DIAGNOSTIC MEASUREMENTS ON POWER TRANSFORMERS

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Power transformers are critical, capital-intensive assets for utilities and industry. Transformers are extremely reliable; however, many of the transformers in use today have already exceeded their design life. Today transformers are not automatically replaced, if they have reached the end of their life span, but left in service as long as possible. In contradiction to the past power transformers are operated nowadays at or above rated power. This accelerates the ageing process of the inner insulation, particularly of the insulation paper, which cannot be easily replaced. Investments of new transformers have to be planed in advance because big transformers cannot be bought ready made from the factory. For a systematic replacement and to avoid unexpected breakdowns diagnostic tools are more and more important. Faults are often indicated by the oil analysis, which is a proved and meaningful tool. For the fault finding modern measuring methods are applied. In many cases they enable also the fault location.

The paper gives an overview about the latest measuring technologies and contains interesting case studies for successful insulation diagnosis and fault locations in power transformers

Diagnostic measurements for fault location

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

- Winding resistance measurements
- On-Load Tap Changer (OLTC) tests
- Turns ratio measurements
- Excitation current measurements
- Measurement of leakage reactance and FRSL measurements
- Frequency Response Analysis (FRA)
- Capacitance and Dissipation factor measurements
- Partial discharge measurements

For all impedance and dissipation factor measurements a test system, shown in figure 1 was used. It has a power amplifier, which generates currents and voltages in a frequency range of 15 to 400 Hz [1]. Therefore tests do not have to be made at line frequency only, but can be made in this frequency range. Using frequencies other than 50/60 Hz and the harmonics, precise results can be obtained even in substations with high electromagnetic interference.

Figure 1:
OMICRON CPC100+TD1

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 limit the short circuit current between the taps which could otherwise become very high due to the interruption-free switching of the contacts. The switching process between two taps takes approximately 40 – 80 ms.

Winding resistance measurement on a 220 kV / 110 kV – 100 MVA transformer manufactured in 1955

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 were more than 10 % or, in absolute values, up to 70 mW (figure 2).

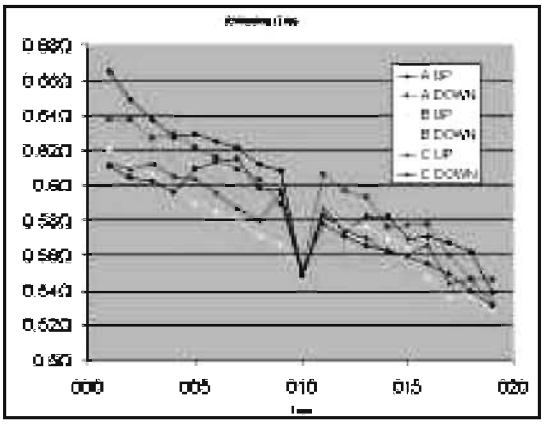


Figure 2: Winding resistance measurement

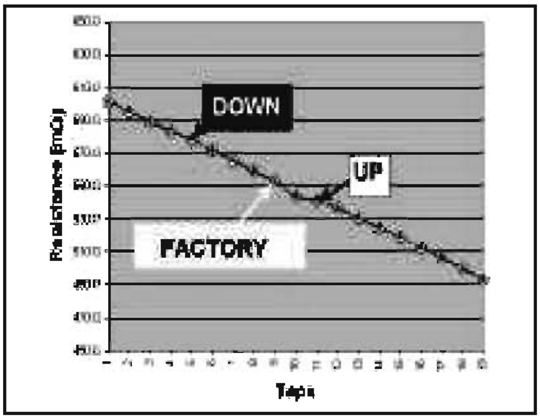


Figure 3: Resistance after maintenance

The deviations between switching upwards and switching downwards are likewise clearly significant. This shows that the high contact resistances are actually caused by the switching contacts of the coarse / fine tap selector. No silver-plated contacts were originally 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 (Figure 3). To examine the results in more detail, it is recommended to graph the difference between "UP" and "DOWN" values (Figure 4). The difference before contact maintenance was up to 30 mW £ 5% and after it was below 1 mW £ 0.18%. This is mainly the influence of the fine tap selector contacts.

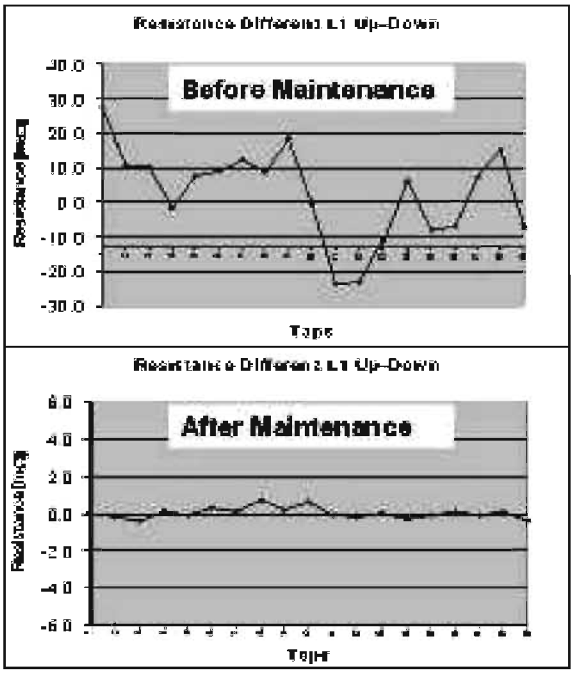


Figure 4: Difference "UP" - "DOWN"

