific transformer under specific operating conditions are not available.

When the evaluation of DGA-results indicates thermal degradation of the cellulose insulation (unusual high content of carbon oxides), the HPLC-technique (High Performance Liquid Chromatography) can be used to detect cellulose decomposition products (furanic compounds). Although the analytical aspects of this method are well defined in IEC 1198 (1993), the quantitative interpretation of HPLC-results is still difficult because the correlation between measured concentrations of furanic compounds in oil and changes in physical properties of aged cellulose (e.g. reduction of tensile strength) is not yet well understood [3][6].

Though both methods, DGA and HPLC, are widely used in Switzerland and elsewhere for incipient fault detection in power transformers, their sensitivity for the assessment of the general condition of an insulating system is limited due to the integral and cumulative nature of these methods. Small defects, even in critical locations, have a very long reaction time due to the large oil volume. With the application on a discrete basis (typical intervals between analysis: 1 to 5 years), there is a risk that fast evolving faults with rapid changes in the transformer's gassing behaviour will not be detected early enough.

2.2 Selection of Advanced Diagnostic Methods

It is obvious from the above that the results of traditional off-line diagnostic methods, mainly obtained from the analysis of the insulating oil, are not sufficient to assess the actual condition of all critical parts in a power transformer. New advanced diagnostic techniques must concentrate on measurable quantities which are directly related to the main stress parameters and/or typical failure modes. Based on practical experience the following methods have been selected for this project:

- ageing under thermal stress, humidity in cellulose: **measurement of the relaxation currents, i.e. polarisation and depolarisation currents (PDC)**
- electrical stress, local defects in HV insulation: **measurement of partial discharges (PD)**
- mechanical stress, deformation of windings: **measurement of transfer function (FRA).**

2.3 Insulation Diagnosis by Means of Relaxation Current Measurements

Integral, electrical diagnostic techniques, such as the measurement of the dielectric dissipation factor (DDF, tan δ) or power factor (PF), can be used to qualify the trends of insulation ageing in power transformers or in other high voltage apparatus. As permittivity and losses in composite oil/cellulose insulation are influenced by ageing products even at power frequency, the deterioration of such insulation systems can be determined quantitatively on a global basis (no information about local defects).

For some time past, also non-traditional methods for insulation diagnosis are applied and discussed: the measurement of (a) the recovery or "bucking" voltage (RVM) [5] to quantify a so-called "polarisation spectrum", (b) "the isothermal relaxation currents" [8], or (c) the "voltage response" [9]. It is quite obvious that each of these traditional or non-traditional methods can be traced back to the same well known phenomena in dielectrics: the existence of various polarisation effects and losses in insulating materials. Under conditions where non-linear effects are avoided, such measurements can be made either in the frequency- or time-domain and the results can be transformed from one domain into the other.

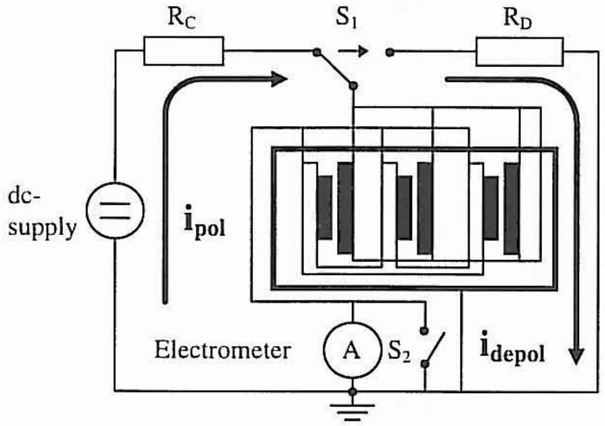

Fig. 1 Circuit for measurement of polarisation and depolarisation currents (PDC).

As proposed recently [10][11][12], the measurement of relaxation currents, i.e. polarisation- and depolarisation-currents (PDC), in the time-domain is the preferred method, as such measurements are easy to apply even on very large power transformers on site. The measuring circuit (see Fig. 1) and the procedure are quite simple: a d.c. voltage source (about 1 kV) is switched onto the insulation system under test (e.g. a HV winding of a transformer) and remains connected during a predetermined time period (e.g. 1 to 2 hours). Then, the voltage supply is disconnected and substituted by a short circuit for at least the same duration of time. During both periods, the currents are recorded at a terminal of a second winding of the transformer which is grounded (see Fig 1). Similar to the procedures applied during DDF-measurements, the complex structure of a power transformer can thus be subdivided into individual insulation sections. The time-dependent currents represent the polarisation current i_{pol} during voltage application and the depolarisation current i_{depol} during the short circuit of the system. In general, both currents follow well known relations of the linear dielectric response theory [11] [12].

