

## **Möglichkeiten und Grenzen der vor-Ort Teilentladungsmesstechnik**

### **Prospects and Limits of on-site PD Measurement Technique**

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#### **Zusammenfassung**

Zur Überprüfung und Diagnose der Isolationsqualität hochspannungstechnischer Geräte wird die Messung von Teilentladungen (TE) durchgeführt. Der Beitrag beschreibt Möglichkeiten und Grenzen bei der vor-Ort TE Messung und TE Ortung, die sich durch die Anwendung und Kombination verschiedener TE-Messmethoden ergeben.

Bei Anwendung der konventionellen Teilentladungsmessung nach IEC60270 kann das Messergebnis durch den hohen Störpegel im Feld nur beschränkt aussagekräftig oder unter Umständen gar nicht brauchbar sein, insbesondere bei on-line Messungen. Die im Beitrag vorgestellte Mehrstellen TE Messung ermöglicht durch das STAR-Diagramm eine vorteilhafte Unterscheidung zwischen verschiedenen TE Quellen und einer Unterdrückung von externen Störungen.

Die UHF Messmethode, als unkonventionelle Messmethode auf Basis elektromagnetischer Sensoren wird vorgestellt. Diese Sensoren werden über einen normalerweise zur Ölbefüllung benutzten Flachkeilschieber bei laufendem Betrieb in den Transformator eingeführt. Durch die Schirmungseigenschaften des Transformatorbessels sind externe elektromagnetische Störungen minimiert und ermöglichen Messungen mit hohem Störabstand, insbesondere bei on-line Messungen. Starke Sender, wie z.B. Mobilfunkstationen, Funkgeräte oder Handys in direkter Nähe zum UHF Messequipment können jedoch die Messungen stören und erfordern mitunter eine individuelle Entscheidung, ob es sich um Teilentladungsimpulse handelt. Ein Nachteil der UHF Messmethode ist die fehlende Möglichkeit zur Kalibrierung im Sinne scheinbarer Ladung, oder ein Nachweis ihrer Empfindlichkeit in Bezug zur IEC 60270 konformen Messung. Ein durchführbarer Funktionstest der Sensoren erlaubt keinen Rückschluss auf die tatsächlich zu erzielende Empfindlichkeit, da die elektromagnetischen Wellen abhängig von ihren Ausbreitungswegen zum Sensor eine i. A. unbekannte Dämpfung erfahren.

Die akustische TE Messung mit piezo-elektrischen Sensoren eignet sich zur laufzeitbasierten Ortung von TE, da die Positionierung ausreichend vieler Sensoren an der Kesselwand in der Regel möglich ist. Allerdings können akustische Sensoren auch empfindlich sein für externe und interne Störquellen wie Koronaentladungen und Kerngeräuschen. Alleinige akustische Überwachungen von Transformatoren ist vor-Ort daher nicht vorteilhaft und bedarf einer empfindlicheren Messmethode zur Detektion der TE. Zur Laufzeitbestimmung von akustischen TE Signalen ist zusätzlich eine Entrauschung notwendig, die im Beitrag durch die Mittelwertbildung der akustischen Signale erreicht und vorgestellt wird. Die Mittelwertbildung basiert hier auf der Triggerung der akustischen Messung durch z.B. UHF Signale. Die akustische TE-Messung stößt in einfacher Form an ihre Grenzen, sofern in einem Transformator mehr als eine TE Quelle detektierbar ist, die TE Quellen im Inneren von Wicklungen positioniert sind oder

wenn innerhalb der vorgegebenen und oft beschränkten Zeit keine Sensorpositionen mit messbaren akustischen Signalen am Kessel gefunden werden können.

Laufzeitunterschiede zwischen Signalen verschiedener Sensoren können sowohl im akustischen wie auch UHF Frequenzbereich zur geometrischen Lokalisierung gemessen werden. Die hier erzielte Genauigkeit bei Verwendung von zwei UHF Sensoren ist ausreichend, um die betroffene Phase zu bestimmen. Da Transformatoren in der Regel nicht mehr als 3 Flachkeilschieber besitzen, sind weiterhin akustische Sensoren notwendig. Die Auswertung der UHF Laufzeiten hilft, die akustischen Sensoren an viel versprechenden Orten an der Kesselwand in der Nähe der TE zu platzieren. Im Beitrag wird ein so entstandenes Ortungsergebnis vorgestellt, das durch eine optische Aktivteilinspektion bestätigt wurde.

Ein weiterer Versuch einer UHF-Akustischen Ortung im Prüffeld scheiterte daran, dass trotz messbarer IEC TE Impulse keine UHF Signale messbar waren. Somit liefert auch die UHF Messmethode mit Ölschiebersensoren abhängig vom inneren Aufbau des Transformators nicht immer eine sichere Aussage über die TE Aktivität eines Prüfobjektes.

## **Abstract**

The paper presents prospects and limits using a combination of different partial discharge (PD) measurement methods both to detect PD in power transformers and to improve interpretation and localisation of their sources.

The use of the conventional PD measurement method according to IEC 60270 has to deal with certain drawbacks like ambient noise on-site or corona discharge when performed on-line. The multi-terminal PD measurement is illustrated here using STAR diagrams for discrimination between different PD sources. Several different PD sources in different phase windings during an off-line measurement on a power transformer were detected and the UHF method confirmed these results and conclusion.

The UHF PD measurement method is usable as single measurement and as a supporting measurement for off- and on-line PD detection. Fundamental knowledge of the PD phenomena is needed for interpretation of measuring results, comparable to knowledge of the lower frequency IEC 60270 measurements. UHF probes are easily installable and useable. The sensitivity of UHF PD measurements is sufficient and normally is not affected by external disturbances. Especially in noisy surrounding it might be a very helpful method to support other PD measurement techniques for example dissolved gas analysis and acoustic localisation of PD. In case of powerful transmitter within the UHF range, e.g. mobiles, mobile communication station or radio sets, UHF PD measurements might be affected and Signals have to be evaluated, if correlating to PD or not. Nevertheless in frequency domain a simple differentiation between natural broad-band PD spectra and the above mentioned noises is possible since the noises are generally narrow-banded modulated carrier signals.

