INVESTIGATIONS OF IN-OIL METHODS FOR PD DETECTION AND VIBRATION MEASUREMENT

M. Beltle[1*], M. Siegel[1], S. Tenbohlen[1]
[1]University of Stuttgart, Pfaffenwaldring 47, 70569 Stuttgart, Germany
*Email: michael.beltle@ieh.uni-stuttgart.de

Abstract: Usually, acoustic partial discharge (PD) and vibration measurements take place on the outside tank wall of power transformers. This contribution determines new approaches for acoustic PD measurements within the oil volume of the transformer combined with electromagnetic in-oil measurements. Scope of the work is an acoustic and ultra-high frequency (UHF) detection of PD and additional recording of transformer vibrations during service. For in-oil measurements a combined sensor is presented, which allows simultaneous detection of all three signals. After a short introduction of measurement principles, the requirements of a combined in-oil sensor are defined including mechanical demands and signal processing. A diplexer integrated into the combined sensor is introduced to separate the considered frequency spectra. Tests in a laboratory setup with a first prototype estimate if these requirements are met. Therefore, the setup uses reproducible, synthesized PD signals generated by an acoustic signal generator and an UHF pulser. Second measurements use a needle-sphere electrode emitting realistic UHF and acoustic signals. Vibrations are simulated with a small winding, which is mechanically excited. The combined sensor is compared to the UHF antennas and acoustic accelerometers. Finally, the influence of the electric field strength being unavoidable at inside-tank measurements is evaluated.

1 INTRODUCTION

Reliable operation of power transformers is essential for supply security. Damages to the insulation of a power transformer, like local defects, must be recognized at an early stage to provide time for retaliatory action. Different diagnostic methods have been established to meet the deriving demands. Considered methods are acoustic and ultra-high frequency (UHF) detection of partial discharges and measurement of transformer vibrations during service. Aim of this contribution is to unite all needed sensor technologies in one device.

1.1 Partial discharge measurement

The partial discharge (PD) measurement represents standard procedure for the estimation of local defects. PD are usually measured electrical according to IEC 60270, which represents the established method [1]. Also newer techniques, not being normed yet, arise. Their essential advantage is localisation of PD by run-time measurements.

1.1.1 UHF PD measurement

An Antenna inside the transformer measures the electromagnetic emission of PD sources. PD represent fast electrical processes radiating electromagnetic waves with frequencies up to the ultrahigh range (UHF: 300 – 3000 MHz) in the surrounding oil [2], [3]. Due to the moderately attenuated propagation of UHF waves inside the transformer tank, the electromagnetic wave detection is very sensitive. The grounded transformer tank with it's electromagnetical shielding effect represents a Faraday cage. Therefore the UHF measurement is less sensitive to external noise like corona or other radiated disturbances.

1.1.2 Acoustic PD measurement

Well-known acoustic effects of PD are audible at corona on overhead lines. However, also internal PD can emit acoustic signals in the ultrasonic range [4]. Usually, the typical acoustic frequency spectrum of internal PD reaches from 80 kHz to 180 kHz. Usually, accelerometers with a resonant frequency of 150 kHz at the outside tank wall are used for measurement. The characteristic noise spectrum for power transformers has a frequency range up to 80 kHz [5]. This is caused by magnetostriction, external loose parts and also rain, hail or wind-blown sand on the transformer. The acoustic measurement is mostly used to locate PD by run-time measurements. This is complicated due to the structure borne path problem [5]. Sonic speed in steel is faster than in transformer oil. The superposition of all possible signal paths measured from the external sensor can lead to faulty run-time detection and therefore erroneous PD localization.

1.2 Vibration measurement

Vibrations are caused by voltage-dependent and load-dependent effects, which lead to oscillations in mechanical structures of power transformers [6]. The voltage-dependent vibration is originated by magnetostriction leading to oscillations of the core (e.g. lamination sheets). The Weiss Domains in metal align themselves along the time-varying magnetic main flux induced by the applied voltage. At load condition, current-related effects superimpose magnetostriction. Forces of the alternating magnetic field affect current-carrying windings leading to an oscillation of the active part. The basic oscillation for both phenomena is twice the electrical frequency [7]. The entire frequency range is usually small, reaching up to approx. 1 kHz [6].