Although a deterioration of the insulation quality is manifested by an increase of amplitudes and by a change of the time-dependence of the relaxation currents, only a very experienced specialist would be able to infer an increase of permittivity or losses from the shapes of these currents. However, these currents can be transformed into the frequency-domain, where the two related quantities, effective capacitance and tan δ, exhibit a clear dependence on frequency. Details about the calculation of capacitance and loss factor in the frequency domain based on time dependent relaxation currents can be found in [10][11]. The following examples demonstrate that this diagnostic method can be applied "on-site", i.e. all PDC-measurements presented here were performed in substations, unless otherwise claimed.

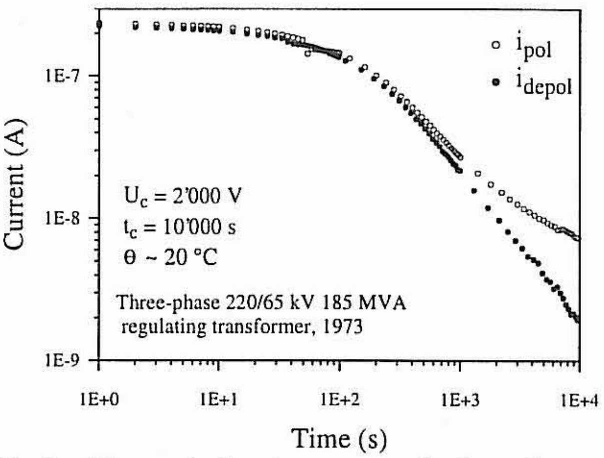

Fig. 2 Measured relaxation currents of a three-phase 220/65 kV 185 MVA substation transformer.

Fig. 2 shows measured relaxation currents of a service-aged transformer (built in 1973, see also section 3), as recorded from the barrier insulation system between the 220 kV and 65 kV windings. Although a quite long time-period of nearly 3 hours was used for the PDC-measurements, the limiting d.c. regime could not be reached in this case. The slopes of the currents display a "dominant relaxation time constant" in the range of about 200 seconds. Here, the sudden decrease of current is due to the interfacial polarisation which is mainly controlled by the oil conductivity and by the volume ratio of oil to pressboard. The calculated results in the frequency-domain (Fig. 4) provide more detailed information.

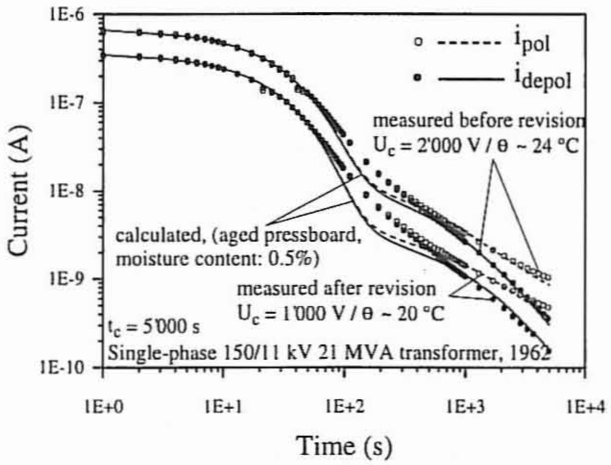

Fig. 3 Measured and calculated relaxation currents of a single-phase 150/11 kV 21 MVA transformer before and after refurbishment.

To demonstrate, that transformers, whose main insulation system is composed of impregnated pressboard barriers with oil-gaps display similar relaxation currents, the recorded currents of a 150 kV/11 kV 21 MVA single-phase unit (built in 1962) from a Swiss hydro power station are shown in Fig. 3. This service aged transformer was subjected to a major overhaul and PDC-measurements were performed before (on-site) and after the refurbishment (at the manufacturers laboratory). A careful inspection of the active part revealed that a replacement of the cellulose insulation was not necessary. In this case refurbishment of the insulation system involved only the usual drying and degassing processes.

When the geometry of a transformer insulation system is known, the relaxation currents of such a system can be calculated from the dielectric properties of the main components, oil and pressboard, as described in [12]. Such calculated currents before and after refurbishment are compared with measurements in Fig. 3, taking into account the actual magnitudes of the applied d.c. voltages and of the temperatures during the measurements. The dielectric properties of the oil as necessary for this calculation have been determined from oil samples taken before and after revision; those of impregnated pressboard have been determined from an artificially aged pressboard sample with a moisture content of 0.5% [12]. The comparison in Fig. 3 between calculated and measured curves shows that the shapes of the relaxation currents are nearly the same before and after revision, confirming that after 35 years of service the insulation of this transformer is still in a very good condition.

Fig. 4 shows the dielectric behaviour of the insulation systems of both transformers discussed above in the frequency domain, i.e. the capacitance C as well as the dielectric dissipation factor (tan δ). Both magnitudes were calculated from the measured relaxation currents (see Fig. 2 and Fig. 3) for the frequency range from 0.1 mHz up to 100 Hz. As the measurements of the relaxation currents do not start immediately after voltage application or the short circuit of the insulation, the calculated values for tan δ are too low for frequencies higher than about 1 Hz [11].

