Fehlereingrenzung an Transformatoren mithilfe elektrischer Messverfahren

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FAULT INVESTIGATION ON TRANSFORMERS WITH ELECTRIC MEASUREMENT METHODS

FEHLEREINGRENZUNG AN TRANSFORMATOREN MIT HILFE ELEKTRISCHER MESSVERFAHREN

ABSTRACT

With advancing age of power transformers, a regular check of the operative condition becomes more and more important. The Dissolved Gas Analysis (DGA) is a proven and meaningful method such that if increased proportions of H_2 and hydrocarbon gases are found in the oil, the fault must be located. In order to find out the reason for high gas rates, further tests have to be performed. Common methods are: winding resistance measurement (static), On-Load Tap Changer (OLTC) test (dynamic resistance test), turns ratio and excitation current measurement, measurement of the leakage reactance and the measurement of capacitances and dielectric losses.

Innovative new tools like the Dielectric Response Analysis with Polarisation-Depolarisation Current (PDC) and Frequency Response Spectroscopy (FDS), the measurement of the transfer function with the Frequency Response Analysis (FRA), capacitance and dissipation factor measurement at different frequencies and the Partial Discharge (PD) measurement with modern synchronous multi-channel and multi-frequency PD systems enable more detailed diagnostic measurements on transformers. For the assessment of the danger potential of PD in transformers the knowledge of the location of the PD faults is essential. A powerful tool for PD location is the acoustical measurement with ultrasonic microphones together with UHF triggering.

The paper describes all these new methods and illustrates them with practical case studies for the diagnosis and fault finding.

Keywords

Frequency response analysis (FRA), dielectric response measurement with PDC and FDS, partial discharge (PD) measurement with synchronous multi-channels and multi-frequencies technology, combined synchronous PD measurement with conventional electrical, UHF and acoustic sensors, PD location

DIELECTRIC RESPONSE MEASUREMENT

Water in oil-paper-insulations goes hand in hand with transformer aging, it decreases the dielectric withstand strength, accelerates cellulose decomposition and causes the emission of bubbles at high temperatures. State of the art for moisture measurements are equilibrium diagrams, where one tries to derive the moisture in the solid insulation (paper, pressboard) from moisture in oil. This method does not deliver very reliable results [1]. To assess the insulation's water content some dielectric diagnostic methods were widely discussed and occasional used during the last decade. The multilayer insulation of common power transformers consists of oil and paper and therefore shows polarization and conductivity effects. Dielectric diagnostic methods work in a range dominated by interfacial polarization at the boarders between cellulose and oil, cellulose conductivity and oil conductivity. Moisture influences these phenomena. Temperature and the insulation construction have a strong impact too [2]. In [3] a comparison of the mentioned methods was analysed. FDS and PDC methods give rather reliable results and reflect also the influence of the temperature and the geometry by using an X-Y model. The results of the PDC measurement can be transformed from the time domain into the frequency domain. Although the results of PDC and FDS methods are comparable both methods have advantages and disadvantages. If the FDS shall be used down to 100uHz, a measuring time of up to twelve hours is needed for one measurement e.g. the insulation gap between HV and LV winding. If also other insulation gaps e.g. HV winding to tank or LV to TV winding shall be measured, even more time is necessary. The PDC measurement needs much less time but is limited to frequencies up to about 1Hz. A new approach combines both methods [4]. The FDS measurement is replaced by the PDC method in the low frequency range and the results are transformed into the frequency domain, whereas the FDS is used for higher frequencies, which can be done rather quickly. Two input channels for simultaneous measurement of two insulation gaps make it even faster. New model curves for aged oil-pressboard insulation, an outcome of a research project at the University of Stuttgart make the results for aged transformers much more reliable compared to the standard model curves for new oil-pressboard insulation which were used up to date.

Onsite measurement on an aged 133 MVA power transformer

The transformer was manufactured in 1967, has a rated power of 133 MVA, a transformation ratio of 230 / 115 / 48 kV. The insulation gaps HV to LV, LV to TV (tertiary winding) and TV to tank were measured separately. The higher moisture content in the TV winding insulation agrees well with the service conditions of the transformer: the TV winding was not loaded. Cellulose at lower temperatures stores more water in a transformer than warmer cellulose. Thus the dielectric methods allow for an elementary localisation of wet areas in the insulation. Contrary to this the moisture content in cellulose as derived from oil samples gives an average value. The result obtained from the relative saturation in oil by advanced equilibrium diagrams agrees well with the dielectric analysis. However the conventional method of deriving the moisture in cellulose from moisture by weight in oil (ppm) gives a too high results. Aging of oil and paper makes the application of equilibrium diagrams from literature sources impossible in most cases. The transformer was dried with an online drying system for about one and a half years. After drying the measurements were repeated. Figure 1 shows the water content in the solid insulation before and after drying. The moisture of the insulation HV to LV was reduced from 2.6% to 1.6%, the moisture of the insulation LV to TV was reduced from 4.3% to 1.5%. The moisture in the insulation from TV to tank is still quite high with 3.3%. To reduce the moisture in the TV winding the winding should be loaded to the increase its temperature.

