Placement of UHF Sensors on Power Transformers

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Abstract

This paper provides recommendations for a useful placement of UHF sensors for PD measurements in power transformers. Further a recommendation will be given about the number of sensors needed to achieve a sufficient UHF PD measurement sensitivity. The recommendations have been evaluated by comparative measurements on a 800/3 MVA transformer and the results have been documented and analysed in this paper. Different types of sensors (a drain valve sensor, several dielectric window sensors) as well as different PD measuring systems (Oscilloscope, Spectrum analyser, different commercial available systems) and different signal generators for simulating UHF PD impulses (rectangular and exponential shapes) have been used to investigate the signal propagation throughout the transformer tank.

1 Introduction

The partial discharge (PD) measurement is very well suited to detect the damage to the insulation of a transformer in a very early stage [1].
Essentially, there are the following four types of PD detection: indirectly by the measurement of dissolved gases (DGA), directly with the electrical PD measurement according to IEC 60270 [2], directly by electromagnetic measurements in the ultra-high frequency range (UHF: 300 MHz – 3 GHz) [3] and the measurement of acoustic PD emissions, which is mainly used to supplement diagnostic measurements for the localization of PD [4].
The UHF method is already established as a trigger for the acoustic localization of PD [4], [5] and for on-site / online diagnoses [6] and is also suitable for permanent PD monitoring of transformers [7]. The UHF method is advantageous because of the shielding effect of the earthed transformer tank against external noise signals during on-site PD measurements [3]. This feature is helpful for various applications, such as e.g. the comparison of undisturbed PD measurements from test field (FAT) to PD measurements on site in a noisy environment after transport and installation, or as an on-site acceptance test [8].
In order to supplement the electrical PD measurement and also to become a recognized quality control factor itself, the UHF method must first prove their reproducibility. So far, there is a lack of a calibration procedure that makes different UHF sensors and different measuring systems (frequency range, time domain, commercial systems) comparable to each other. Furthermore, a guideline for appropriate mounting of UHF sensors on the transformer is missing.
This paper provides recommendations for a useful placement of UHF sensors for PD measurements in power transformers. Further a recommendation will be given about the number of sensors needed to achieve a sufficient UHF PD measurement sensitivity. Additionally, the paper ends with a discussion, if the findings support to develop a procedure, which allows under certain conditions a general quantitative comparability of the UHF PD measuring method.

2 Exemplary UHF Measurements

2.1 Measuring Object

For comparative UHF measurements, an 800/3 MVA single-phase transformer of the voltage level 420/247/33 kV was available. All measurements were carried out without high voltage and the transformer disconnected from the grid. Figure 1 defines the positions of the 8 permanently installed UHF sensors [9]. In addition, two UHF drain valve sensors (see chapter 3) were temporarily inserted through two oil drain valves.

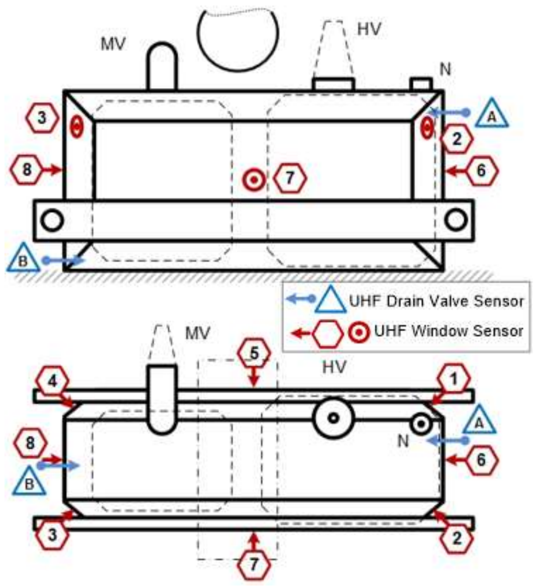

Figure 1 Positions of sensors at 800/3 MVA Transformer for comparative UHF measurements

2.2 Performance Check

The term performance check describes the process where, an artificial pulse is emitted with one sensor as transmitter into the transformer tank and measured with a second sensor (or further sensors) as the receiver. This provides evidence that both sensors are installed properly, meaning that they are able to receive UHF PD signals from the inside of the transformer. The performance check corresponds to the second part of the Cigré sensitivity test performed on GIS UHF PD measurements [10]. The performance check would be negative if the sensor cannot receive any signals due to electromagnetic shielding or high signal damping. For example, when a drain valve sensor is installed at an oil valve with a rising pipe inside or when metallic objects are mounted directly in front of the sensor.