This restriction, however, does not apply to the calculated frequency dependence of the effective capacitance C, as the equivalent circuit of the insulation system can be normalised to the measured capacitance at power frequency. The significant increase of C in the very low frequency range is essentially due to the dominant time constant of the relaxation currents decay as mentioned above. This increase can be explained by the fact, that the electric field within the oil-gaps will vanish after the interfacial polarisation has settled. Thus, for extremely low frequencies, the capacitance of the pressboard alone will appear. The differences between this increase of C for both transformers (Fig. 4) can mainly be explained by details of the insulation design and partly by the fact that the pressboard of the 185 MVA transformer is more dispersive than that of the 21 MVA unit. According to the dielectric theory, a large change of the capacitance (or effective permitti-vity) in the frequency domain is always accompanied by a pronounced peak of the losses, i.e. the DDF, which is clearly visible in Fig. 4.

Finally, it should be mentioned, that the results of all "non-traditional" integral diagnostic methods (e.g. [3][5][8][9]) can be calculated from time dependent relaxation currents. As these currents can easily be recorded also under difficult on-site conditions, if suitable measuring devices are used, the application of the PDC-technique can substantially improve the condition assessment of large power transformers or other high voltage apparatus.

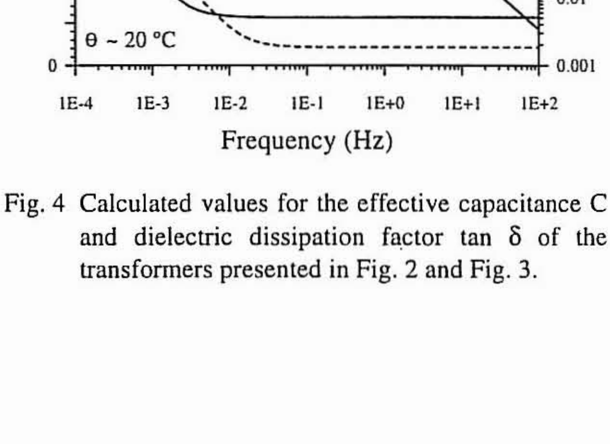

Fig. 4 Calculated values for the effective capacitance C and dielectric dissipation factor tan δ of the transformers presented in Fig. 2 and Fig. 3.

2.4 Detection of Partial Discharges (PD)

It is generally accepted that partial discharge (PD) detection, using electrical and/or acoustic techniques, is one of the most effective diagnostic method to reveal incipient faults and local defects in a HV insulation [3] [4] [5]. There is a sufficient strong link between PD-activity and insulation performance of large power transformers to support the use of PD detection techniques for on-site condition assessment and on-site quality control, e.g. after installation of new strategically important units or after refurbishment or repair of old service-aged power transformers [13].

Conventional PD detection systems (e.g. according to IEC 270), as used in shielded HV laboratories, are not suitable for on-site applications on power transformers, because external electromagnetic interference from operating substations or energized power lines severely hamper the detection sensitivity. Therefore an advanced diagnostic system (Fig. 5) for electrical off-line PD detection was developed as part of this project, having the following key elements:

- PD-free, test voltage source, not synchronized to power frequency, for the excitation of the transformer under test
- multi-terminal PD-signal detection using special HF-current transformers (0.2 to 30 MHz) directly connected to all bushing tap-offs
- background noise suppression using a spectrum analyser as a selective bandpass-filter with gating facility of the input
- computer controlled PD-impulse acquisition and digital signal processing using a phase resolving partial discharge analyser (PRPDA).

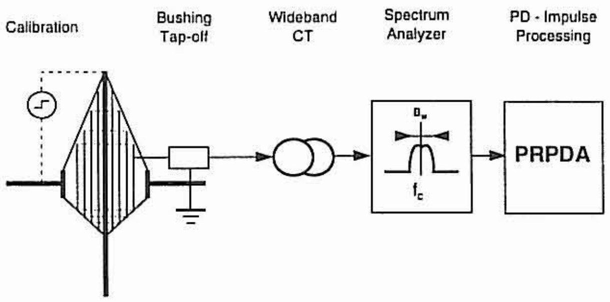

Fig. 5 Off-line PD detection system for power transformers

Efficient discrimination between PD-signals and background noise (mainly due to corona discharges synchronized to 50 Hz) is achieved by digital impulse acquisition and storage as well as by statistical data processing correlating all PD-events with the phase position of the applied test voltage [14] (see example in Fig. 7).

Figure 6 shows two different circuits for test voltage generation which have been utilised for these tests: (a) three phase excitation of the compensating (delta) winding from a mobile motor-generator set (induced voltage test), and (b) application of a frequency tuned series resonance circuit [15] (single phase separate source test). During off-line PD tests, voltage levels of 110% to 120% of the normal service voltage were applied for a duration of typically 60 minutes. No standard yet exists which specifies the limits of PD during on-site tests. As a rather practical rule, however, it is agreed that there should be no measurable discharges above background noise level at a test voltage level near service voltage.