2 COMBINED IN-OIL MEASUREMENT

Both, acoustic measurements for PD and vibrations cope with the problem of the stiff, self-supporting tank, which is influencing both, the signal strength (damping) and the signal to noise ratio (SNR). Therefore, methods for measurents directly inside the transformer oil are determined. Piezo-electric sensors represent a suitable technology to detect changes of pressure caused by acoustic waves. Their frequency range is suited for vibration and PD acoustic measurements.

Unfortunately, the access to the transformers inside is limited by the amount of available oil valves. Most transformers are equipped with only 2-3 valves, which can be used for in-oil measurements. Therefore, a sensor is required, that is able to measure pressure changes by the piezo-electric effect and electromagnetic waves simultaneously. Thus, the sensor should work from 100 Hz up to the GHz range. Separate signal outputs should be available for vibrations, acoustic PD and UHF PD. The mechanic design of the sensor has to be attachable to existing oil valves. A prototype designed to meet the requirements is shown in Figure 1. Compared to the combined acoustic sensor presented in [8], this version is also suited for UHF signals. A diplexer with three output N-connectors is integrated in the handle of presented sensor.

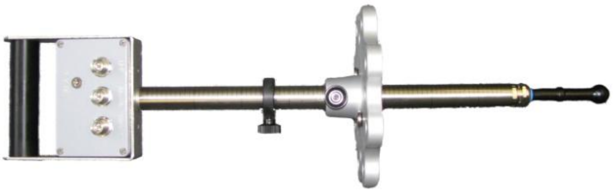

Figure 1: Combined sensor for UHF PD, acoustic PD and vibration measurement. Right: sensor head, middle: oil valve adaptor, left: three N-connectors for separated signal outputs

2.1 Mechanical requirements

For the application to power transformers the sensor is designed and tested to meet the following demands

- mountable to DN 80 and DN 50 oil valves
- variable insertion depth, the sensor head reaches into the transformer tank
- oil-proof, temperature resistant up to 80° C continuous, 120° C short-term and pressure resistant up to 5 bar

2.2 Principle of measurement

The block diagram in Figure 2 illustrates the mode of operation. All signals, piezo-electric or UHF, couple into the physical sensor unit. The UHF signal is filtered by a passive high pass, providing 50 Ohms impedance up to 1 GHz. Because the piezo-electric effect provides only very low output voltage, the signal has to be amplified by a circuit with high input impedance (in the GOhm range). The amplifier also operates as low pass (LP) to supress frequencies within the UHF range. The amplified signals are separated by an active low pass filter for vibrations. PD acoustics are filtered by an active band pass (BP) ideally operating from 55 kHz to 200 kHz. Active filters are used due to their amplification, smaller dimensions and better pass band tuning.

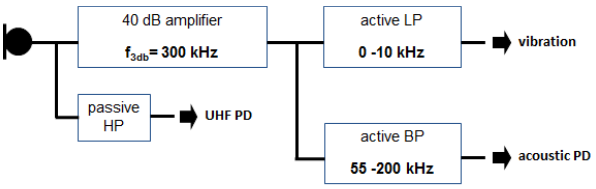

Figure 2: Block diagram of diplexer to separate signals from UHF PD, acoustic PD and sinusoidal vibration signals to separate outputs. On the left: sensor receiving all signals simultaneously

The transfer functions of the three separated signal paths within the diplexer are shown in Figure 3.