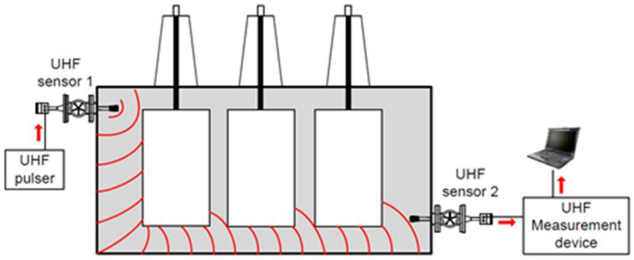

Figure 2 Performance Check on a transformer with 2 drain valve sensors [11]

There are UHF sensors on the market that provide an additional input for a single port performance check beside the actual measurement output. Here an artificial signal is fed in and directly coupled to the actual UHF antenna. However, this test cannot give any indication whether the sensor is installed correctly and not affected by electromagnetic shielding inside the transformer, since the coupling of the signal is only inside the sensor itself.

2.3 Conducted Measurements

The purpose of the measurements at the transformer described above is to compare the different used measurement systems (time domain, frequency domain, commercial PD measuring devices) on the ten installed UHF sensors and to give a recommendation for the optimal number and placement of the UHF sensors based on the results of the measurements.

The following measurements based on the performance checks have been carried out for this by using all different measuring systems and methods:

- inject constant artificial impulses into sensor 6 and record the sensor output amplitudes on each of the other 9 sensors
- inject constant artificial impulses into sensor 5 and measure the amplitudes on all other sensors
- measure the amplitudes on sensor 5 and inject constant artificial impulses into all other sensors

2.4 Impulse Generators and Measuring Devices used

Two different kind of impulse generators respectively impulse shapes are being used for performance checks on transformers, impulses in exponential, respectively capacitor discharge shapes and short rectangular shapes. The exponential impulse shapes are basically limited in their frequency components towards higher frequency ranges (above several hundred MHz), whereas short rectangular impulse shapes are providing a flat frequency spectrum up to several GHz [12] [13]. For the comparative measurements, carried out for this paper, both types of impulse generators have been used.

Two different commercial PD systems, an digital sampling oscilloscope (to represent the time domain measurements) and a spectrum analyzer (to represent the frequency domain measurements) have been used to compare the different measurement principles.

2.5 UHF Signals in Time- and Frequency - Domain

To get an information about the damping phenomena of UHF signals transferred through the active part of the transformer, the responses of the defined rectangular pulse (50 V) injected at UHF sensor No. 6 at three UHF sensors placed at different positions on the tank, were recorded in time- and frequency-domain. Using both, digital oscilloscope (4 GHz analog bandwidth, 40 GS/s sampling rate) and spectrum analyzer (2 GHz analog bandwidth), all signals were recorded and analyzed. An example of coupled signals in time- and frequency-domain to the UHF sensor No. 8, which is far from the injected signal, is shown in Figure 3.