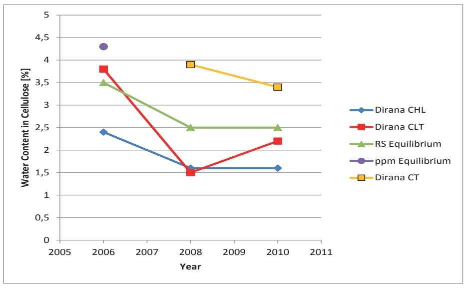


Fig. 1 *Water content before and after drying*

DISSIPATION FACTOR MEASUREMENT ON HIGH VOLTAGE BUSHINGS

Bushings with high moisture in the insulation show increased 50/60Hz tan δ values particularly at higher temperatures. Figure 2 shows the Dissipation Factor (DF) of OIP bushings at 50Hz for different water contents as function of the temperature [5], in figure 3 it can be seen that the DF at low frequencies is a very sensitive parameter also at ambient temperatures. This is important if measurements are made on built-in bushings which cannot be heated.

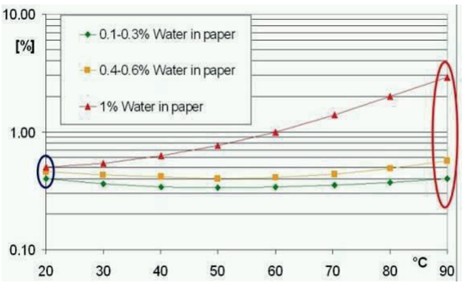


Fig. 2 *tan δ (T) at 50Hz with different moisture*

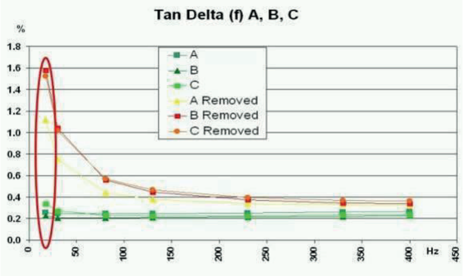
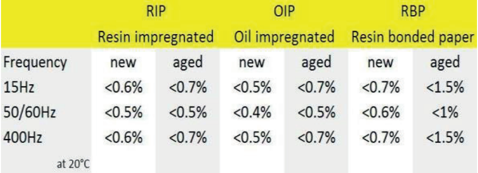


Fig. 3 *tan δ (f) at 30°C with different moisture*

Limits for the dissipation factor

In the existing standards limits are given for 50/60Hz only. The measurement of the dissipation factor at other frequencies should be also included in the standards. Low frequency results (e.g. 15Hz) allow for a very sensitive moisture assessment, measurements at high frequencies (e.g. 400Hz) allow a very sensitive detection of contact problems at the measuring tap or at the layer connections. Also high impedance partial break downs between grading layers can be detected. Figure 4 shows indicative limits for new and aged bushings at different frequencies [6]. The indicative limits were extracted out of more than 2000 different measurements. They were calculated as average values plus two times the standard deviation. That means that 95% of the results were below these values [7].



	RIP		OIP		RBP	
	Resin impregnated		Oil impregnated		Resin bonded paper	
Frequency	new	aged	new	aged	new	aged
15Hz	<0.6%	<0.7%	<0.5%	<0.7%	<0.7%	<1.5%
50/60Hz	<0.5%	<0.5%	<0.4%	<0.5%	<0.6%	<1%
400Hz	<0.6%	<0.7%	<0.5%	<0.7%	<0.7%	<1.5%
at 20°C						

Fig. 4 *Indicative limits for bushings [6]*

FREQUENCY RESPONSE ANALYSIS (FRA)

Sweep Frequency Response Analysis (SFRA) has turned out to be a powerful, non-destructive and sensitive method to evaluate the mechanical integrity of windings and the core within power transformers by measuring the electrical transfer functions over a wide frequency range. This is usually done by injecting a low voltage signal of variable frequency into one terminal of a transformer's winding and measuring the response signal on another terminal. This is performed on all accessible windings following according guidelines [8], [9]. The comparison of input and output signals generates a frequency response which can be compared to reference data, to other phases, or to sister transformers (figure 5). The core-and-winding-assembly of power transformers can be seen as a complex electrical network of resistances, self- and mutual inductances, ground capacitances and series capacitances. The frequency response of such a network is unique and therefore it can be considered as a fingerprint. Geometrical changes within and between the elements of the network cause deviations in its frequency response. Differences between FRA fingerprints and the results of an actual measurement are an indication of positional or electrical variations of the internal components. Different failure modes affect different parts of the frequency range and can usually be discerned from each other. Practical experiences as well as scientific investigations show that currently no other diagnostic test method can deliver such a wide range of reliable information about the mechanical status of a

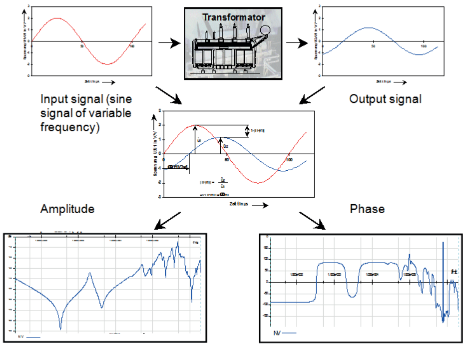


Fig. 5 *Principle operation of SFRA*

transformer's active part. A transformer for 115kV was switched off by the differential relay after a ground fault in a substation. The FRA result is shown in figure 6.

