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The Swiss experience of on-site high voltage tests and diagnostic measurements on large power transformers

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SUMMARY

In 1992 Swiss utilities initiated a research program with the aim to investigate and develop new diagnostic methods and surveillance tools to improve the service reliability of large power transformers. The program was coordinated by FKH (Fachkommission für Hochspannungsfragen); project partners came from the Swiss Federal Institutes of Technology and from utilities and industry.

Based on the results of this program, FKH has been performing diagnostic measurements on a large number of new and aged power transformers for Swiss utilities and power producers: 271 units have been tested since 1993. 155 units were new and 116 units were aged transformers. 83 units have been tested in the laboratory of the manufacturer and 188 units were tested on site in a substation or a power plant. These tests included transformers with nominal voltages up to 525 kV and unit powers ranging from 15 to more than 500 MVA.

Advanced off-line partial discharge (PD) measurement techniques were used during applied and/or induced voltage tests in the factory and on site. On-site tests with applied voltage were carried out using series-resonance circuits. On-site induced voltage tests have been performed with electronic frequency converters or diesel generators. The PD-measurement technique was based on a computer controlled PD-acquisition system with digital processing for phase-resolving analysis of the detected PD-pattern. Multi-terminal calibration and PD-source localization in the frequency and time domain was carried out using all bushings of the transformer under test.

The PD measurement was completed with polarisation/depolarisation measurements (PDC) and frequency response analysis (FRA), as well as standard methods such as winding resistance or ratio measurements.

Before and after the dielectric tests in the factory and on site, dissolved gas analysis (DGA) was performed as a complementary tool to support the findings of the PD-measurements.

KEYWORDS

Power transformer diagnostics – Partial discharge – Polarization depolarization current – Frequency response analysis – Dissolved gas analysis – Life management

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1. INTRODUCTION

In 1992 Swiss utilities started a research program with the aim to develop diagnostic methods and surveillance tools to improve the service reliability of large power transformers. Since 1993 the following methods were regularly applied on new and service aged transformers in the factory and on site [1 - 7]:

- Phase resolving partial discharge measurements (PRPDA) on all bushings
- Frequency response analysis (FRA)
- Polarisation and depolarisation current measurements (PDC)
- Dissolved gas in oil analysis (DGA)

2. APPLIED DIAGNOSTIC METHODS

2.1 On-site partial discharge measurement during induced or applied voltage tests

Induced voltage tests were conducted on site with a frequency converter (42 kVA) or with a diesel generator (up to 800 kVA). The single phase frequency converter with an output filter enables PD measurements with less than 1 pC noise originating from the source. The frequency converter is normally used for induced voltage tests of single phase transformers or for single phase testing of three phase transformers (usually for the localization of PD sources). For single phase separate source tests (applied voltage test) this frequency converter is also used as feeding unit in a frequency tuned series resonance circuit [2]. For the induced voltage tests of three phase transformers or single phase transformers with higher no load losses (> 40 kW), a diesel generator is used. The generator is usually set to 60 Hz which enables testing of 50 Hz transformers with 120% of the rated voltage. Various exciter transformer are available to step-up the 400 V output of the generator to the voltage level of the secondary or tertiary windings of the transformer under test. The noise level originating from a diesel generator is usually not higher than 20 pC on the injection side. Figure 1 shows the test set-up for an on-site test with induced voltage using a diesel generator.

Figure 1: Example of an on-site test of a 75 MVA transformer (132/50 kV). In the middle the exiter transformer (0.4/50 kV); on the right side (red box) the diesel generator (360 kVA).

The detection sensitivity of on-site partial discharge measurements on power transformers using conventional PD detection systems is usually severely hampered by external noise. Therefore, a measurement in the frequency range defined by IEC 60270 is often not possible. However, with advanced PD-measuring systems based on a spectrum analyzer used as a tunable bandpass filter and a phase resolving partial discharge analyzer (PRPDA), it is possible to obtain detection sensitivities in the range of 5 to 20 pC even under rough conditions [2],[4],[6],[7]. Advanced digital PD measuring systems enable to choose the center frequency in the range of 0 Hz to 32 MHz with variable bandwidths. Depending on the local interference environment, the PD measurement is often performed with center frequencies between 1 MHz and 6 MHz. It has to be considered that at higher center frequencies the correct evaluation of the apparent charge according to IEC 60270 may be inaccurate.