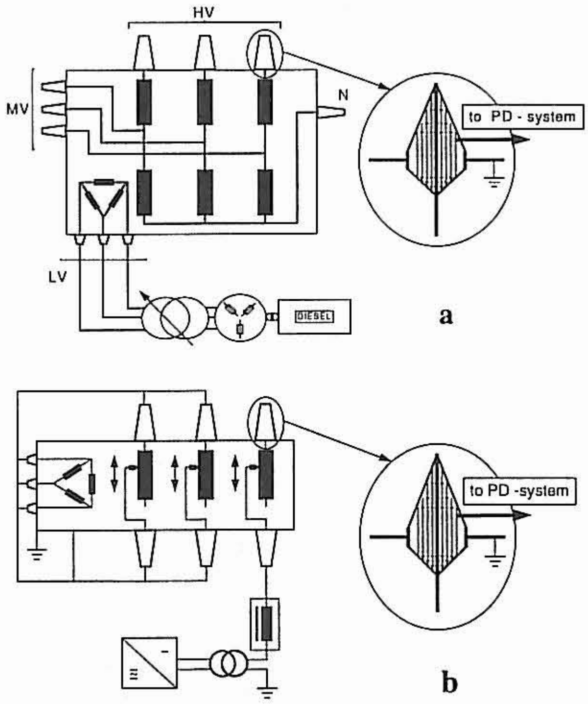

Fig. 6 Test voltage generation for off-line PD diagnostics: (a) induced voltage test on a auto-transformer, and (b) separate source voltage test using a series resonance test set on a regulating transformer.

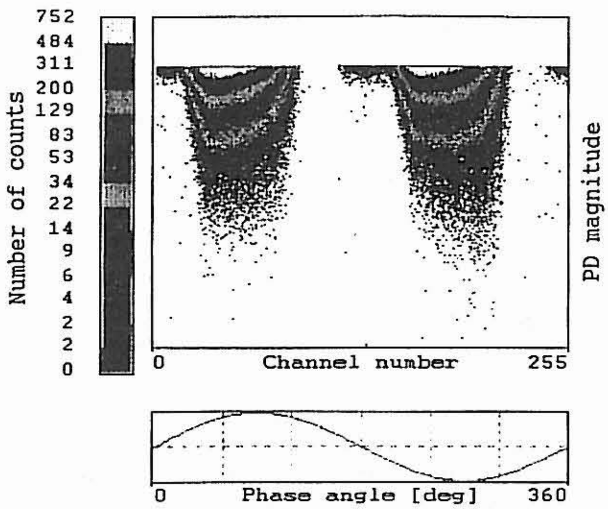

Fig. 7 Phase resolved partial discharge pattern of a 220/400 kV 400 MVA autotransformer at 80% U_n, 400 kV terminal (see text).

The result of a PD-measurement using a phase resolving PD-analyser is a three-dimensional pattern (phase angle, discharge magnitude and number of counts), which can be considered as a fingerprint of the PD-activity of a specific defect a transformer. The PD-pattern shown in Fig. 7 was recorded during an on-site test of a new 220/400 kV 400 MVA autotransformer. The detected PD-activity was significant even below service voltage level (i.e. at 80%) and exhibited high PD-magnitudes (> 500 pC). The pattern indicates a too high moisture level in the cellulose insulation of the 400-kV terminals outlets which were installed on site. After careful drying of this part of the transformer it could be demonstrated in a second PD-measurement that the PD-activity completely disappeared.

The off-line PD detection technique described above has been applied successfully to several substation transformers (100 MVA class) and to three 220/400-kV autotransformers after installation. In all cases a detection sensitivity of better than 50 pC was reached, even when HV power lines or HV equipment were operating in the same substation.

2. 6 Measurement of the Transfer Function, Frequency Response Analysis (FRA)

During its life a transformer can be subjected to several short circuits with high fault currents. The dynamic forces of these external short circuit currents may cause deformations or displacements of the winding assemblies. In particular, the winding insulation of old transformers can become rather vulnerable to short circuit forces because of the reduced mechanical strength and the shrinkage of the aged paper which may result in a loss of the winding clamping pressure.

In most cases, however, a displacement of a winding after an external short circuit does not immediately lead to a transformer failure, but there is a high risk that a mechanical damage in the turn or coil insulation due to abrasion or crushing of the aged, brittle paper may eventually cause an insulation breakdown at the next over-voltage stress. Therefore, simple non-intrusive off-line methods for detection of winding movement and failures are of high importance, because opening a transformer and visual inspection is time consuming and expensive.

Traditional electrical measurements of turns ratio, impedance and inductance at 50 or 60 Hz are not sensitive enough for the detection of small winding displacements. As deformation results in minor changes of the internal inductance and capacitance of the winding structure, a change in the characteristic frequency response (e.g. impedance, admittance) can be detected at the terminals of the transformer by frequency response analysis (FRA) and the so-called transfer function (TF) method, or in the time domain by the low voltage impulse (LVI) method [16][17][18].