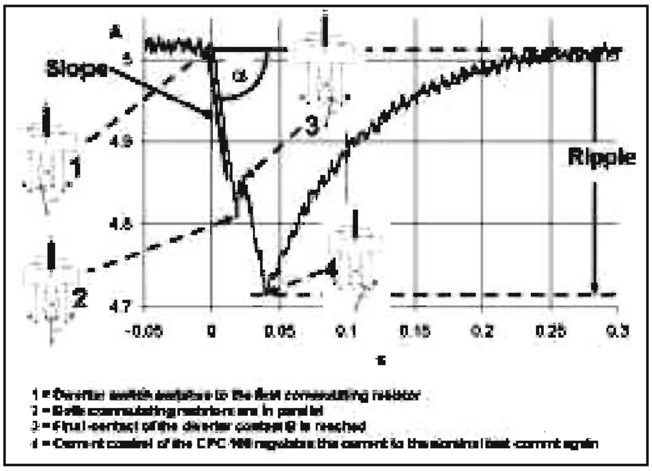


Figure 5: Dynamic resistance measurement for analysis of the diverter switch

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 = Charging the additional windings

Figure 6a: Ripple of good diverter contacts

Figure 6b: Slope of good diverter contacts

Dynamic behavior of the diverter switch

To date, only the static behavior of the contact resistances has been taken into account in maintenance testing. With a dynamic resistance measurement, the dynamic behavior of the diverter switch can be analyzed (Figure 5). For the dynamic resistance 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 shortening the open contacts internally. 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. Figure 6a shows the ripple and 6b the slope curves of good diverter switch contacts, Figure 7 the ripple of aged contacts and Figure 8 shows one of the aged contacts.

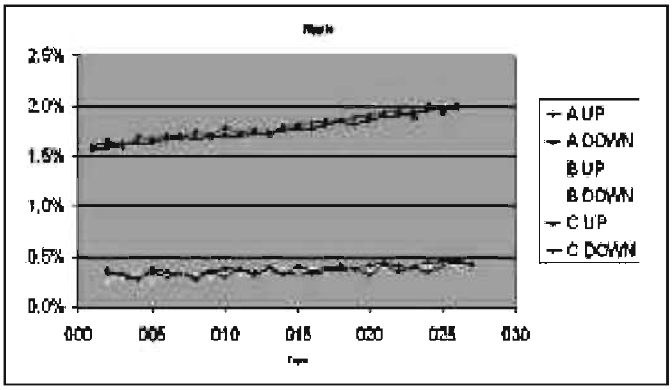


Figure 7 the ripple of aged contacts and

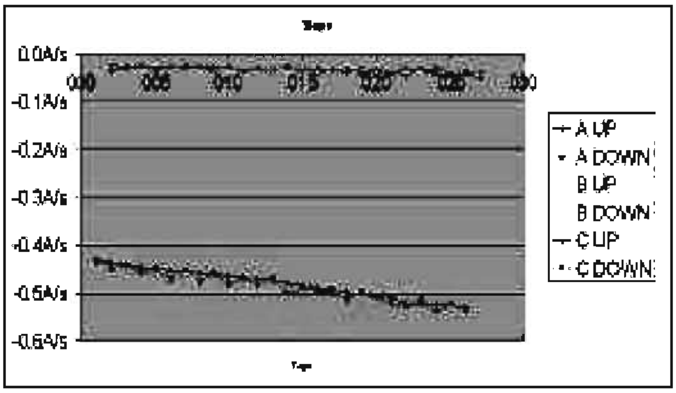


Figure 8 shows one of the aged contacts.

