Innovative Test Techniques and Diagnostic Measurements to Improve the Performance and Reliability of Power System Transformers

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1. Introduction

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, a regular check of the operating conditions becomes more and more important. The Dissolved Gas Analysis (DGA) is a proven and meaningful method such that if increased proportions of hydrocarbon gases are found in the oil, the fault must be located as soon as possible. Hence important preventative maintenance can be performed in time to avoid an unexpected total failure (Fig. 1) [1].

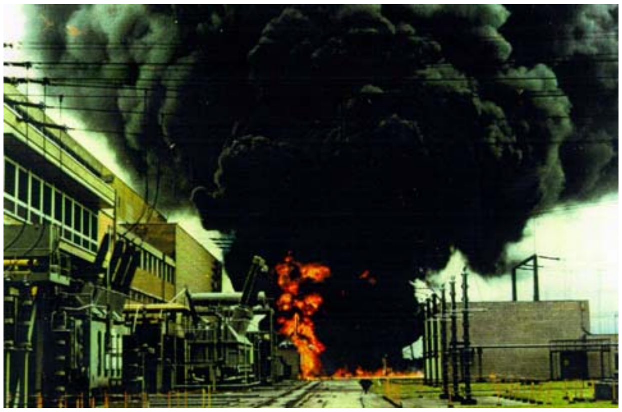

Fig. 1: Transformer fault due to a defective bushing

The most frequent sources of faults are the tap changers, bushings, the paper-oil insulation and the accessory equipment (Fig. 2) [2].

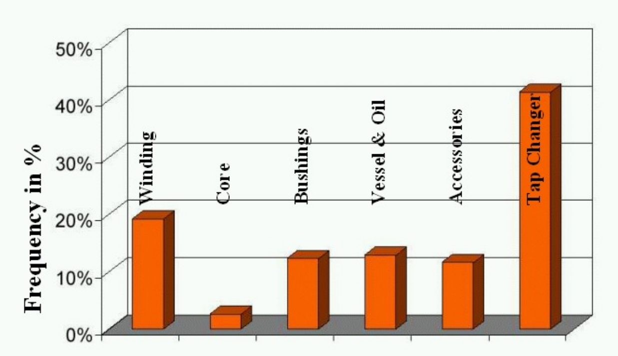

Fig. 2: Sources of transformer faults [2]

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

- Static and Dynamic winding resistance measurement
- **O**n-**L**oad **T**ap **C**hanger (OLTC) test
- Turns ratio and excitation current measurement
- Measurement of leakage reactance and FRSL
- **S**weep **F**requency **R**esponse **A**nalysis (SFRA) measurement
- Frequency dependant capacitance and dissipation factor measurement
- **P**artial **D**ischarge (PD) measurement
- Di-electric Response Analysis

2. 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.

Static winding resistance measurement on a 220 kV/110 kV/10kV - 100 MVA transformer

The transformer under test was found to have conspicuously high quantities of gas in the oil, from which the conclusion was drawn of inner overheating. Except for the middle tap all taps showed a significant increase compared to the original measured values. The differences are more than 10 % or, in absolute values, up to 70 mΩ (Fig. 3).

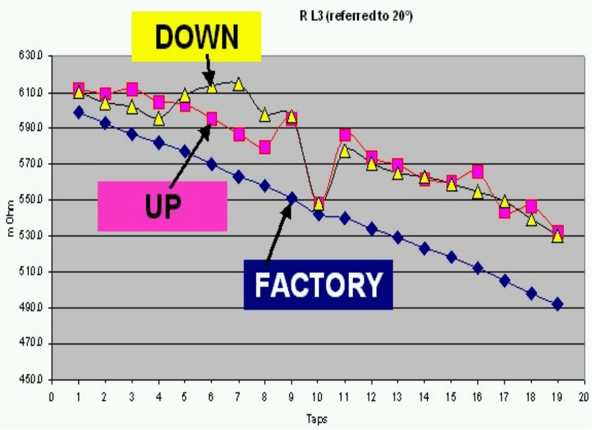

Fig. 3: Winding resistance measurement H1-H0

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 surface was 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. 4). To examine the results in more detail, it is recommended to view the difference between "UP" and "DOWN" values (Fig. 5). The difference before contact maintenance was up to 30 mΩ (or 5%) and after it was below 1mΩ (or 0.18%).