When capacitor bushings with tap-off connectors are available, a high frequency current transformer is directly connected to the bushing tap-off (see left side of figure 2). If bushing tap-off connectors are not available, coupling capacitors are placed close to the bushings (see right side of figure 2). In this case, a higher background noise has to be expected because of the large loop formed by the bushing and the coupling capacitor. The high frequency current transformers can also be combined with a secondary capacitor for the measurement of the voltage (e.g. for synchronization of the PD measuring system).

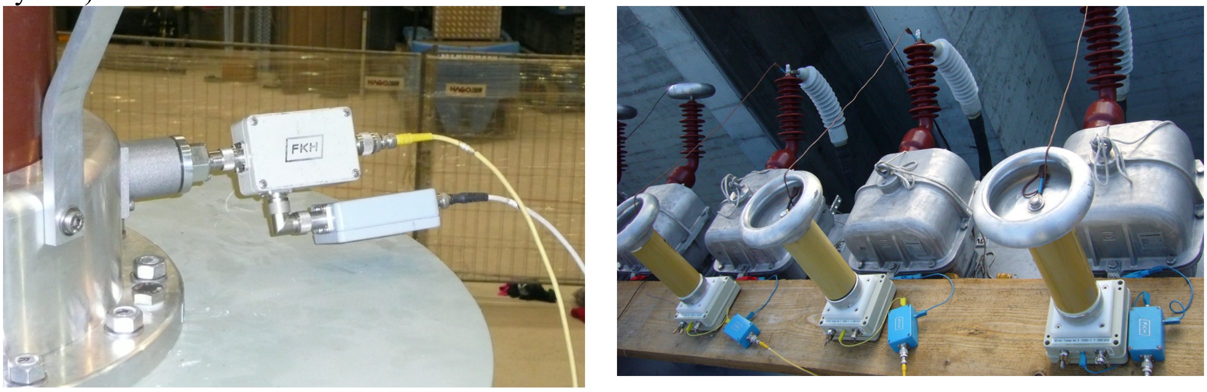


Figure 2: Connection of a high frequency current transformer (with secondary capacitance for voltage measurement) to the tap-off connector of a capacitor bushing (left); or use of external coupling capacitors (right)

The following testing parameters and acceptance levels were established and used for these tests:
- In the factory: Phase resolving PD measurement on all bushings at 130% U_m during 60 min
- On-site: Phase resolving PD measurement on all bushings at 120% U_m during 60 min
- PD acceptance levels range between “no phase correlated PD at U_m“ and “ < 50 pC at 130% U_m”

2.2 Frequency Response Analysis

FRA measurements were systematically made on new and also aged transformers to gather reference data which would be used in the case of a suspected transport damage or a damage due to short-circuit currents. New transformers are usually measured in the factory before the transport and then again on site after completion of the installation [2]. A commercially available sweep frequency response analyzer was used for these measurements. For the connection of the measuring cable to the bushings of the transformer, a copper bar fitted with a BNC through-connector is solidly screwed to the flange of the bushing or the tank of the transformer. At this grounding reference point a BNC to 4 mm adaptor is connected and an unshielded cable leads to the top of the bushing (see figure 3). In order to minimize the external loop inductivity and for optimum reproducibility, this lead has always to be kept straight and as short as possible.

