Various Partial Discharge measurement and evaluation techniques
Adapted to different transformer types

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Abstract
For an efficient power transmission and distribution it is imperative that the used high
voltage equipment operate at their maximum load without sustaining any malfunctions.
Especially transformers, which are needed at the junctions of energy supply systems, have
an exposed importance due to the widespread negative consequences resulting out of a
failure.

For power levels up to 24 MVA with a maximum voltage up to 36 kV beside paper-oil
insulated transformers so called dry type transformers usually insulated by epoxy-resin are
used. These transformers are especially sensitive to Partial Discharges (PD) often resulting
in irreversible degradation and destruction of the insulation, thus finally a breakdown of the
whole system is unavoidable. Therefore in this contribution some aspects of PD
measurements on dry type transformers are presented with a special focus on the problems
arising under noisy conditions, which are typical for measurements on-site. It is described
how the quality of an online measurement can be improved using different techniques for
measuring and evaluating partial discharges. Furthermore a new PD monitoring system is
introduced enabling not only the detection of the discharges but also the localization of the
PD-origin. This system is efficient and cost-effective and can be easily installed at almost all
categories of dry type transformers.

For paper-oil insulated transformers other PD-evaluation methods are preferable due to the
distinctions of the insulation type and the higher voltage levels used. Different techniques
for measuring partial discharges are compared and a new method is introduced, which
enables beside the determination of the apparent charge a localization of the PD-source by
using the transfer functions of the transformer coils. The advantages and disadvantages of
this new technique compared to conventional methods are discussed leading to an outlook
on future trends in PD-analysis on power transformers in operation.
INTRODUCTION
The major part of transformers needed at the junctions of power supply systems are in service for several decades without any knowledge concerning the question how long they will operate satisfactorily, because of the uncertainty of their insulation condition. Therefore a partial discharge measurement and localisation is useful for an insulation diagnosis with the aim to optimise both maintenance and life-risk management.

Nowadays used PD measurement techniques on oil filed power transformers can be subdivided in chemical, acoustical and electrical measurements. Chemical methods are based on the analysis of dissolved gas generated inside the transformer due to PD activity. The integral characteristic of these regularly performed analyses allow indications on the long term behaviour of the PD activity and therefore on the insulation condition. For information on the actual PD occurrence acoustic and electric PD measurements are preferable. The focus of acoustic or ultrasonic measurements is based on a PD location, whereas the electric measurements are orientated to a precise determination of the apparent charge, although investigations have shown, that sometimes a PD location is possible but complicated [1]. A combination of both techniques with the aim to make an exact determination of the PD origins and the apparent charge available seems to be large-scaled and ineffective.

Narrowband electrical PD measurements are carried out offline, thus an enormous effort concerning the required equipment is unavoidable. Beside the measurement apparatus an external generator generally with a higher voltage frequency than the normally used one is necessary in order to discriminate noise generated by power frequency from phase correlated PD signals and to avoid saturation of the core, if test voltages at higher than the nominal voltage are required. Due to the fact that this measurement is performed offline both the electrical and thermal condition of the insulation differs from the online situation, thus the results have to be scrutinized.

Consequently up to now no efficient online PD analysis techniques are available, thus new methods have to be explored. Preliminary investigations have shown that wideband electrical decoupled PD signals can in general be efficiently evaluated by various pattern recognition methods in order to determine the PD origin and its apparent charge [2]. The functional principle of these methods is based on the evaluation of the characteristic distortion of a PD signal caused by its transmission from the origin through the winding to the decoupling point. That means that all PD impulses coming from the same origin can be identified, because they are all subjected to the same distortion, whereas PD signals from other origins are characterised by a different deformation and can therefore be distinguished. Using classifiers like neural networks it is possible to divide on this basis measured PD patterns into various classes; each of them representing a different PD origin or respectively another category of failure.

Furthermore a new method for the evaluation of electric measured partial discharges has been developed. This method uses the transfer functions of a transformer for a PD location [2] and enables additional possibilities which are discussed in one of the subsequent chapters.

On the distribution level close to the consumer and especially in residential areas dry type transformers have become increasingly popular due to their reduced maintenance expenditures and improved environmental compatibility. A disadvantage of these also as epoxy resin insulated known transformers is their sensitivity against partial discharges (PD). Opposite to liquid insulations there are no self healing effects in solid insulation materials, thus PD activities may cause serious damages inside the insulation leading to interturn short circuits of single windings leading to larger short circuits. Therefore a detection of insulation defects in time is essential to improve the operation
reliability, thus consequently PD measurements ensure the dependability of a transformer or at least allow statements about the actual condition of the insulation.