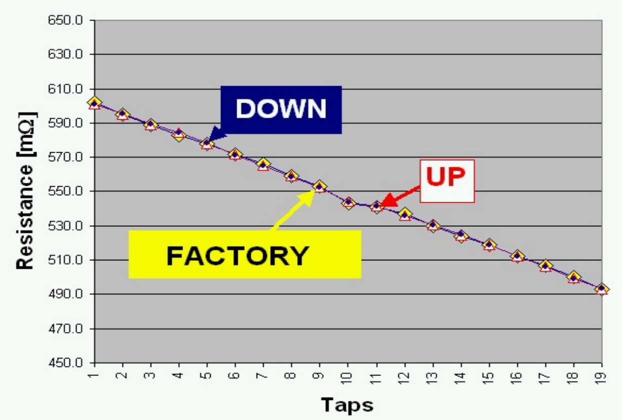

Fig 4: Resistance after maintenance

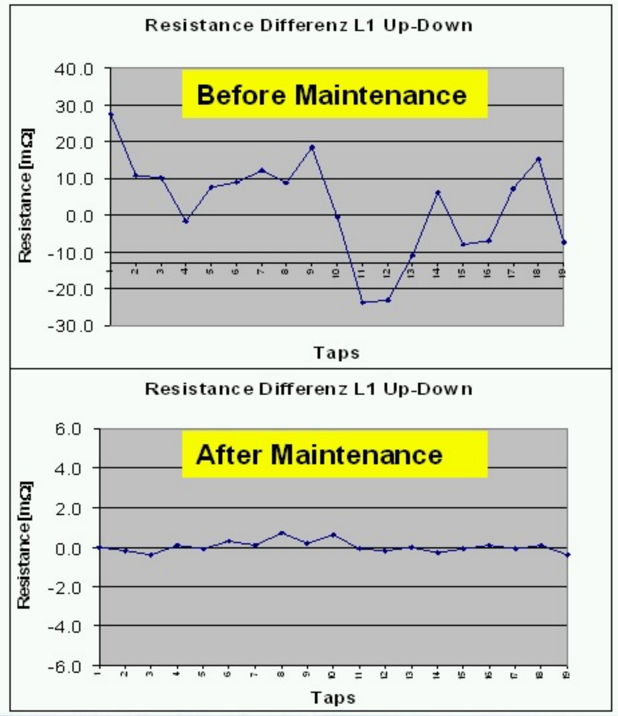

Fig. 5: Difference "UP" - "DOWN"

Dynamic behaviour of the diverter switch

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. 6).

Comparison to "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 500us, the ripple and the slope of the current change dramatically.

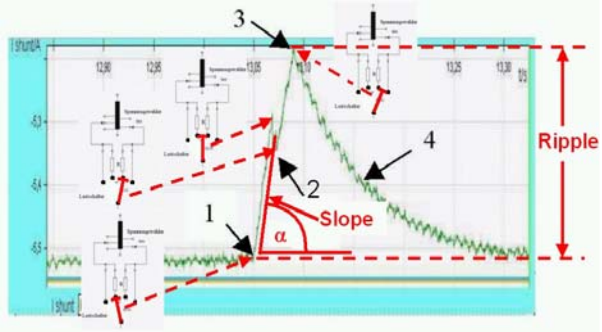

Fig. 6: Dynamic resistance measurement for analysis of the diverter switch

1 **=** diverter switch commutes from the first tap to the first commutation resistor
2 = the second commutation resistor is switched in parallel
3 = commutation to the second tap (direct contact)
4 = regulation back to the set current value

For tap changers in good condition the ripple and slope measurements for all three phases tapping UP should be similar as well as those for tapping DOWN should be similar. Fig. 7 shows a ripple measurement for a diverter switch in a good condition

