PRACTICAL ASPECTS OF DIFFERENT NEW DIAGNOSTIC METHODS FOR THE CONDITION ASSESSMENT OF POWER TRANSFORMERS

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Abstract: The major part of transformers needed at the junctions of power supply systems are in service for several decades without any precise knowledge concerning the question how long they will operate satisfactorily due to the uncertainty of their insulation conditions. Nowadays different advanced methods for the condition assessment of power transformers are available, but it has to be decided case by case which measurement procedure should be used for which kind of problem. In this contribution some examples of advanced diagnostic methods are shown resulting in recommendations of optimised procedures for a condition assessment of power transformers. The benefits of special condition assessment methods but also their limitations are shown on practical examples, thus a clear strategy can be developed for assessing critical, failed transformers.

INTRODUCTION

Transformers belong to the most important and expensive components of power transmission and distribution systems. Therefore it is of special interest to prolong their life duration while reducing the service and maintenance expenditure for these apparatus. In order to reach these aims and to give recommendations about their future life expectation it is necessary to keep the transformers under surveillance during operation which is done by using various kinds of so-called monitoring systems. However, almost all monitoring systems, that are recently available on the market, can only acquire conventionally measured values extend from the calculation of temperature distributions via the analysis of the hydrogen content of insulation liquids up to the evaluation of various transfer functions. Regarding this data only an insignificant statement about the present condition of the insulation of the transformer is possible, because due to the integral characteristic of almost all measured values only an information about the long-term behaviour of the insulation can be given. Therefore different advanced offline diagnostic methods have been developed in the past and are available for a more precise condition assessment of a power transformer. As a basis often the so-called DGA (dissolved gas analysis) and SOT (standard oil test) are used, because these methods allow based on the analysis of different parameters in the liquid insulation a first statement concerning the existence of a critical failure or worse condition in the active part of the transformer. Based on this first information some additional techniques are performed in order to precise the condition assessment. Typically the following basic methods are used:

- Winding resistance measurement
- Turn ratio measurement
- Megger test
- Determination of the short circuit voltage
- Measurement of dielectric dissipation factor and capacitance of active part and bushings
- Measurement of grounding system of active part if accessible.

Depending on the result of an oil analysis not all methods have to be performed in any case or even not all together can give the needed additional information for an appropriate condition assessment. In those cases additional more advance methods like:

- FRA (Frequency Response Analysis)
- FDS (Frequency Domain Spectroscopy) or DFR (Dielectric Frequency Response)
- OLTC (On Load Tap Changer) vibration measurement
- Winding clamping force detection
- Thermovision Scan
- Partial Discharge (PD) measurements
- High Voltage (HV) tests

can be performed, leading to a detailed statement if the transformer can be put into operation again or not.

In the paper some of these additional techniques are discussed on practical examples in order to show their benefits and limitations.

FRA

Using the FRA (Frequency Response Analysis) method a transfer function of the transformer windings are determined, which changes if the RLC-network of a winding is changing – e.g. in case of a failure like a turn to turn short circuit. Therefore this method is based on comparing a fingerprint achieved after the production, overhaul or repair of a transformer with an actual signature after a failure event. In case of significant mismatch between those 2 curves it can be concluded that due to the change in the transfer function the RLC-network of a winding has changed too and therefore that the winding itself has a certain defect.

However, it is proven that especially the set-up during the measurement can have enormous influence on the results, especially at higher frequencies, thus usually only the frequency spectrum up to 1 or maximum 2 MHz is taken into account [1]. Beside these problems concerning the repeatability at the moment there is still no standard available for the interpretation of deviations in transfer functions and there is almost no case known in which a defect on a transformer could be only determined by using the FRA method. In almost all cases failures in the winding system can be determined by winding resistance measurements or the measurement of the short circuit voltage. In seldom cases FRA was helpful concerning problems with core grounding, grounding system on the active part or shields on floating potential, but even in this cases a clear statement was almost impossible. One example is shown in Figure 1, in which the transfer functions from one HV phase of a 40MVA/110kV transformer are given. The upper graph shows measurements before and after an incident – the lower graph shows measurements with small differences in the grounding connection in the set-up. In both cases the winding itself did not have any defect, although the measurement – especially the upper one – shows clear deviations.