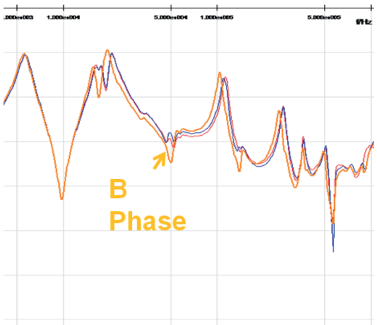


Fig. 6 *FRA LV winding*

It can be clearly seen that there is a systematic shift of several resonances of phase B to lower frequencies. This is a typical sign for a deformation of the winding. This kind of deformation is called "Buckling". The deformation of the low voltage winding can be seen in figure 7.

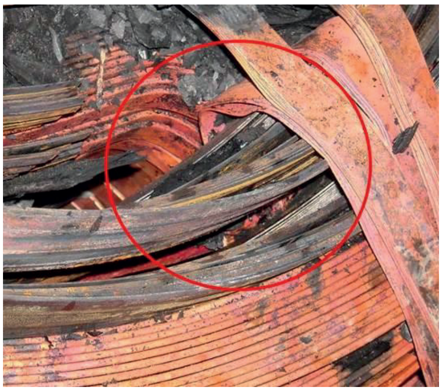


Fig. 7 *Damaged LV winding*

ELECTRICAL MEASUREMENT OF PARTIAL DISCHARGES

Partial Discharge (PD) measurement is a proven tool for quality control of high voltage apparatus in the factory and on site. Different PD measuring techniques are using different physical peculiarities of the PD phenomenon, e.g. electric discharge currents (acc. to IEC 60270 [10]), gas formation (DGA - dissolved gas analysis), electromagnetic (UHF Measurement) or acoustic radiation (some tens of kHz). Partial discharge measurements according to IEC60270 standard are often the basis for acceptance tests of the insulation system of high voltage (HV) equipment

Outside screened laboratories PD signals are very often superposed by noise pulses, a fact that makes a PD data analysis more difficult for both human experts and software expert systems. Therefore the handling of disturbances is one of the main tasks when measuring PD. PD measurements are often conducted under noisy conditions. The PD signal is superposed by stochastic noise pulses or even multiple PD sources, which will lead to a complex phase-resolved PD pattern that is not easy to analyse. For DC PD measurements where the expected PD rate might be very low, even single disturbance pulses can influence the test result significantly.

Modern methods of data evaluation

A new field of evaluation methods is opened by fully synchronous multi-channel PD acquisition in order to gain more reliable measuring results combined with effective noise suppression. A technical overview of the system is given in [11].

Being able to perform synchronous multi-channel PD measurements, the 3-Phase-Amplitude-Relation-Diagram (3PARD) was introduced as a new powerful analysis tool to distinguish between different PD sources and noise pulses when measuring 3-phase high voltage equipment such as power transformers, rotating machines and cross-bonded cable systems.

PD measurement on a repaired transformer

Figure 8 shows a PD measurement with four simultaneously measuring channels which are connected to the three HV bushings and the star point. It can be seen in figure 9 that the three different clusters in the 3PARD diagram are generated by three different PD sources: statistical noise, pulse disturbances and inner partial discharges.

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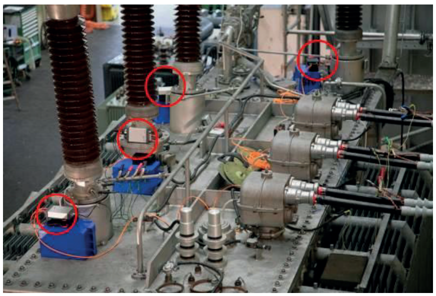

Fig. 8 *PD measurement on a 110kV transformer*

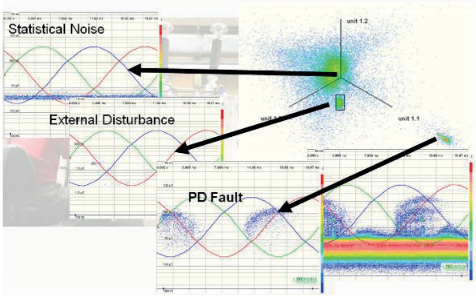

Fig. 9 *3PARD filtering on the 110kV transformer*

As an enhancement of 3PARD the 3-Center-Frequency-Relation-Diagram (3CFRD) was introduced as an additional tool for PD data analysis and PD fault separation in real-time on single-phase test objects [12]. The synchronous consideration of three different frequency parts of the PD spectrum of a single PD pulse provides information on its discharge nature and indicates its possible PD fault location due to PD signal propagation and attenuation. The 3CFRD method requires 3 different PD band-pass filters, measuring every PD event simultaneously at their predefined centre frequencies. Here the proper selection of these 3 band-pass positions in the frequency domain is the key to get the optimum benefit from this method. These 3 filters have to be set in a way that the spectral differences of PD pulses and other pulses are at their maximum. Figure 10 shows the spectra of three PD pulses and the three filters marked as blue bars. The red arrows indicate the absolute charge values of PD pulse 1 (shown in red) at the discrete filter frequencies.