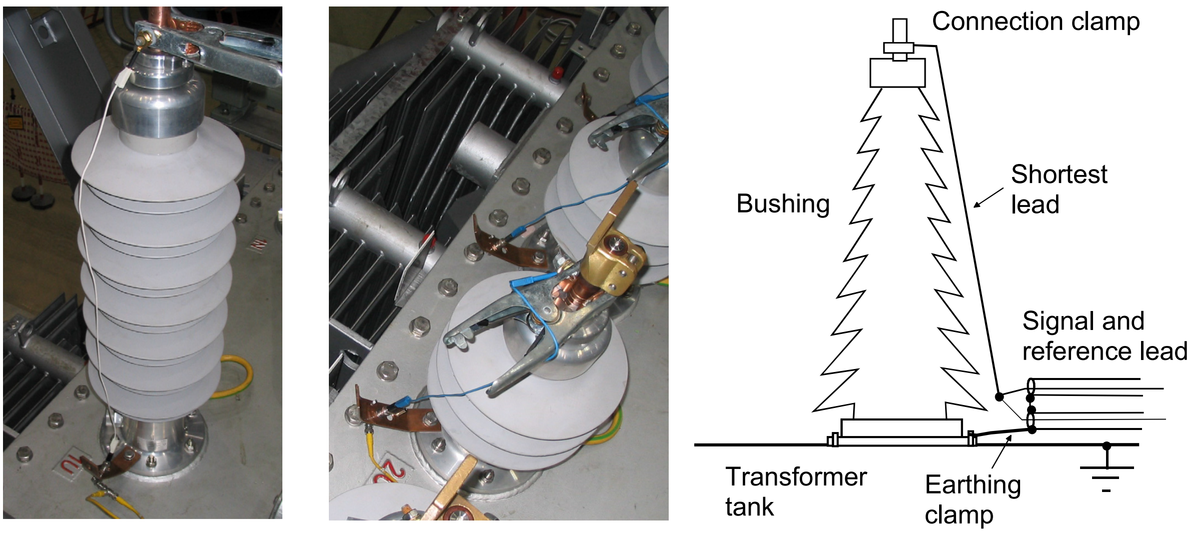


Figure 3: Connection to bushings (left: signal input and reference measurement; middle: response measurement, right: principle of connections)

This connection technique has the advantage that the screens of the measuring (coaxial) cables are connected directly at the location of the transformer tank aperture, which is important particularly for high measuring frequencies. The selected earthing solution prevents a high frequency voltage drop between the transformer tank and the cable screen. With this set-up the measured spectrum is not dependent on the individual geometrical arrangement of the coaxial cables. The experience has shown that this connection technique yields a very good reproduceability of the measurement results and that the measurement is not prone to external interference.

2.3 Polarisation and depolarisation current measurements

Polarisation and depolarisation current measurements were applied to monitor the humidity in the cellulose part of the insulation [2],[3],[5]. Frequency domain methods were not applied, because of their much longer measuring times. For new units, the measurements were performed in the factory and then repeated on site after the transformer was refilled and the oil was treated (if applicable). These measurements are used as reference data for the surveillance of the humiditiy in the insulating system during the transformer life. For aged units the method allows to determine directly the percentage of humidiy in the solid insulation (transformerboard/cellulose), and to decide, whether further measures are necessary (e.g. re-drying by low frequency heating, LFH).

3. STATISTICS AND EXPERIENCE OF TESTS PERFORMED DURING 16 YEARS

3.1 Overview

Figure 4 gives an overview of the number of units tested in the last 16 years and of the applied diagnostic methods applied during the tests.