UHF oil filling valves are often electro magnetically shielded from the internal tank by tubes for directing the oil flow. Sensitive UHF measurements are in some cases still possible, and additionally broadband amplifiers can be used for measuring UHF signals sensitively. But the UHF method misses the possibility of a calibration because electro-magnetic UHF waves are attenuated by internal structures according to their travelling paths to the sensor. Thus the sensitivity of UHF measurements can't be determined in terms of pC. Normally a clear decision can be made concerning the PD activity of a test object but the paper presents an example of an off-site measurement in a test field where no UHF signals were detectable whereas IEC and acoustic method confirmed PD activity.

Run times measured in the UHF range can be used for geometrical PD localisation. The accuracy with e.g. two UHF sensors seems to be adequate to determine the phase where the PD is located. Additionally, different measurable UHF amplitudes support an estimation of the PD location. However, since transformers rarely offer more than three UHF oil valves, an additional acoustic measurement method is usually required for localisation. Using the knowledge gained from the UHF sensors, acoustic sensors can be placed near to the PD source at the transformer tank. During an on-line measurement a PD source localisation was performed with the help of measured UHF run times and acoustic run times.

# 1 INTRODUCTION

The reliability of electrical energy networks depends on the quality and availability of primary electrical equipment such as the power transformer. Localised internal insulation failures can, however, lead to catastrophic breakdowns and incur high outage and penalty costs. To reduce such risks it is normal for power transformers to have passed a range of factory tests including one for partial discharge (PD) activity before acceptance and commissioning. Once installed it is costly to energise with e.g. induced test voltage or resonant sets, and the results are often restricted by high site interference. Many users then rely on integrated detection methods such the use of dissolved gases in the oils. However, this need not be the case. The UHF, acoustic and multi-terminal PD measurement methods are using different physical peculiarities of the PD phenomenon, e.g. electric currents according to IEC 60270 [1], electromagnetic waves (UHF-range) and acoustic radiation.

The electrical PD-measurement set-up according to IEC 60270 usually has sensitivity limitations for on-site/on-line measurements because of the noise level in field. Due to the existing coupling of the three phases in a transformer, single partial discharge pulses in one certain phase can also be measured as cross coupling signals in all phases. Evaluation of multi-terminal PD measurements establishes an approach to clearly distinguish between multiple PD sources and to remove external disturbances [2].

The so called “UHF PD measuring method” (UHF: Ultra High Frequency) is based on the facts that PD under oil are very fast electrical processes and radiate electromagnetic waves with frequencies up to the ultrahigh range (UHF: 300 – 3000 MHz). Due to the moderately attenuated propagation of UHF waves inside the transformer tank, the electromagnetic waves are detectable sensitively [3]. UHF probes [4] can be inserted into the transformer during full operation through the oil filling valve. As a result of shielding characteristics of the transformer tank against external electromagnetic waves, normally a clear decision can be made concerning the PD activity of the test object.

When electrical or UHF PD measurements confirm PD activity, a three dimensional localisation of PD sources is the next step for risk evaluation of PD phenomena. With three space coordinates and a time dimension relating to a single PD event, the number of unknowns’ requires four sensors for arrival time measurements and location. UHF technology offers this possibility but access for most designs is normally limited to 3 sensors or less. Because there is no limit in the number of piezo-electric acoustic sensors that can be mounted on transformer tanks, the acoustic measurements remains attractive for localization purposes. However, acoustic sensors are normally more sensitive to external disturbances than to the internal PD originated sound waves. They are also affected by distortion within the tank from the winding core and support structures in the transit path which influences partly can be eliminated with appropriate signal processing afterwards. The compromise is therefore, to use a combination of the two methods, using sensitive UHF signals to provide triggering and by using averaging [5] of acoustic signals for de-noising.

# 2 COMPARISON OF MULTI-TERMINAL PD MEASUREMENT AND UHF PD MEASUREMENT

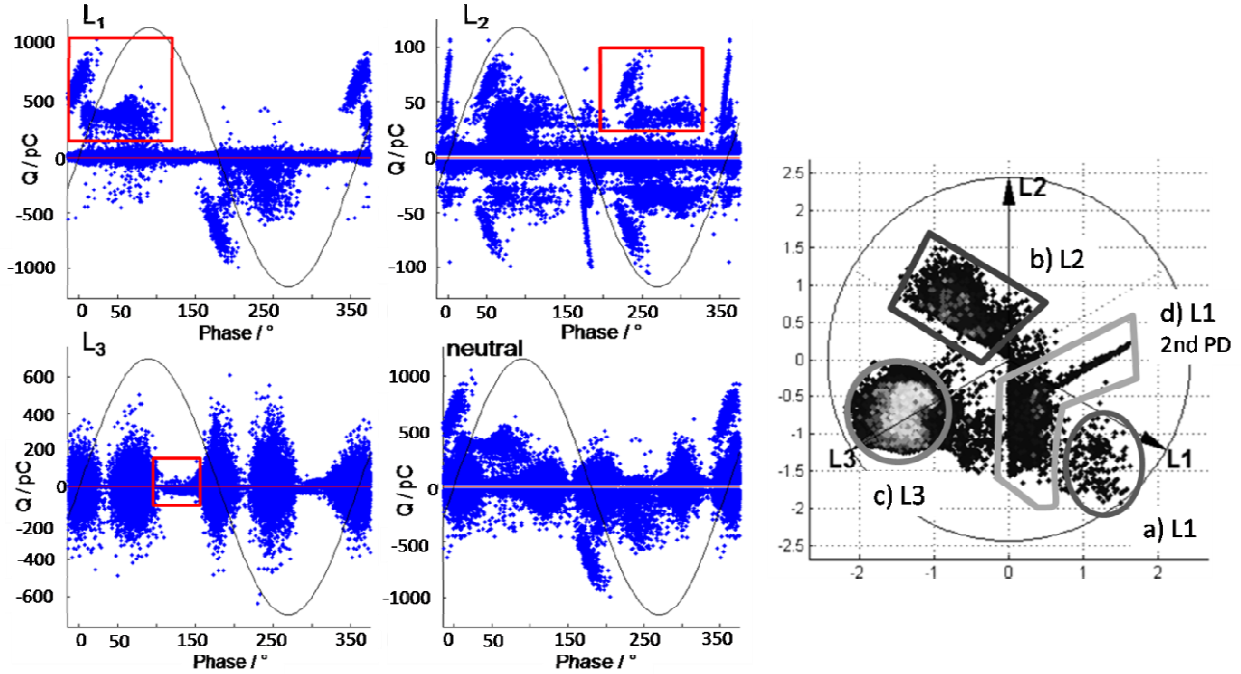
On-site multi-terminal electric and UHF PD measurements were made on a generator step-up transformer 110/10 kV, 120 MVA, see Figure 1. This on-site measurement was performed with the transformer off-line and energised using a three-phase PD free generator unit (110 kVA) to minimize the influence of the external disturbances. The transformer was excited via the 10 kV windings.



