Experience with Diagnostic Tools for Condition Assessment of Large Power Transformers

Jitka Fuhr
ABB BA Power Transformers
CH-3700 Spiez, Switzerland
jitka.fuhr@ch.abb.com

Thomas Aschwanden
BKW FMB Energy Ltd
CH-3000 Berne, Switzerland
thomas.aschwanden@bkw-fmb.ch

Abstract: **The application of advanced off-line methods and procedures for condition assessment of new and service-aged power transformers are discussed. The selection of the diagnostic methods is based on the main operational stresses (electrical, mechanical, thermal) and on typical failure modes: (1) detection of polar components in the paper/oil insulating system using frequency domain spectroscopy (FDS) or using measurements of polarisation/depolarisation currents (PDC) in the time domain, (2) localization of inhommogenities in the insulating system using sensitive partial discharge detection (PD) and (3) detection of deformations and movement of windings in the active part using measurement of the transfer function (FRA).**

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 transport to the factory, repair and financial losses due to power outage. Therefore, utilities have a clear incentive to assess the actual condition of strategically important transformers, with the aim to minimise the risk of failures and to avoid forced outages. Special attention in this respect is given to large power station step-up transformers, large substation transformers or any large autotransformers in a HV transmission system.

In case of a problem during operation of a new or service-aged transformer (i.e. Buchholz alarm, differential protection, bushing explosion etc.), utilities are challenged with the following questions: (1) what is the origin of the problem? (2) Does the problem affect the reliable operation of the transformer? (3) Is it possible to do a repair on-site? (4) Is a replacement with a new transformer necessary?

To answer these questions a project was initiated in Switzerland in collaboration with utilities, technical universities and the transformer industry to investigate and explore new diagnostic methods and surveillance systems for large power transformers [1]. This paper describes three advanced diagnostic methods developed in this programme and the experience with their application on new and service-aged transformers. Several serious failures have been detected in new transformers just after the assembly on-site and some incipient faults on older units have been found.

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. Traditional diagnostic methods such as dissolved gas-in-oil analysis (DGA) are used for routine assessment of the condition of power transformers. In case of an alarm or of an electrical failure (breakdown) in the insulating system of a transformer, three advanced diagnostics methods are preferably applied for the judgement of the seriousity and for the localization of the problem.

2.1 Advanced Diagnostic Methods

It is obvious, 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 are concentrating on measurable quantities, which are directly related to the main stress parameters and/or typical failure modes. Based on practical experience and on the availability of modern measuring equipment, the following methods have been evaluated and tested under practical conditions: (1) control of the content of polar components in cellulose and oil using measurements in frequency domain (dielectric spectroscopy) or in time domain (polarisation-depolarisation currents, PDC), (2) detection of inhommogenities in the insulating system using sensitive partial discharges (PD) measurements, (3) detection of deformations and movement of the windings by frequency response analysis (FRA).

2.1.1 Measurement of polarization effects

When a dielectric material is exposed to an electrical field E it gets polarised. The polarisation P(t) of the material is added to the vacuum polarisation to form the electric displacement D(t).

$$D(t) = e_0\, E(t) + P(t). \qquad (1)$$

In the transformer insulating system we assume, that the polarization P(t) is proportional to the intensity of the applied electric field E(t), i.e. we are observing linear polarisation effects [2].

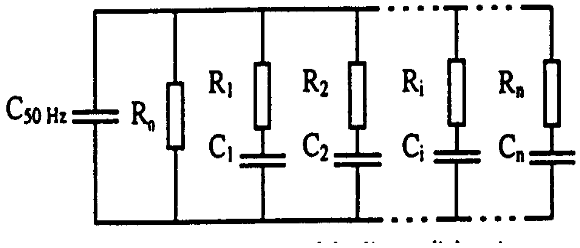

Figure 1 - Theoretical model of linear dielectrics, R_0 = DC resistance, R_i, C_i = individual elements, $C_{50Hz} = e_r.C_0$

If we switch on the electric field at time = 0, the polarisation P(t) takes some time to react. This delay or memory effect is a specific property of each dielectric material or of a specific combination of materials like oil, cellulose, spacers and pressboard barriers in the main insulating system of a transformer. The measurement of these polarisation effects is based on the detection of the memory effect which is not only dependent on the material properties but also on the geometrical structure of the insulating system. This memory effect will change if polar components like humidity or polar aging products are added to the insulating system during normal or exceptional service conditions (thermal overload).

