

Assessment of Insulation Condition of Large Power Transformers by On-Site Electrical Diagnostic Methods

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Abstract: This contribution describes an off-line partial discharge (PD) detection technique for large power transformers in the substation environment. It is demonstrated that off-line PD-analysis is one of the most meaningful method to assess the insulation condition of large power transformers. Details of an advanced PD-detection technique and on-site measuring procedure are described and illustrated with practical examples. The interpretation of results from PD-tests needs complementary diagnostic methods, such as dissolved gas-in-oil-analysis or integral dielectric measurements.

INTRODUCTION

Since large power transformers belong to the most expensive and strategically important components of any power generation and transmission system, their reliability is of crucial importance for the energy system operation. A serious failure of a large power transformer due to insulation breakdown can generate substantial costs for repair and financial loss due to power outage. Most power utilities are therefore highly motivated to assess the actual condition of the insulation system of their transformers.

However, the driving force behind the development and application of advanced methods for insulation diagnosis is the increasing age of the transformer population (30 to 40 years in most European countries). It is evident that market liberalization with changed investment strategies leads to an extension of transformer lifetime and requires cost reduction in maintenance and refurbishment. Hence for utilities, both condition based maintenance and reduction of outage cost of large power transformers are the main incentives to utilize advanced diagnostic methods on site, i.e. in a substation or in a power station.

In the course of recent Swiss research projects different methods for the assessment of the insulation condition of large power transformers have been evaluated and successfully applied on site to several new and also to service aged transformers [1]. The methods investigated in these projects include partial discharge measurement (PD), measurement of relaxation currents (PDC) and frequency response analysis (FRA). This paper describes details of the PD-measurement technique developed in the mentioned project and applied to power transformers in the range of 50

MVA to 600 MVA. In a final section synergies between PD-measurement and other diagnostic methods are indicated.

ON-SITE PARTIAL DISCHARGE TESTS

Off-line excitation of power transformers

The detection sensitivity of existing PD-monitoring systems is still too low (range of 1000 pC) to detect dangerous PD-defects at an early stage [2,3,4]. Although state-of-the-art PD-sensors and digital signal processing techniques are used in such on-line systems, the corruption of weak PD-signals by high amplitude wide-band disturbances is still an unsolved problem. Therefore, off-line PD techniques using a mobile, PD-free power source for the excitation of the transformer under test is highly favored.

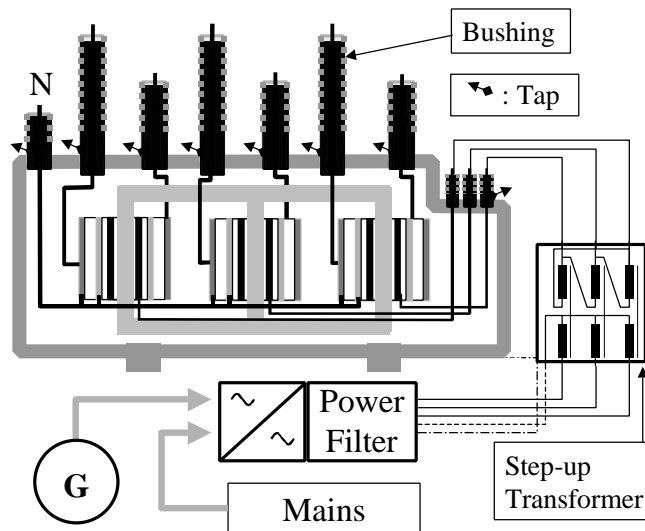


Figure. 1 Induced voltage test on a power transformer using a diesel generator and/or a frequency converter.

For the excitation of power transformers on-site, it is essential to use an ac-source which fulfills the following requirements: (a) mobile unit with PD-free output voltage, (b) frequency of the test voltage is different from and higher than power frequency (50 Hz or 60 Hz) to discriminate noise generated by power frequency against phase correlated PD-signals and

to avoid saturation of the iron core at test voltages higher than nominal voltage (U_n), and (c) variable test voltage (10% - 120% U_n) to investigate PD-onset and PD-extinction of detected faults.