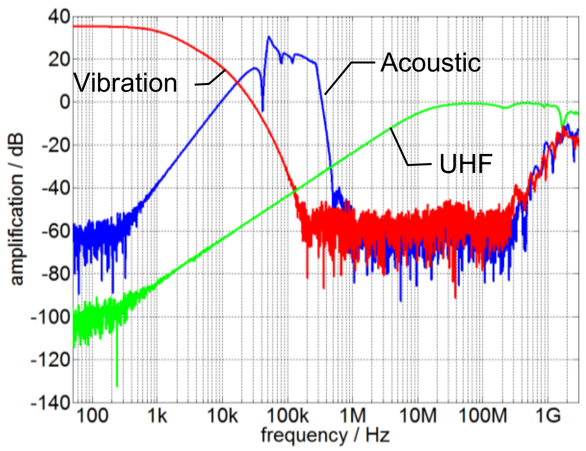

Figure 3: Transfer function of diplexer, red: low pass filter for vibration measurement blue: band-pass filter for acoustic PD (both active), green: high pass filter for UHF PD (passive)

3 TEST MEASUREMENTS IN LABORATORY SETUP

The prototype is tested in a small test tank filled with mineral oil. Two types of tests are performed. The first uses stable, reproducible synthetic signals for vibrations, acoustic and UHF PD. The second uses a needle-sphere electrode for realistic acoustic and UHF PD signals. A sketch of the test tank is shown in Figure 4.

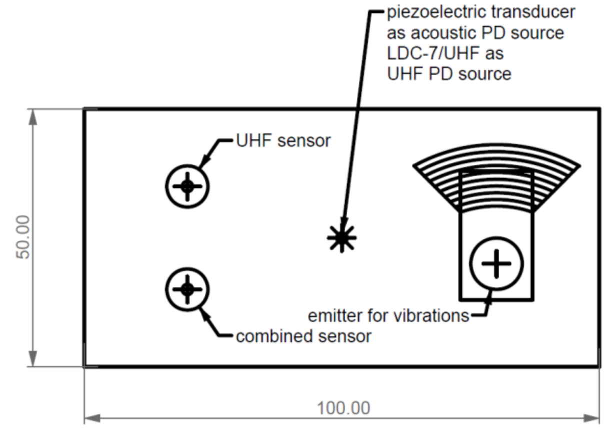

Figure 4: Laboratory test setup for combined PD and vibrations measurements

Vibrations are generated by a winding part, which is mechanically excited by a low frequency transducer. PD acoustic signals are inserted by a tuneable signal generator. The measurement setup is shown in Figure 5. A piezo-electric transducer converts amplified, synthesized voltage signals to in-oil sonic sound. As artificial UHF source a LDC-7/UHF pulser from Doble Lemke is used. Figure 4 shows the position of the combined sensor and UHF antenna [9], used as reference. Figure 5 illustrates the setup for PD acoustic and vibration measurement. Accelerometers are used for the outside tank wall of vibrations and PD acoustics. In both cases, whose output is amplified by 40 dB. All sonic signals are recorded in time domain by a digital storage oscilloscope (DSO) with 400 MHz analogue bandwidth. UHF signals are recorded in time domain by a DSO with 3 GHz bandwidth.

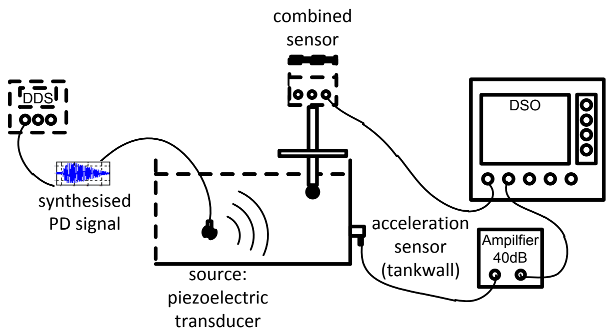

Figure 5: Laboratory test setup for reproducible acoustic PD measurements

The synthetic acoustic PD signal is shown in Figure 6. The basic oscillating frequency is adjustable as well as the rise time and the fall time. To avoid interaction between two sequenced signals, the signal repetition rate is set to 200 ms. The position of the piezoelectric transducer is static. Boundary effects like reflections on the tank wall do not change during measurement. Using this setup, the acoustic PD output of the combined sensor is compared to the outside tank wall acceleration sensor (resonance frequency f_{res} = 150 kHz).