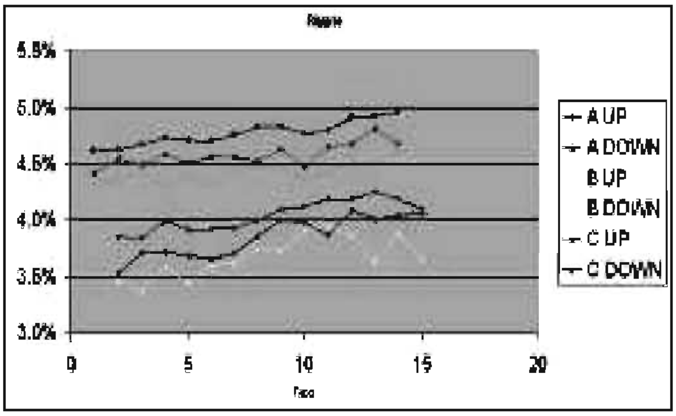


Figure 6a: Ripple of good diverter contacts

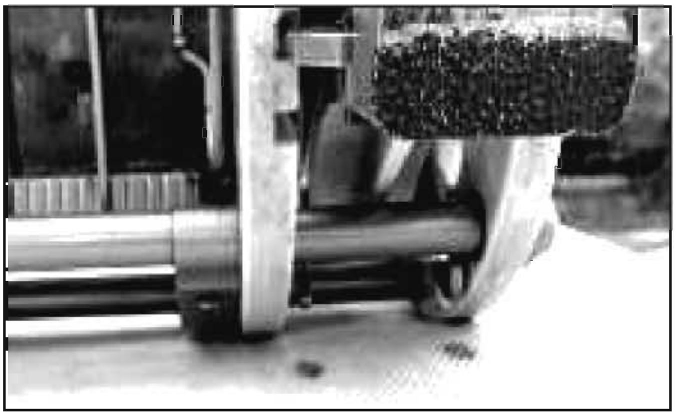


Figure 6b: Slope of good diverter contacts

Frequency response analysis 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 15Hz up to 400Hz. The resistance curves of the three phases are compared. The 15Hz 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 can be the reason for this behavior. Local overheating can cause dangerous breakdowns (see figures 9-16)

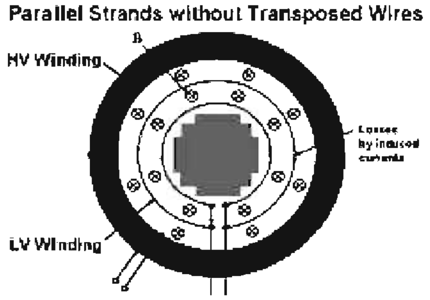


Figure 9: Parallel strands without transposed conductors

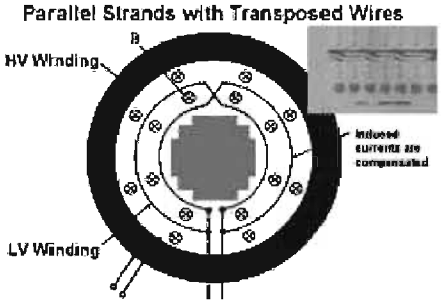
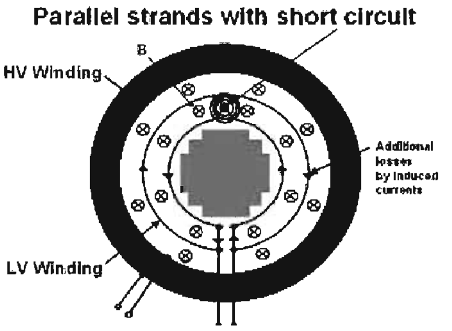
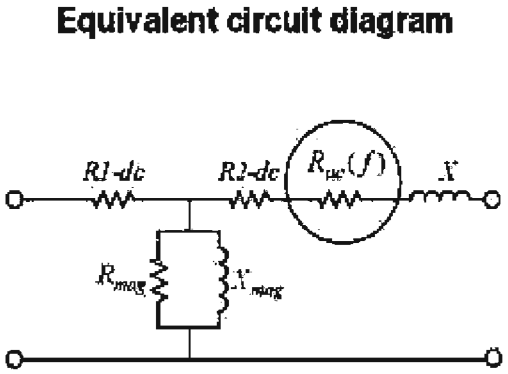


Figure 10: Parallel strands with transposed conductors (CTC)





Capacitance and dissipation factor (tan d) measurement

In the past, the dissipation or power factor was measured at line frequency. With the described test system it is now possible to make these insulation measurements in a wide frequency range. Beside 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.

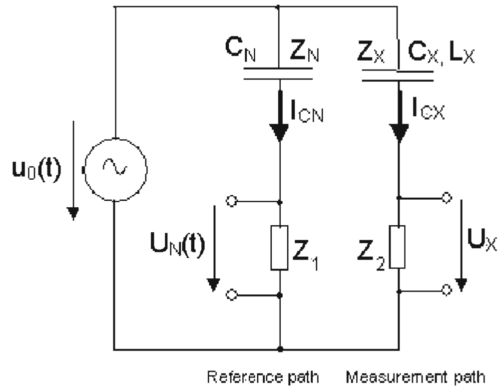


Figure 17: CP TD 1 measuring principle

Figure 17 shows the C-tan d measuring circuit. It can be used for a wide frequency range without balancing a bridge. CN is high precision gas insulated reference capacitor with losses lower than 10-5. A transformer contains a complicated insulation system like it was already discussed for the PDC and FDS measurements. High and low voltage windings have to be insulated to tank and core and against each other. The dissipation factor is an indicator of the oil-paper insulation quality of the single gaps. Degradation of oil, water content and contamination with carbon and other particles increase the dissipation factor. Figure 18 shows a dry winding insulation, figure 19 shows an insulation with a high water content.