The typical memory effect of an oil/cellulose insulation system can be detected by investigation of various phenomena: (1) return voltage polarisation spectra using recovery voltage measurement (RVM), (2) isothermal relaxation currents using the measurement of polarization/depolarisations currents in time domain (PDC), (3) frequency dependent impedance Z using measurement of voltage and current in a selected frequency range, typically from 0.001Hz to 1000Hz (FDS).

Under conditions where non-linear effects are avoided and the methods are correctly applied to the test object, these methods deliver similar information about the memory effect, i.e. about the existence of various polarisations effects and losses in the investigated insulating system [2].

The advantage of PDC (time domain) and FDS (frequency domain) is the possibility to transform the result from one domain into the other [2].

When the geometry of the transformer insulating system is known, the measured values in the time domain (PDC) or in the frequency domain (FDS) can be calculated from the dielectric properties (DC-conductivity and permittivity) of the oil and cellulose parts. The dielectric properties of the oil can be determined from the oil samples taken from the transformer under test, the dielectric properties of oil impregnated pressboard are determined from measurements performed on pressboard samples at different conditions: (1) new pressboard with different moisture content, (2) artificially aged pressboard with well defined moisture content. Using a simulation model (Figure 1) it is possible to determine (curve fitting) approximately the amount of the polar components, i.e. the humidity or polar aging products in the transformer insulation system as shown in Figure 2.

For the analysis of the results both the comparison between measured curves on sister transformers or measured curves before (fingerprints) and after revision or repair as well as the comparison between calculated and measured curves are used (see Figure 2).

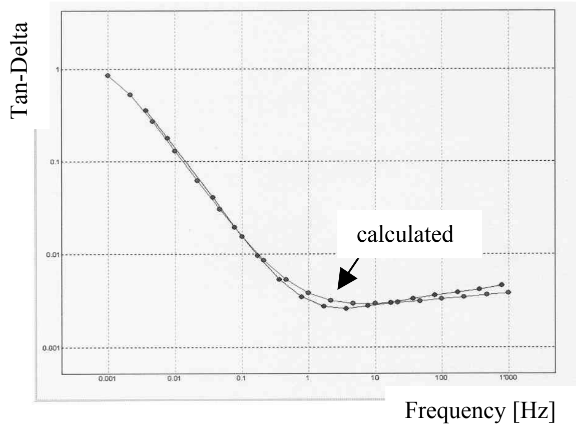

Figure 2 - Measured and calculated loss tan delta in a large autotransformer, 400 MVA, 400/220 kV (FDS-method)

In Figure 2, the moisture content in the insulating system is approximately 1.5 % according to the simulation by using the following parameters for curve fitting: (1) measured oil conductivity of 0.259 pS /m, (2) geometrical capacitance (cylindrical capacitance for core type transformer) of the main insulating system of 2.5 pF (vacuum capacitance). The insulation structure in the duct was represented by the relative amount of barrier content of 30% and spacer coverage of 20%.

2.1.2 Detection of Partial Discharges (PD)

Partial discharge (PD) is an electric breakdown in a weak region in the insulating system of a transformer (see Figure 3). Electric breakdown occurs if the following conditions are fulfilled: (1) local electric filed E in kV/mm is greater than the breakdown field strength E_b of the specific insulating material, (2) primary electrons are readily available. Sufficient electric field to ignite a PD in a weak region of the transformer insulating system is present when the transformer is energized. The applied field stress during on-line PD-tests is typically 10 to 20 % higher compared to normal service conditions.