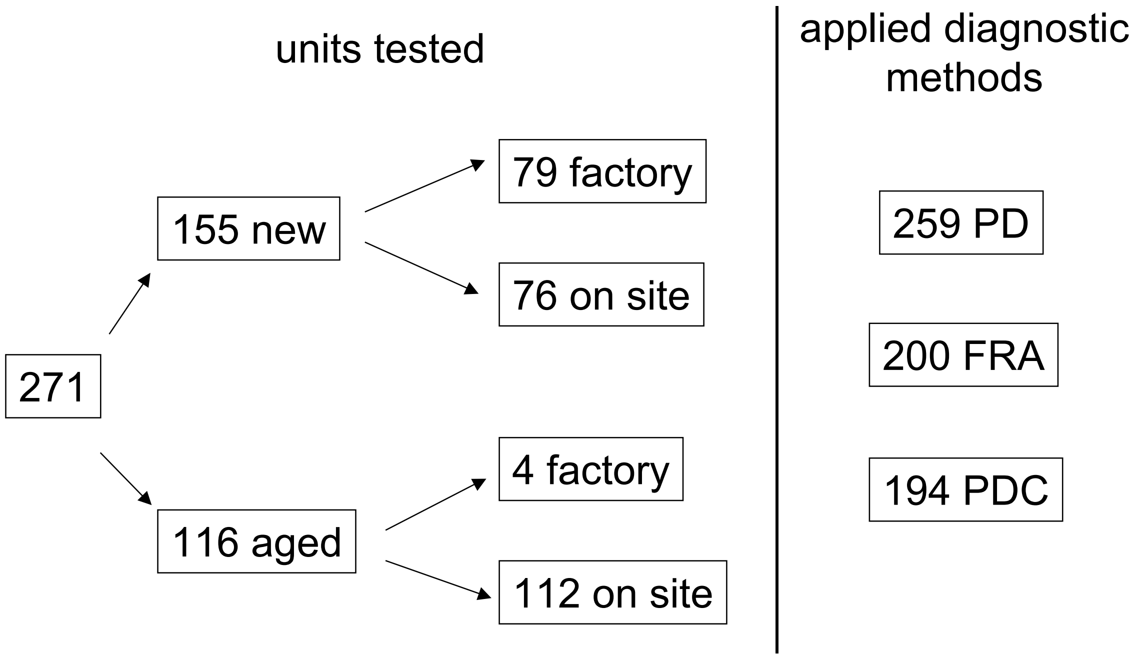


Figure 4: Summary of the tests performed

3.2 Partial discharge measurements

Figure 5 gives an overview of the cases where PD has been detected and corrective measures were necessary. The overview covers only measurements on transformers installed in Switzerland or factory tests of units of Swiss customers. In the factory tests, only results of PD measurements performed by FKH are considered. Other failures in the factory tests, such as breakdown during impulse voltage tests or during induced voltage tests are discarded. The figures shown are related to the active parts contained in one transformer tank: i.e. three phase transformer or single phase transformer poles.

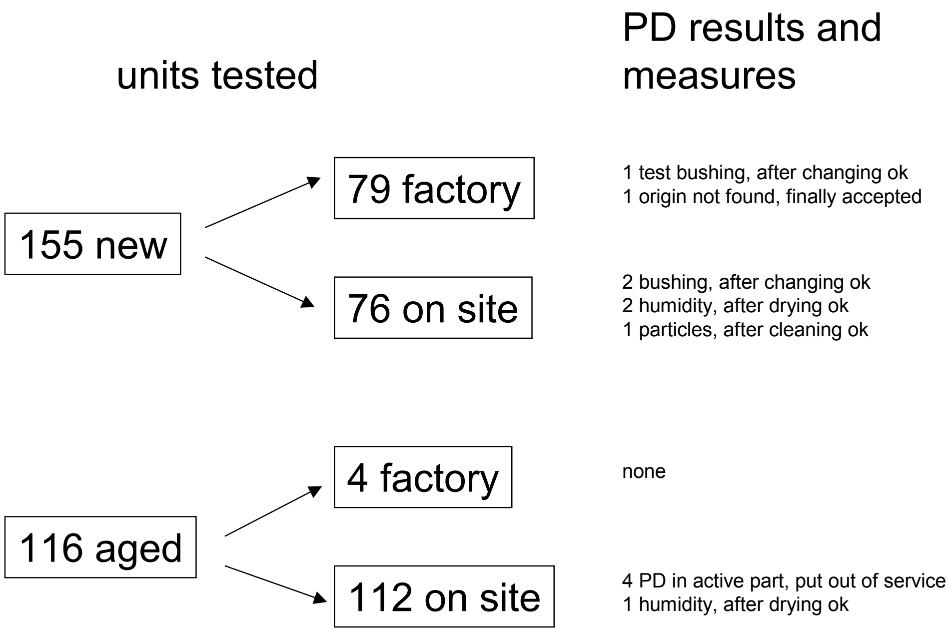


Figure 5: Results of PD measurements and measures taken

1.) PD measurements in the factory on new units (79 units)
With a background noise level of a few pC, in most cases no phase correlated partial discharges are visible, or the PD level was less than 25 pC. In two cases minor PD (around 50 pC) were detected. In one case it was a test bushing, in the other case the origin of the PD could not be identified.