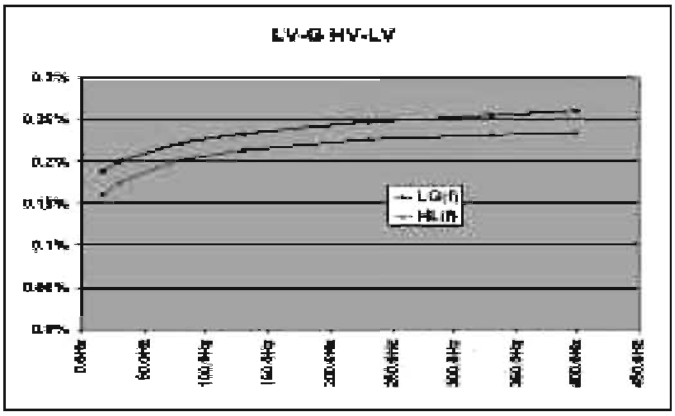


Figure 18: Dry winding insulation

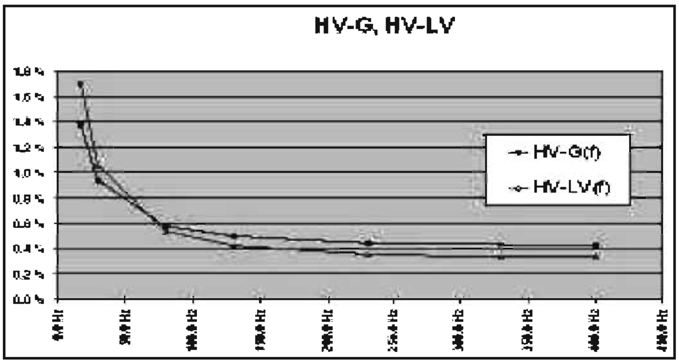


Figure 19: Insulation with high water content

Figure 20 shows the dissipation factor measurement results of a 133 MVA transformer. Although the frequency range is much smaller compared to the FDS measurement, the different water content can be identified clearly.

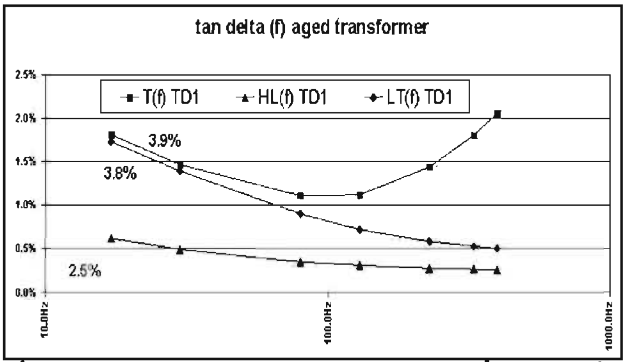


Figure 20: DF measurement 15 to 400Hz on the 133MVA transformers (figure10)

C-tan d measurement on high voltage bushings

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. Most of these bushings have a measurement tap-point at their base flange 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) can be measured. An increase of C1 indicates partial breakdowns of the internal layers. To determine bushing losses, dissipation factor tests are also 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 sweeps are performed. In Figure 21 the DF of new resin impregnated paper (RIP) bushings can be seen. All bushings show the same behavior. Figure 22 shows the results of resin bonded paper (RBP) bushings from 1971 in a very good condition. Figure 23 and 24 show a measurement on a 400kV OIP bushing and the DF measurement results.

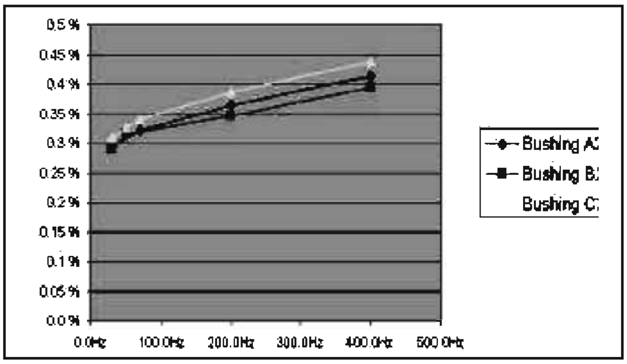


Figure 21: DF of RIP 145 kV bushings (new)

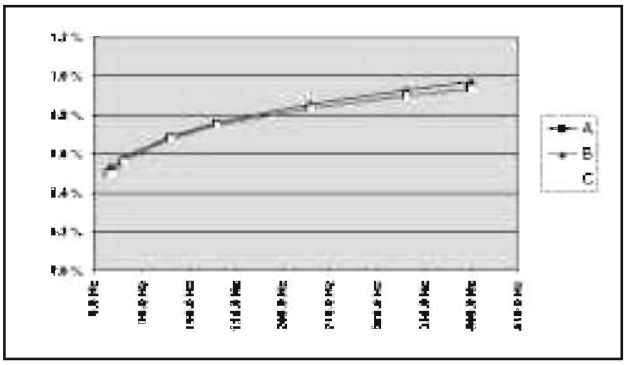
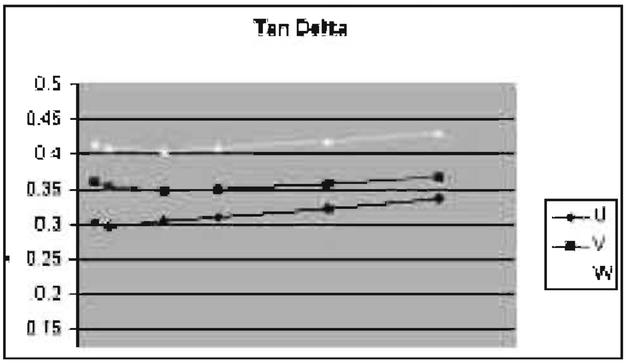


Figure 22: DF of RBP bushings (1972)



Figures 25 and 26 show 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 the third after more than 7 months. The three curves show how the humidity, which came into the insulation, changes the curves.