PD measurement techniques like ultrasonic measurements are not applicable for dry type transformers due to the high acoustic damping of the solid material. Also chemical analyses like DGA (Dissolved Gas Analysis), as they are frequently used for oil filled transformers, can not be used. For these reasons only electrical PD measurements, which can be subdivided in wide- and narrow-band techniques, are applicable for dry type transformers. In contrast to wide-band PD measurements, which are quite large-scaled, narrow-band methods offer the advantage to suppress noises by choosing a convenient center frequency and frequency range. Thus sensitive PD measurements as they are requested in the standard IEC 60726 [3] are possible, although the frequency parameters especially under noisy conditions as they appear during measurements on transformers in operation have already not been sufficiently investigated, even if the standard IEC 60270 [4] defines limitations of the frequency ranges.

Therefore some recommendations for optimizing a PD measurement in an extremely disturbed environment as they result out of our experiences are presented in this contribution, thus offering some guidelines for further evaluations.

**ONLINE PD MEASUREMENTS ON A DRY TYPE TRANSFORMER**

On a three phase 10 kV / 400 V / 400 kVA dry type transformer various electrical PD measurements have been performed using the setup shown in Figure 1. As illustrated a coupling capacitor of 1200 pF has been connected to the upper clamp of the high voltage phase W, thus via a quadrupole the current caused by the PD can be transformed into a voltage signal which is filtered by a band-pass. The band-pass filter itself has been realized using different devices in order to optimize the measurement procedure and the sensitivity. For evaluating the PD signals using φ-q-n or φ-q patterns a second capacitor is connected as voltage divider in series to the 1200 pF capacitor for determining the high voltage phase relation, which is analyzed by the PD evaluation unit. Furthermore with an antenna external noise pulses can be suppressed using gating techniques, which interrupt the

**Figure 1:** Measurement setup on site a 400 kVA dry type transformer
At first, calibration measurements have been performed using an impulse generator, which has been connected in parallel to the PD detection circuit as depicted in Figure 1. Using a band-pass filter with a lower cut-off frequency of 40 kHz and an upper cut-off frequency of 800 kHz without enabling the gating, the $\phi$-q pattern shown in Figure 2 has been determined during a measurement time of 500 cycles.

![Figure 2: Calibration measurement (apparent charge 100 pC, frequency range 40 kHz – 800 kHz)](image)

It is obvious that with this configuration a sensitive PD detection according to the IEC 60726 is not possible, because according to this standard all occurring partial discharges with an apparent charge above 20 pC have to be proven, but in this case not even the calibration impulses with a charge of 100 pC could be identified. A repetition of the above depicted measurement using a reduction of the frequency range between 100 kHz and 250 kHz, which is in accordance with the revision of the IEC 60270, allows a significant reduction of the noise signals, thus making the calibration pulses with an apparent charge of 100 pC visible as shown in Figure 3. With an additional masking of the external disturbances with the gating technique using the antenna, the sensitivity of the measurement procedure can be increased again, as it is depicted in Figure 4 for a measuring time of 500 cycles. Nevertheless, there are still many noise signals, which are characterized by vertical lines in the shown diagram and can therefore be suspected as influences of thyristor power electronics due to the phase constant appearance of the disturbances. Thus an optimized adjustment of the measurement setup has already not been reached, especially because the minimum detectable apparent charge is still above the required 20 pC.

![Figure 3: Calibration measurement (marked apparent charge 100 pC, frequency range 100 kHz to 250 kHz)](image)  
![Figure 4: Calibration measurement equivalent to the measurement shown in Figure 3 but with reduction gating)](image)

A further improvement of the noise suppression could be achieved by another reduction of the measurement bandwidth down to 9 kHz with a center frequency of 2.4 MHz which seemed to be the most convenient frequency below 5 MHz, although this center frequency is out of the limits defined in the IEC 60270. As depicted in Figure 5 the vertical lines previously representing disturbances, are
suppressed during the measurement time of 500 cycles, while a separation between positive and negative apparent charges is not possible any more, due to the characteristics of the preprocessing system behind used band-pass filter.

