Online acoustic PD-measurements of oil/paper-insulated transformers - methods and results

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Abstract: Online acoustic PD measurement methods have the benefit that electrical disturbances like broadcasting stations or corona have little or no influence and a PD detection can be managed by one sensor. However, a fundamental understanding and knowledge of the whole acoustical transmission system of the transformer is needed. Beside the mechanical disturbances on site, found in or at the transformer itself, such as 50 Hz components, magnetostriction or external loose parts, also the mechanics of the tank have to be considered in a modal analysis. The adaptation of the sensors and hardware on the various propagation paths in the insulating system, determining the signal damping, is the basis for sensitive capturing of PD signals.

With the aid of sophisticated digital signal processing algorithms, like the newly developed "FFT2D", a detection and more important a distinction between mechanical disturbances and PD`s can be reached easily. Comparisons to other signal processing techniques show the improvement in the ability of PD recognition.

The resulting sensitivity on site is furthermore demonstrated using recent online-measurements of various oil/paper insulated devices. Several examples of measurements on transformers will be discussed.

1. Introduction

Among others, conditioned based maintenance for high voltage equipment needs a way to measure and assess the insulation characteristic of the insulating system continuously. The PD examination is a reliable and well-known method for quality tests in the laboratories of the manufacturers. Recently PD measurements were performed as well on site and online in both version – electric and acoustic [1].

The different PD measuring techniques thereby encounter different relevant disturbances on site. In the electric case quite severe ones appear compared to shielded laboratory conditions, whereas the acoustic method comes upon almost the same "noises" in each area.

2. Aspects of online PD measurements

Online electric PD measurements

For decoupling of the PD signals ferrit cores mounted on the measuring tap of the bushings and in the neutral of the transformer are used. As the electric on site conditions are noisy complex filtering and compensations are necessary. Main disturbances on site are narrowband noises of radio stations, impulses of power electronics and corona pulses.

While the narrowband noises can be handled with mulitband suppression transfer characteristics of digital FIR filters a two branch "digital bridge" principle is applied to distinguish between internal PD`s, and the above mentioned external impulses [2]. Other sensitivity limiting effects for the "digital bridge" are electromagnetic radiation (EM-pulses) and varying tap changer positions.

Acoustic ambient characteristics on site and insulating materials used in transformers

Comparing the acoustic noise ambience of laboratories to the on site realities does not show great differences. Strong disturbances like magnetostriction in the core appear unchanged in the laboratory too. Important to mention is the insensitivity of the acoustic measuring system to the electric disturbances since this is an outstanding benefit.

Even though mechanical disturbances like magnetostriction or external loose parts have an measurable influence, environmental "noises" as hail, sand, etc. do not have that high spectral components as a PD has. This is shown in Figure 1 which demonstrates how the "noise" and PD spectra act up to a frequency of 500 kHz.

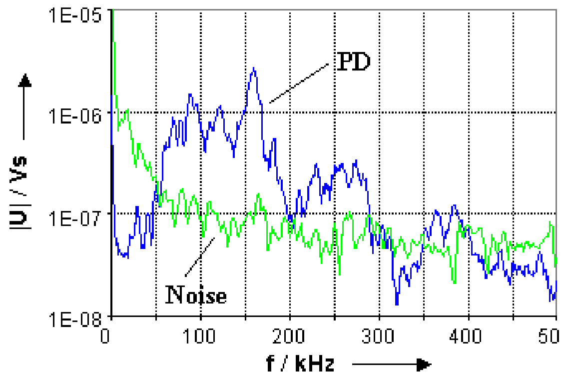

Figure 1: Frequency spectra of acoustic measurements (PD. and disturbances): disturbances (0...50 kHz) and PD (50...200 kHz)

Numerous parameter studies have been carried out in the insulating materials sector to determine frequency dependent damping and reflection coefficients of components like pressboards or winding packages. An experimental oil filled steel tank was used therefore to have fixed acoustic conditions [3]. With this acoustic transfer functions for parts of the propagation path can be established.