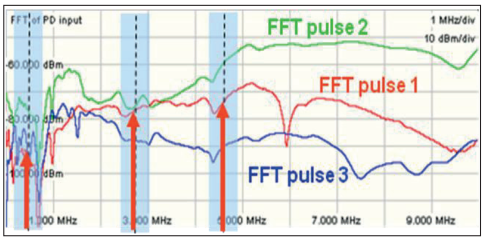

Fig. 10 *FFT of three different PD pulses*

The charge values are drawn into the star diagram as shown in figure 11. The lengths of the vectors represent the measured charge and the axes indicate the respective filter. By geometrically adding the PD responses one single dot is the final representation of the initial triplet. The use of this principle is shown in two examples.

The first example is the 3CFRD measurement on a high voltage bushing. Figure 12 shows the phase resolved pattern of different PD sources. The overlaying of different patterns doesn't allow a detailed analysis. Figure 13 shows a separated pattern of one source by 3CFRD filtering.

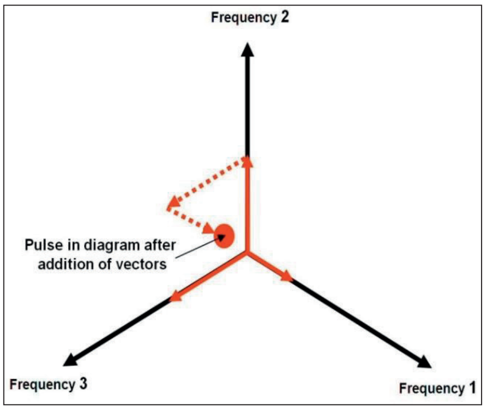

Fig. 11 *3CFRD of the red spectrum in figure 13*

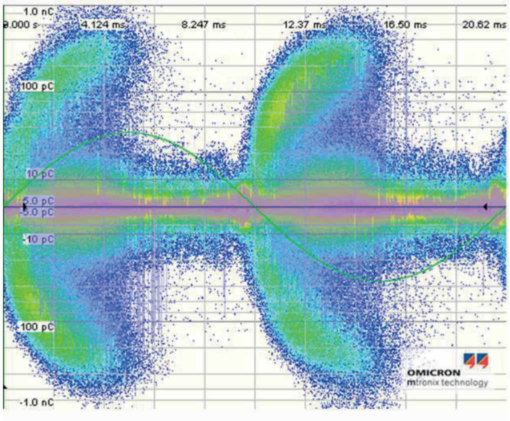

Fig. 12 PRPD pattern without 3CFRD filtering

PD measurement on a Dry-Type transformer

A second example for 3CFRD filtering is a measurement on a Dry-Type Epoxy transformer. Figure 14 shows the PRPD at app. 40kV. The noise is about 10pC. An analysis with the 3CFRD is shown in figure 15. The filtered signal (figure 16) shows a clear pattern of internal void discharges with 5pC, although the PD's are below the noise level.