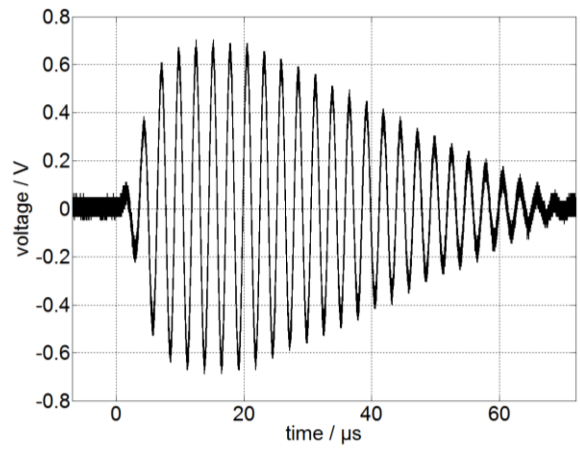

Figure 6: PD signal generated by direct digital synthesis (DDS) with variable parameters: frequency, rise time and fall time (here: 180 kHz, 4 periods rise and 10 periods fall time)

3.1 Acoustic PD measurements

Acoustic PD measurements are mostly used for localisation purposes by determining run-time differences. Therefore, focus of the presented analysis lies on the detectability of the starting time of acoustic signals. All signals show single shot measurements, no averaging for noise reduction is used. The first measurements use the synthetic signal setup with a basic oscillating frequency of 150 kHz. Simultaneously, the winding fragment is excited with 100 Hz to simulate transformer vibrations. Figure 7 shows the recorded acoustic PD signals of both sensors.

The signals are triggered on the reference output of the signal generator. The delays between signal start and trigger are caused by the sonic speed in oil of approx. 1400 m/s [10]. Both sensor output signals are amplified by 40 dB and have a clearly detectable start time (marked by the coloured arrows at 250 µs for in-oil and 400 µs for tank-wall measurement). The combined sensor has a steeper derivation, which is advantageous for start time detection. The noise levels are approximately equal. Both channels show multiple local maxima, indicating reflections on the tank wall. Eventually, both signals are well suited for start time detection.

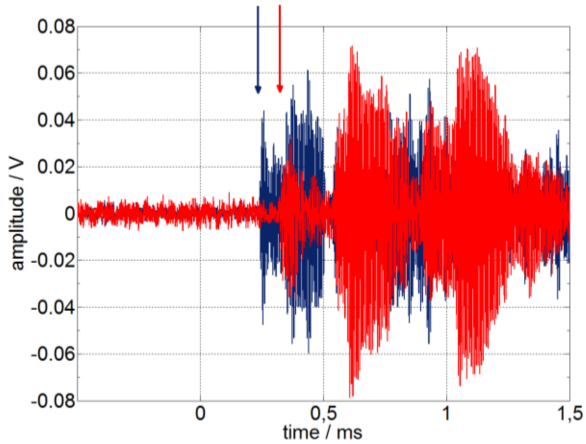

Figure 7: Signal of in-oil (blue) and outside tank wall measurement (red). PD signal frequency 150 kHz

Figure 8 shows a measurement at an increased basic oscillating frequency of 180 kHz. The piezo-electric source has low sonic coupling at this frequency resulting in smaller signal strength. The coloured arrows mark the actual arrival time of PD signals at the positions of the combined sensor (blue) and accelerometer (red). It becomes apparent, that the start time is still detectable in the in-oil measurement, but not on the outside tank wall. In contrast, higher amplitudes at 600 µs, which are caused by reflections, would indicate a delayed start time and hence result in an erroneous PD source localisation. Considering the SNR of both sensor locations, the in-oil measurement is also advantageous.