To perform a three phase induced voltage test, a typical power source consists of a mobile diesel generator unit and a step-up transformer connected to the compensating (delta) winding of the unit under test as shown in Figures 1 and 2.



Figure 2 - Off-line test set-up for PD-diagnosis on a 220/50-kV transformer using a 300 kVA diesel generator unit and a step-up transformer 0.4/50 kV (left). Transformer under test with torus electrodes at the HV-bushings to avoid corona discharges (right).

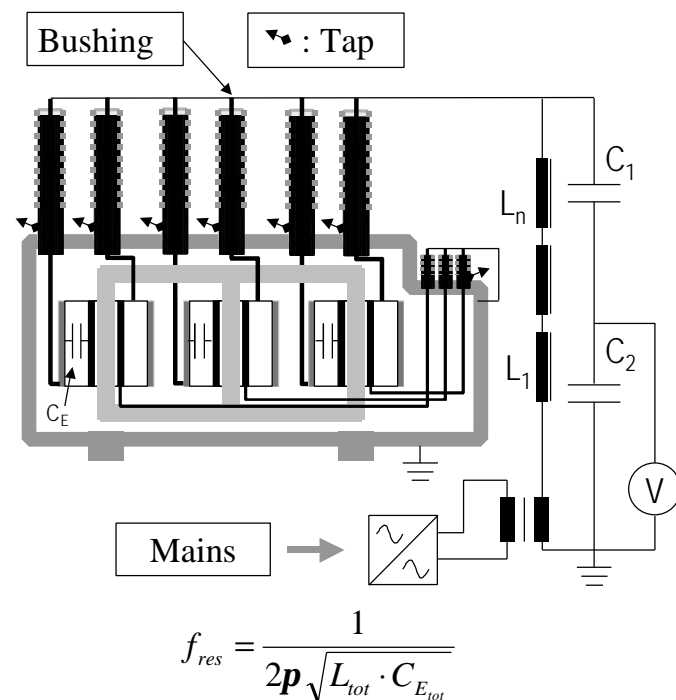


Figure 3 Separate source voltage test using a frequency tuned series resonance test set on a regulating transformer.

During off-line PD-measurements, the maximum voltage levels of 110% to 120% U_n were applied for a duration of typically 60 minutes.

Figures 3 and 4 show the application of a frequency tuned series resonance circuit [5] to a transformer which has an insulation system with uniform insulation level. In this special case a separate source test at 100% U_n (or higher if needed) is most efficient under on-site conditions because lightweight resonance test sets are available [1].



Figure 4 - Off-line test set-up for PD-diagnosis on a 380/220-kV separated regulating transformer unit using a frequency tuned series resonance test set. The resonance reactors and capacitors are situated in the center of the photograph.

PD-detection circuit

Commercially available PD detection systems (e.g. according to IEC 60270), as used in shielded HV laboratories, are not suitable for on-site applications to power transformers, because electromagnetic interference from operating substations or energized power lines severely hamper the detection sensitivity. An advanced PD-detection and registration system was developed to cope with severe interference situations existing on-site [1]; details of this system are described in the following text.

PD-coupling device

High-frequency current transformers (HF-CT) are used as wideband coupling devices (0.2 to 30 MHz). To provide multiterminal detection capability, HF-CT's are directly connected to capacitive taps of all transformer bushings. If bushing taps are not available, coupling capacitors directly connected to the bushings are used as coupling devices. From the coupling devices the PD-signals are transmitted to the PD detection system by shielded coaxial cables.

PD-measuring system

The PD-measuring system (see Figure 5) consists of the following components:

- Spectrum analyzer used as a tunable bandpass-filter to suppress background noise.
- Computer controlled Phase Resolving Partial Discharge Analyzer (PRPDA) for PD-impulse acquisition and digital signal processing [6].