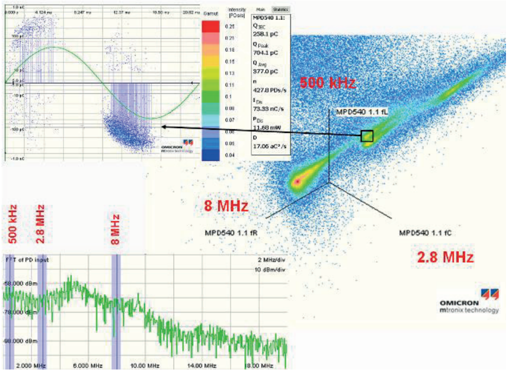

Fig. 13 PRPD of one PD source with 3CFRD filtering

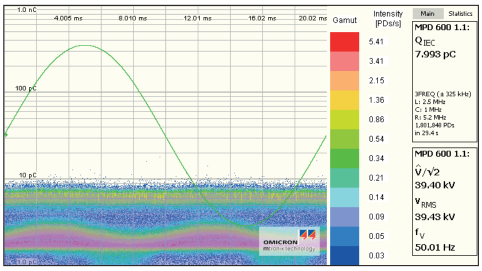

Fig. 14 PRPD of one PD source without 3CFRD filtering

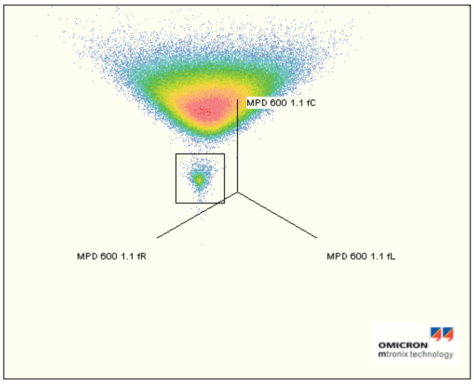

Fig. 15 3CFRD of the measurement in fig. 7

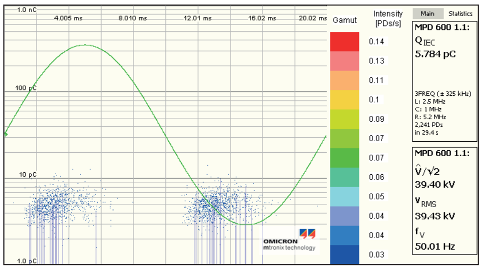

Fig. 16 PD pattern of voids with 3CFRD filtering

ACOUSTIC PD MEASUREMENT AND LOCATION

The main benefits of acoustic PD measurement are the possibility of localising the PD source with an accuracy of some ten centimetres. In case of an evidence for PD, the location of the potential PD source can be important to estimate the risk of a complete breakdown. The knowledge of PD location is also crucial for the assessment of the asset and the process of maintenance or repair. The acoustic signals are detected by several ultrasonic sensors on the tank wall of the transformer. The low level of electric interferences from outside the measurement setup constitutes one of the strengths of this method [13].

The propagation behaviour of acoustic PD signals in transformers

The acoustic response of PD inside a transformer is typically measured by piezoelectric sensors in the frequency range of some tens of kHz up to some hundreds of kHz.

Due to the resonant character of the sensors, the measured acoustic PD signal is inherent overlaid by oscillations as illustrated in Figure 17. For that reason the determination of the frequency content and proper signal form is difficult. Using the difference in arrival time of the acoustic PD signal at multiple sensors, algorithms compute the location of the PD source. The complex physical processes involved in sound propagation and the large structural differences between different transformers may be challenging during the measurement. The following parameters have to be considered:

- The PD source position and the inner structure of the transformer mainly influence the propagation path.
- More than one propagation path from source to the sensor is possible (direct oil, reflection, steel path).
- The speed of sound depends on the propagation path (crossed medium), the frequency and temperature.
- Depending on the position of the source and the inner structure of the transformer, direct oil paths propagation may prevent a proper measurement by attenuating the signal too much.
- The individual consideration of the measurement setup and the inner structure of the transformer are necessary, and a cautious interpretation of the measurement results by experienced persons is essential.

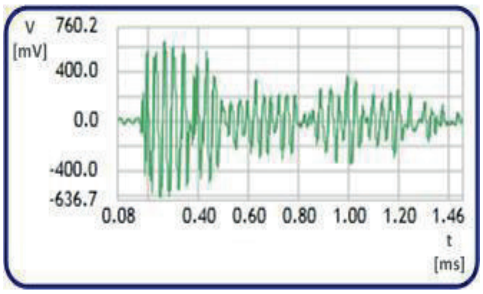

Fig. 17 *Acoustical signal from a partial discharge*

Figure 18 shows the variation of the velocity of sound in transformer oil for different temperatures. For example, the propagation speed decreases during the heat-up period of the transformer by approximately 15%, from about 1400 m/s at 20 °C to 1200 m/s at 80 degrees Celsius.

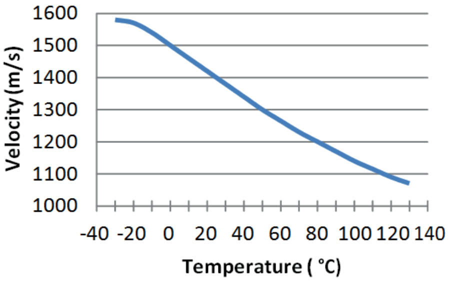

Fig. 18 *Dependency of the propagation speed in oil on temperature for 150 kHz*

The propagation path is often complex. According to Figure 19 multiple propagation paths of the emitted sound wave are possible. Depending on sensor and PD location, multiple acoustic wave components of the same PD event are potentially detected by one sensor and overlay the direct oil signal as illustrated in Figure 20. The acoustic wave can be reflected by the tank wall, core, winding, flux shields and other components.