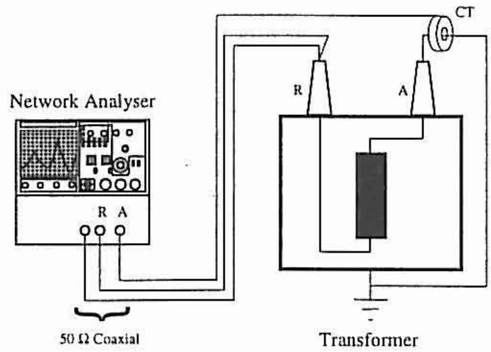

Fig. 8 Set-up for frequency response analysis (FRA)

In this project, the frequency response of transformer windings was analyzed off-line using a commercially available network analyser. The principle of this FRA-technique is schematically presented in Fig. 8. The output of a swept sinusoidal signal (2 V rms) and one measuring input (R) of the analyzer are connected via screened coaxial cables to one terminal of the winding under test. The other end of the winding (e.g. neutral terminal) is connected via a current transformer (CT) to the second input (A) of the network analyzer. In the normal case, the windings not tested are grounded. The frequency response of a winding is determined by measuring the signal ratio (A/R), i.e. the frequency dependent impedance and/or admittance of each winding are evaluated in amplitude and phase for two standard frequency scans: (a) 50 Hz to 500 kHz, and (b) 200 kHz to 2 MHz. The measured frequency responses of each winding are analysed in the following way:

- changes of resonances, poles (reference necessary)
- differences between the responses of the three phases of the same transformer
- differences between the responses of a transformer of the same design.

The FRA-method has proved to be sensitive to detect typical winding faults; it is immune to electromagnetic interference and easy to perform on site. In particular the results are very repeatable, i.e. identical results can be obtained from transformers of the same design. Figure 9 shows a winding failure in a single phase transformer which could be identified by comparing the FRA-measurement with the result of the reserve unit.

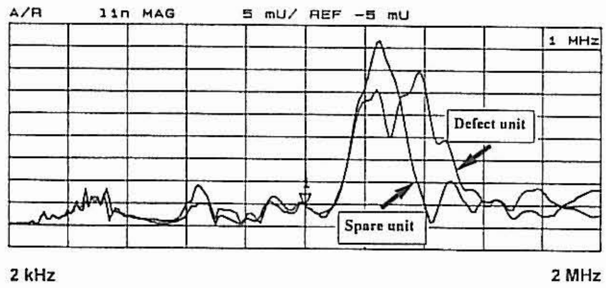

Fig. 9 FRA-measurement for a 220/12 kV 21 MVA single phase transformer showing a short circuit between two discs of the HV winding.

3. ON-LINE TRANSFORMER MONITORING

The major goals to be achieved by an on-line transformer monitoring or surveillance system are:

- prevent catastrophic failure
- better utilise load capacity
- optimise maintenance
- extend remaining life

Whatever goals or priorities are set, each on-line transformer monitoring system needs the following main components: (a) built-in sensors to detect changes, (b) models for analysis of the status, and (c) a decision-making process.

3.1 Traditional Monitoring

Recently many sensors have been developed to monitor permanently the transformer's operating state: one can find commercial products to measure oil properties (temperature, gas content and moisture) and tank vibrations [3][4]. The classical way to process (analyse) sensor data is to define one or several thresholds for each measurement in order to set alarms. If an alarm occurs, the transformer is switched off and an off-line diagnosis is done.

Alarm-based monitoring systems are commonly used because they are simple to install and provide an automatic detection of incipient faults. However, the setting of the thresholds is critical: they may be set too high and an early fault detection may fail. On the other hand, when an alarm occurs too often (false alarm), its relevance might be altered. In case of real fault, the transformer might be switched off too late and be subject to damages with severe financial consequences.

3.2 Model-Based Monitoring

The strategy of the model-based transformer monitoring has been developed in the early 90's in the MIT [19]. Its main characteristic is to use adaptive thresholds that differ depending on the working conditions of the transformer. In order to calculate these adaptive thresholds, models are needed. For each sensor, a computation provides the expected measurement value and, at any time, the calculated value is subtracted from the actual one (see Fig. 10). Then, taking a given confidence level into account, the range of the residual is used to decide whether a faulty condition (e.g. due to an internal failure) exists or not.

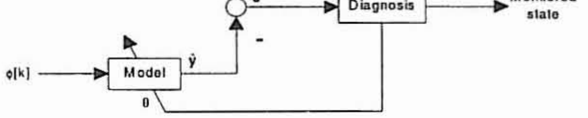

Fig. 10 Residual analysis

Models

Mathematical models are based on analytical expressions for computing the output of each sensors from values in the past (time-dependent data) and the decision variables (external conditions or operator decision). Every input-output can be based on one global model or on several models (one for each sensor). If the behaviour of the system and the operating conditions are well defined, physically inspired models can be used.

In the case of sensors signals of a transformer, more or less empirical expressions with linear coefficients are usually used [19][20].

However, the transformer problem is not well defined and has some non-linear components. Therefore, it is worth to consider a neural network based models as well [21]. For a sample k, the general expression can be written as

$$\hat{y}[k] = f\left(\phi^{T}[k] \cdot \theta\right)$$

where f represents a non-linear function with defined properties. In this case, the estimation of the parameters is more complicated than for a linear case and must be computed with iterative methods.