Extending the spectra of known acoustic PD incidences simulating different types of PD flaws in laboratory setups -like a large air filled gas bubble against the grounded housing- is still subject of ongoing research.

To render acoustic characterization also with real transformers additionally a calibration PD source with small geometric size which can be inserted in devices without damaging the insulating system was developed and used [4].

Used sensors and hardware

When monitoring for example an "working" transformer it is very often asked for a nondestructive outer application of a measuring system, because a penetration into the transformer housing is not acceptable. The used piezoelectric sensors support a convenient mounting on the outside of the tank wall and provide a wideband conversion of mechanical waves to meet signal classification needs. Beeswax and magnetic clamps could do the acoustic impedance matching between the ceramic sensors and the steel tank wall to minimize losses of this junction.

Generally an acquisition system for acoustic signals may consist of transient recorders able to work with preamplifiers directly connected to the sensors. Digital recording is favourable to allow digital signal processing after the signal has been registered. The system developed and used for the measurements presented in this paper is shown in Figure 2. For on site measuring convenience an embedded PC (doing the digital signal processing) and the digitizing unit are combined in one device. Up to 16 channels can be controlled which is most of the time unnecessary but enlarges the probability of receiving good quality signals.

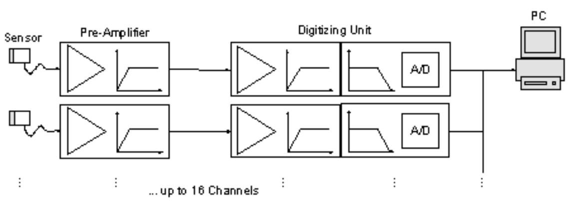

Figure 2: Digital system for acoustic PD monitoring (PC allows digital signal processing)

Acoustic behavior of the tank wall (housing)

In principle the transformer housing with its undesirable damping influence on the piezoelectric sensors (compared to sensors immersed in the tank e.g. hydrophones) acts as a wave guide with a certain frequency dependent behavior. From a purely monitoring point of view this could -to some extent- be an advantageous property extending the observed region.

Dispersion as frequency dependent sonic velocity is the decisive effect for the transformation of the acoustic signals while traveling along the steel tank wall. But additionally the tank wall supports wave propagation only in certain frequency ranges and has a high damping factor in other ranges.

Regarding the most favorable sensor arrangement regions of local damping maximums due to construction should be omitted. Useful positions are e.g. large and thin steel plates oscillating especially well in their middle.

3. Signal processing methods of acoustic signals

A basic difference between acoustic PD measuring in the laboratory (to localize an already electric detected PD) and on site (monitoring or detection purpose) should be well emphasized. In the laboratory it is feasible to use a sensitive electric PD measuring simultaneous and furthermore trigger acoustic measurements with the electric signal. With a stable phase relation of a PD on the one hand and an uncorrelated noise on the other hand an averaging which increases the accuracy can be achieved. In on site and online measurements the possibility of triggering on a reasonable electric signal is lost. This makes it impossible to do an averaging.

In case of only observing acoustic signals on site the first and at the same time common signal processing action is separating the noises from the wanted signal by using a high pass filter as the PD spectrum covers the higher ranges from some 50...200 kHz (according to Figure 1). This is of course only possible because the spectra of the noises and the PD are so well separated.

Further possibilities for signal processing are e.g. wavelets or a newly developed algorithm based on a short-time-fourier-transform (multiple time-windowed FFT) called "FFT2D" as shown in Figure 3. In this algorithm the signal in the time domain is cut in parts of constant length and a fourier-transform is done for every one of them. Afterwards the spectra are displayed at appropriate time indexes with the spectral amplitudes assigned to gray scales.