**Figure 1: UHF probes installed at a 120 MVA generator step-up transformer**

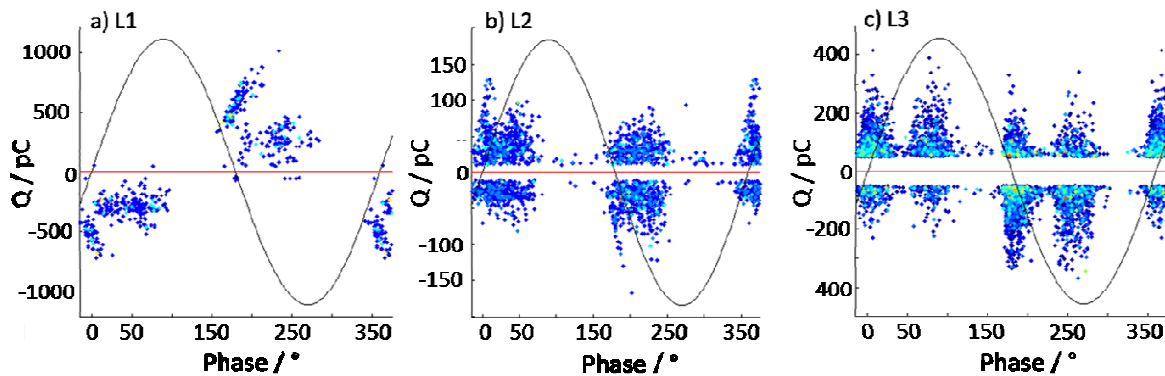
## 2.1 Multi-terminal PD measurement

The calibration of the measurement arrangement in terms of apparent charge was done separately for all three measurement devices with a defined calibrator impulse. The multi-terminal measurements were performed with PD Smart from Doble Lemke and mpd540 from Omicron [7]. Results of the measurements at the 110 kV side are shown in Figure 2.



**Figure 2: PRPD pattern of the transformer on phase L<sub>1</sub>, L<sub>2</sub>, L<sub>3</sub> and the neutral; STAR-diagram with four clusters: a) L<sub>1</sub>, b) L<sub>2</sub>, c) L<sub>3</sub>, d) L<sub>1</sub>-2nd PD**

On the left hand side the upper diagrams show the PRPD pattern of phase L<sub>1</sub> (left) and L<sub>2</sub> (right) and the lower diagrams present the PRPD of phase L<sub>3</sub> (left) and the neutral (right). The rectangles show the PD in L<sub>1</sub> and the respective coupling on phase L<sub>2</sub> and L<sub>3</sub>. The measurement on the neutral is a good method for comparing the UHF PRPD pattern (see Figure 5) with the multi-terminal PD pattern because all internal PDs are shown in one diagram in different magnitudes. By means of the STAR-diagram, see Figure 2 (right), four different PD sources can be distinguished, one in phase L<sub>2</sub>, one in phase L<sub>3</sub> and two in phase L<sub>1</sub>. The reverse transformations of each cluster confirm the four PD sources. The pictures in Figure 3 are the clusters of the PD sources in L<sub>1</sub> (a), L<sub>2</sub> (b) and L<sub>3</sub> (c). The pattern of phase L<sub>2</sub> could be a void in oil. The PD source of L<sub>1</sub> with the maximum of 1000 pC was the highest detectable value and occurred after some minutes during the measurement also showing characteristics of void PD pattern. The PD source in L<sub>3</sub> was the first occurring signal at 40 kV. The level of the PD increased with increasing voltage showing cross-coupling from PD of other phases.

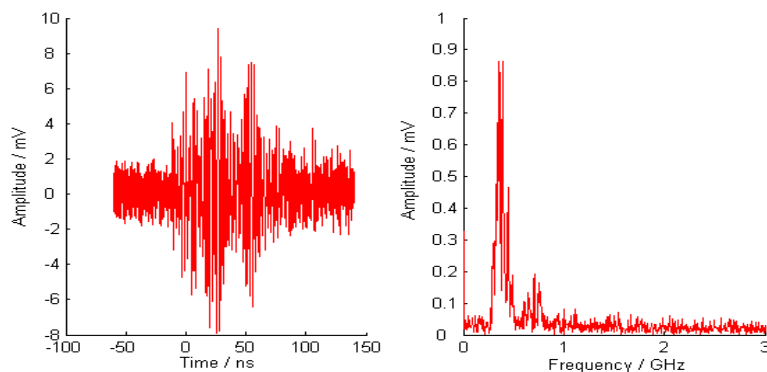


**Figure 3: PRPD pattern of the generator step-up transformer after retransformation of the clusters in the STAR-diagram in Figure 2: a) L<sub>1</sub>, b) L<sub>2</sub> and c) L<sub>3</sub>**