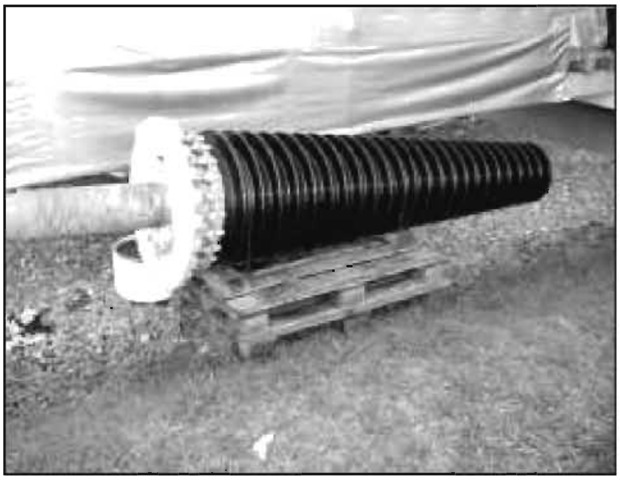


Figure 25: RIP bushing stored outside

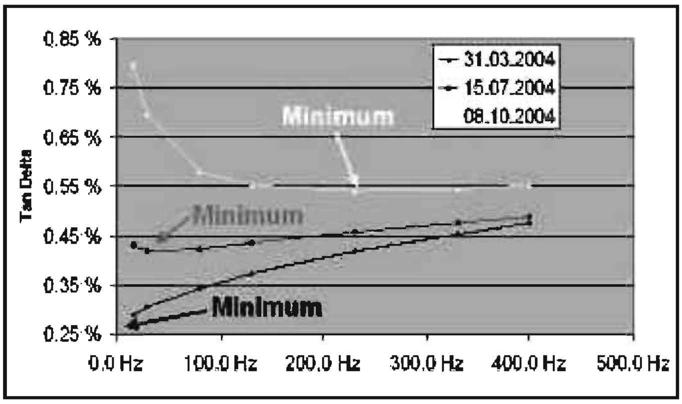


Figure 26: RIP bushing stored outside

Figures 27 and 28 show aged oil impregnated paper (OIP) bushings. Although the results are close together and acceptable at line frequency, already small differences can be seen between the different bushings due to different water content in the insulation.

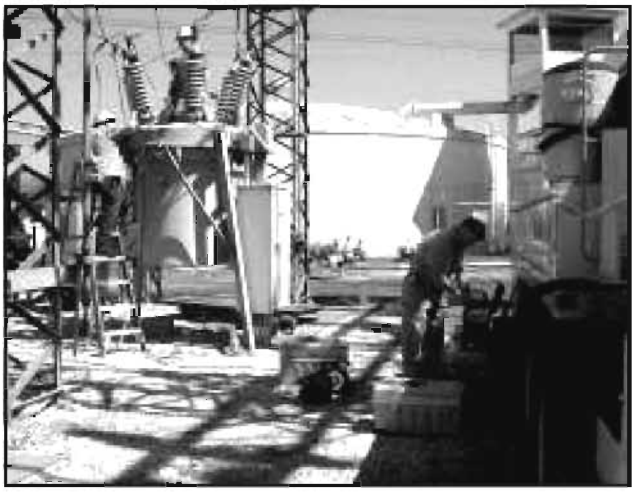


Figure 27: DF of OIP 66kV bushings (aged)

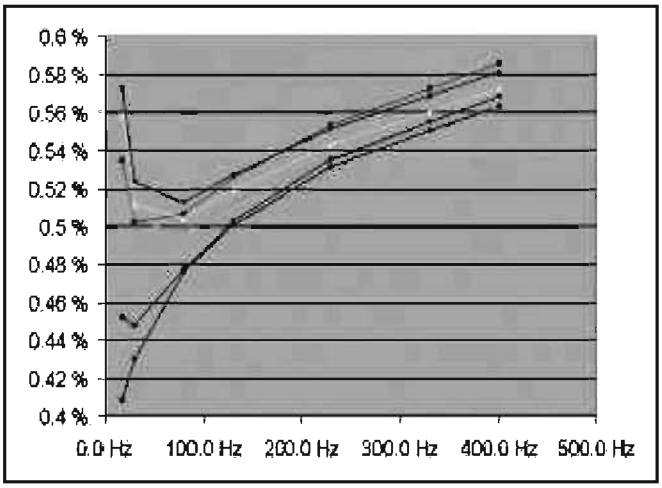


Figure 28: DF of OIP 66kV bushings (aged)

The Figures 29 and 30 show a bushing with a defective contact between the measurement tap and the outside capacitive layer. The DF increases with the frequency nearly linearly. This behavior equals a serial circuit diagram of an ideal capacitance and a resistance. Figure 32 shows a typical curve of such a bad contact over the test voltage. With higher voltages the DF decreases due to the lower contact resistance. This can cause total breakdowns due to the local heat development.

