Effective maintenance test techniques for power transformers

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Due to ever-increasing pressure to reduce costs, the power industry is forced to keep old power facilities in operation as long as possible. In most European countries about one third of the transformers are older than 30 years. With the advancing age of transformers, regular checks of the operating conditions become more and more important.

Dissolved Gas Analysis (DGA) is a proven and meaningful method. If increased levels of hydrocarbon gases are found in the oil, the fault must be located as soon as possible. Hence important preventative maintenance must be performed in time to avoid an unexpected total failure (Fig. 1) [1]. The most frequent sources of faults are the tap changers, bushings, the paper-oil insulation and the accessory equipment (Fig. 2) [2].

In order to find the source and reason for high gas values, further tests have to be performed on the transformer. Common test methods are:

- Turns ratio, vector group and excitation current measurement
- Static winding resistance measurement
- Dynamic winding resistance measurement to test the on-load tap changer (OLTC)
- Sweep frequency response analysis (SFRA) measurement
- Frequency dependant capacitance and dissipation factor measurement
- Di-electric response analysis
- Partial discharge (PD) measurement

Turns ratio, vector group and excitation current measurement

The transformer turns ratio test (TTR) is performed by applying a test voltage (typically 500 V L-L) to the HV winding of a transformer and measuring the LV voltage. The test can either be performed as single-phase or three-phase and typically is performed for each tap step of a tap-changer. In the case of a three-phase injection and if testing a YD or DY transformer, the injected or measured voltage on the delta winding needs to be adjusted by a factor of $\sqrt{3}$. A typical result is shown in Fig. 3.

The vector group test (VG) is performed in a very similar fashion as the TTR test – except that it is performed by injecting a balanced three phase voltage, i.e. this test is not possible with a single phase injection. The typical result for the vector group test of a Ynd1 transformer is shown in Fig. 4.

Excitation current is measured by applying a test voltage (typically 500 V L-L) and measuring the current drawn on each phase. The excitation current should be of similar proportion for all three phases. Fig. 5 shows the results for transformer with a faulty B phase.

Dynamic winding resistance measurement

Winding resistances are measured in the field to check for loose connections, broken strands and high contact resistance in tap changers. A transformer under test was found to have conspicuously high quantities of gas in the oil, from which the conclusion of inner overheating was drawn. Except for the middle tap all taps showed a significant increase compared to the original measured values. The differences were more than 10 % or, in absolute values, up to 70 mΩ (Fig. 6).

The deviations between switching upwards and switching downwards are likewise clearly significant. This indicates high contact resistances caused by the contacts of the tap selector switches. No silver-plated contacts were used and the copper contact surfaces were now coated by oil carbon. After a full maintenance of the tap selector, no significant difference to the values measured at the factory in 1954 could be observed (Fig. 7). The difference before contact maintenance was up to 30 mΩ (or 5%) and after it was below 1 mΩ (or 0,18%).

Dynamic Winding Resistance Measurement to Test the On-Load Tap Changer (OLTC)

To date, only the static behaviour of the contact resistances has been taken into account in maintenance testing. With a dynamic resistance measurement, the dynamic behaviour of the diverter switch can be analyzed (Fig. 8). Comparison of results with "fingerprint" results, which were taken when the item was in a known (good) condition and to the other phases, allows for
an efficient analysis. A glitch detector measures the peak of the ripple (I_{max} - I_{min}) 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.

For tap changers in good condition the ripple and slope measurements for all three phases tapping upwards should be similar, as should those for tapping downwards. Fig. 9 shows a ripple measurement for a diverter switch in a good condition. Fig. 10 shows the ripple measurements for the three phases of an aged diverter switch. The differences of the ripple values were due to the advanced aging of the diverter switch contacts, which proves the sensitivity of the measurement principle to changes of the contact surface.

**Sweep frequency response analysis (SFRA) measurement**

Treating a power transformer as a complex R-L-C filter network and utilizing network analysis techniques, the frequency response can be recorded. This is done by injecting a low-level voltage with variable frequency and measuring both the injected voltage (reference) as well as output voltage (measurement) accurately in terms of amplitude and phase angle, while sweeping the frequency in a range from 10 Hz up to 2 MHz. The amplitude response (output amplitude divided by input amplitude) is plotted vs. frequency in dB. The phase response. Utilizing sweep frequency analysis techniques, core deformation and core movement (clamping), faulty core groundings, fault on magnetic cores (shorted laminates), bulk winding movement, coil deformation (axial and radial), buckling of windings, broken or open internal connections as well...
as inter-winding and inter-turn short circuits can be detected. In Fig. 11 for instance, phase B (1V 1U) had an internal short circuit, indicated by a major shift of the first resonant frequency for this phase.

**Capacitance and Dissipation Factor Measurement on Windings**

In the past, the dissipation or power factor was measured at line frequency. Nowadays power amplifiers enable measurements in a wide frequency range. In [4] the Dissipation Factor (DF) of pressboard was measured at different frequencies (Fig. 12). The four curves show the tan δ for water contents of 0.2%, 1%, 2.5% and 4%. A transformer contains a complicated insulation system. High and low voltage windings have to be insulated to tank and core and against each other. The dissipation factor is a good indicator of the oil-paper insulation quality of the single gaps. The dissipation factor increases with degradation of oil, water content and contamination with carbon and other particles.