Due to the reason that also with this setup the noise level is still in a range of about 35 pC and therefore above the required 20 pC, a further band-pass filter realized by a spectrum analyzer has been applied. Using the spectrum analyzer at a center frequency of 14.6 MHz calibration impulses with an apparent charge of 20 pC could be detected without doubt, as it is depicted in Figure 6. Also during this measurement, which lasted 500 cycles, a separation between positive and negative calibration impulses was not possible due to the preprocessing properties of the spectrum analyzer.

The performed calibration measurements show, that especially the PD evaluation with the help of the spectrum analyzer at a center frequency of 14.6 MHz is favorable due to its superior noise suppression capability. A major disadvantage of this procedure is beside the fact that the apparent charge of a detected PD can not be assigned correctly due to the decreasing PD spectrum at higher frequencies, that only partial discharges characterized by a wide frequency spectrum are detectable. Therefore additional investigations in the laboratory have been performed in order to prove if partial discharges in epoxy resin have the necessary frequency spectrum. The used measurement setup for these experimental investigations is similar to the setup shown in Figure 1, only the specimen has been changed, i.e. instead of the transformer an epoxy resin block with a needle plane electrode configuration inside has been used, on which high voltage is applied to the needle [5]. The result of the measurement using the setup with the spectrum analyzer is illustrated in Figure 7, where two clusters of occurring partial discharges can be seen. This represents a typical $\phi$-q pattern for PD activities inside voids of solid insulation materials.

The performed experiments lead to the conclusion, that partial discharges in the regarded solid insulation material have indeed parts in the high frequency range, thus the described measurement technique using high center frequencies is applicable for offering statements concerning the PD activity on dry type transformers. However, the PD signals are subjected to a distortion during their run from the source through the coil to the decoupling point, thus also the frequency spectrum of the partial discharges is modified. Nevertheless, this is less important for the high frequencies of the
spectrum, because these parts were mainly transmitted via the winding capacities, so that the damping of these frequencies is rather small.

Therefore with the described method further measurements during transformer normally operation have been performed, lasting for about 15000 cycles. The recorded data is illustrated in Figure 8, in which the original shape of the applied high voltage is displayed, whereas the preceding diagrams containing the calibration measurements, i.e. excluding Figure 7, show only symbolic sine waves for reference purposes.

As shown in Figure 8 during the PD measurement only signals at the end of the period have been detected, which may represent partial discharges. However, in this case these signals can be identified as noise pulses due to two different reasons. The first one is the fact, that the PD cluster is twice interrupted, thus being an indication for an active gating and therefore for the occurrence of noise pulses at this time. Furthermore the same PD cluster can be observed during a subsequent calibration measurement similar to the measurement shown in Figure 6, but during the time of peak-load power when the noise level extends, which is depicted in Figure 9. In this diagram the shown reference sine wave is in correlation with the measured high voltage sine shape displayed in Figure 8, thus it becomes obvious that the position of the noticed PD cluster is the same in both measurements and can therefore be indisputable identified as noise pulses.

Summarizing it can be stated from the presented measurements, that the monitored transformer showed no PD activity.

However, although this measurement technique can be applied successful in this case it has some disadvantages which are partly mentioned above. A further inconvenience is beside the expendable adjustment of the measuring parameters the inability of a PD source location, which may enable preventive measures like the replacement of single coils. Therefore a prototype of a new PD detection device has been developed, which is briefly described in the following chapter.

**PROTOTYPE OF A NEW PD DETECTION TECHNIQUE FOR DRY TYPE TRANSFORMERS**

The main idea of the new PD detection technique is the measurement of the electromagnetic radiation originating from the partial discharges with sensors mounted directly on the surface of the transformer coil [6], which is shown in Figure 10.
A localization becomes possible, because on sensors, which are close to the PD source a higher signal can be achieved than on sensors, which are placed far away from the PD origin, as it is clarified in Figure 10. Using a convenient band-pass filter the noises can be sufficiently suppressed and an increased noise damping is possible by evaluating the differential signals from two neighbored sensors. A determination of the apparent charge is also applicable by performing calibration measurements before the PD monitoring begins, provided that the selected center frequency of the band-pass filter is in an adequate frequency range. In order to prove whether the sensors do not influence the electrical field in such a way that they can cause corona or even enforce PD-inception inside the insulation it is necessary to test this technique. These investigations can of course not be performed on a transformer in operation, thus it was necessary to carry out adequate experiments on a transformer model in the laboratory which are described in the following.