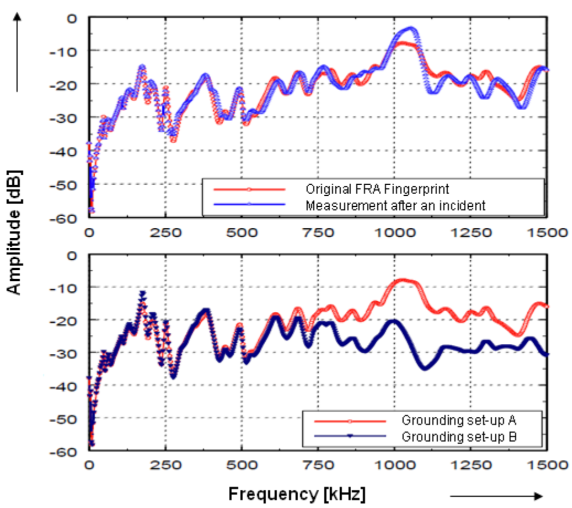

Figure 1: Example of a FRA measurement on the middle HV phase of a 40MVA/110kV transformer without any defect

Based on almost 10 years of experience with this method it has to be concluded that the FRA method do not allow a reliable statement concerning defects in windings, thus other methods are more preferable. Based on this experience it is questionable if FRA should be further recommended to be performed after production of a transformer as a fingerprint – in case of a failure it will be detected using more precise methods.

DFR / FDS

The DFR method is used in order to determine the moisture content inside the solid insulation, which was done in the past by using equilibrium curves between the water content in the oil and in the paper. Due to the fact that this old-fashioned procedure was not precise enough due to several reasons, the FDS technique was developed some 10 years ago [2].

Using the FDS procedure the dielectric loss factor is measured over the frequency on the insulation system, which is in an equivalent circuit approximated by a capacitor with certain dimensions. The dielectric loss factor $\tan\delta$ consists of 3 components according to equation 1:

$$\tan\delta = \tan\delta_L + \tan\delta_P + \tan\delta_{TE} \qquad \textbf{(1)}$$

In this equation $\tan\delta_L$ represents the loss factor influenced by charge carrier conduction - mainly ionic conduction, $\tan\delta_P$ the part, which is produced by polarisation losses and $\tan\delta_{TE}$ the loss factor as a result of partial discharges at higher voltage levels, which can be neglected for the FDS method, because this procedure is performed at voltages below 1kV.

The $\tan\delta_P$–part is depending on the conductivity and therefore on the temperature of the insulating medium, while the polarisation losses are defined by the 3 different kinds of polarisation: interfacial, polarisation and orientation polarisation.

In order to describe these phenomena the complex permittivity $\underline{\varepsilon}_r$ is used, which consists of the real part of the complex permittivity ε'_r and the imaginary part the so-called dielectric loss number ε''_r according to equation 2 and 3:

$$\underline{\varepsilon}_r = \varepsilon'_r - j \bullet \varepsilon''_r \quad \text{an} \qquad \textbf{(2)}$$

$$\tan\delta_P = \varepsilon''_r / \varepsilon'_r \qquad \textbf{(3)}$$

The real part and imaginary part of the permittivity are in particular depending on the frequency as well as on the moisture of the insulation, which is used as the functional principle of the FDS method. The measurement itself is compared with a fingerprint, but in contrast to the FRA method this fingerprint can be simulated by using a simple model according to Figure 2, in which the oil-paper insulation system of a transformer is regarded as a capacitor.