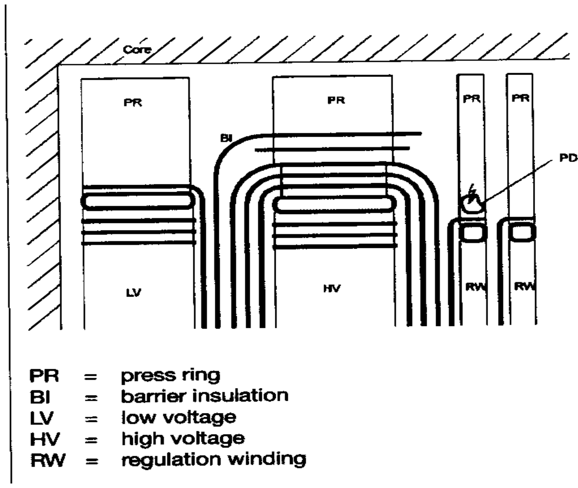

Figure 3 – PD-source in the insulating system

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 local defects and incipient faults in a HV insulation [3]. 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.

Conventional PD detection systems (e.g. according to IEC 600270), 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 for electrical off-line PD detection was developed and successfully used on more then 150 transformers. The key elements of an on-site PD-test set-up are: (1) PD-free test voltage source, not synchronized to power frequency, for the excitation of the transformer under test, (2) multi-terminal PD-signal detection using special HF-current transformers (0.1 to 30 MHz) directly connected to all bushing tap-offs, (3) background noise suppression using a spectrum analyser as a selective band pass-filter with gating facility of the input, (4) computer controlled PD-impulse acquisition and digital signal processing using a phase resolving partial discharge analyser (PRPDA) [3].

Efficient discrimination between PD-signals and background noise (mainly due to corona discharges) 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 [3].

The result of a PD-measurement using a phase resolving PD-analyser is a three-dimensional pattern (phase angle, discharge magnitude and number of events), which can be considered as a fingerprint of the PD-activity of a specific defect in a transformer insulation system. Each specific PD-defect, such as a tip electrode or voids in solid material, has their specific PD-pattern describing the physical processes of the discharge [3]. PD-pattern are not influenced by the damping phenomena of an extended insulating system.

The PD-pattern shown in Figure 4 was recorded during a PD-test in a substation on an autotransformer 400 MVA, 400 / 220 kV after repair on-site. Already at 100 % U_n PD activity of 70 pC (maximal value) was detected on the repaired phase V at the 220 kV bushing. The PD-pattern indicated moisture in the cellulose insulation. From the analysis of the PD-signals in the frequency and time domain there was a strong indication that the PD-source was close to the 220 kV bushing.

After a close inspection of the whole repair- and drying-process, the PD-source was identified: due to a closed venting tube at the dome of the 220 kV bushing of the phase V, drying of the bushing outlet with circulating hot oil was not possible.

After applying two additional drying cycles with hot oil at 90ºC the PD-source was successfully removed.

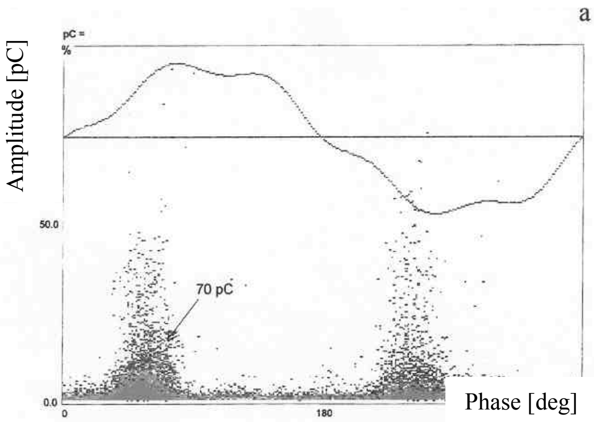

Figure 4 – PD-pattern at the 220 kV bushing of a 400 MVA autotransformer.

For the analysis of the PD-problem the following basic characteristics of the detected PD-pattern should be analysed: (1) phase position of the PD-signals, (2) symmetry of the PD-signals during the positive and negative sine wave, (3) number of PD-signals per cycle, (4) reproducibility of PD-pattern [3].