EXPERIMENTAL INVESTIGATIONS FOR A PD-LOCALISATION ON DRY TYPE TRANSFORMERS USING A MULTIPLE SENSOR SYSTEM

On a single high voltage coil of a dry type transformer, in whose center a grounded metallic tube has been positioned in order to simulate the transformer core, 7 sensors have been placed, i. e. one on each winding package. At the upper clamp of the coil high voltage has been applied, whereas at the lower clamp at first a test vessel containing a needle-plane electrode arrangement inside an epoxy resin block, which has been embedded in silicone liquid to avoid surface flashovers, has been connected for the generation of PD-signals. In a second experiment a grounded needle has been used instead of the test vessel for creating PD-pulses, which is depicted in Figure 11.
Figure 11: Measurement setup

The signals of the sensors have been amplified with a battery powered differential amplifier versus a reference potential, which is grounded via a 1 GΩ resistor. Ground can not be used as reference potential, because in this case the voltage difference between ground and the sensors, which have a floating potential close to the applied high voltage, would destroy the inputs of the amplifier, thus finally the sensors itself are connected to the ground and modify the electrical field surrounding the coil significantly. The amplified signal is transmitted via a fiber optic line and an optic receiver to a multiplexer, whose second input is coupled to a quadripole, which is in series to a capacitor of 6000 pF for a conventional decoupling of the PD-signals. The multiplexer is inside a wide-band PD instrument using a frequency range between 100 kHz and 250 kHz, which is in accordance to the IEC-60270.

Using this measurement setup the PD-signals at the sensor and at the quadripole can not be determined simultaneously, thus a comparison of the PD-patterns of subsequent measurements has to be performed for localizing the PD source. The major advantage of this method is the reduction of the measurement equipment and consequently of the costs, because a simultaneous recording of 8 channels or even more for larger coils requires special instruments, which are usually quite expensive.

At first two calibrations have been performed: one for the decoupling via the quadripole and a second one for the sensors. Primarily calibration impulses with an apparent charge of 1 pC have been injected in parallel to the capacitor for adjusting the determination of the PD-signals through the quadripole. Afterwards impulses have been inducted into the lower clamp of the coil, thus sensor 7 could be calibrated, because this sensor is placed directly at the winding package containing this clamp. Assuming that all sensors are uniformly positioned to their according winding sections this calibration is valid for all sensors.

Thereafter the test vessel has been disconnected and high voltage has been applied to the upper clamp in order to prove that the whole setup does not show any PD-activity. From the phase-charge-histogram, as it is displayed in Figure 12, it becomes obvious that during the 60 s of continuous measurement no PD-signals above the background noise could be detected at the quadripole up to a voltage level of about 10 kV, which is equal to the normal operating voltage of this transformer coil.
Now the test vessel has been connected to the lower clamp and a voltage of 4.5 kV has been applied to the upper clamp of the coil for 120 s at a measurement session. During each session PD-signals on two channels have been recorded alternately, in such a way that each channel has been active for in total 60 s, but a switching of the channels takes place every 10 s. On channel 1 always the pattern from the quadripole has been determined, whereas at channel 2 successively all sensors have been connected. The acquired PD-patterns are illustrated in Figure 13, where on the left hand side the pattern from the quadripole and on the right the pattern gathered by the sensors are shown. It is obvious from the signals gathered at the quadripole that during the measurement the PD behaviour is more or less constant, whereas the apparent charges measured at the sensors increase from sensor 1 to sensor 7. Therefore in this case the PD source is correctly localised nearby sensor 7, because there the largest apparent charges have been measured.

Beside the possibility of a localisation of the PD-origin this technique offers also a more precise determination of the apparent charge. Regarding Figure 13 a maximum charge of about 13 pC has been measured at sensor 7, whereas with the conventional PD-measurement technique using the quadripole a maximum apparent charge of about 8 pC has been determined, although both systems have been calibrated correctly. The reason therefore is that the PD-signal is subjected to distortion and reflection on its way from the source to the decoupling point, thus the signal is damped leading
mentioned before the basic operating principle of the localisation.