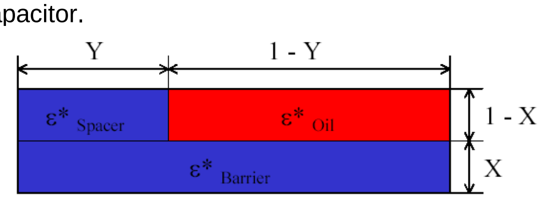

Figure 2: Equivalent capacitor of the oil-paper insulation system

The model curve is depending on the dimensions, which are known from drawings of the transformer or can be estimated as well as from the moisture of the insulation system, thus the moisture parameter is varied until the measurement matches with the simulation. An example of a measurement on a 40MVA/115kV transformer is shown in Figure 3, in which the moisture was estimated to 3.9%. After the measurement the transformer active part was de-tanked and various paper samples have been taken along the windings in order to analyze DP (Degree of Polymerization of the paper) and moisture profile. The moisture content was between 3.7 and 4.3%, thus the FDS-result gave a good average value.

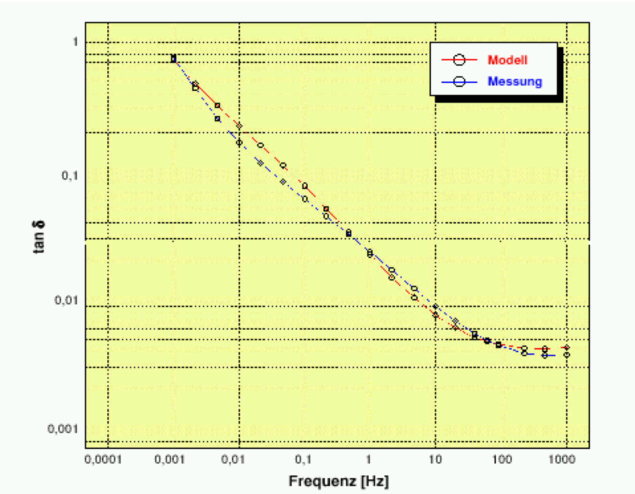

Figure 3: FDA measurement and simulation on a 40MVA/115kV transformer

Depending on the operation condition of a transformer there is always a certain profile of DP and moisture, but the FDS measurement turns out to be very reliable and precise. Based on an experience including more than 1000 FDS measurements and many cases in which a comparison between measurement and paper samples was possible, the preciseness of the FDS measurement is in a range of 0.5% moisture content. That means in the mentioned example of the 40MVA transformer with an estimated moisture of 3.9% the correct average moisture content should be between 3.4 and 4.4% - in this case even the moisture profile of the transformer was in that range. Based on this experience the FDS measurement is to be recommended especially in cases, in which the SOT indicates an increased moisture content.

HV-TEST AND PD MEASUREMENT

The best way to prove the reliability of an insulation system is a HV-test with PD measurement, what is the reason why this is performed as FAT (Final Acceptance Test) after the production of a high voltage equipment. In the past it was difficult to repeat parts of the FAT on-site because the HV-test system could not be transported to site easily, but nowadays there are different mobile HV-test systems available for AC and impulse testing [3].
An example of a modern AC test system is shown in Figure 4, in which a static frequency converter is used instead of a motor generator set for feeding the adaption transformer. Using this system three phase induced voltage tests up to 90kV and applied voltage tests up to 500kV become possible, with a total available power of 2MVA, thus almost all transformers can be tested on-site.