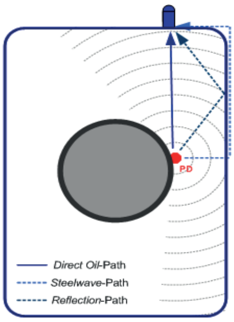

Fig. 19 *Propagation paths*

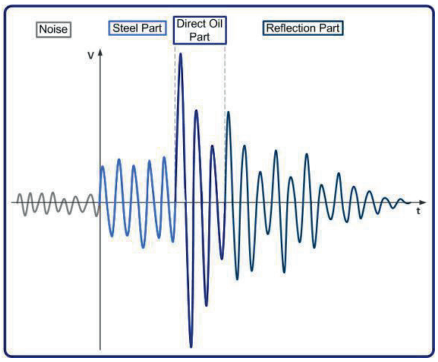

Fig. 20 *Acoustic PD signal components according to different propagation paths*

The measurable direct oil signal at the sensor position depends on the intensity of the PD event and on the damping in the propagation path. Therefore, the attenuation by core, winding, transformer board, flux shielding etc. should be as low as possible. For that reason, the search for sensor positions that ensure good signal quality is essential during measurement procedure. The knowledge about the inner structure of the transformer is helpful for a good positioning and repositioning of the sensors.

Localization of PD

Different algorithms can be used to perform a time-based localization of PD. The input information used by the algorithms is the time of arrival of the signals propagating on direct oil path wave at multiple sensors. The exact time of arrival has to be determined by evaluating the measured signal. A criterion for the starting point can be found e.g. by investigation of energy steps [14] or by threshold criteria.

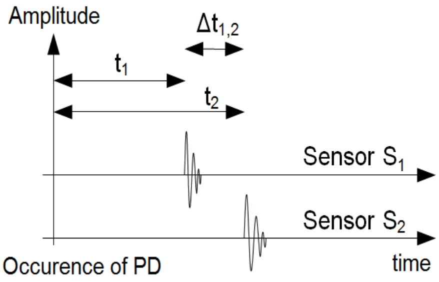

Fig. 21 Absolute and relative times in a two-sensor-setup

The relative arrival times at different sensor positions lead to time differences ($\Delta t_{1,2}$). These time lags are the only available data in all-acoustic measurements, when the data acquisition is triggered by the acoustic signal at one of the sensors. If the time delay between occurrence of a PD and the arrival of the associated acoustic wave is available, the absolute propagation times (t_1, t_2) from source to sensor can be used for localization (figure 21). The exact timing of the emission of the PD signal can be estimated e.g. by an electrical PD measurement according to IEC 60270 or a measurement in the ultra-high frequency (UHF) range. In the latter case, sensors within the transformer walls can be used to collect the high frequency electromagnetic wave that is emitted during PD. The principle and a measurement setup are shown in figures 22 and 23.

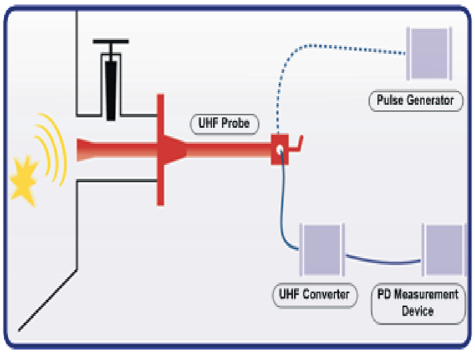

Fig. 22 *UHF sensor setup for triggering*

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Fig. 23 UHF sensor mounted on the main drain valve

The distance between sensor and source is calculated using the available absolute or relative propagation times and an assumptive average propagation speed. With the determined distances and the sensor positions a geometrical localization of the PD source can be performed in several steps. Another advantage of the UHF triggering is the possibility of using average out of many equally triggered signals to reduce the randomly occurring noise [13].

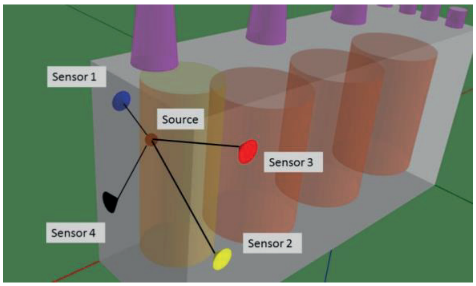


Fig. 24 Piezoelectric sensors on the tank wall

Case Study

A new transformer showed a strong increase of H_2 within a few weeks. The result of the acoustic PD location is shown in figures 24 and 25. An internal support of the tap changer was touching the OLTC compartment. This caused surface discharges which could be detected acoustically on the tank wall.

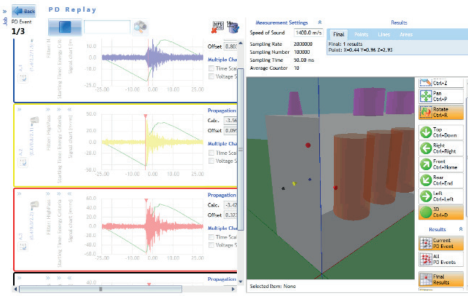


Fig. 25 Acoustic PD location with 4 microphones

ON-LINE MEASUREMENT OF PD, CAPACITANCE & DISSIPATION FACTOR AND TRANSIENT OVER_VOLTAGES ON HIGH VOLTAGE BUSHINGS

Some commercial C-tan δ systems are using the sum of the currents through C1 of the bushings of all phases to detect any abnormal changes in the capacitances C1 and the dielectric losses. The voltages of the three phases can be very unsymmetrical (figure 26). This makes it impossible to use this method for a sensitive monitoring of capacitances and losses of the bushings.