In the second experiment instead the test vessel a needle, which has been slightly impressed at the fourth winding package, was connected, thus at sensor 4 a maximum signal should be detected. The results of the performed measurements, which are similar to the last preceding ones with the exception that only a high voltage of approximately 2.5 kV has been applied to the upper clamp of the coil, are shown in Figure 14. Again from each subsequent measurement the PD-patterns achieved from the quadripole and from the sensors are displayed similar to Figure 13. The PD-patterns gathered by the quadripole are for each measurement session quite equal, thus implicating that the PD-behavior has been almost uniformly during the different measurements.

![Figure 14: PD patterns injected nearby sensor 4 using a grounded needle](image)

From Figure 14 it becomes obvious that the apparent charges determined at the sensors increase noticeable up to sensor 4, whereas between the sensors 4 to 7 only small discrepancies can be observed. This phenomenon can be explained by the fact that the major part of the PD-current flows via the upper coil, the capacitance and the quadripole to ground and causes therefore an alteration of the potentials at the sensors 4 to 1. Only a minor part of the PD-current closes to ground via the lower part of the coil and stray capacitances, thus at the sensors 4 to 7 more or less the same potential or respectively PD-pattern is measured. Consequently in this case it can be stated that the PD-origin has to be most closely to sensor 4, which is indeed the case.

**ONLINE MONITORING OF NEGATIVE PD EFFECTS**

Usually such a describe PD detection technique is too expensive for an online monitoring of partial discharges on dry type transformers. However as mentioned before dry type transformers are extremely sensitive to PDs thus they often can lead sooner or later to the destruction of the solid insulation, due to the absence of self healing effects as they exist in liquid or gaseous insulating systems. Ultimately partial discharge activity causes interturn short circuits, because of the disintegration of the winding insulation material, thus local overheatings arise, which have an increasing influence on the partial discharge behavior due to the rising operation temperature. If this chain reaction is once initiated a breakdown of the whole system is unavoidable and is in some cases accompanied by fire hazards, which can entail dreadful damages often more expensive than the purchase costs of the transformer itself. In order to prevent such a scenario it is necessary to keep the
transformers under observation during operation, which may be performed using an overheating monitoring systems.

Many dry type transformers are equipped with a PTC (Positive Temperature Coefficient) temperature fuse integrated in the low voltage coils for signalizing a temperature extension due to an excessive current. As explained before local overheatings can also appear at the high voltage coils due to interturn short circuits caused by the destruction of the solid insulation by partial discharges. These local overheatings, which can not be detected by the PTC systems, represent a pre-stage of a breakdown resulting possibly in burns, as it happened on a 400 kVA transformer depicted in Figure 15. Thus it is useful to monitor the temperature distribution at the high voltage phases offering the possibility to disconnect the transformer in time and avoid thereby subsequent damages.

Figure 15: Burned 400 kVA dry type transformer

Using a new developed overheating protection system, which guards both the high and low voltage coils as well as the core against overheating, such a breakdown resulting in enormous costs often higher than the transformer cost prize due to the destruction in consequence of a fire can be avoided. The system consists of a fiber optic sensor and a control unit, which processes the measured data and signalizes an alarm to the control center of the

Figure 16: Principle of operation of the fiber optic sensor
power supply station if an overheating appears.

The patented principle of operation bases on the temperature dependant modification of the optical transmission properties of an optic fiber cable, thus the optic sensor does not cause any electromagnetic interference or influences the operation of the transformer in any other way. If a light signal is injected by an optical transmitter into one side of the fiber optic sensor it can be detected at the opponent end with an optical receiver as shown in Figure 16. If an extended temperature arises at the surface of the fiber optic sensor the damping of the light transmission is increased until a certain temperature limit is reached, where the light transmission is interrupted. In this case an alarm is given, thus the transformer should be disconnected, which also can be automated and controlled by the protection system if necessary.

As shown in Figure 17 the sensors are mounted vertically on the coils, because due to the annular spread out of the overheating inside a winding package, which causes the typical ring-shaped resin color changes, it is not necessary to place the sensor directly on a hot spot but on any position above the overheated winding package. Therefore a special mounting technique as shown in Figure 17 is used, where the fiber optic sensor is situated at 4 different positions on the inner and outer surface of the coil, thus totally 8 areas per coil are monitored.