Because the transformer behaviour is changing (e.g. due to ageing processes), the parameters of the models have to be adapted regularly. This can be done by reformatting the training set every day with the most recent data (which don't represent a faulty state).

Monitoring

Basically, the monitoring function can be divided into two parts: (a) detection of a faulty condition, and (b) detection of an incipient fault or dangerous ageing state.

The detection of a faulty condition is derived directly from the residual analysis. The confidence level is adjusted to the quality of the models used: after the computation of the parameters, the mean of the quadratic error and its standard deviation σ are calculated for the model applied on the training set. Finally, the confidence range is set to 3σ.

The incipient failure and the ageing monitoring are evaluated by looking at the variation of the model over the time. An abnormal (to fast) rate of change will point out a incipient fault or the end of life of the device.

3.3 Diagnosis Concept

Once the monitoring system has produced a message or a signal showing that a faulty condition exists, a diagnostic layer is needed in order to localise and qualify the failure. Generally, the two following approaches can be considered.

Data based learning diagnosis system

The concept of this method is to collect as many data as possible of every operating condition of the transformer and store them in a database. Measured data of the sensors or trends of values are then compared with the database and the monitoring system will associate the actual situation with a condition of the transformer which is known. The database must contain every possible conditions, including faulty ones. The problem is that no general model exists to simulate a large power transformer. Only measured data can be used to build-up the database. At present, the on-line monitoring experience of transformers is rather limited and there are only few failure data available.

Expert based diagnosis system

Usually, because of the situation described above, only data about the normal condition are available. Using the residual method, it is possible to decide whether the status of the transformer is normal or not. If a failure occurs, the range of the residual has to be analysed and interpreted. In order to diagnose the origin of the failure, the relations (rules) between faulty conditions (data monitored) and the causes are needed. This information mainly comes from human experts; as explained before, only few data are available from measurements.

3.4 Pilot Installation of a Monitoring System for a Strategic Transformer

The first on-line monitoring system in Switzerland has been installed on a 220/65 kV 185 MVA three-phase power transformer (see Fig. 11) which is located in Fiesch in a mountain region and is directly connected to a hydro power station and to the 220 kV transmission grid.

Nine important parameters are measured on-line by nine different sensors:

- transformer load;
- top oil temperature;
- tank and air temperature;
- dissolved gas and moisture in oil;
- tank vibrations;
- overvoltages and short-circuit currents at each phase.

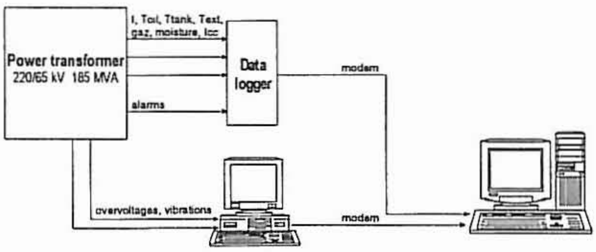

Fig. 11 On-line monitoring system: measuring set-up

The sensor signals are acquired by two systems on site (Fiesch) and data are transmitted via modem to a central computer.

A commercial data-logger collects data on load, temperatures, gas-in-oil, moisture-in-oil, short circuit currents and operating alarms (Buchholz relay, cooling system and overload). Additionally, a digital oscilloscope is used to record overvoltages and vibrations of the tank.

The commercial data-logger is a flexible and low cost product. Its main technical characteristics are 17 analog configurable channels which can be either current inputs (4-20mA, 0-5 A or 0-50 A) or voltage inputs (-10 to +10 VCC or 0-300 VAC) and 16 digital inputs. The channels sample rate is fixed at 150 Hz excepted for the short-circuit current that are digitised at 1920 Hz. In order to save memory, those data are reduced to one value per hour for each channel. With this configuration, the memory of the system is nearly equivalent to 3 months of measurements (FIFO buffer). The modem connection between the data logger and the PC allows us either to download the measurements or to upload new configurations from a remote site.

Overvoltages are measured through a special connector of the 65 kV-bushings including an internal capacitive divider. Normally, this system is used to perform partial discharge measurements off-line. For security reasons, this connector must be short-circuited while the transformer is in operation, but we have placed three current probes on these short-circuits, in order to get three-phase recording of the overvoltages. Preliminary tests have shown that it is possible to obtain a very accurate picture of the (over)voltage by numerical integration of the current.

For the monitoring of vibrations, an industrial accelerometer has been fixed on the external wall of the transformer. The vibrations are measured periodically and each time an overvoltage is recorded.

Finally, in order to build-up the database which is needed to evaluate the diagnostic tools, all the sensors outputs described above are collected and pre-processed on the same central computer.

3.5 Results

Data have been collected since January 1997. The rough measurements are showing that, if the obvious link between tank and top oil temperature is not considered, no strong immediate linear correlation can be found in the data set. This result doesn't mean that there is no correlation at all but that the connections between the values are more complex. Therefore, the use of an artificial intelligence based system is justified.