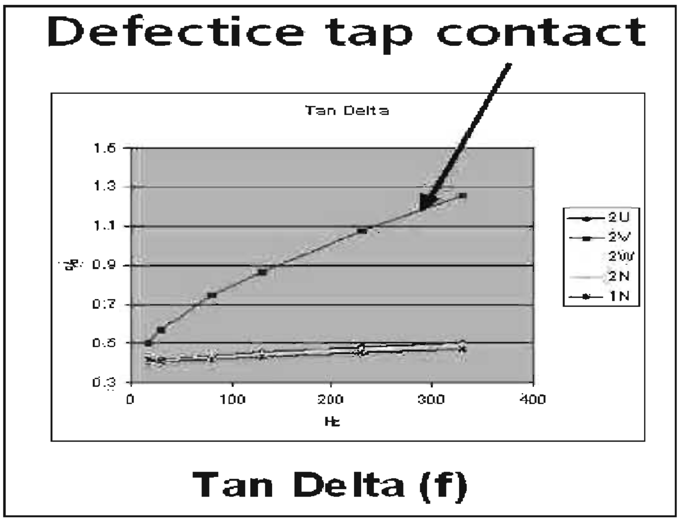


Figure 29: Defective tap contact DF (f)

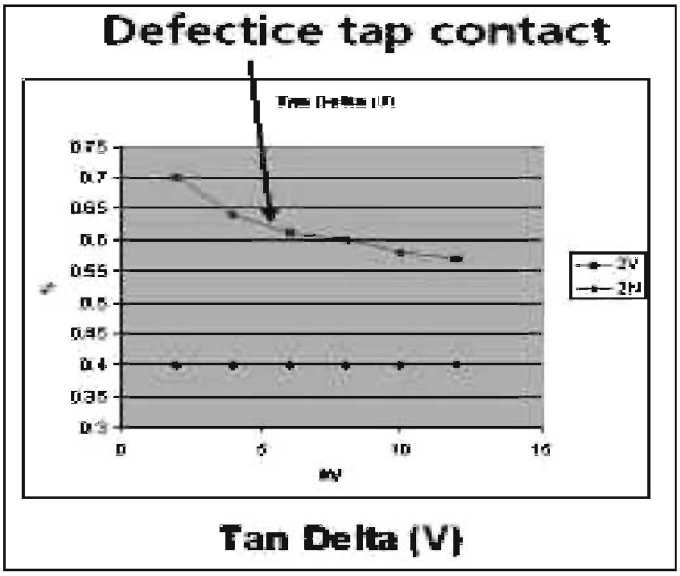


Figure 30: Defective tap contact DF (U)

33kV OIP bushings are shown in figure 31. The bushings were dismounted from the transformer because their dissipation factor was very high at high temperatures. Figure 32 shows the DF of OIP bushings at 50Hz for different water contents as f(T) [2].

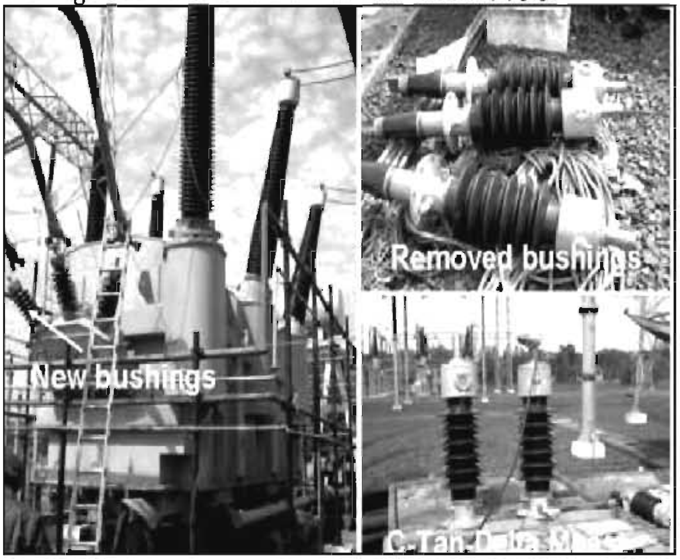


Figure 31: DF measurement on 33kV OIP bushings

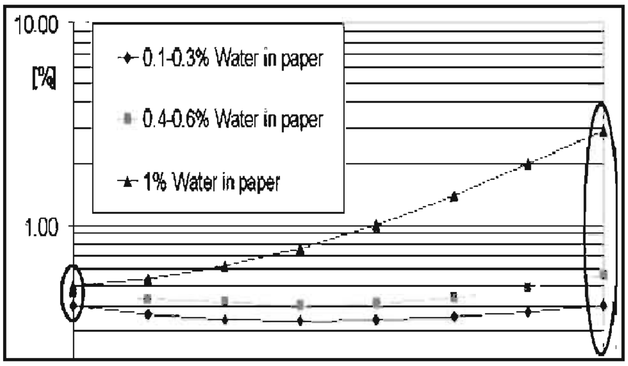


Figure 32

The dissipation factor is in the same order for lower temperatures, whereas the different water contents are well indicated at higher temperatures. The three wet replaced bushings and the three new ones in the transformer were measured again at 30□C from 15 to 400Hz. The results are shown in figure 33.