Fig. 13 shows a DF measurement of different insulation gaps: HV to LV winding (HL), LV to TV winding (LT) and TV winding to the core (T). It is obvious that the HL gap has the lowest water content (2.5%) in the paper and the lowest dissipation factor at low frequencies, whereas LT and TV have higher water contents (3.8 and 3.9%) and higher dissipation factors. The TV winding is not in use and hence has a lower temperature during service. It can be deduced that the water in the insulation paper is not homogeneously distributed.

**Capacitance and dissipation factor measurement on high voltage bushings**

The high voltage bushings are critical components of the power transformer and particularly, capacitive high voltage bushings need care and regular tests to avoid sudden failures. These bushings have a measurement tap-point at their base and both the capacitance between this tap and the inner conductor (normally called C1) and the capacitance between the tap and ground (normally called C2) are measured. An increase of C1 indicates partial breakdowns of the internal layers. To determine bushing losses, dissipation factor tests are performed. Most of bushing failures may be attributed to moisture
Fig. 15: 245 kV RIP bushing stored outside.

Fig. 16: Tan delta of a 245 kV RIP bushing stored outside.

Fig. 17: Combined di-electric response measurement.

Fig. 18: PD ellipse diagram.

Fig. 19: PD amplitude relation diagram.

Also the minimum of the curve has shifted to higher frequencies with increased humidity.

Di-electric response measurement

Water content inside the cellulose is a good indicator of accelerated aging or de-polymerization (DP) taking place inside the insulating paper. As described above, using the frequency dependant measurement of the dissipation factor (DF) or tan δ over a range of frequencies, the water content in the paper can be determined. A variety of techniques to achieve such a measurement exist:

Polarisation / de-polarisation current measurement (PDC)

In this technique the time dependant current response to an injected square wave is measured. The result is transposed into the frequency domain and then plotted vs. frequency. In the low frequency range (<0.1 Hz) this technique yields good measurement results.

Frequency domain spectroscopy (FDS)

This technique is based on measuring the DF for various frequencies in the range of 0.01 Hz to 5 kHz. Disadvantage of this technique is the length of a test at very low frequencies, i.e. below 0.1 Hz.

The ideal is a combined test technique, i.e. PDC of frequencies in the range of 0.1 m Hz up to 0.1 Hz and FDS for frequencies of 0.1 Hz to 5 kHz. The typical response for such a combined di-electric response measurement is shown in Fig. 17. Modeling the complex transformer winding insulation system consisting of the oil, spacers and barriers, the water content in the paper can be determined with an integrated curve fitting algorithm. This example shows the HV winding to contain a moisture content of 2.4%, whereas the unused LV winding was at a higher 3.4% due to the lower operating temperature of this winding.

ingress. As already shown with the winding-to-winding insulation, analysis of bushing insulation is much more detailed when frequency scans are performed. Fig. 14 shows the dissipation factor of resin impregnated paper (RIP), resin bonded paper (RBP) and oil impregnated paper (OIP) bushings in good condition. The frequency response is rather flat over frequency and shows low values for the dissipation factor particularly at low frequencies.

Fig. 15 shows a RIP bushing which was stored outside without any protection. The first measurement was made directly after the bushing was removed from the transformer, the second measurement after three and a half months and a third measurement after more than seven months. Fig. 16 shows a consistent increase of the dissipation factor as the bushing was subjected to ambient humidity and rain.
Partial discharge measurements

Partial discharge measurements can be performed both online and offline. The discharge pulses resulting from the minute discharge current spikes can be measured by filtering the discharge currents with a suitable coupling capacitor and selecting a sensible frequency measurement band. Plotting the discharges in relation to the reference voltage the typical PD ellipse diagram (Fig. 18) and/or PD amplitude relation diagram result (Fig. 19). PD always takes place in the region of highest voltage gradient, as indicated in the figures below.

In a three phase transformer the remaining question is whether a PD phenomenon is internal to the transformer or is measured from some PD source outside the transformer. The 3-phase amplitude relation diagram (3 PARD) shown in Fig. 20 is a useful tool to distinguish between internal and external PD.

Summary

With advancing age of transformers, regular checks of the operating conditions become more and more important. The analysis of the gas in oil is a well-proven method of analysis but must be complemented by efforts to locate any faults indicated by excess hydrocarbon gases in the oil. In this way important maintenance can be performed in time to avoid sudden and/or total failure.

Possible fault locations can be investigated successfully by performing electrical tests such as turn ratio test, vector group test, excitation current measurement, static and dynamic winding resistance measurement, sweep frequency response analysis, frequency dependant dissipation factor measurement on both windings and bushings, frequency domain spectroscopy as well as partial discharge measurements. Modern power amplifiers enable the injection and measurements in a wide frequency range which enhance the diagnosis methods. By comparing measured results to previously measured results (i.e. fingerprints) it is possible to detect degradation in the insulation mediums of both transformer windings as well as bushings at a very early stage.

References


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