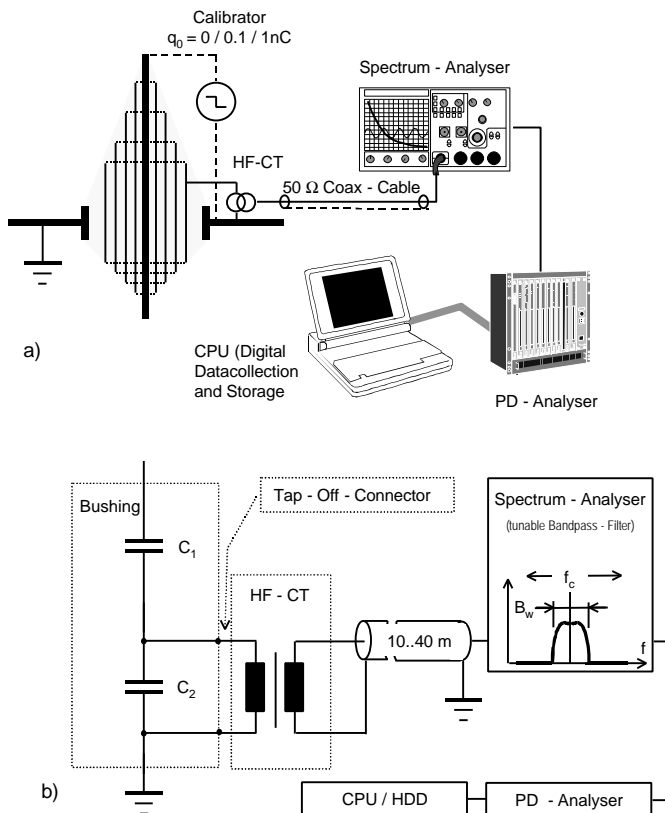


Figure 5 - Off-line PD detection system for power transformers, a) Set-up of principal components, b) electric circuit.

Measuring procedure

Characterization of test object

In a first step, a calibrated PD-source (0, 100 and 1000 pC, Figure 5a) is directly connected to the bushings and the full span spectra (up to 10 MHz) of the calibrating impulses are registered with the spectrum analyzer to find a suitable center frequency f_c for narrowband PD-detection for each measuring terminal. The center frequency for narrowband-filtering is selected by the optimum signal to noise ratio within a frequency range of 200 kHz to 5 MHz. Center frequencies much higher than 1 MHz may lead to satisfactory signal to noise ratios, however, too large differences in the sensitivity

of the individual bushings and vice versa are observed in this case.

In a second step, the spectrum analyzer is used as a narrowband filter (Figure 5b) for the calibration (100 pC) of the whole PD-detection circuit. The calibration is performed at the selected frequency f_c . The PD-measuring system (PRPDA) is calibrated in values of apparent charge according to the calibrating source.

In a third step, the signal transfer of the calibrating impulse (usually 1000 pC) between the bushing with the calibrating source and all other PD-measuring terminals (normally bushing taps) are systematically registered in the frequency domain (full span frequency spectra) and also in the time domain. An example of the calibration signal (1000 pC) measured at two different bushings taps is shown in Figure 6. This last step in the procedure is important for the successful localization of PD-sources during the PD-tests.