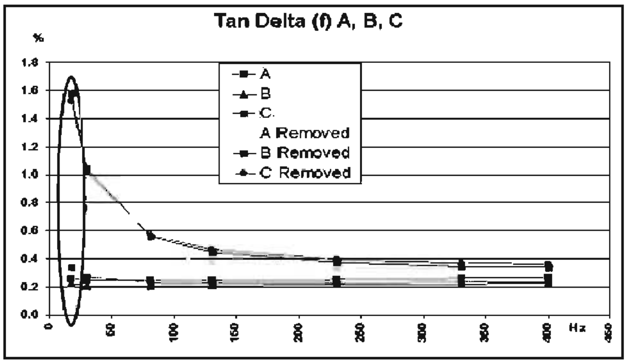
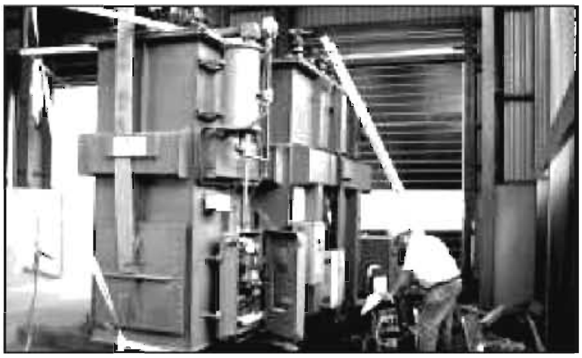


Figure 33: DF measurement on 33kV OIP bushings at 30°C dependent on the frequency

With the frequency sweeps the influence of the humidity is clear visible in the low frequency range.

Case study of fault location on a furnace transformer



The furnace transformer shown in **figure 34** was switched off by the Buchholz relay. The overpressure valve had spitted out about 200 liters of oil.

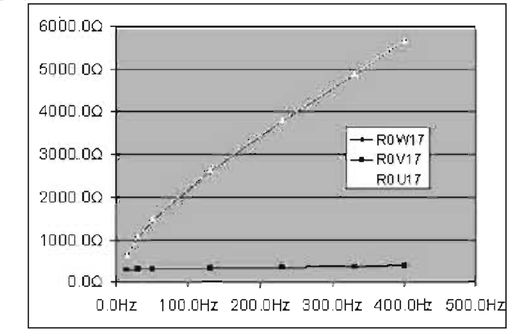


Figure 35a: Resistance of no-load impedance R0 (f)

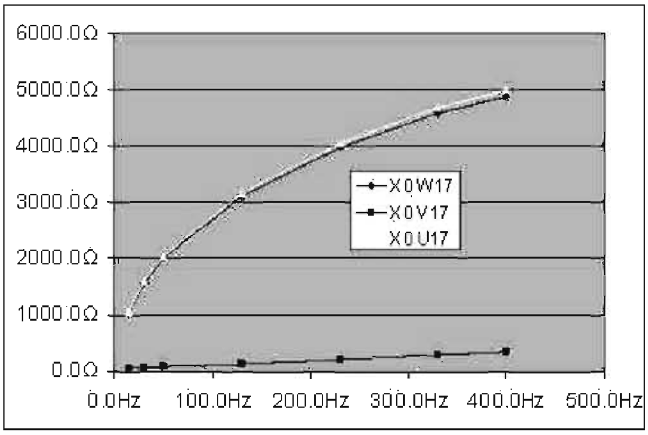


Figure 35b: Reactance of no-load impedance X0 (f)

The no-load impedance was measured from 15 to 400 Hz (figure 35). The V phase showed a totally different behavior, particularly for higher frequencies. Also the excitation current was about eight times higher in the V phase than in U and W phases. This is a clear indication for shorted turns. Figure 36 shows the Frequency Response Analysis (FRA) results. Here also the V phase was totally different from U and W. In the lower frequency range between 50 Hz and 5 kHz the damping is much lower in V compared to U and W. The behavior is similar to a transformer with a short circuited winding on the same limb. A high voltage withstand test combined with a Partial Discharge (PD) measurement showed charges up to 4.5 nC at very low test voltages (figure 37). A complete breakdown occurred at a test voltage of 2 kV. The transformer was opened and the fault was obvious (figures 38 and 39). The clamping screws had been getting loose and touched the core. Due to high eddy currents the local heat melted the screws. Some drops of the melt fall down into the HV winding and shorted two turns.