For a precise capacitance and tan δ measurement a reliable reference is needed. In high voltage laboratories pressured gas capacitors are well proven to give stable and precise results. In the literature air capacitors between the bushing head electrode and auxiliary electrodes are mentioned as reference.

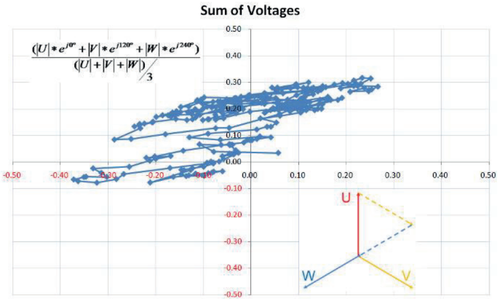


Fig. 26 Sum of the voltages in a 3 Phase 400kV system

Those capacitors have values in the order of a few picofarads. So the measured signals are extremely small compared to the received electromagnetic interference. A better choice is the use of voltage transformers or of bushings on other transformers which are directly connected to the same phase (figure 27).

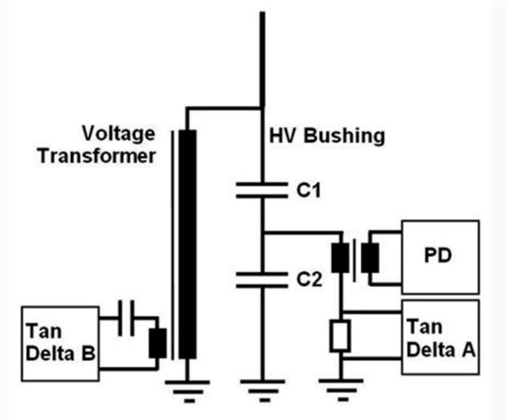


Fig. 27 *Voltage transformer as reference*

A pilot project was started on a three phase 400kV transformer, to gain experience with such a system. The system delivers very stable values. The capacitance values vary within +/- 0.5%. The tan δ differs from 0.27% to 0.3%.

The PD level is very much dependent on the outer interference and can go up to 5nC and even higher. So a warning level of some 100pC would lead to a lot of false alarms. It could be observed that within a certain period of e.g. 24 hours the PD level was reduced to values lower than 200-300pC. This phenomenon could be used for an automatic assessment. Additionally all the filtering methods of 3PARD and 3CFRD and the described UHF triggering can be used with success to eliminate the noise and enable online measurements.

Figure 28 shows the monitoring system MONTRANO mounted on an old transformer which showed a strong increase of H_2 (figure 29). The PD intensity measured with MONTRANO (figure 30) showed a good correlation to the PD measurement which was repeated with MPD 600 (figure 31). The fault could be located with the acoustic PD system PDL600 at the oil end of the 1V bushing (figures 32 and 33).

Fig. 28 *Bushing monitoring system MONTRANO*

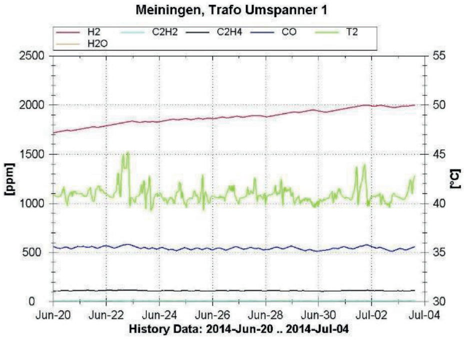


Fig. 29 *Gas development H_2 = red trace*

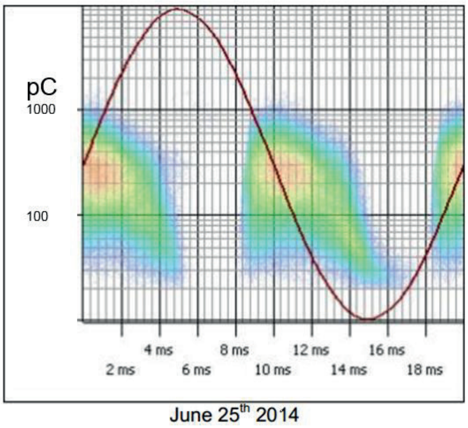
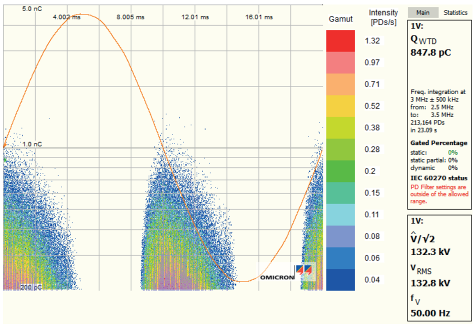


Fig. 30 *PD measurement with MONTRANO*



1V:
Q_{WTD}
847.8 pC

Freq. integration at 3 MHz ± 500 kHz
from: 2.5 MHz
to: 3.5 MHz
213,164 PDs
in 23.09 s

Gated Percentage
static: 0%
static partial: 0%
dynamic 0%

IEC 60270 status
PD Filter settings are outside of the allowed range.