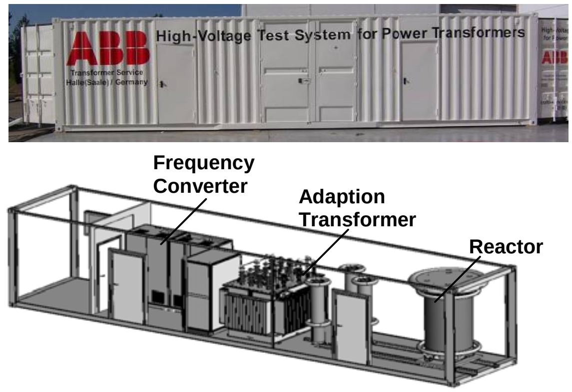

Figure 4: Mobile AC HV-Test system installed in a 40" container

The heart of this system is a static frequency converter, in which the three-phase line voltage is first rectified, thus the direct voltage can be buffered by a capacitor bank. The DC voltage feeds then the inverter module, which consists of power transistors (IGBT's) and is driven by a micro-controller, thus sinusoidal modulated voltage pulses of adjustable frequency and amplitude could be generated. A controlled power sine wave filter connected to the converter output is used to filter the fundamental wave, which finally feeds a step-up transformer. For the induced test the adaption transformer is connected via HV-Filters with the transformer under test, on which the electrical PD measurement can be performed using the measurement taps on the HV-bushings. The frequency can usually be adjusted between 15 and 200Hz in 0.01Hz-steps, which is advantageous for the applied voltage test, which is done using a resonant circuit consisting of the HV-reactor and the transformer under test, which represents a capacitive load during the applied voltage test [4]. As shown in Figure 5 the applied voltage is measured with a capacitive divider, which is installed together with the reactor under one common HV-shield, which enables a simple set-up on-site.

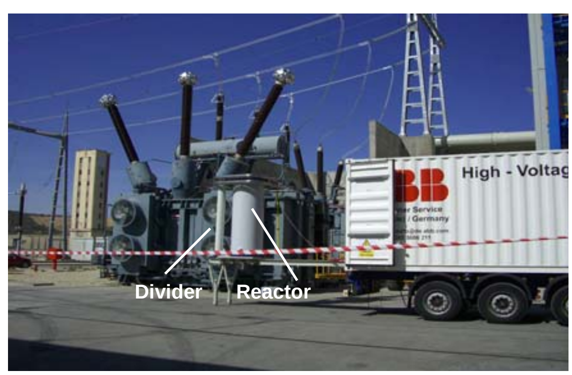

Figure 5: AC HV-Test on site on a 400kV transformer

Beside AC test also impulse test on-site are possible today using special developed impulse generator, which is also installed into a 40" container as shown in Figure 6.

Figure 6: Impulse test on a 600MVA/400kV GSU

The results of some HV tests on-site on the depicted GSU in Figure 6 are shown in Figure 7, in which it is obvious that AC-test including a PD measurement as well as impulse test can be performed on-site with a high preciseness and quality, thus nowadays there is almost no significant difference between HV-tests in the lab and on-site [5].

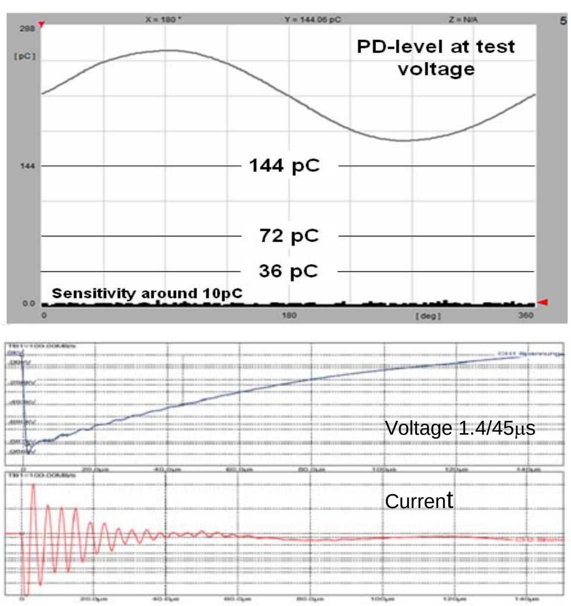

Figure 7: PD (top) and impulse (bottom) test results

CONCLUSION

A precise condition assessment of power transformers can be achieved by combining standard measurements like winding resistance or turn ratio measurements with different advanced diagnostic methods like FRA, DFR or PD-measurements.

However, not all techniques are highly useful, thus the FRA method turns out to be a not efficient measurement that gives no additional information, thus by only using a FRA measurement a defect in a transformer can not be detected reliable.

In contrast to that the DFR methods can be used as the most precise method in order to determine the moisture content of the solid insulation without having access to the inner active part.

HV-test on-site becomes more and more popular because nowadays mobile HV-test systems allow stress tests on-site, which seems to be the most efficient method for a precise condition assessment of the insulation. AC tests including PD-measurements as well as impulse tests can be performed with a high quality on-site, thus the difference between HV-test in the lab and on-site becomes more and more negligible.

Anyhow, which diagnostic methods are needed in case of a failure investigation has to be decided case by case based on all information that are available after the failure has been occurred.

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