![Figure 17: Positioning of the fiber optic sensor](image)

The sensors for each coil, which are fixed using a special 2 component epoxy resin putty, are connected in series thus only one optic fiber sensor and only one control unit is required for observing a transformer in operation as it is shown in Figure 18. The temperature threshold for an alarm release can be adjusted over a wide range from about 80°C up to 170°C or more if necessary, but this is generally not practicable for monitoring dry type transformers, because their operation temperature is typically between 60°C and 100°C. The threshold regulation can be varied with the selection of the material of the fiber optic sensor and furthermore a fine tuning is possible by modifying the properties of the transmitter and receiver. The first prototype has been online for about 2 years as shown in Figure 18. In the meantime more than 50 dry type transformers in Germany are equipped with such a system and in one case a serious damage could be prevented by the online overheating protection system. In case of such an overheating alarm only the failed coil have to be changed or repaired, whereby the defect coil can be determined by a frequency response or a resistance measurement.

The most important advantages of the new developed overheating protection systems can be summarized in brief outlines as follows:

- Overheating of both insulation and core can be detected online.
- In case of a local temperature extension an alarm reduces the risk of fume, fire or damage of the insulation.
- No electromagnetic interference, surface discharges or any other impairment of the environmental conditions.
- Safe overheating detection in a range of 80°C up to 170°C which is well tried in practical operation.
- Cost efficient and easy to install.
- Processing unit enables due to an intelligent design self control and supports several interfaces as well as remote access.

![Overheating protection system in operation](image)

**Figure 18: Overheating protection system in operation**

**PAPER-OIL FILLED TRANSFORMERS**

Due to the different insulation media and the different construction for paper-oil insulated transformers other techniques than for dry type transformers have to be used, but also for these transformers PD activity and its consequences are most suitable to be considered. Therefore a new PD evaluation technique has been developed which is explained in more details in the following.

**THEORETICAL BACKGROUND**

The properties of a linear time-invariant system can be described by its transfer function completely and unambiguous, thus such systems can be visualized by a block diagram as indicated in Figure 19.

![Linear time-invariant system](image)

**Figure 19: Linear time-invariant system**

Using the convolution theorem in time domain (1) for any time discrete input signal $x[n]$ the output signal $y[n]$ can be determined and vice versa if the transfer function $h[n]$ is known.

Equation (1) can be simplified
by transferring the signals into the frequency domain via a Fourier Transform as shown in Equation 2.

\[ y[n] = x[n] * h[n] = \sum_{k=-\infty}^{\infty} x[k] \cdot h[n-k] \]  

(1)

\[ y[e^{j\omega}] = x[e^{j\omega}] \cdot h[e^{j\omega}] = h[e^{j\omega}] \cdot x[e^{j\omega}] \]  

(2)

The transfer function itself is defined as the system response of a so called delta impulse, thus it can be determined by a measurement using as input signal a steep impulse approximating the delta impulse or by a frequency response analysis. For the last-mentioned method input signals with various frequencies are used and compared with their output signals in order to determine the damping and phase shift for each frequency.

More complex systems consist of multitude subsystems, which can be described by separate transfer functions, thus the whole system may be characterized by a series arrangement of subsystems as illustrated in Figure 20.

\[ \prod \]

(3)

If the output signal \( y[n] \) is measured any signal \( x_i[n] \) inside the system as shown in Figure 20 can be computed by using (4).

\[ y[n] \xrightarrow{\text{Fourier}} y[e^{j\omega}] \]

\[ x_i[e^{j\omega}] = \frac{y[e^{j\omega}]}{h_i[e^{j\omega}] \cdot h_{i+1}[e^{j\omega}] \cdots h_n[e^{j\omega}]} = \frac{y[e^{j\omega}]}{\prod_{k=i}^{n} h_k[e^{j\omega}]} \]  

(4)

The model shown in Figure 20 can be transferred to a coil of a transformer, which is represented by an equivalent circuit consisting of various resistances \( \frac{\partial R}{\partial s} \), inductances \( \frac{\partial L}{\partial s} \) and capacitances \( \frac{\partial C}{\partial s} \).
per unit length \( s \) as shown in Figure 21 according to an extended iterative network model from Wagner [7]. The signal \( x_i[e^{i\omega}] \) inside the system can be interpreted as the voltage \( U_i[e^{i\omega}] \) caused by a partial discharge, thus this signal can be calculated similar to \( x_i[e^{i\omega}] \). The different sub transfer functions represent a certain winding section, e.g., one winding package. However, this theory is only applicable for linear time-invariant systems as mentioned before, thus it is necessary to verify if a coil of a transformer fulfills these requirements. This is the case if the following two equations are valid:

**Linearity:**

\[
x_i[n] \rightarrow y_i[n] \quad i = 1, 2
\]

\[
a \cdot x_1[n] + b \cdot x_2[n] \rightarrow a \cdot y_1[n] + b \cdot y_2[n] \quad a, b = \text{const.}
\]

**Time-invariance:**

\[
x[n] \rightarrow y[n]
\]

\[
x[n - n_0] \rightarrow y[n - n_0]
\]

The coil of the transformer belongs without restrictions to the class of time invariant systems, because it consists only of passive elements, thus if an input signal has a delay the output signal will have the same delay.