2.) PD measurements on site on new units (76 units)
Background noise levels of 5 to 20 pC can be reached under on-site conditions. In five cases, PD ranging from 100 pC to 1.5 nC were detected. For new transformers, PDs appear typically in the region of bushings and bushing connection ducts or they are related to insufficient impregnation of the cellulose. Successful reparations included: changing of bushings (2); re-drying (2); removal of metallic particles (1, see section 4.1).

3.) PD measurements in the factory on service-aged units (4 units)
These measurements have been performed after revision of the transformers. No PD results asking for measures were obtained.

4.) PD measurements on site on service-aged units (112 units)
There are two reasons for this type of measurement:

PD measurements on units which are in service without problems
Units, which have been in service for more than 30 years, often show PD levels ranging form 50 pC to several hundreds of pC. If possible, PDs were located, and, with the knowledge of the origin of the PD, an assessment of their potential danger was made. For this assessment it is important to have detailed information about the design of the transformer and all other important data such as dissolved gas analysis (DGA) have to be considered.

PD measurements on units for which other diagnostic methods showed a problem (usually DGA results or Buchholz-relay alarm)
In four cases the transformers were put out of service and replaced. In one case (see section 4.2) the PD measurement allowed the localization and identification of the source of gas production.

Figure 6 shows a scetch of a transformer with the indication of the position and the type of the most frequent defects.

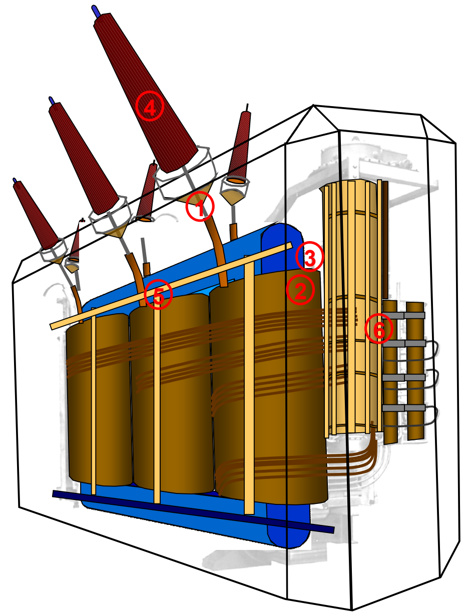


Figure 6: Causes and typical locations of PD findings

① Output duct cone or bellow
② Humidity in oil and cellulose
③ Free particles
④ Bushings
⑤ Clamping structures and fixation of connections
⑥ Contact problem in tap changer

3.3 Frequency Response Analysis (200 units)

The reproduceability of the measurements in the factory and on site was generally very good, even if different testing staff executed the measurements. It is of course very important that the measurements are well documented (e.g. with pictures) and that all "boundary conditions" are defined (tap changer position, grounding or short-circuiting of bushings etc.). It was also found that results obtained with different SFRA instruments do satisfactorily match. In a limited frequency range, this is also true for the comparison of data from the sweep frequency and the impulse voltage method.

In the 200 measurements performed only once a mismatch of FRA data from the factory and the on-site test was observed. The reason was that during the factory test, the core and the core clamp ground was not yet realised, which was overseen by the test engineer.

In the present review, we have no example of a winding damage detected by FRA during service. This is due to the lack of reference data (older units) or due to the fact that damages were so evident that they could be detected by standard methods such as winding resistance measurements.

3.4 Polarisation and depolarisation current measurements (194 units)

PDC measurements on new transformers always showed low values of humidity in the pressboard/cellulose-insulation ranging form 0.25 to 1%. Measurements on aged units showed often higher values, which may reach 2.5% to 3% after some 40 years of service. In our measuring experience no transformer was detected with an unacceptable high water content of the pressboard/cellulose. PDC measurements were also used to monitor the effect of the re-drying of a transformer (e.g. by LFH).

4. EXAMPLES

4.1 PDs detected during on-site test of a new transformer

During the on-site test of a 250 MVA phase-shifting transformer (220/150/24 kV) partial discharges with a magnitude of about 1500 pC were recorded at 50% of the nominal voltage at the 220 kV bushing 1U (see figure 7 for the PD pattern).