2.1.3 Frequency Response Analysis (FRA)

The transfer function *H (jw)* of a two port network is defined as a ratio of the output signal to input signal (see Figure 5). In case of a linear network the transfer function is independent on the shape and on the amplitude of the input voltage.

$$H(jw) = V_2(jw) / V_1(jw) \qquad (2)$$

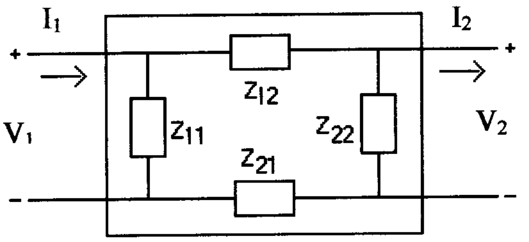

Figure 5 – Two-port network

The active part of the transformer can be described as a two-port network consisting of the following passive elements: resistance (R), inductance (L), capacitance (C) and mutual inductance M. The characteristic frequency response of the active part of the transformer can be detected at the terminals by frequency response analysis (FRA) in the frequency domain or in the time domain either by the low voltage impulse (LVI) method or in the HV-laboratory during lightning impulse tests using FFT-signal processing.

Our results have been obtained using measurements in the frequency domain with a network-analyser. The output of a swept sinusoidal signal (10 V peak to peak, 10 Hz –> 10 MHz) and one measuring input (reference) of the analyzer are connected via screened coaxial cables to one terminal (bushing). The third lead (response) of the analyser is connected to the other end of the winding (e.g. neutral terminal). The frequency response of the winding is determined by measuring the voltage ratio “response” / “reference” evaluated in amplitude and phase (see Figure 6).

For a network-analyser having 50 Ohm input impedance, the frequency dependent transimpedance and/or transadmittance of each winding can be determined as follows:

$$H(jw) = V_2(jw) / V_1(jw) = 50 / (Z(jw) + 50) \qquad (3)$$

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. Although winding deformations result only in minor changes of the internal inductances and capacitances of the winding structure, such changes are visible in the characteristic frequency response of a FRA-measurement [4].

Analysis of the FRA-results are based on the investigation of: (1) changes of resonance’s and poles (reference necessary), (2) differences between the responses of the three phases of the same transformer, (3) differences between the responses of a transformer of the same design.

The example in Figure 6 shows the effect of short-circuited windings, simulated by shorted tap-positions of the regulating winding, (regulating winding with 17 taps).

The FRA-method is sensitive enough to detect typical winding faults under practical conditions [4]. In particular this method is immune against electromagnetic interference and easy to perform on site. FRA results are very repeatable, provided that standardized procedures are applied.

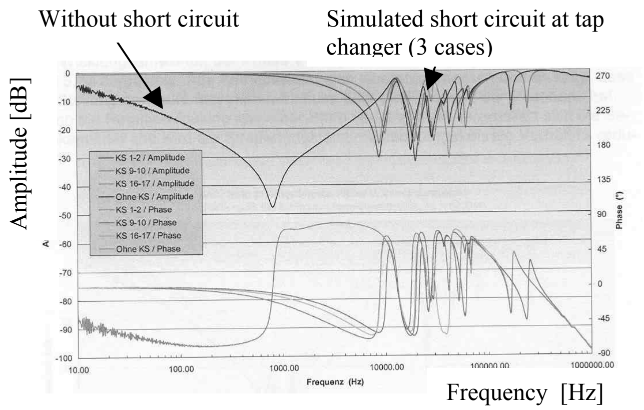

Figure 6 - Example of FRA-measurement with short circuit at the tap changer (regulating winding of a 220/49 kV unit)

4. CONCLUSIONS

Advanced off-line diagnostic methods as described in this paper have been applied during the last 10 years on more than 150 new and service-aged transformers (typically 100MVA or more). All three methods (FDS, 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.

For all PD-measurements, a detection sensitivity of better than 50 pC was reached, even when HV-power lines or HV-equipment were operating in the same substation.

On service-aged transformers different failures have been identified: dangerous PD-sources, high moisture content in cellulose parts and several mechanical defects.

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