1V:
$\hat{V}/\sqrt{2}$
132.3 kV
V_{RMS}
132.8 kV
f_V
50.00 Hz

Fig. 31 *On-site PD measurement with MPD600*

Fig. 32 *PD locator PDL600*

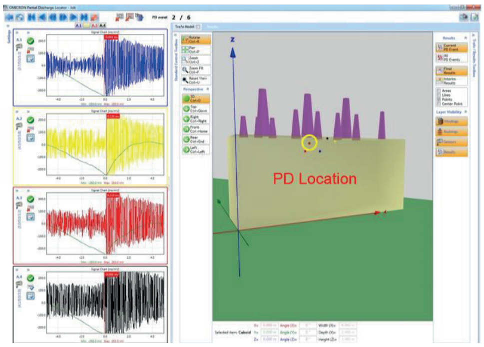


Fig. 33 *PD location with PDL600*

An additional interesting feature of MONTRANO is the monitoring of transient over-voltages at the bushings. The capacitance C1 of the bushing has a very small inductance and can be ideally used for the measurement of fast transient signals. Transient over-voltages can harm the bushings or the transformer windings and they deliver also interesting information about the other assets of the surrounding grid. Figure 34 shows an auto-reclosure of one phase. The transient voltage signal of channel L2 shows some irregularities during the switching process.

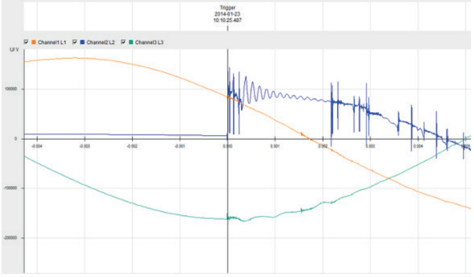


Fig. 34 *Transient voltage signals on transformer bushings – L2 (blue trace) after auto-reclosure*

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BIOGRAPHY

Michael Krüger is Principal Engineer at OMICRON electronics GmbH, Austria with special focus on testing and diagnosis of electric power equipment. He studied electrical engineering at the University of Aachen (RWTH) and the University of Kaiserslautern (Germany) and graduated in 1976 (Dipl.-Ing.). In 1990 he received the Dr. techn. from the University of Vienna. Michael Krüger has more than 35 years of experience in high voltage engineering and insulation diagnosis. He is member of VDE, Cigre and IEEE and works in several working groups of OEVE, IEC and Cigre.

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Fehlereingrenzung an Transformatoren mithilfe elektrischer Messverfahren

ZUSAMMENFASSUNG

Mit zunehmendem Alter eines Leistungstransformators wird eine regelmäßige Kontrolle der Betriebs-tüchtigkeit immer wichtiger. Die Gas-in-Öl-Analyse ist eine erprobte und aussagefähige Methode. Wenn beispielsweise erhöhte Werte für Wasserstoff und Kohlenwasserstoffgase im Öl detektiert werden, müssen Fehlerursachen gesucht und der Fehler sobald wie möglich gefunden werden. Um derartige Fehler herauszufinden und zu lokalisieren werden zahlreiche verschiedene elektrische Messmethoden angewandt. Gebräuchliche Methoden sind: statische und dynamische Messung der Wicklungswiderstände zur Stufenschalterdiagnose und zum Auffinden von Kontaktproblemen, Übersetzungsmessungen, Messung der Magnetisierungsströme, die Messung der Kurzschlussimpedanzen und der Streuverluste (FRSL) und die Messung von Kapazitäten und Verlustfaktoren. Neuartige Messverfahren wie die Frequency Response Analyse FRA, dielektrische Antwortmessungen mit FDS und PDC und Teilentladungsmessungen mit modernen synchronen Mehrkanalsystemen ermöglichen eine detailliertere Diagnostik an Transformatoren. Teilentladungsmessungen an Transformatoren waren in der Vergangenheit nur in geschirmten Prüffeldern sinnvoll möglich, z.B. beim Hersteller während der Endprüfung. Moderne digitale Messtechnik und neue Verfahren und Algorithmen haben es möglich gemacht, Teilentladungen (TE) auch vor Ort mit ausreichender Empfindlichkeit und Störunterdrückung zu messen und zu orten. Als wichtige Werkzeuge sind dabei die 3-Phase-Relation-Diagram-Filterung (3PARD) und die 3-Centre-Frequency-Relation-Diagram-Filterung (3CFRD) zu nennen. Auch die Triggerung von akustisch gemessenen Signalen durch elektrische Signale von den Durchführungen oder von den UHF Signalen, die mit speziellen Sonden aus dem Tank ausgekoppelt werden, haben neue Möglichkeiten geschaffen. Die digitale Messtechnik hat es auch ermöglicht, on-line Verlustfaktormessungen und die Messung schneller transienter Überspannungen zu integrieren.

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