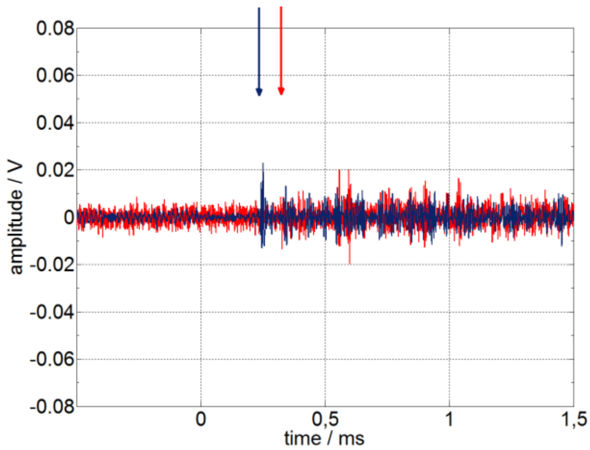

Figure 8: Signal of in-oil (blue) and outside tank wall measurement (red) at 40 dB amplification. PD signal frequency 180 kHz

The results from the synthetic test setup are confirmed using a needle-sphere electrode acting as PD source. Figure 9 shows the sensor output voltages recorded with a DSO. As trigger an additional UHF antenna is used. It becomes apparent, that there is a small coupling of the UHF signal into the acoustic PD path. This is tolerable because it does not affect the detectability of the acoustic start time. Due to the high level the correct acoustic start time can be detected on both sensors. Again, the SNR of the in oil measurement is better than outside tank wall measurement, whereas the absolute signal amplitude of the accelerometer is higher in this case.

For real transformer measurements the in-oil measurement indicates significant advantages due to the fact, that the signal strength often lies below the noise level of outside tank wall mounted sensors, because of the too low SNR.

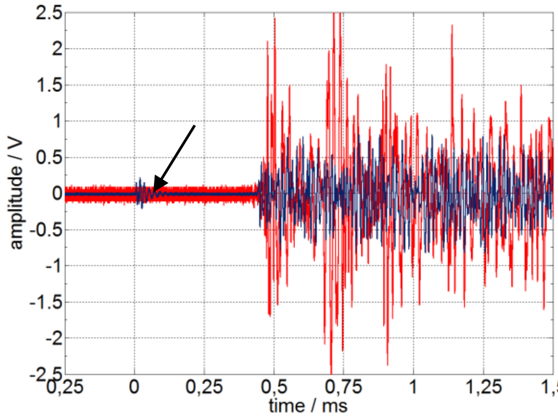

Figure 9: Acoustic measurement of needle-sphere PD source, triggered on UHF antenna. Low frequency coupling of electromagnetic components in combined sensor

3.2 UHF PD measurements

The sensitivity of the combined sensor in the UHF range is determined using a reproducible synthetic signal and real UHF PD signals form the needle-sphere electrode. An UHF antenna (also it is the signal trigger) acts as reference. The setup is used like shown in Figure 4. A single shot is shown in Figure 10. The blue curve shows the output of the passive UHF filter from the combined sensor and the UHF antenna output (coloured in red).

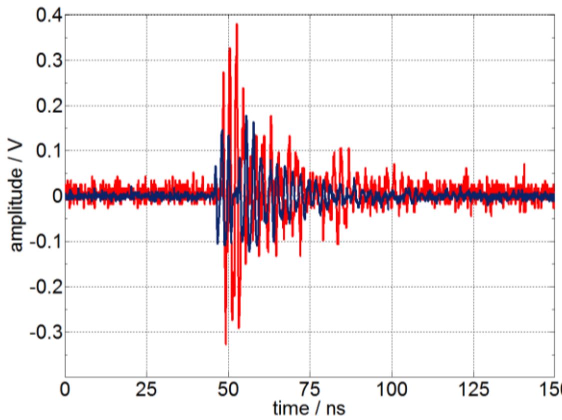

Figure 10: UHF measurement of LDC-7 pulser. Red: UHF antenna, Blue: UHF diplexer output

The distances between source and sensors are equal. The antenna shows nearly double levels at approx. double noise amplitude compared to the combined sensor, thus their SNR is comparable. With both sensors UHF triggering is possible. The combined sensor can be disadvantageous at small UHF amplitudes.Figure 11 shows the frequency domain of the single shot. Red is the reference from the UHF antenna. Direct comparison shows a lower noise floor of the combined senor.