## 2.2 UHF PD measurement

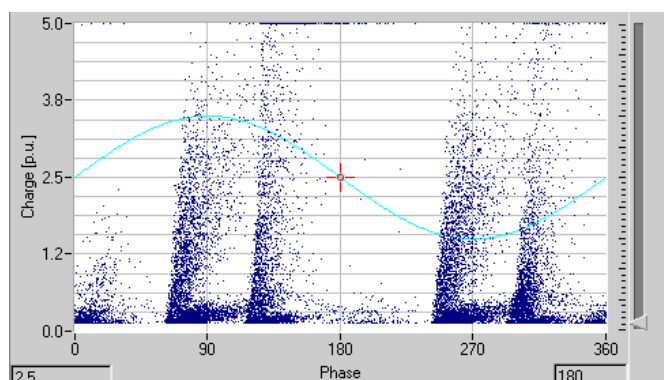
The transformer possesses two oil filling valves, see Figure 1. The first valve is underneath the tap changer housing at the same height as the lower yoke. The second valve is on the opposite side underneath the oil expansion tank in the cover of the transformer.

The first measurement, a so-called dual port Performance Check [6], demonstrates the sensitivity of the measuring system. Wide-band signals of a signal generator were fed over the first UHF sensor into the transformer tank and measured with the second UHF sensor. Figure 4 represents the received time signal and its transformation in the frequency domain. During this measurement the transformer was not excited.



**Figure 4: Dual port Performance Check**

From the illustration it is evident that a wide-band signal (right, frequency portions up to 1 GHz) was travelling through the transformer and its active part. Likewise the signal-to-noise ratio is sufficient in the time signal (left). Therefore the sensors have been shown to be correctly installed and attached to the measuring instruments and a sensitive UHF measurement is possible. During the measurements with energisation UHF signals were measured with both probes. Run time differences allow a localisation of the PD source with additional analysis [7]. The measurable UHF PD events of sensor 1 were synchronised to phase  $L_3$  of the AC test voltage and stored for a period of three minutes, see Figure 5.



**Figure 5: UHF PRPD-pattern of 120 MVA Generator Step-up Transformer – 3 min**

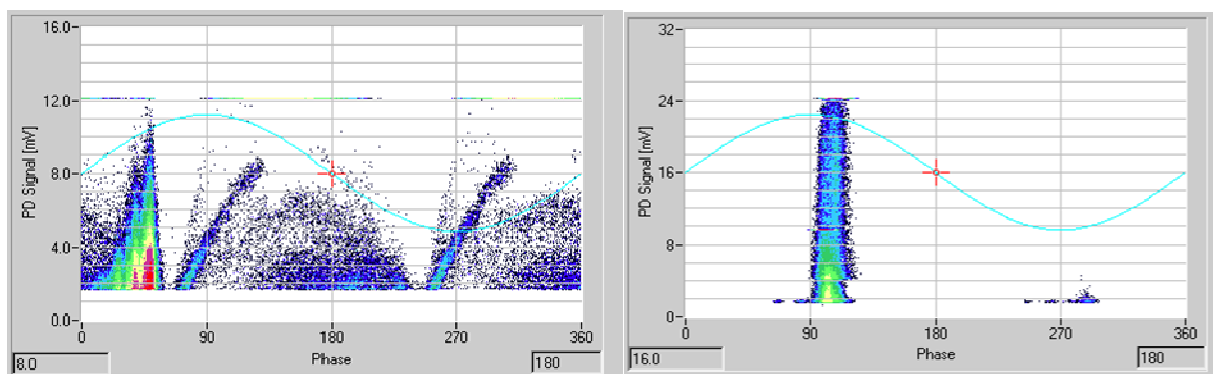
The resulting pattern shows an overlap of the internal PD activity on the phases. The comparison of the UHF PD data with IEC conform measured data reveals comparable patterns as seen in Figure 2.

## 2.3 Acoustic Measurements

Because of runtime information of the two UHF sensors and due to the availability of a sensitive trigger event for PD by UHF signals, an acoustic measurement was performed off-line. The IEC measurements and the arrival time information of the UHF signals allowed a rough localisation of the PD sources. Due to that rough localisation the acoustic sensors were installed at corresponding locations at the transformer tank, but no single acoustic signals were detectable. Due to the fact, that more than one PD source is active in the transformer the de-noising method of averaging acoustic signals with UHF trigger (described in next chapter of this contribution) was not applicable, because of possibly interfering acoustic signals of different sources which didn't overlay constructively.

## 2.4 Partial Discharge Monitoring

The operation of the generator step-up transformer is monitored regarding the occurrence of PD by means of UHF measurements (LDS6/UHF) and measurement of the hydrogen concentration in oil (Hydran sensor). Additionally different information like top oil temperature, ambient temperature and transformer load are monitored for cross correlation purposes which might allow a deeper understanding of the PD effect in that transformer. In Figure 6 two examples of phase resolved UHF PD patterns are shown which are measured both for a time interval of one hour. They are measured with approx. 35 dB amplified UHF signals of sensor 1 with a bandwidth of 9 MHz at a centre frequency of 505 Mhz.