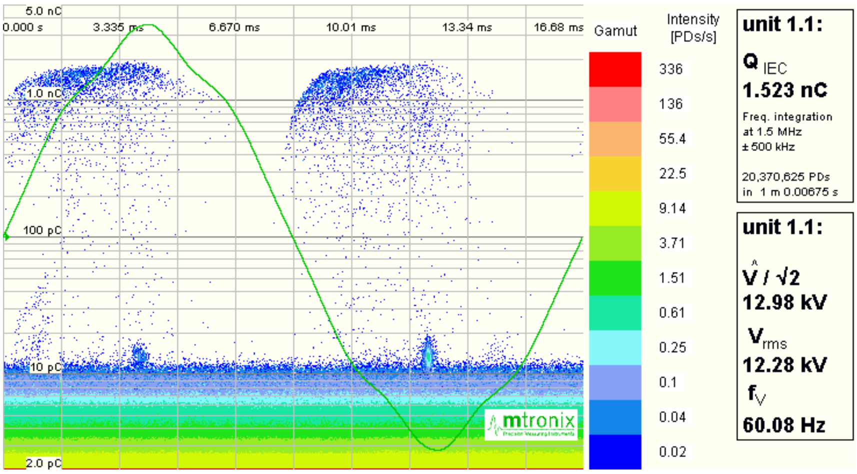
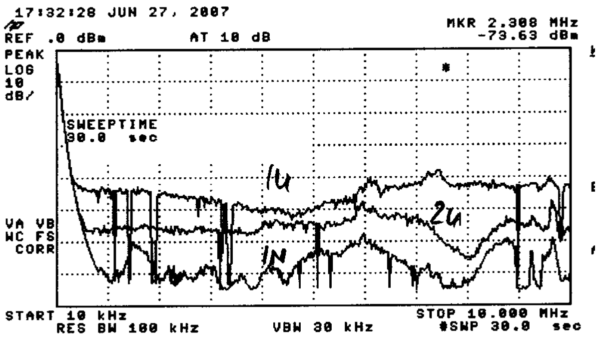
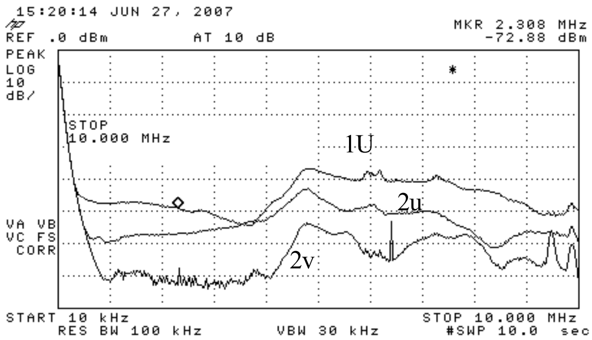


Figure 7: PD pattern at 1U (220 kV bushing) at 50% U_n

The localazation of the PD source is based on the comparision of frequency and time domain data of the real PDs and of calibrator signals recorded on different bushings (see Figure 8).



Measured PDs on 1U, 2u and 1N



Calibrator signals injected in 1U, measured on 1U, 2u and 2v

Figure 8: Comparison of frequency domain spectra of real PDs and calibrator signals

The analysis of the measurement indicated that the PD source should be close to the bushing 1U. The replacement of the bushing didn't yield the expected result, the same PD-pattern was still present. Acoustic localization showed that the PD source must be some 40 cm below the tank cover. The inspection through a man-hole showed particles on the press-plate. After removal of the particles, the transformer was partial discharge free.

4.2 Fault localization on an aged transformer

After a revision, a 75 MVA transformer (132/50 kV) showed multiple Buchholz-relay alarms. It was decided, to perform an off-line partial discharge measurement to localize the origin of the gas production. Very strong PDs (about 100 nC) were recorded at the two 50 kV bushings 2u and 2v (see figure 9). The pattern is typical for local humidity.