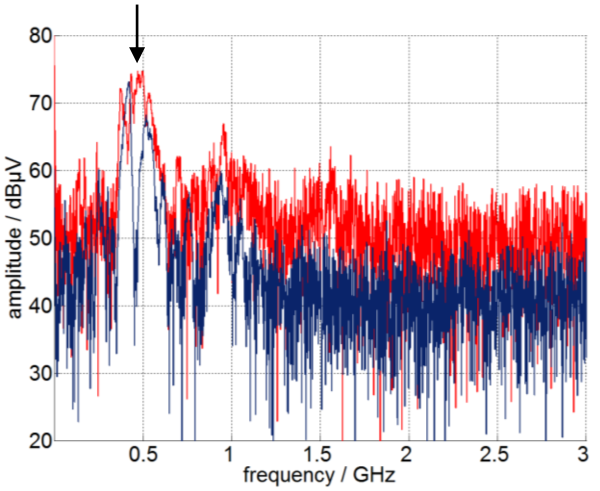

Figure 11: Frequency spectrum of time domain measurement form Figure 10. Red: UHF antenna, blue: UHF output of diplexer from combined sensor

Levels up to 400 MHz are comparable but then the combined sensor's sensitivity decreases with a local minimum at 500 MHz. Antenna and sensor differ approx. with 40 dB. For higher frequencies the sensor is 10 dB below antenna level on average (for noise and the second local maximum at 900 MHz).Time domain measurement is also performed with needle-sphere electrode to confirm the results from the synthetic measurements, see Figure 12.

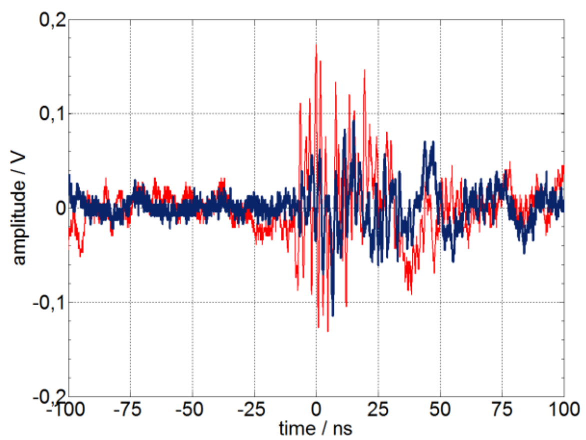

Figure 12: UHF measurement of needle-sphere electrode. Red: UHF antenna, Blue: UHF output of diplexer from combined sensor

It can be stated, that the combined sensor is able to detect UHF signals, but might be disadvantageous if the UHF signal strength is very low.

3.3 Vibration measurements

The evaluation of vibrations is also performed with the setup described in Figure 4 and Figure 5. The winding part is mechanically excited with different frequencies being typical for vibrations: 100 Hz and its harmonics. Measurements are performed in time domain and transferred into frequency domain using Fast Fourier Transformation (FFT). Figure 13 shows the frequency spectrum of the combined sensor compared to an accelerometer mounted at the outside tank wall. The winding is excited with 100 Hz and the signal is level measured (no moving parts). Both sensors use 40 dB amplification, thus the signals' levels are comparable. The combined sensor has higher amplitudes with a very good SNR at basic frequency showing 20 dBµV higher levels than the accelerometer. Harmonics and sub-harmonics of the basic frequency can be measured with both sensors, which are caused by the mechanical resonance frequency and stationary waves from the tank geometry. The combined sensor shows a significantly increased SNR.

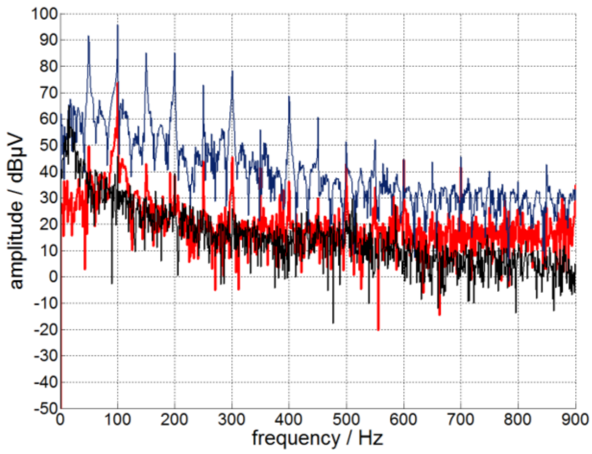

Figure 13: Frequency spectrum of vibration measurement at 100 Hz excitation.
Blue: in-oil measurement of combined sensor
Black: noise measurement in-oil
Red: Acceleration measurement outside tank wall