**Figure 6: UHF PD Patterns (PRPD) measured by means of online PD monitoring system**

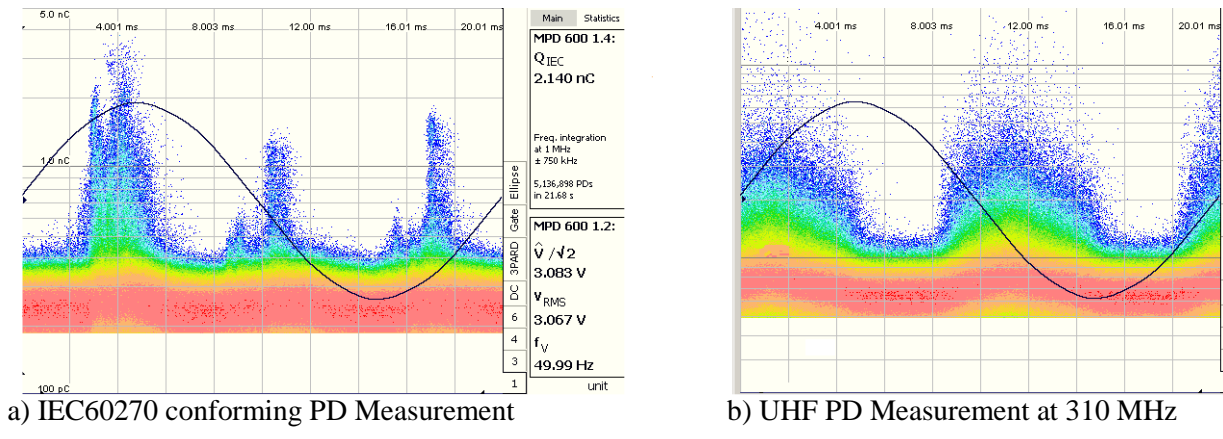
The shape of the patterns differ, e.g. the activity during the negative half cycle is missing and the strongest activity is shifted from approx.  $60^\circ$  to  $100^\circ$ . Additionally the maximum amplitude of UHF signals increased from 12 mV to 24 mV. Normally the measured pattern looks like the pattern in Figure 6 left. The higher amplitudes like in Figure 6 right were just measurable for approx. four hours and were followed by a strong increase of the hydrogen concentration in oil. But experience in UHF PD pattern analysis is yet very limited and will be the aim of future research activities.

## 3 CASE STUDY ON PD LOCALISATION WITH COMBINED UHF AND ACOUSTIC MEASUREMENTS ON GRID CONNECTED 333 MVA TRANSFORMER

Because of increasing gas-in-oil values, a 333 MVA grid coupled single-phase autotransformer was tested on-site on-line for PD. The high noise level at site strongly disturbed the conventional PD measurements made according to IEC 60270 at sub 1 MHz frequencies. Consequently, UHF PD measurements for PD detection in combination with acoustic measurements for PD localisation were performed in order to get reliable results. By means of several PD decoupling ports for IEC 60270 measurements a multi-terminal PD measurement was performed. Thus external disturbances like corona should be measured on all terminals with similar pulse shape and amplitude and it should be possible to distinguish between multiple PD sources and external noise by means of the respective STAR diagram [7]. But in this case the 400 kV bus bar above the transformer disturbed the multi-terminal measurement so much that the STAR diagram delivered no feasible results.

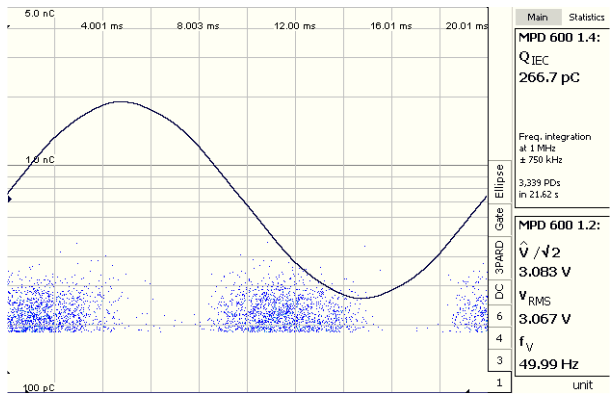
A lower frequency IEC 60270 measured PRPD-pattern is shown in Figure 7 (a). The external disturbing corona discharges with the phase shift of  $120^\circ$  of the three different phases become visible in the pattern with a level above 2000 pC. Internal UHF probes uses the tank wall as shielding against external disturbances and Figure 6 (b) shows the pattern of one internal UHF sensor. According to this pattern only one internal PD source can be identified. The  $120^\circ$  shifted disturbances are no longer detected. Due to the missing possibility of UHF calibration no PD quantity in terms of pC can be given.

Using the UHF signals of internal PDs as a trigger or in other words gating signal for the IEC method, the PD measurement leads to the pattern of Figure 7 (c). The combination technique is called “Gating” or “Windowing” [5] and allows an estimation of the apparent charge of only the internal PD in case of heavy external disturbances. For the internal PD the apparent charge might be estimated to be at about 300 pC. Compared to Figure 7 (a) with disturbances of around 2000 pC the sensitivity of IEC measurements is improved by means of the UHF signal significantly.



