Common methods are: winding resistance measurement (static), On-load tap changer (OLTC) test (dynamic resistance test), turns ratio and excitation current measurement, measurement of the leakage reactance and the measurement of capacitances and dielectric losses. Innovative new tools like the frequency response of stray losses (FRS), the measurement of the transfer function with frequency response analysis (FRA), capacitance and dissipation factor measurement at different frequencies, dielectric response analysis with polarisation/depolarisation current (PDC) and frequency response spectroscopy (FDS) and the partial discharge (PD) measurement with modern synchronous multi-channel PD systems enable a higher level of diagnostic measurements on transformers. This paper describes all these new methods and illustrates them with practical case studies.

Dielectric response measurement

Water in oil-paper-insulations goes hand in hand with transformer aging. It decreases the dielectric withstand strength, accelerates cellulose decomposition and causes the emission of bubbles at high temperatures. State of the art for moisture measurements are equilibrium diagrams, where one tries to derive the moisture in the solid insulation (paper, pressboard) from moisture in oil. This method fails for several reasons [1]. To assess the insulation’s water content some dielectric diagnostic methods were widely discussed and occasionally used during the last decade. The multilayer insulation of common power transformers consists of oil and paper and therefore shows polarisation and conductivity effects. Dielectric diagnostic methods work in a range dominated by interfacial polarisation at the borders between cellulose and oil, cellulose conductivity and oil conductivity. Moisture influences these phenomena. Temperature and the insulation construction have a strong impact too [1].

In [1] a comparison of the mentioned methods is analysed. FDS and PDC methods give rather reliable results and also reflect the influence of temperature and geometry by using a X-Y model. The results of the PDC measurement can be transformed from the time domain into the frequency domain. Although the results of PDC and FDS methods are comparable and can be transformed from the time domain into the frequency domain and vice versa, both methods have advantages and disadvantages. If FDS is used down to 100 Hz, a measuring time of up to twelve hours is needed for one measurement e.g. the insulation gap between HV and LV winding. If other insulation gaps e.g. HV winding to tank or LV to TV winding are to be measured as well, even more time is necessary. The PDC measurement needs much less time but is limited to frequencies up to about 1 Hz. A new approach combines both methods [2].

The FDS measurement is replaced by the PDC method in the low frequency range and the results are transformed into the frequency domain, whereas the FDS is used for higher frequencies, which can be done rather quickly. Two input channels for simultaneous measurement of two insulation gaps make it even faster. New model curves for aged oil-pressboard insulation, an outcome of a research project at the University of Stuttgart, make the results for aged transformers much more reliable compared to the standard model curves for new oil-pressboard insulation which were used until recently.

Onsite measurement on an aged 133 MVA power transformer

The transformer was manufactured in 1967, has a rated power of 133 MVA, a transformation ratio of 230/115/48 kV. The insulation gaps HV to LV, LV to TV (tertiary winding) and TV to tank were measured separately. The higher moisture content in the TV winding insulation agrees well with the service conditions of the transformer: the TV winding was not in use. Cellulose at lower temperatures stores more water in the transformer than warmer cellulose. Thus the dielectric methods allow for an elementary localisation of wet areas in the insulation. Contrary to this the moisture content in cellulose as derived from oil samples gives an average value.

The result obtained from the relative saturation in oil by advanced equilibrium diagram agrees well with the dielectric analysis. However the conventional method of deriving the moisture in cellulose from moisture by weight in oil (ppm) gives a result which is too
The FDS curves (Fig. 1) are measured from repeated measurements after drying. The moisture in the insulation before and after drying was reduced from 2.6% to 1.6%, the moisture in the insulation LV to TV was reduced from 4.3% to 1.5%. The moisture in the insulation from TV to tank is still quite high at 3.3%. To reduce the moisture in the TV winding the winding should be loaded to increase its temperature.

For all impedance and dissipation factor measurements described in this paper a test system with a power amplifier, which generates current and voltage in a frequency range of 15 to 400 Hz was used. Therefore tests do not have to be made at line frequency only, but can be made in a wide frequency range. Using frequencies other than 50/60 Hz and their harmonics, precise results can be obtained even in substations with high electromagnetic interference by filtering out the 50/60Hz with very effective digital filters.

Winding resistance measurement and OLTC test

Winding resistances are measured in the field to check for loose connections, broken strands and high contact resistance in tap changers. Additionally, the dynamic resistance measurement enables an analysis of the transient switching operation of the diverter switch. In most cases, the tap changer consists of two units. The first unit is the tap selector, which is located inside the transformer tank and switches to the next higher or lower tap without carrying current. The second unit is the diverter switch, which switches without any interruption from one tap to the next while carrying load current. The commutation resistances R or inductance L limit the short circuit current between the taps which could otherwise become very high due to the switching of the diverter contacts during the period, where both taps are connected. The switching process between two taps takes approximately 40 – 80 ms.