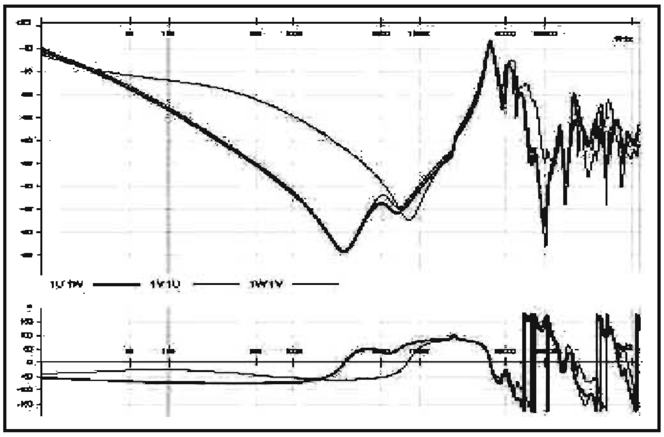


Figure 36: FRA measurement with OMICRON FRAnalyzer

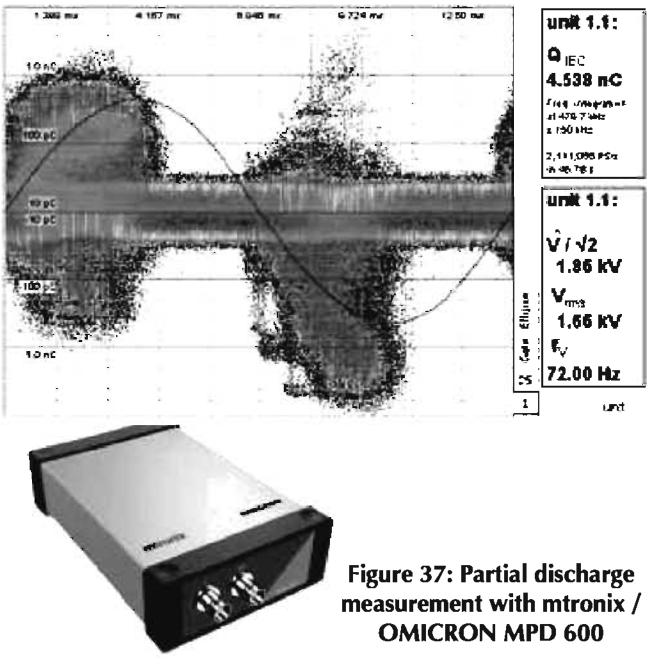


Figure 37: Partial discharge measurement with mtronix / OMICRON MPD 600

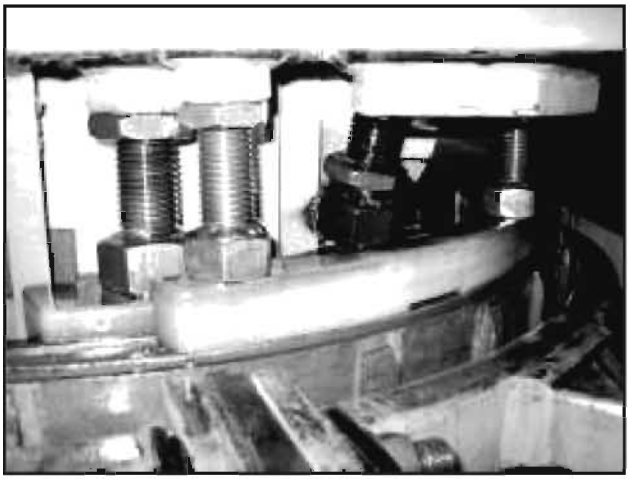


Figure 38: Loose clamping screw touching the core

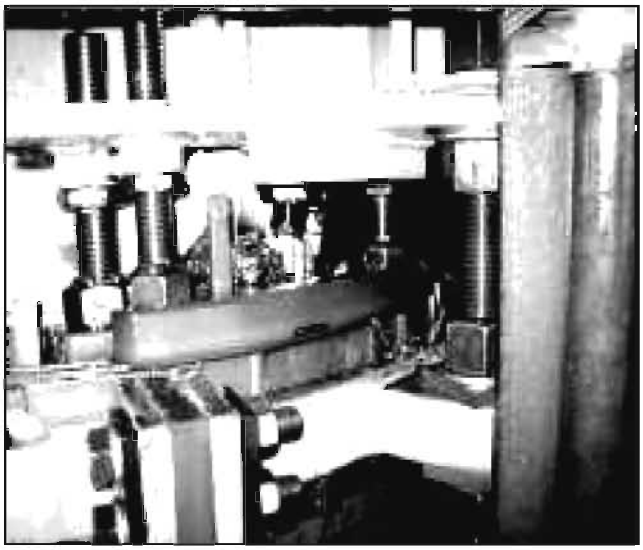


Figure 39: Melted screws were falling into the HV winding and short circuited turns

Summary

With advancing age transformers require regular checks of the operating conditions. Measurement of the water content in oil-paper insulation is a helpful tool for making an assessment of the ageing of the cellulose. 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. This way important maintenance can be performed in time to avoid a sudden total failure. The fault location can be successfully performed using modern type test equipment for resistance, winding ratio, short circuit impedance, C tan d, FRA and PD measurements.

References

[1] Hensler, Th., Kaufmann, R., Klapper, U., Krüger, M., Schreiner: S., 2003, "Portable testing device", US Patent 6608493

[2] ABB, "Dissipation factor over the main insulation on high voltage bushings", product information, ABB 2002

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