a) IEC60270 conforming PD Measurement

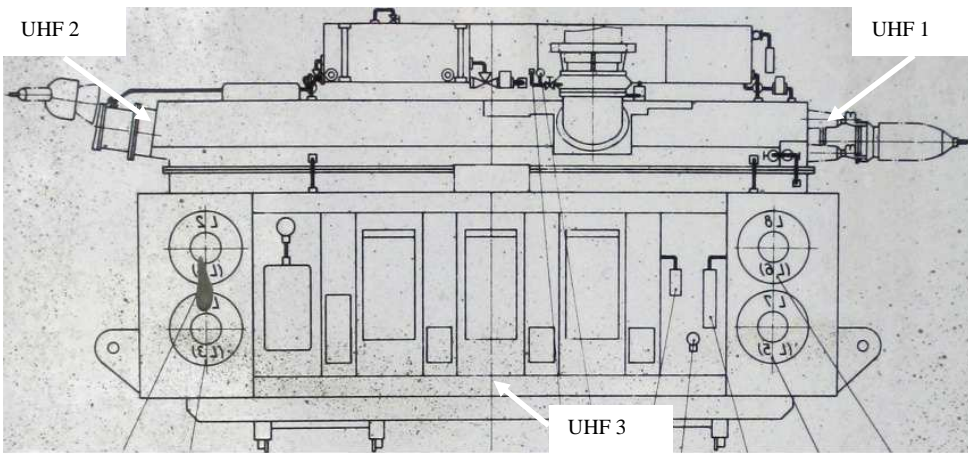
b) UHF PD Measurement at 310 MHz



c) Windowing or Gating of IEC measurements by UHF signals

**Figure 7: Gating of IEC measurements by UHF signals at 333 MVA transformer**

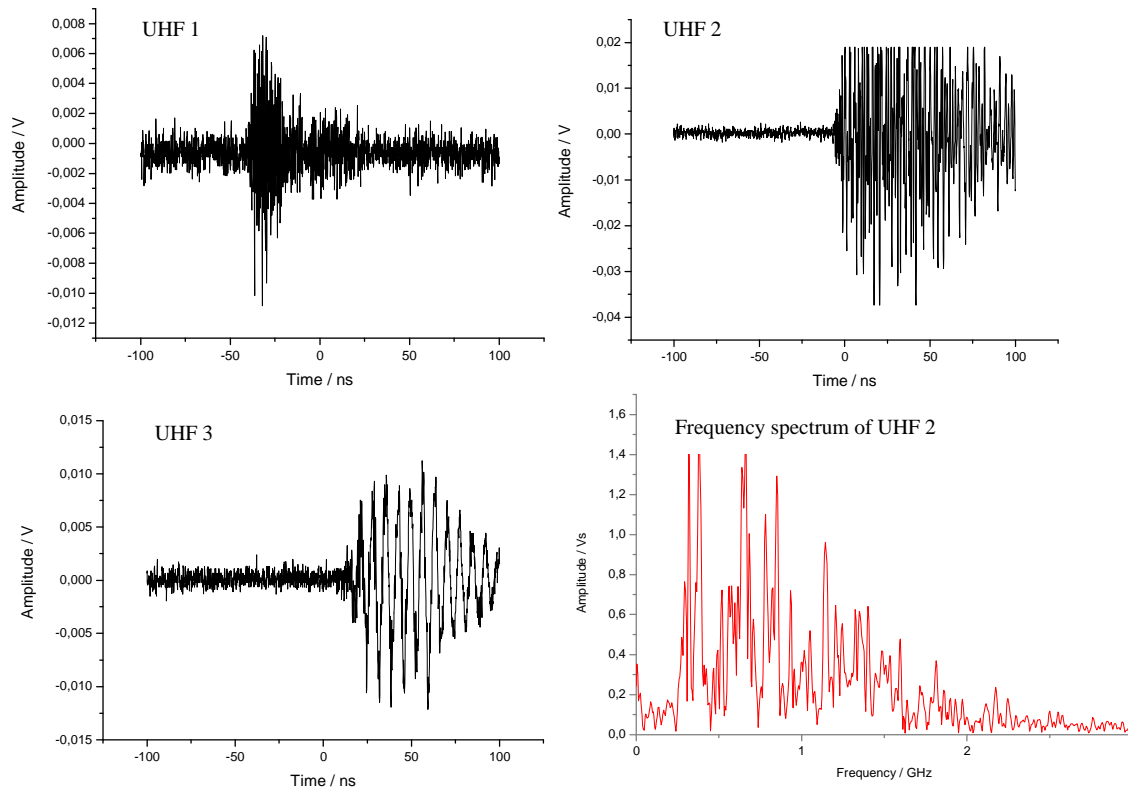
In this case the transformer possessed three oil filling valves and three identical UHF Sensors were installed. Figure 8 shows the positions of the UHF probes (UHF 1 – UHF 3). Two probes are opposite each other at the top of both front ends of the tank and the third (UHF 3) is located at the bottom in the middle of the transformer side, see Figure 8.



**Figure 8: Positions of UHF Probes at 333 MVA single phase autotransformer**

First, the so called dual port Performance Check was done, compare to paragraph 2. Artificial UHF impulses were injected at each probe with a signal generator (60 V at 50 Ω). It was not possible to detect the artificial impulses at any combination of emitting and receiving probe. The explanation by the transformer manufacturer was that there are tubes behind the oil filling valves directing the oil flow around the winding. According to the unsuccessful dual port Performance Check it could be stated, that the probes are electro magnetically decoupled from each other. Furthermore they might be also shielded against UHF pulses from internal PD.

But nevertheless, at nominal voltage, UHF signals from internal sources were detectable with all three probes. I.e. the internal PD cause UHF signals with higher energy content than the former artificial impulses. It can be concluded that the dual port Performance Check is thus just a worst-case estimation of the sensitivity. But in case the Performance Check is not successful, sensitive UHF measurements might still be possible. In Figure 9 the measured signals of the UHF probes are shown, measured without amplification.



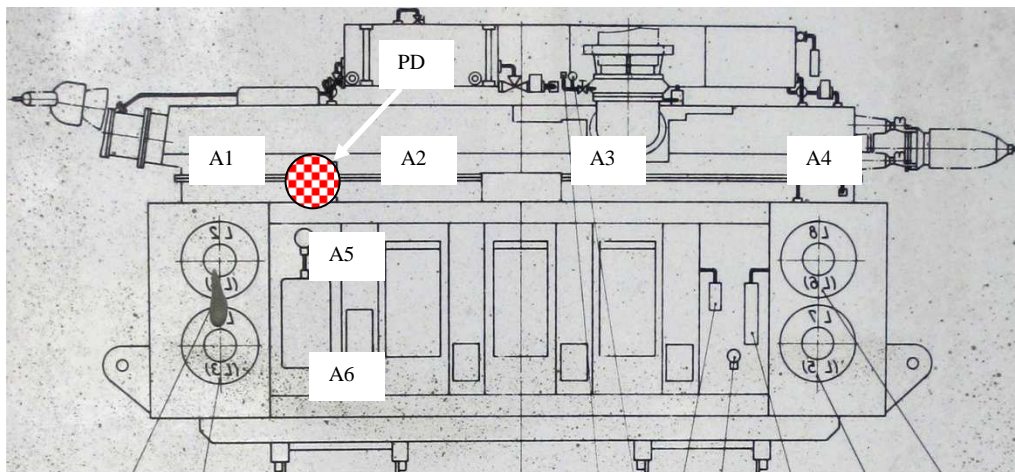
**Figure 9: Measured run time differences between three UHF probes at different locations and Frequency spectrum of signal of probe “UHF 2” to prove broad-band emission**