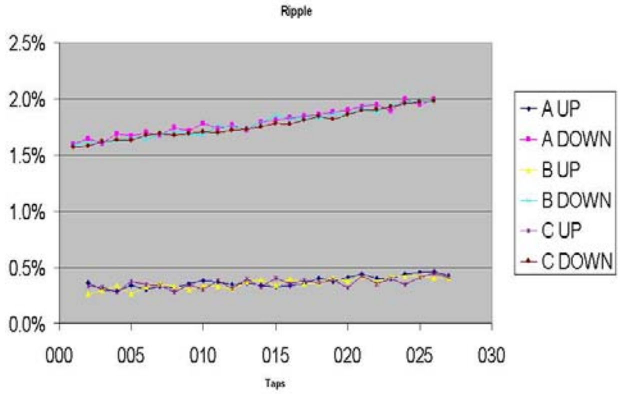

Fig. 7: Ripple measurement of a good diverter switch

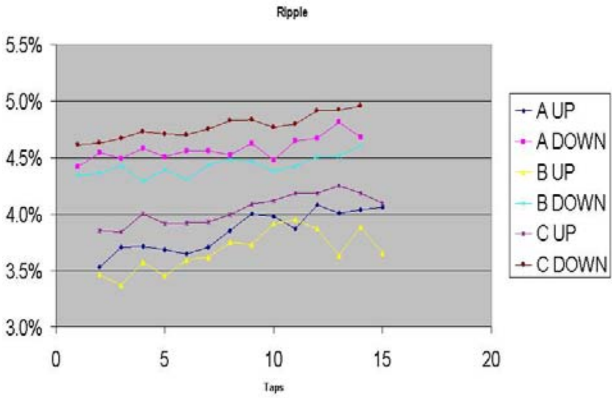

Fig. 8: Ripple measurement of an aged diverter switch

Fig. 8 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 (Fig. 9), which proves the sensitivity of the measurement principle to changes of the contact surface.

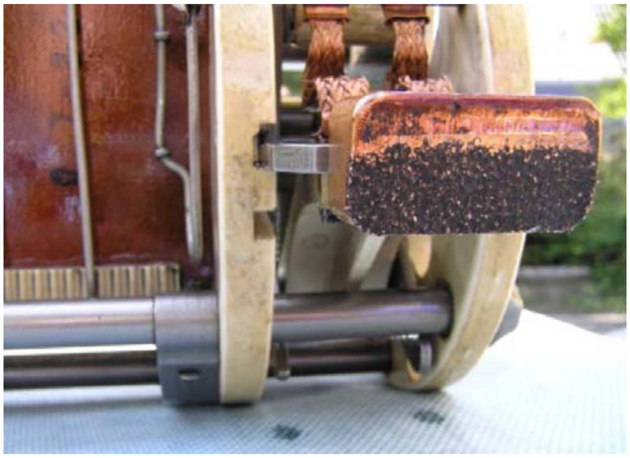

Fig. 9: Aged diverter switch contacts

3. Diagnosis of a defective transformer

A 220kV / 110kV /10kV 100MVA transformer was damaged by a marten. It short circuited the 10 kV side and caused a through fault current of 54kA. Although the transformer was switched off within 100ms, Phase A of the 10kV winding was short circuited to the core.

First of the ratio was measured (Fig. 10). A large difference of approximately 20% indicated a failure with 20% of the turns. The excitation current of phase A was 340 mA whereas the excitation current of the remaining phases was 10 mA.

Fig. 10: Impedance measurements on defective transformer

Leakage reactance and FRSL measurement

As a second test the leakage inductance was measured. The used test instrument has a power amplifier which allows measurements from 15 to 400 Hz (Fig. 10) [3].

Fig. 11 shows that for low frequencies the leakage inductance of the faulty phase A is much higher than for phase B and C. For high frequencies the values are similar.