Dynamic behaviour of the diverter switch

In the past only the static behavior of the contact resistances was taken into account in maintenance testing. With a dynamic resistance measurement, the dynamic behavior of the diverter switch can be analyzed (Fig. 4). For this measurement, the test current should be as low as possible otherwise short interruptions or bouncing of the diverter switch contacts cannot be detected. In this case, the initiated arc has the effect of shorting the open contacts internally. Comparison to “fingerprint” results, which were taken in a known (good) condition and to the other phases, allows for an efficient analysis. A peak detector measures the peak of the ripple (I<sub>pp</sub>) and the slope (di/dt) of the measuring current, as these are important criteria for correct switching. If the switching process is interrupted, even for less than 500 μs, the ripple and the slope of the current change dramatically.

Frequency response of stray losses (FRSL)

The frequency response measurement of stray losses is a tool to determine short circuits of parallel strands. The resistive part of the short circuit impedance is measured over a frequency range from 15 Hz up to 400 Hz. The resistance curves of the three phases are compared. The 15 Hz values are very similar to the DC values of the primary winding resistance plus the resistance of the secondary winding multiplied by the square of the ratio. If the curve of one phase is more than 2 – 3% different from the other phases a short circuit fault between parallel strands could be the reason for this behavior. Local overheating can cause dangerous breakdowns.

Measurement of capacitance and dissipation factor (tanδ)

In the past, the dissipation or power factor was measured at line frequency only. With the described test system it is now possible to make these insulation measurements in a wide frequency range. Besides the possibility to apply frequency sweeps, measurements can be made at frequencies different from the line frequency and their harmonics. With this principle, measurements are possible also in the presence of high electromagnetic interference in high voltage substations.

Limits for the dissipation factor

In the existing standards limits are given for 50 Hz only. The measurement of the dissipation factor at other frequencies should be also included in the standards. Low frequency results (e.g. 15 Hz) allow for a very sensitive moisture assessment, measurements at high frequencies (e.g. 400 Hz) allow a very sensitive detection of contact problems at the measuring tap or at the layer connections. Also high resistive partial breakdowns between grading layers can be detected.
A new field of evaluation methods is opened by fully synchronous multi-channel PD acquisition in order to gain more reliable measuring results combined with effective noise suppression. A technical overview of the system is given in [5]. Being able to perform synchronous multi-channel PD measurements, the 3-Phase amplitude relation diagram (3 PARD) was introduced as a new powerful analysis tool to distinguish between different PD sources and noise pulses when measuring 3-phase high voltage equipment such as power transformers, rotating machines and cross-bonded cable systems.

**PD measurement on a repaired transformer**

Fig. 7 shows a PD measurement with four simultaneously measuring channels which are connected to the three HV bushings and the star point. It can be seen in Fig. 8 that the three different clusters in the 3PARD diagram are generated by three different PD sources: statistical noise, pulse disturbances and inner partial discharges.

**On-line PD, capacitance and tan delta measurements on high voltage bushings**

Some commercial C-tand systems sum up the current through C1 of each phase of all phases to detect any abnormal changes in the capacitances C1 and the dielectric losses. The voltages of the three phases can be very unsymmetrical. This makes it impossible to use this method for a sensitive monitoring of capacitances and losses of the bushings. A better choice is the use of voltage transformers or of bushings on other transformers which are directly connected to the same phase (Fig. 9). A pilot project was started on a three phase 400 kV transformer to gain experience with such a system. The system delivers very stable values of the capacitance values varying within ± 0.5%. The tan δ differs from 0.27% to 0.3%.

**References**


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**Sweep frequency response analysis (SFRA)**

Sweep frequency response analysis (SFRA) has turned out to be a powerful, non-destructive and sensitive method to evaluate the mechanical status of a transformer’s active part. The tan δ differs from 0.27% to 0.3%.

**On-line PD, capacitance and tan delta measurements on high voltage bushings**

Some commercial C-tand systems sum up the current through C1 of each phase of all phases to detect any abnormal changes in the capacitances C1 and the dielectric losses. The voltages of the three phases can be very unsymmetrical. This makes it impossible to use this method for a sensitive monitoring of capacitances and losses of the bushings. A better choice is the use of voltage transformers or of bushings on other transformers which are directly connected to the same phase (Fig. 9). A pilot project was started on a three phase 400 kV transformer to gain experience with such a system. The system delivers very stable values of the capacitance values varying within ± 0.5%. The tan δ differs from 0.27% to 0.3%.

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**FRA on a damaged 110 kV transformer**

A 110 kV/30 MVA transformer showed unbalanced voltages on the LV windings after a short circuit close to the transformer. The FRA measurement results are shown in Fig. 6. The phases U and W are very similar whereas phase V is totally different. The transformer was transported to a workshop and analysed. The short circuit current on the LV side caused an interruption of one of the two parallel windings of the phase V. The winding was interrupted at one end.

The whole clamping structure with the press rings and the spacers was broken. It was decided to recycle the transformer.

**Partial discharge measurement**

Partial discharge (PD) measurement is a worldwide accepted tool for quality control of high voltage apparatus. Outside screened laboratories PD signals are often superposed by noise pulses, a fact that makes a PD data analysis more difficult for both human experts and software expert systems. Therefore the handling of disturbances is one of the main tasks when measuring PD.