Recognizable are run time differences in the range of nano seconds (ns) between the signals. Taking run time differences caused by different lengths of measuring lines into account, a first estimation of the geometric PD location led to the tap changer. That is supported by the measured UHF amplitudes of the three UHF probes. The probe nearest to the tap changer (probe UHF 2) has the highest reading output with over 40 mV, whereas the other probes did not reach more than 10 mV. According to that, probe UHF 2 was used for triggering and determining the starting time for measuring run time differences. Simultaneous IEC 60270 measurements were highly disturbed by audible corona discharges. Additionally to the presented “Gating” method in Figure 7, frequency analyses and phase related UHF PD patterns confirmed that the UHF measurements are not affected by the external corona discharge. An exemplary frequency analysis of the measured signal of probe UHF 2 proofed the shielding characteristic of the tank; see Figure 9 (bottom right). The signal features frequency content up to 2 GHz, as emitted by a broad band emitter of UHF waves like internal PD in oil. External disturbing sources would have been narrow banded, e.g. at around 500 MHz for digital video broadcasting or around 900 MHz or 1800 MHz for GSM (global system for mobile communications) since there are modulated carriers often. For further proof that the signals correlate to PD, PRPD’s of the signals were recorded, synchronized to the voltage supply of the measuring unit (LDS6/UHF). Similar to the IEC 60270 PD measurements typical patterns were visible, comparable to Figure 5. Phase stable UHF pulses showed correlation to internal PD.

PD also produces acoustic waves, which are measured with piezo-electric sensors installed at the outside tank wall. Their measurable frequency range is between 50 and 200 kHz. Due to comparatively high acoustic signal attenuation within the solid and liquid insulation material and structures inside the transformer sensitive acoustic measurement are sometimes hard to achieve [8]. Additionally acoustic signals of PD might be covered by ambient mechanical noise and inherent noises within the transformer (core noise). Summarising, exclusive acoustic PD measurement or on-line monitoring is only useful to a



limited extent. To increase the sensitivity of acoustic measurements the method is combined with the more sensitive UHF measuring method. UHF signals are used as trigger signals in order to activate the acoustic measurement during the occurrence of UHF PD signals. By using averaged signals (averaging in time domain, here approx. 100 times), the 60 dB amplified acoustic PD pulses remain constructively overlapped whereas the white background noise is averaged to zero. Figure 10 shows the positions of the used acoustic sensors (A1 – A6).



**Figure 10: Position of acoustic sensors and localised PD source**

The UHF measuring method is based on electromagnetic waves, which spread with approximately two-thirds of speed of light inside the transformer. Thus for localisation UHF signals are detected almost the same time PDs occur. Conversely, the speed of acoustic waves is 1400 m/s, producing transit times within the range of milliseconds. Geometrical distances between sensors and the source of PD (calculated from the run times of the individual acoustic sensors) result in a spherical area inside the transformer. With at least three acoustic sensors and corresponding run times, it is possible to calculate the intersection of the spheres and thus to determine the PD location. It must be assumed that the acoustic waves travel directly in the line of sight from the PD source through the oil and through the steel tank to the sensor without any reflections. But furthermore the location process has also to deal with acoustic waves travelling faster in the tank wall than in the oil. The run times of the acoustic signals can be computed objectively with the help of the Hinkley criterion [5, 8]. It is based on the signal energy of the measured signal and results in an absolute minimum for the starting point of the signal.

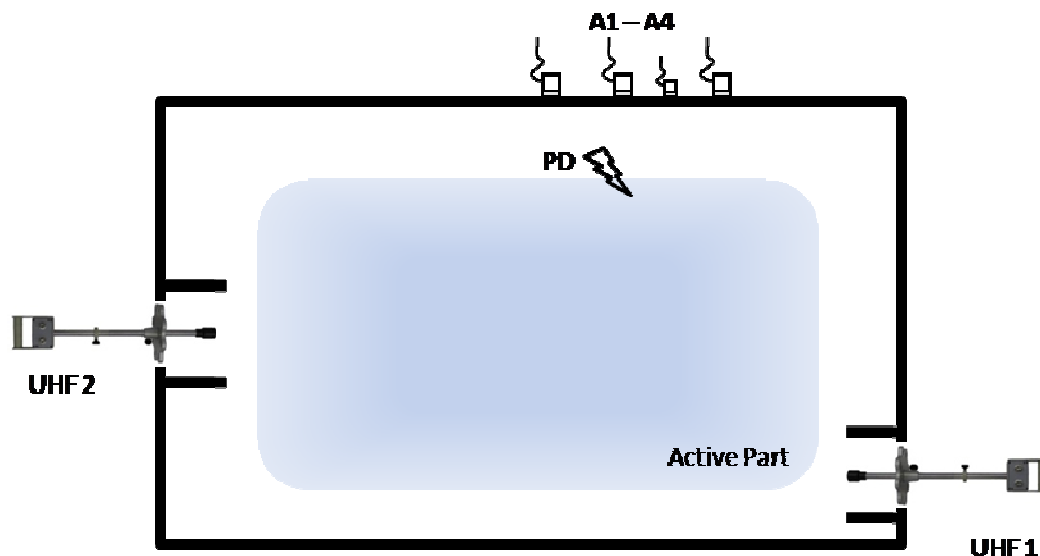
As illustrated in Figure 10, the supposed position of the PD source is in the vicinity of the tap changer. Geometrical inaccuracy is thereby within the range of approx. 40 cm on all space axes. This inaccuracy is caused by using different combinations of run time differences and different localisation methods [5]. The different run time differences was measured with six different sensors which are the three UHF Sensors (UHF 1 – UHF 3) and the three acoustic sensors placed near to the PD source (A2, A5, A6).

After transportation of the transformer to the manufacturer the localisation result was proofed by an IEC triggered acoustic measurement in test field and the transformer was detanked for repair. The optical inspection of the active parts at the tap changer confirmed the localisation results.