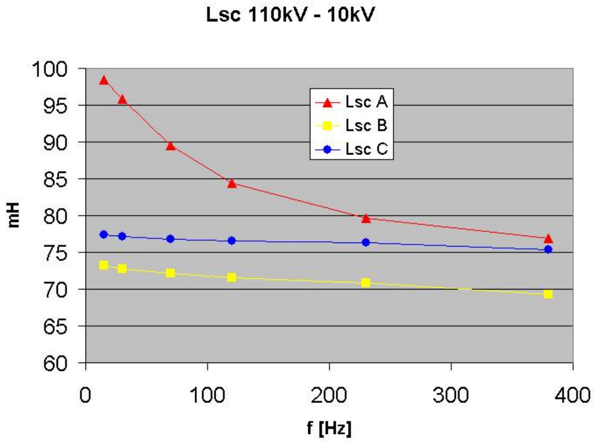

Fig. 11: Leakage inductance Lsc = f(f)

For the measurement of the Frequency Response of Stray Losses (FRSL) the resistive part of the short circuit impedance Rsc is measured from 15 to 400Hz. The FRSL is an indicator for short circuited parallel strands of transposed conductors. Fig. 12 shows the comparison of the three phases. The A phase shows much higher losses.

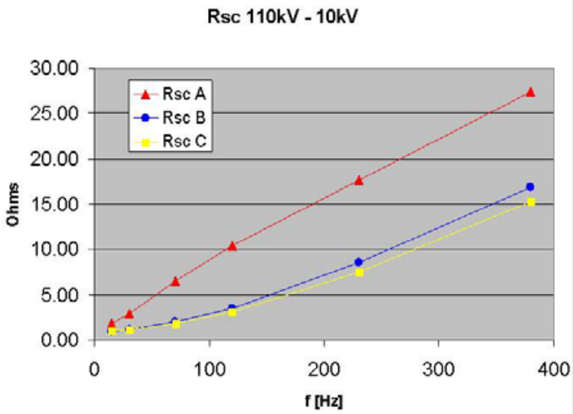

Fig. 12: FRSL measurement Rsc = f(f)

SFRA measurement

Also the measurement of the Sweep Frequency Response Analysis (SFRA) showed a clear difference between phase A and the phases B and C.

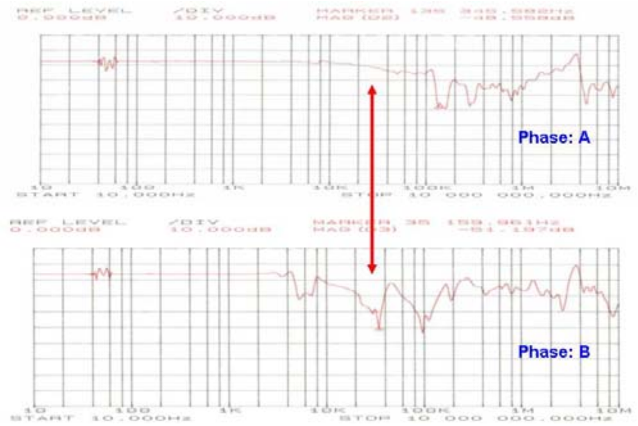

Fig. 13: SFRA measurement

Conclusions of defective transformer

The conclusion was that the faulty winding was interrupted and parts of the winding were contacting the core. This resulted in a part of the secondary short circuit current flowing through the core. With higher frequencies the current was displaced to the core surface due to the skin effect (Fig. 14).

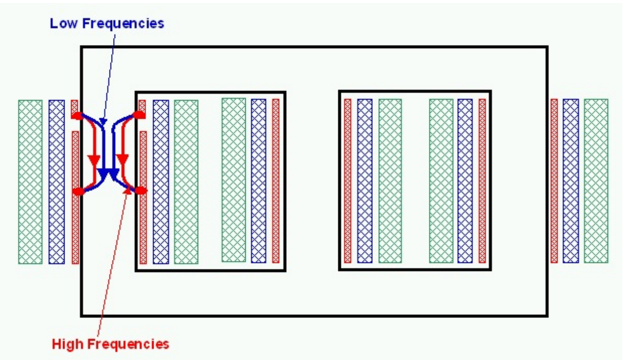

Fig. 14: Model of the defective winding

Opening of the defective transformer

The transformer was opened three months later. Fig. 15 shows the totally damaged 10kV winding. The interruption of conductors can be seen clearly.