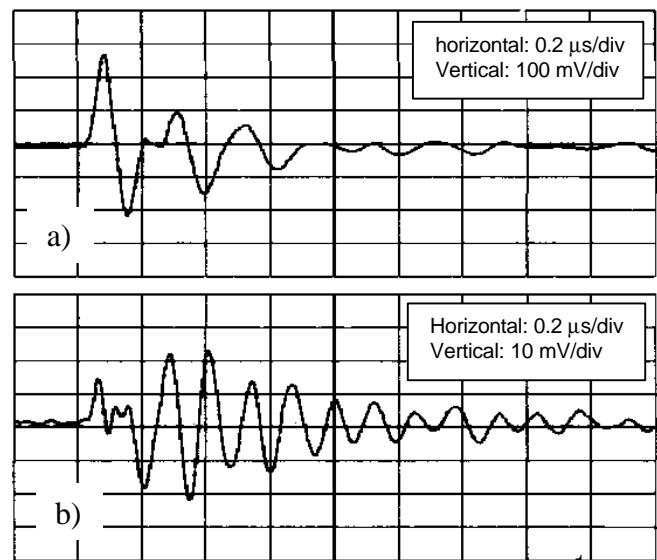


Figure 6 - Calibrating signal measured at different bushing taps (regulating transformer 220 kV / 110 kV, 160 MVA).

Upper trace a: signal at the 220 kV bushing tap.

Lower trace b: signal at the 110 kV bushing tap of the same phase.

PD-Test

During the measuring procedure the steps one and two, described for the characterization of the test circuit, are repeated under defined test voltage conditions. The first data registration is performed at 10 % U_n to define the real background noise condition of the whole test set-up. At each following level of the test voltage (up to 120 % U_n) the full span spectra and the PD-activity (Figures 7 and 8) are observed. The registration of the frequency spectra during PD measurement must be performed to recognize a possible change of the defined center frequency f_c caused by the real PD-activity in the test circuit. In this case the calibration of

the measuring system must be repeated after the test at this specific center frequency.

Efficient discrimination between PD-signals and background noise (mainly due to power frequency synchronous corona discharges) is achieved by producing a non synchronized test voltage combined with a digital impulse acquisition and storage with statistical data processing correlating all PD-events with the phase position of the applied test voltage.

In Figure 7 an example of the full span spectra of a real PD-source is shown.

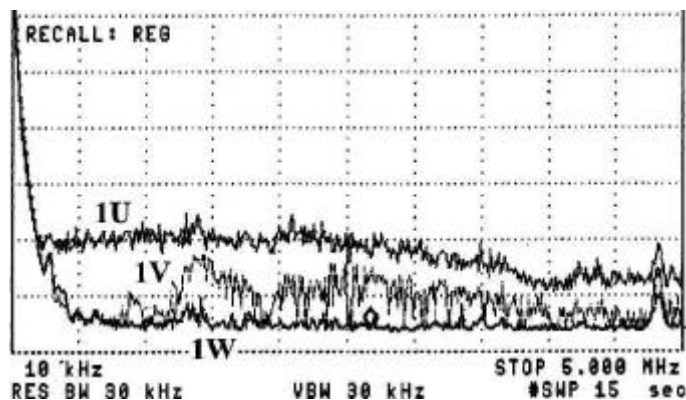


Figure 7 - Spectra of PD impulse signals measured at the bushing taps of an auto-transformer 220 kV / 110 kV / 10 kV at 100 % U_N :

Upper trace 1U: power spectrum of partial discharge signal with a PD-source near the bushing phase U.

Middle trace 1V power spectrum at the bushing of phase V showing reduced spectral response.

Lowest trace 1W: power spectrum at the bushing phase W, with longest distance to the PD source.

Interpretation of PD-results

If PD-activity is detected in on-site test, the interpretation cannot be achieved by the analysis of the phase resolved PD-fingerprints alone, i.e. apparent charge, phase distribution, mean impulse frequency. The analysis of PD-results and the decision about further activities (e.g. repair on site or transportation to the factory) requires both: (1) detailed investigation of the behavior of the PD-activity and localization of the PD-sources within the transformer under test, (2) consideration of complementary information including additional diagnostic measurements. In the following section the most important parameters needed for the final assessment of the condition of the insulating system of the transformer are summarized:

Behavior of the PD-activity

- PD-discharge inception and extinction voltage
- stability and hysteresis of the PD threshold
- PD fingerprints at different test voltages

- Characterization and localization of PD-source (coupling path to different measuring terminals, frequency spectra, time resolved signals)

Service condition and maintenance history

Service age, load history, occurrence of overvoltages and short-circuit currents, release of alarms, refurbishment activities, oil treatment.