The linearity according to (5) of the coil is given, if the differential equation for calculating the output voltage \( U_y(t) \) from the input voltage \( U_x(t) \) is linear. Regarding Figure 21 this equation is of order \( 3n \) and linear if all elements are linear. However, the inductance of the coil is only linear for a certain frequency range, due to the nonlinear core characteristic, thus the described model can be used for certain frequencies only, which have to be determined in each case. If this is verified and all sub transfer functions are determined the model can be used for a PD location for which the principle is shown in Figure 22.

The coil of the transformer belongs without restrictions to the class of time invariant systems, because it consists only of passive elements, thus if an input signal has a delay the output signal will have the same delay.
If the signals caused by a PD are measured at the two opposite ends of the coil, i.e. at the bushing $y_B[e^{j\omega}]$ and at the neutral $y_N[e^{j\omega}]$, the input signals $x_B[e^{j\omega}]$ and $x_N[e^{j\omega}]$ at the different subsystems have to be reckoned back from both sides. The location, where the signals recalculated from both sides are most similar, must therefore be the real origin of the PD according to (7).

$$x_B[e^{j\omega}] = \frac{y_B[e^{j\omega}]}{h_1[e^{j\omega}].h_2[e^{j\omega}]....h_n[e^{j\omega}]} = \frac{y_B[e^{j\omega}]}{\prod_{k=1}^n h_k[e^{j\omega}]}$$

$$x_N[e^{j\omega}] = \frac{y_N[e^{j\omega}]}{h_1[e^{j\omega}].h_2[e^{j\omega}]....h_1[e^{j\omega}]} = \frac{y_N[e^{j\omega}]}{\prod_{k=1}^n h_k[e^{j\omega}]}$$

if $x_B[e^{j\omega}] = x_N[e^{j\omega}] \Rightarrow i = \text{origin of PD}$

(7)

This technique has been tested on a transformer in the laboratory as is described in the following chapter.

PD LOCALISATION

On a specially prepared distribution transformer (10 kV / 380 V, 200 kVA), which has been pulled out of its vessel, 7 clamps have been mounted along phase V with equidistant spaces comprising 2 winding packages as shown in Figure 23. Into each clamp 150 PD-pulses have been injected spread equal to three different PD-types generated by a needle-plane arrangement in air, oil and pressboard, in order to simulate different failures. Thus in total 1050 PD-pulses have been digitised at the bushing and at the neutral via a 50 $\Omega$ resistor using a sampling rate of 100 MHz and a low-pass filter with a 20 MHz cut-off frequency. Afterwards all sub or respectively sectional transfer functions from each clamp or respectively origin to the bushing and to the neutral including in both cases the termination resistor of 50 $\Omega$ have been determined using a network analyser. The transfer functions have been recorded with 1601 equidistant points between 10 kHz and 5 MHz, thus only this frequency range has been considered when the measured signals.

![Figure 24: Sectional winding transfer functions](image)
were transformed via the FFT and processed according to Equ. (1). The magnitude spectrum of all sectional transfer functions is displayed in Figure 24. As expected it becomes obvious from Figure 24 that the damping generally increases with ascending numbers of winding sections between origin and decoupling point. Thus a network analyser with a dynamic range of about 90 dB
is needed for a frequency range up to 5 MHz, while for frequencies up to 1 MHz a dynamic range of approximately 60 dB is sufficient, which can be used to reduce the efforts for the measurement equipment. Furthermore, it is noticeable that transfer functions from origin number n to the bushing have significant similarities up to a frequency of about 1 MHz to those from origin number 8-n to the neutral (compare e.g. origin 4 in Figure 24). This fact can be explained by the comparable size of the winding sections these transfer functions include, thus resulting in a similar behaviour for lower frequencies for which mainly the inductive signal transmission is responsible. For higher frequencies above 1 MHz the dissimilarities are primarily caused by differences in the stray capacitances as well as by the influences of the other coils. However, the similarities at lower frequencies could be used for the determination of the sectional winding transfer functions by computation and modelling.