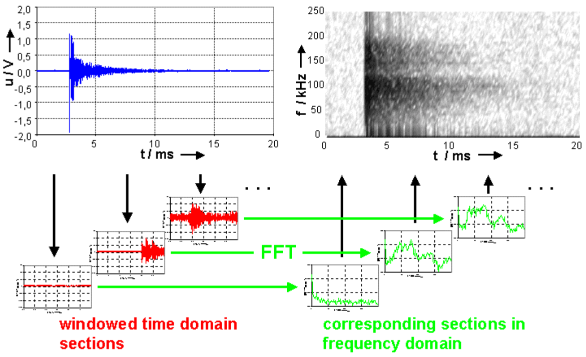

Figure 3: "FFT2D"-algorithm based on a short-time-fourier-transformation for identification of acoustic impulses

Various signatures of disturbances and PD signals can be distinguished clearly by patterns of this algorithm. Small-band disturbances and harmonic signals lead for instance to more or less sharp horizontal lines in the patterns, whereas short broad-band impulses (one criteria for a PD as well) result in vertical lines.

The "FFT2D" proved to be a sensitive mean of pointing out weak PD impulses in noisy signals. This is illustrated with the Figures 4 and 5.

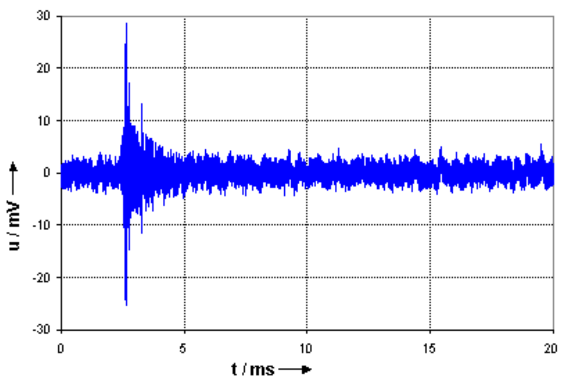

Figure 4: Acoustic PD signal (1.3 MVA transformer, damping of 6 mm steel tank + 4 layers HV winding + 1.20 m distance)

Performing measurements on transformers the signal looks similar to the one presented in Figure 4. It shows an impulse originating of an electrical PD of 660 pC (true charge). The defect was located in an 1.3 MVA transformer in a distance of 1.20 m including a 6 mm steel wall and a 4 layer HV-winding in between. The sensitivity with a PD in this spot is 80 pC (true charge). An "electric" online monitoring system qualifyied for the same detection sensitivity should have a sensitivity of at least 10 pC (apparent charge).

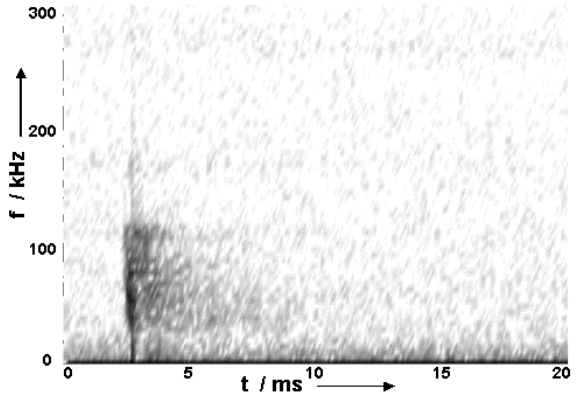

Figure 5: Pattern of the time signal of Figure 4 yielded with the short-time-fourier-transformation algorithm "FFT2D"

Aspects on location of PD flaws

An acoustic PD detection ("PD yes/no") can be managed by one sensor whereas an exact geometric localization of the PD origin needs signals recorded on more sensors (in case of doing computations with traveling times). Two settings can be distinguished. A simultaneous electric and acoustic PD measuring needs minimum three acoustic signals (triggered with the electric signal) to render a localization. In contrast an exclusive acoustic measurement requires at least four sensor signals (with defined impulse beginnings) to solve a linear equations system with four unknowns (three coordinates in space and the unknown time origin).

As dispersion and frequency dependent damping is also observable in the patterns of the "FFT2D" algorithm a completely different way of localization is possible. The above mentioned corruptive effects loose their unfavorable countenance in the signal patterns and can be utilized to estimate an approximate localization of a PD defect.