The model-based monitoring method has been applied to the data-logger measurements (top oil temperature, moisture and gas). Both linear and non-linear models were tested. Considering the confidence level plotted in dotted dashes, the results in Fig. 12 show that the implemented models are able to predict accurately the normal condition of the transformer. In average, the linear correlation coefficient between the calculated outputs (thin curve) and the actual measurements (thick curve) is more than 0.95 and the mean error is less than 5 % of the values.

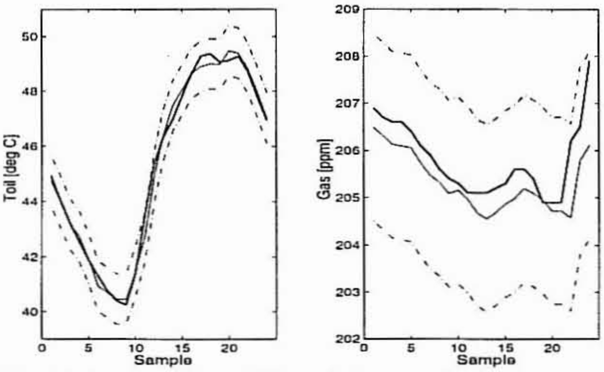

Fig. 12 Forecasting ability of the monitoring system: left: oil temperature, right: gas-in-oil content.

The information, which will be used for diagnostic purposes, is the residuals. Figure 13 presents the visualisation of the residuals corresponding to the measurements presented in Fig. 12. The confidence levels are also plotted in doted dashes. If one of the measured values is not contained within the interval defined by the two adaptive thresholds, the corresponding sensor does not follow the model and an alarm has to be set in.

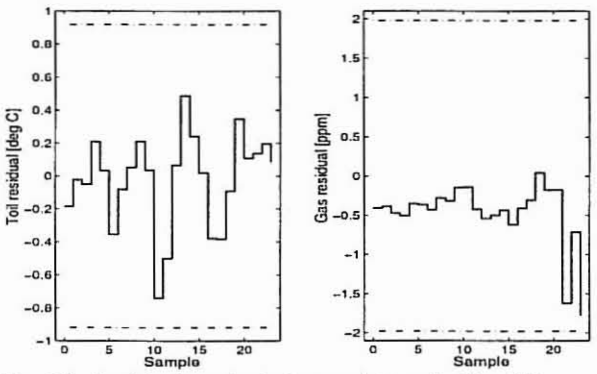

Fig. 13 Residual analysis (same data as in Fig. 12).

The overvoltage measurement is effective and several events have been recorded during the summer 1997. Figure 14 shows such an overvoltage.

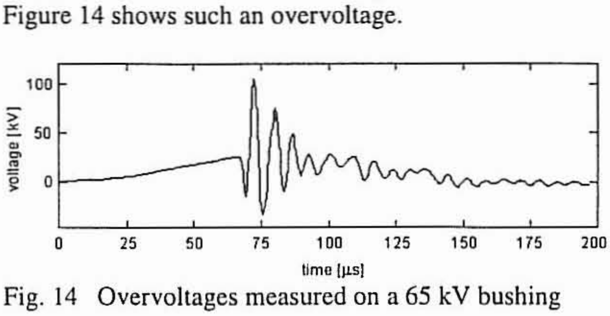

Fig. 14 Overvoltages measured on a 65 kV bushing

At present, there are not enough abnormal operating conditions recorded to find a correlation between overvoltages, short-circuit currents and the transformer condition.

For the vibrations, using a self-organising map (Kohonen network) [21], we have made a classification of the 18 first harmonics, in order to find out typical operational states of the transformer, in correlation with the other measured parameters. Depending on the difference between the best fitting operational state and the actual measurements of the vibrations, an error signal is generated for diagnostic purposes. Figure 15 shows a typical measurement of the vibrations.

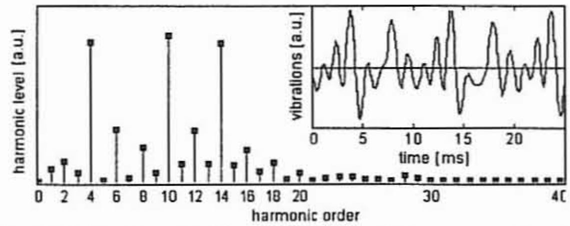

Fig. 15 Vibrations in time domain and frequency domain

4. CONCLUSIONS

Advanced off-line diagnostic methods as described in this paper have been applied to more than 30 new and service-aged transformers. The experience gained and the results can be summarised as follows:

- All methods (PDC, PD, and FRA) are suitable for on-site use; however, reproducibility and immunity to electromagnetic interference can only be achieved when standardized set-ups and procedures are used for each method
- A reference data set about the condition of 10 new transformers after installation was established for units in the range from 50 MVA up to 600 MVA and voltages up to 400 kV.
- A comparison with measurements in the manufacturer's laboratory demonstrated the consistency and reproducibility of these reference data measured on site.
- On service-aged transformers different failures have been identified: PD-sources, high moisture content in cellulose and mechanical defects.