The results obtained with the transfer functions convoluted with the measured PD-signals are exemplarily shown in the Figures 25 and 26. In Figure 25 a discharge has been injected into one clamp using the needle-plane electrode configuration in air. On the top diagram in Figure 25 the signals measured at the bushing and at the neutral are displayed, while the other diagrams show the signals at the 7 origins calculated back from the measured data. The recalculated signals from the bushing and from the neutral are almost identical at origin 3, thus indicating that there is the actual origin of the measured PD-pulses. The small discrepancies between the signals at the actual origin can be traced back to measurement inaccuracies.

Another question is what happens if a partial discharge occurs at an origin from which the transfer function to the bushing and to the neutral is unknown. To simulate this problem a partial discharge produced by the needle-plane arrangement in oil has been injected right into the middle of a winding package between two clamps. The result of this experiment is shown in Figure 26, where similar to Figure 25 the signals measured at the bushing and at the neutral as well as the calculated signals at all origins are displayed. At origin 4 and 5 the calculated signals have the most significant identicalness.
thus indicating that the actual origin has to be between these origins, which is indeed the case. A further evidence therefore is that the signal calculated at the bushing lag the signal calculated from the neutral at origin 4, but lead at origin 5.

Due to the unambiguousness of this localisation technique also two PD-pulses from the same origin following each other within short time distance, can be evaluated correctly as depicted in Figure 27, where partial discharges initiated in pressboard have been injected into clamp 5.

Again it becomes clear from Figure 5 that the similarity of the calculated signals at the actual origin is remarkable. Due to this fact also a doubtless localisation is possible if the frequency range is reduced by modifying the lower or upper cut-off frequency or by changing both, thus allowing a measurement in a certain frequency range in which disturbances can be suppressed efficiently.

In all cases the conformity of the calculated signals at the actual origin is so evident, that all measured PD-signals can be doubtless localised with 100 % correctness independent on how the discharge has been generated or on where it has been injected. The evaluation of the calculated signals is also facilitated by the fact that signals far away from the actual origin have significant dissimilarities especially concerning their maximum amplitudes. This is why a certain voltage level at the bushing or at the neutral can be caused by a lower / higher input voltage at an origin closer / further from the decoupling point due to the lower / higher damping.

**Conclusion**

Drytype transformers usually insulated by epoxy resin are especially sensitive to partial discharges, which are usually accompanied by irreversible degradation and destruction of the insulation that may finally lead to a breakdown of the whole system. In order to prevent such failures it is necessary to monitor the transformers regularly during operation, which can be performed using PD measurement techniques preferable based on the electrical decoupling of the PD signals. Applying this method the selection of a convenient frequency range in which the PD pulses are detectable can optimize the sensitivity of the measurement due to the suppression of noise pulses as they appear on-site. This is demonstrated on a 400 kVA dry type transformer in operation under extremely noisy conditions leading to guidelines and recommendations for an adequate measurement procedure using high frequency ranges above 10 MHz. Furthermore, based on these investigations and experiences a prototype of a new PD detection system is introduced, which can be effortlessly applied and enables beside the determination of the apparent charges a localization of the PD source, thus maintenance procedures can be initiated in time for ensuring a uninterruptable power supply.
The online monitoring of PD-activities on power transformers can offer information on the actual condition of their insulation leading to an estimation of their reliability. Thus enabling maintenance in time if necessary, which may result in a life prolongation of these components and consequently to a technically and economically optimised energy supply.

Actually used PD-measurement techniques on transformers can not be performed efficiently online, thus an integration into monitoring systems is impossible wherefore other methods have to be investigated. The presented method has been tested in the laboratory and fulfils the most important requirements as

- precise PD-localisation
- accurate determination of the apparent charge
- determination of the PD-type

by convoluting wide-band measured PD-signals decoupled at the bushing and at the neutral using the sectional winding transfer functions of the transformer coil. With this procedure the PD-signal becomes visible at its origin, which is not possible with any other known method, thus the convincing results encourage further investigations under online conditions. Although more experiences are needed for the determination of the required sectional transfer functions an integration of this technique into future monitoring system is imaginable.

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