Fig. 15: Defective winding with interrupted conductors

4. Capacitance and dissipation factor measurement

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. 16). 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.

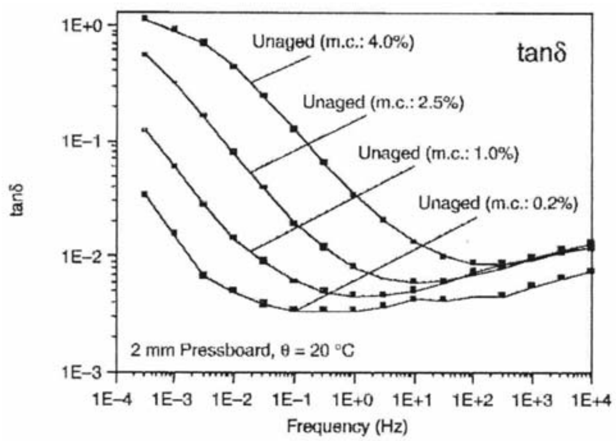

Fig. 16: Losses in Pressboard = f (f, water content)

Fig. 17 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 T 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 homogenously distributed.

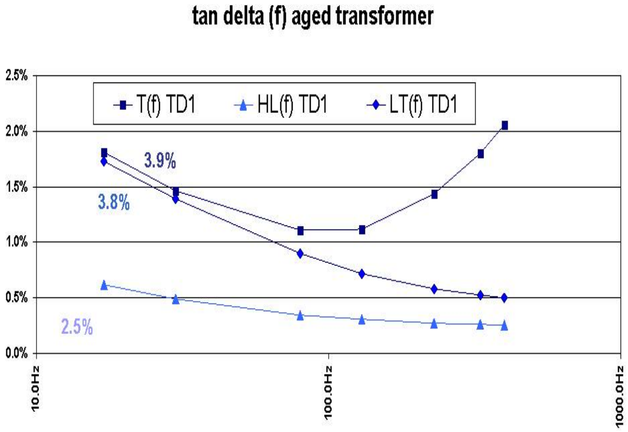

Fig. 17: Losses in different insulation gaps

C-tan δ 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 ingress. As already shown with the winding-to-winding insulation, analysis of bushing insulation is much more detailed when frequency scans are performed. Fig. 18 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.

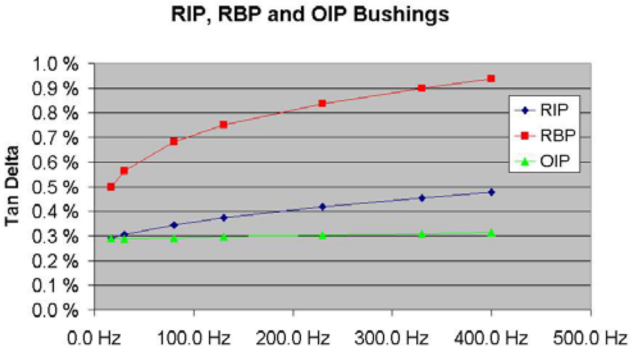

Fig. 18: RIP, RBP and OIP bushings in good condition

In Fig. 19 a RIP bushing is shown, 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 7 months.

Fig. 19: 245kV RIP bushing stored outside

Fig. 20 shows a consistent increase of the dissipation factor as the bushing was subjected to ambient humidity and rain. Also the minimum of the curve has shifted to higher frequencies with increased humidity.