For the on-line monitoring system the following conclusions can be drawn:

- The pilot-installation is operating well. The implemented adaptive threshold concept for fault detection improves the reliability of this important transformer.
- More measured data are needed for the decision process of such a system. In particular, data about unexpected events and also about long term effects such as ageing are necessary for the fault identification.

Therefore, future work has to concentrate on the correct interpretation of diagnostic results and on reliable criteria for the decision process for implementation in on-line monitoring systems. To reach this goal, we need not only a consequent application of advanced diagnostic methods on new and service aged transformers, but also more fundamental work to understand the physics of the ageing processes in transformer insulation systems. The experience with this project has demonstrated that progress in this field requires a close co-operation between utilities, transformer manufactures, independent testing organisations and universities.

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REFERENCES

[1] CIGRE WG 12-05: *An international survey on failures in large power transformers*, ELECTRA, No. 88, 1983, pp. 21-48.

[2] *VDEW-Störungs- und Schadensstatistik*, Frankfurt, VWEW, 1994.

[3] *Diagnostic and Maintenance Techniques*, CIGRE Symposium, Berlin, 1993.

[4] *Dielectric Diagnostics and Life Assessment*, Joint Session 15/21/33, CIGRE Session 1996.

[5] C. Boisdon, M. Carballeira, J. Poittevin, P. Guuinic, P. Luccioni, M. Tudrej: *Condition diagnosis and monitoring of transformers - possibility of estimating transformer lifetime*, CIGRÉ 1992 Session, paper 12-106.

[6] H.J. Knab, P. Boss, E. Ecknauer, R. Gysi: *Diagnostic tools for transformer in service*, CIGRE Symposium, Berlin, 1993, paper 110-05.

[7] D. Reichelt, A. Frey, M. Schönenberger: *Life Expectancy of Power System Apparatus and Components*, CIGRE Session 1996, paper 23-102.

[8] H.G. Kranz, D. Steinbrink, F. Merschel: *IRC-Analysis: a new test procedure for laid XLPE-cables*, 10th Intern. Symp. on High Voltage Engineering (ISH), Montreal 1997, Vol. 4, pp. 207-210.

[9] E. Nemeth: *Measuring the voltage response, a diagnostic test method of insulation,* 7th Intern. Symp. on High Voltage Engineering (ISH), Dresden 1991, paper 72.06.

[10] V. Der Houhanessian, W. S. Zaengl: *Time Domain Measurements of Dielectric Response in Oil-Paper Insulation Systems,* Conf. Rec. of the 1996 IEEE Intern. Symp. on Electr. Insul., IEEE Publication 96CH3597-2, pp. 47-52.

[11] V. Der Houhanessian, W. S. Zaengl: *Vo[illegible] Diagnose für Leistungstransformatoren,* Bull[illegible] SEV/VSE, No. 23, 1996, pp. 19-28.

[12] V. Der Houhanessian, W. S. Zaengl: *Applicati[illegible] of relaxation current measurements to on-sit[illegible] diagnosis of power transformers*, Annual Report of the 1997 Conference on Electrical Insulation and Dielectric Phenomena, IEEE Publication 97CH36046, pp. 45-51.

[13] G. Breen, *Essential Requirements to Maintain Transformer in Service,* CIGRE Session 1992, paper 12-103.

[14] B. Fruth, J. Fuhr, *Partial discharge pattern recognition - a tool for diagnosis and monitoring of ageing*, CIGRE Session 1990, paper 15/33-12.

[15] W. S. Zaengl, F. Bernasconi, B. Bachmann, W. Schmidt, K. Spinnler, *Experience of AC voltage tests with variable frequency unsing lightweight on-site series resonance device,* CIGRE Session 1982, paper 23-07.

[16] E.P. Dick, C.C. Erven, *Transformer diagnostic testing by frequency response analysis*, IEEE Trans. PAS, vol. 97, 1978, pp. 2144-2153.

[17] R. Malewski, E. Gockenbach, R. Maier, K. Fehlmann, A. Claudi, *Five years of monitoring the impulse test of power transformers with digital recorders and the transfer function*, CIGRE Session 1992, paper 12-201.

[18] J. A. Lappworth, P.N. Jahrman, *Winding movement detection in power transformers by frequency response analysis (FRA)*, Proc. Conference on Condition Monitoring in HV substations, Dorking, U.K.,1996.

[19] Crowley, T.H., *Automated Diagnosis of Large Power Transformers Using Adaptive Model-based Monitoring*, MIT-LEES Technical Report, TR 90-003, June 1990.

[20] IEC 354, *Loading guide for oil-immersed power transformers,* second edition, 1991.

[21] El-Sharkawi, M. A., Niebur, D., *A Tutorial Course on Artificial Neural Networks with Applications to Power Systems*, IEEE Power Engineering Society, 1996.