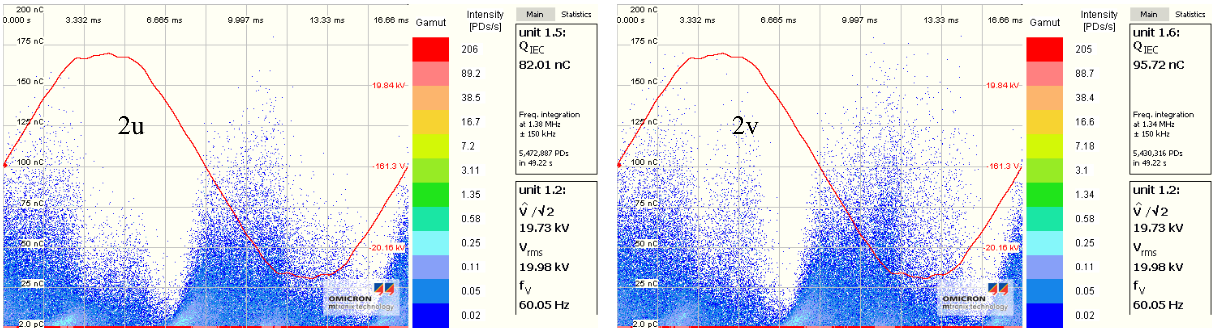
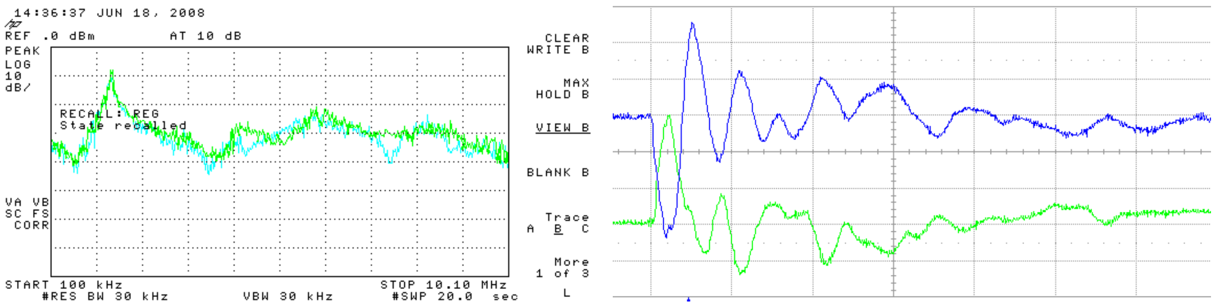


Figure 9: PD pattern at the two 50 kV bushings at 44% U_n

The frequency and time domain data at the two bushings were quite similar (see figure 10) and also similar to calibrator signals injected in the two bushings.



2u and 2v frequency domain 2u and 2v time domain (2 V / div; 100 ns / div)

Figure 10: Comparison of frequency domain spectra of real PDs at terminals 2u and 2v

The measurement indicated that the PD signals run through a similar propagation path and that the source was not too far from the bushing (i.e. not in the winding). Acoustic measurements allowed to pin-point the PD source in the 50 kV leads. The transformer was subjected to a low frequency heating (LFH) treatment. In a subsequent test, no partial discharges were detected, and the transformer was put into service again.

5. CONCLUSIONS

Since 16 years, Swiss utilities apply diagnostic measurements such as PD, FRA, PDC and DGA systematically on all large power transformers in the factory and on site. Whereas methods like FRA and PDC are basically applied to gather reference data for condition assessment, partial discharge measurements allow a direct check of the dielectric integrity of the insulation system.

Without doubt, the off-line PD test with a mobile source for transformer excitation (applied and induced voltage tests) is the most effective diagnostic tool on site. Due to extensive experience and development during the last years, PD measurement procedures on-site have reached an attractive cost/benefit ratio. With only few exceptions, large transformers in power stations and in the power grid above 50 MVA are tested on the occasion of commissioning. Even smaller power transformers for substations in urban areas in the range of 20 to 50 MVA are regularly PD tested during commissioning.

PD investigations on aged power transformers have a different background. The most frequent motivations are: power trips by a protection relay, findings of decomposition gases during oil analysis and in older units: assessment of the insulation condition with respect to an optimization of the life time.

Several on-site tests with new transformers in this review demonstrated the benefit of PD measurements, especially to detect assembling errors. With service-aged transformers the application of PD measurement as a diagnostic has proven its usfullness to localize PD sources, which is essential for the elimination of a defect.

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