#### **4 PD LOCALISATION WITH COMBINED IEC60270 AND ACOUSTIC MEASUREMENTS ON HVDC TRANSFORMER IN TEST FACILITY**

During an acceptance test inside a test facility a 320 MVA HVDC transformer was tested on PD. IEC 60270 measurements detected PD with an apparent charge of approx. 1500 pC. For localisation purposes acoustic measurements were performed with averaged signals triggered by IEC conform measured PD signals. Combined UHF and acoustic measurements were performed in order to confirm the localisation of the PD. The transformer offers two oil-valves for application of a UHF sensor. After installation of the two sensors according to Figure 11 a Performance Check was performed, according to paragraph 2.2. It was not possible to detect a signal originating from the second sensor acting as source, i.e. the sensors are electro-magnetically decoupled from each other. The manufacturer confirmed that there are tubes behind the oil filling valves for directing the oil flow (illustrated schematically in Figure 11). These tubes shield the UHF oil valves sensors and reduce their receptiveness for internal PD UHF signals.

After energisation of the transformer, PD signals were measurable with IEC60270 conform measurements but no UHF signals were detectable within the UHF range. But again the PD localisation was confirmed by different acoustic measurement equipment with the use of the still available electrical trigger. The localisation led to a PD position at the bottom of the transformer active part near to the tank wall; see top view of transformer in Figure 11.



**Figure 11: Topview - UHF and acoustic set-up with localised PD at 320 MVA HVDC transformer**

The UHF measurements were carried out as broad-banded measurements, 50 Ohm coupling and without amplification using an oscilloscope. Filtering and subsequent amplifying might mitigate the shielding influence of the oil flow guiding tubes and improve the reachable sensitivity. As identified with the failed Performance Check, the sensors are shielded against internal PD pulses and thus no PD impulses were measurable. One conclusion is that in this case with internal tubes in front of the oil valves the UHF method should possibly not be applied with oil valves sensors but with so-called top hatch sensors instead.

These Hatch UHF sensors can be installed as retro-fit by changing original hatches with new hatches with incorporated UHF sensors. The benefits are: i) possibility to install various sensors, ii) less blocking/shielding metal structures in front of sensor. For an on-site testing case the additional needed efforts for sensor installation must be surely justifiable with e.g. the strategic importance of the transformer or the needed information of the PD measurement.

The acoustic sensors were located near the PD source, see Figure 11, and the averaged acoustic signal was detectable with the use of the IEC conform trigger impulses. Other positions of the acoustic sensors didn't lead to measurable acoustic signals. Due to the confirmed localisation result the transformer will be detanked and repaired.

## 5 CONCLUSION

The electrical PD-measurement set-up according to IEC 60270 usually has sensitivity limitations for on-site/on-line measurements because of the high noise level in field. The multi-terminal PD measurement can be advantageously used by means of STAR diagrams for discrimination between external noise clusters and internal PD sources. Different PD sources at different phases were found in one generator step-up transformer and the UHF method confirmed the results of multiple PD sources inside the transformer. Overly strong noise on-site nevertheless might make the method of STAR diagram unfeasible.

The UHF PD measurement method is usable as single measurement and supporting measurement for off- and on-line PD detection. Fundamental knowledge of the PD phenomena is needed for interpretation of measuring results, comparable to the knowledge needed for IEC 60270 measurements. UHF probes are easily installed and are useable. The sensitivity of unamplified UHF PD measurements is sufficient and normally not affected by external disturbances. So especially in noisy environments it is a very powerful and sometimes superior method to support other PD measurement techniques.

Due to possible strong UHF noise on-site, UHF PD measurements might be affected and signals have to be evaluated, if correlating to PD or not. This is done beneficially in the frequency domain to distinguish between natural broad-band PD spectra and generally narrow-banded noises active as modulated carrier signals in mobile telephone technology, mobile communication stations or radio sets. Oil filling valves used for the installation of UHF-sensors are often electro magnetically shielded from the internal tank by tubes for directing the oil flow. Nevertheless sensitive UHF measurements are in some cases still possible and improvement might be the use of amplification of UHF signals.

Run times measured in the UHF range can also be used for geometrical PD localisation. Acoustic sensors should be placed near to the PD source at the transformer tank to get acoustic signals of the PD. Due to the fact, that normally no transformer offers more than three UHF oil valves, the acoustic measurement method is still helpful for PD localisation. However, acoustic sensors are normally more sensitive to external disturbances than to internal PD originated sound waves. They are also affected by distortion within the tank from the winding core and support structures in the transit path. That influences partly can be eliminated with appropriate signal processing afterwards. Therefore, the compromise is a combination of methods, e.g. using sensitive low-frequency electric or UHF PD signals to provide triggering and by using averaging [5] of acoustic signals for de-noising. In case of more than one PD source, acoustic localisation can become difficulty because of interfering signals.

Referring to the presented case studies the experiences are summarised in Table 1. At the presented transformers each measuring method was tested if there are any measurable signals. In Table 1 “+” means, that the measurement method was successfully used in the purpose of detection or localisation of PD, whereas “-“ represents inefficacy of the method.

**Table 1: Successful “+” and not successful “-“ measurements of PD during four case studies**

		<b>IEC / Multi-Terminal IEC</b>	<b>UHF/ drain valve sensor</b>	<b>Acoustic</b>
<b>120 MVA, 110/10kV</b>	Off-line	+	+	-
<b>120 MVA, 110/10kV</b>	On-line	-	+	-
<b>333 MVA, 220/110kV</b>	On-line	-	+	(+) triggered by UHF
<b>320 MVA, HVDC</b>	Test Facility	+	-	(+) triggered by IEC

Experiences can be concluded as follows:

- IEC PD measurements are the most sensitive method for laboratory or test facilities and are also useful for off-line measurements. There are certain drawbacks for IEC PD measurements like ambient noise on-site or corona discharge when performed on-line.
- UHF PD measurements can easily support PD measurements even on-line and are mostly sensitive enough against PD. As a result of shielding characteristics of the transformer tank against external electromagnetic waves, normally a clear decision can be made concerning the PD activity of the test object.
- Acoustic PD measurements should not be used exclusively and benefit from a sensitive trigger method as e.g. UHF for double checking and noise suppression.

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