Design and construction

Details of the design and construction, in particular of the highly stressed insulating parts

Common maintenance diagnosis

Dissolved gas-in-oil-analysis (DGA) and investigation of the oil condition, measurements of winding resistance, ratio and $\tan \delta$ [7].

Complementary diagnostic results

- Measurement of relaxation currents of the transformer insulation, i.e. polarization and depolarization currents (PDC) which allows an evaluation of the overall aging state of the insulation due to thermal stress and humidity in cellulose [8].
- Measurement of transfer function (FRA) of the transformer to detect deformations due to mechanical short circuit stress [9, 10].

Example of the interpretation

The PD-pattern in Figure 8 shows a PD-defect (voids) located at the shield of the connection of the HV-bushing (220 kV) to the winding. This PD-source was unambiguously identified using the described multiterminal PD-detection technique. As shown in Figure 7, the full span frequency spectrum (upper trace 1U) indicates, that the PD-source is very close to the HV-bushing 1U. On the other hand the full span frequency spectrum detected at the bushing 1V (middle trace) shows the coupling of the PD-signals to this measuring terminal. At the bushing of the phase 1W (lower trace) only the background noise could be measured. In this case acoustical signals at the transformer tank have not been detected.

Based on the results of the on-site PD-measurements and on the information about the increasing trend of the dissolved gas-in-oil values it was decided to repair the transformer on-site. This decision was supported by the very difficult transport of the 200 MVA unit. The repair of the transformer (new bushings and shields of the connections) revealed at the phase 1U solid decomposition products (x-wax) and carbonized tracks on the HV-shield of the bushing connection to the 220 kV windings.

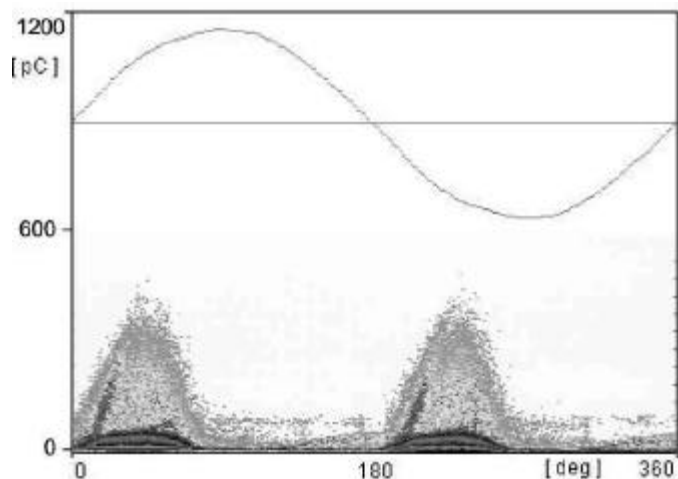


Figure 8 - Phase resolved partial discharge pattern of a 220 kV / 110 kV / 10 kV, 200 MVA auto-transformer pole at 100% U_n , at the 220 kV terminal of phase U.

CONCLUSION

The off-line PD detection procedure described above has been applied successfully to several substation transformers (power range from 50 MVA up to 600 MVA) and to seven 220/400-kV new autotransformers after installation. In all cases a detection sensitivity of better than 50 pC was achieved, even when HV power lines or HV equipment were operating in the same substation.

With the application of the presented method, two defects caused by the final on-site assembly of the new transformers and several critical PD-defects in old transformers have been detected. For the old units not only fatal defects with outages were prevented but also cost-saving maintenance or refurbishment has been proposed.

In the future, a consequent application of the described advanced diagnostic methods to new and service aged power transformers is highly desirable. More fundamental work is needed to fully understand all the complex physical and chemical processes relevant to the aging of transformer insulation systems.

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