3.4 Influence of the electric field

Figure 14 shows a simulation of the electrical field strength in the given setup geometry by a finite element method solver. Maximum applied test voltage is 70 kV_{RMS}. The electric field strength at the sensor position with used operation voltage for PD generation in the measurement setup (30 kV) and at a increased voltage of 70 kV are determined. The value E_{RMS} ~9 kV/m at an operation voltage of 30 kV and ~22 kV/m for a test voltage of 70 kV. For both cases the influence on the output signals of the combined sensor is determined. The UHF and acoustic PD outputs are not influenced by 50 Hz due to high damping, see Figure 3.

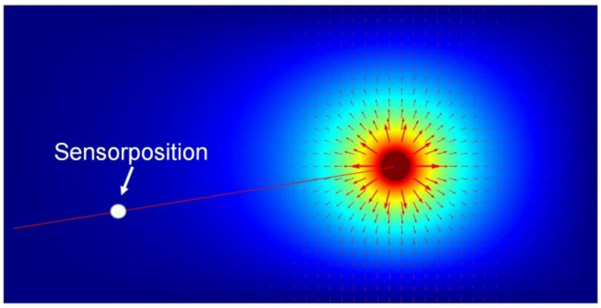

Figure 14: Simulation of the electrical field strength in the test tank setup at applied voltage V_{RMS} = 70 kV

However, vibration measurement is influenced by the electric field. Figure 15 shows the influence compared to a noise measurement of the combined sensor. At 50 Hz the effect of the electric field results in an increased noise level. Because 50 Hz is usually not considered for vibration analysis, the interference is acceptable. At 100 Hz the maximum coupling of the electric field into the vibration measurment path is max. 10dB above noise and hence sufficiently low. Concluding, the effect of the electric field on vibration measurement is tolerable.

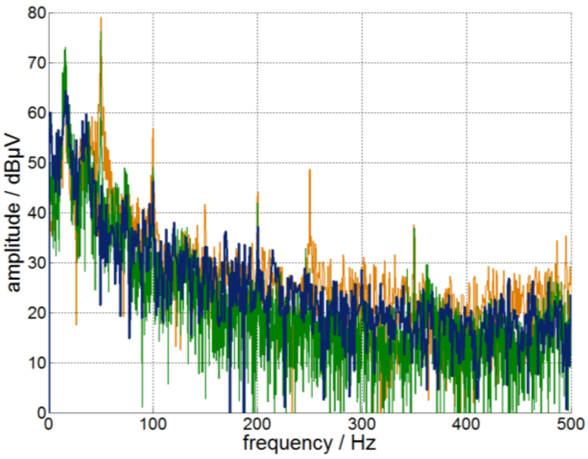

Figure 15: Frequency spectrum comparing vibration measurement and influence of the electric field. blue: noise measurement of combined sensor green: coupling at E_{RMS} ~9 kV/m,
orange: coupling at E_{RMS} ~22 kV/m

4 CONCLUSION

The contribution presents a prototype of a combined sensor being able to measure transformer vibrations, PD acoustics and UHF PD signals simultaneously. Signals are separated by an included frequency diplexer. The combined sensor is designed for application inside power transformers. Laboratory tests evaluate proper operation of the combined sensor. Its abilities and limits compared to conventional sensors are determined. The combined sensor is advantageous to conventional techniques concerning signal quality and SNR. Outside tank wall sensors suffer signal damping by the structure. The sensitivity of UHF of the combined sensor is slightly smaller in comparison to dedicated antennas. It is considered suitable for simultaneous threefold measurements. Tests on power transformers will have to evaluate its usability in practice.

5 REFERENCES

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