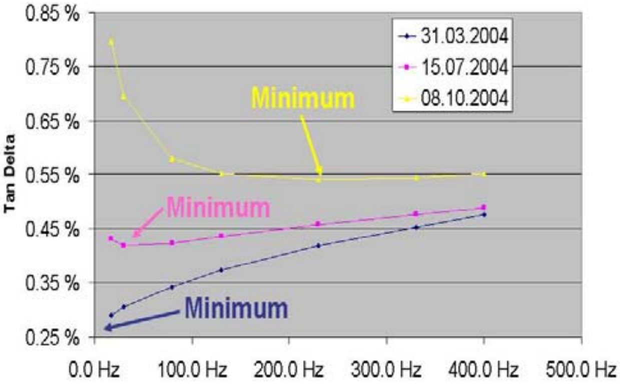

Fig. 20: Tan Delta of a 245kV RIP bushing stored outside

In Fig. 21 33kV-OIP-bushings are shown. The bushings were dismounted from the transformer because their dissipation factor was very high particularly at high temperatures. Fig. 22 shows the DF of dry and wet OIP bushings at 50Hz for different water contents as a function of temperature [5].

Fig. 21: 33kV OIP bushings

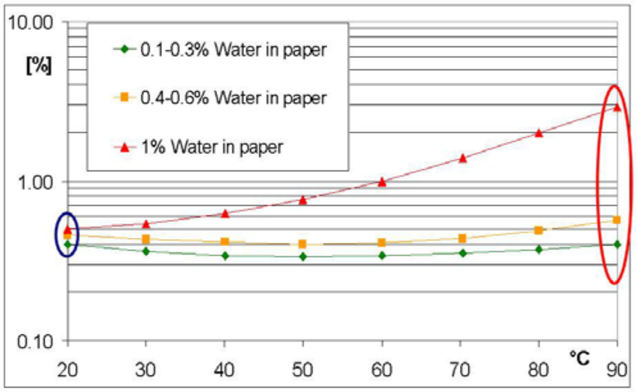

Fig. 22: TanDelta @ 50Hz = f(T)

The tests show and increased sensitivity of the dissipation factor measurements at high temperatures compared to ambient temperature. However, in the field it is not so easy to heat up bushings before measurement.

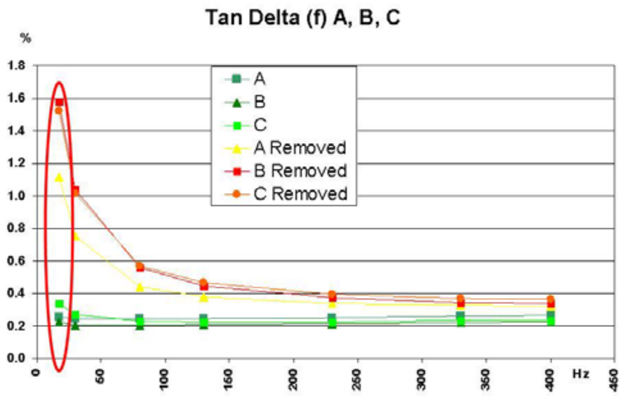

Fig. 23: TanDelta @ 30°C = f(f)

In a second test the dissipation factor for a set of replaced bushings and a set of new ones was measured at 30°C, but this time at different frequencies. The replaced bushings show high tan δ values particularly at low frequencies. The new bushings have flat frequency responses with low losses also at low frequencies. These tests indicated an increased sensitivity at low frequencies, which can be realized easier than the 50Hz measurement at high temperatures.

The examples show, that the measurement of the dissipation factor over a wide frequency range enable for a better diagnosis of the insulation compared to measurements at power frequency only. Particularly the low frequency range makes the measurement much more sensitive for water contents in the insulation mediums.

5. Summary

With advancing age transformers require 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 static and dynamic winding resistance, winding ratio and excitation current measurements, leakage reactance and frequency response of stray losses measurements as well as sweep frequency response analysis. Modern power amplifiers enable measurements in a wide frequency range which will enhance the diagnosis methods.

By comparing dissipation factor frequency response curves to fingerprints it is possible to detect degradation in the insulation mediums of both transformer windings as well as bushings at a very early stage.

Literature

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