4. Acoustic online-measurements results

An impulse which is with a high probability caused by a PD was recorded at a 40 MVA transformer and interpreted by means of the "FFT2D" algorithm. The resulting patterns are shown in Figure 6. In the upper right pattern the criteria for a PD are fulfilled most clearly. It features a initiatory broad-band impulse as well as a persistence of the fading impulse around 40 kHz. Additionally the signal energy in the lower frequency range increases only slightly compared to the 40 kHz range.

Another pattern belonging to a 350 MVA transformer located in Großgartach, Germany is presented in Figure 7.

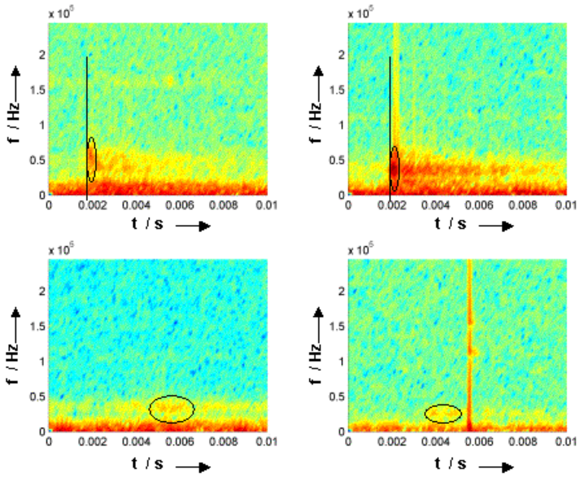

Figure 6: Impulse with a high probability caused by a PD recorded on four channels (40 MVA transformer) with marked estimated impulse beginnings resp. remainders

The pattern (Figure 7) measured at a permanent installed acoustic monitoring system shows beside several small-band signals nothing alarming which should be so while the transformers "operating age" is about six years.

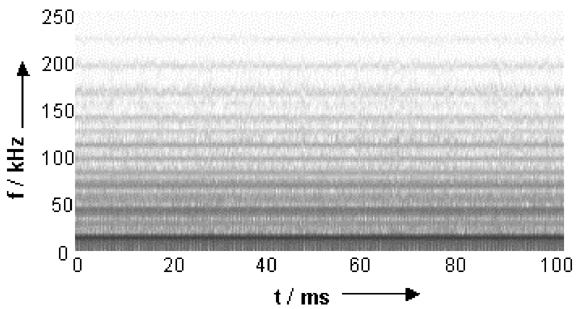

Figure 7: Pattern of a 350 MVA transformer (Großgartach) showing no PD or impulse disturbances just several small-band signals

The consistence of the appropriate time signal of harmonic noises was not evident in the time signal itself as shown in Figure 8.

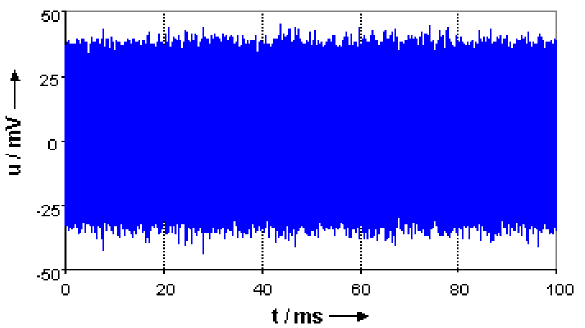

Figure 8: Acoustic time signal of a 350 MVA transformer (Großgartach)

The "FFT2D" algorithm permits an easy interpretation of this fact leaving enough space in the frequency ranges between the noises to clearly detect and identify acoustic impulses.

5. Conclusion

The acoustic PD measuring method features a high sensitivity in on site and online use, beyond that of an online electric PD measurement. This is a result of the insensitivity of the acoustic measuring system to the electric disturbances which is an outstanding benefit. Furthermore the acoustic noise ambience of laboratories remains mostly unchanged compared to the on site realities. Another additional advantage is that a simple highpass filtering of the acoustic signals suppresses disturbances sufficiently to produce afterwards easy interpretable patterns with the presented "FFT2D" algorithm. Working with this algorithm simplifies detecting a PD and distinguishing it from disturbances in the frequency-time domain.

6. References

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