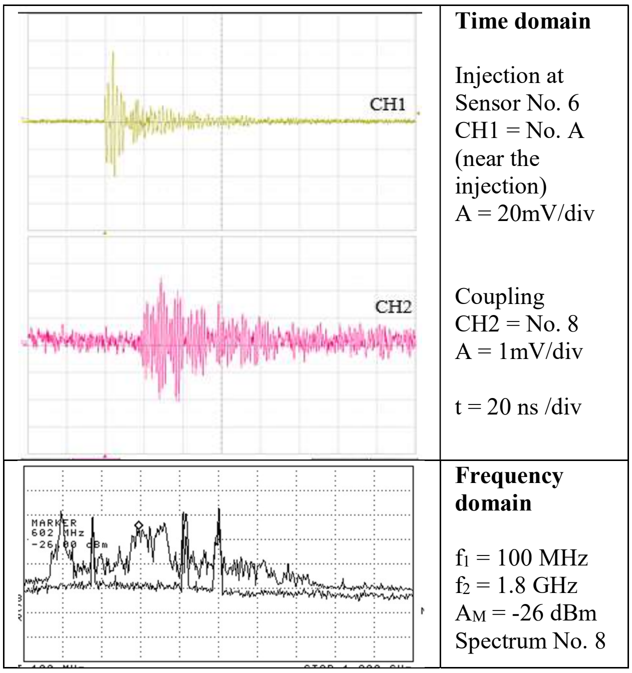

Figure 3 Example of injected and coupled UHF signals in time- and frequency-domain

The UHF signal measured at CH1 (near the injection) has a fast edge and a short back. In the contrary the signal at CH2 (far from the injection) shows a typical filtered longer impulse shape. In the he frequency spectrum the PD signal is clearly visible between approx. 200 MHz and 1 GHz.

2.6 Commercial PD Measurement Systems

There are basically to different types of commercial available UHF measurement systems: Conventional PD measuring instruments (IEC 60270) with frequency converter accessories for UHF range and systems which are using directly impulse detection in the UHF range. Depending on the system used or the settings, different bandwidths and measuring frequencies can be used to generate phase-resolved PD patterns (PRPD, 2D, 3D) [14] or to support acoustic PD localization systems [15]. The measuring systems for transformers typically cover a frequency range from some hundreds of MHz to approximately 1.5 GHz. Figure 4 shows measured PRPDs and the Spectra of an artificial UHF impulse coupled through the transformer.

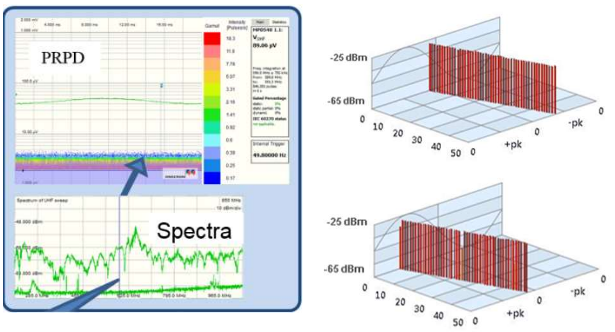

Figure 4 Industrial PD measurement systems providing Spectra, PRPDs or 3D-PRPDs

2.7 Comparison and Summary of Measurement Results

The characteristics of the recorded spectra, measured with spectrum analyser and industrial PD measurements systems, are very similar. The respective unaccounted amplification factors of the preamplifiers or missing calibration result in an unquantified variation of the measured signal levels.

The following Table 5 shows the mean of the spectra given above, comparable to the CIGRE proposal for Average Power (AP) in [10]. The frequency range from 300 to 800 MHz was used for narrowband systems. In the broadband PD system, the AP was used in the frequency range 300 MHz to 1500 MHz. In the case of the oscilloscope time domain signal the "maximum value" was used and converted into dBm, additionally the time signal was transferred into the frequency domain by an FFT, where the AP was also estimated to the above-mentioned Frequency ranges (300 – 800 MHz^{*1}, 300 – 1500 MHz^{*2}).

Table 1: Comparison of different measuring methods

50 V Injection in Sensor 6	Sensor 8	Sensor 5	Sensor 1
Oscilloscope	2.5 mV = -39 dBm -79.8 dBm^{*1} -83.4 dBm^{*2}	7 mV = -30 dBm -73.4 dBm^{*1} -77.9 dBm^{*2}	20 mV = -21 dBm -68.5 dBm^{*1} -65.9 dBm^{*2}
Spectrum Analyzer	-35 dBm	-30 dBm	-25 dBm
Narrowband Commercial	-89 dBm	-84.5 dBm	-76 dBm
Broadband Commercial	-57 dBm	-43 dBm	- 30 dBm

The conducted transfer characteristic experiments show that for the UHF PD diagnosis on power transformers, narrowband as well as broadband systems and measuring instruments in the time domain as well as in the frequency domain can be used. For the selection of the most suitable system, the requirements of the respective application must be observed. The quantitative results are comparable in the form that all measuring systems clearly indicate an increasing attenuation with increasing distance between signal source and measuring sensor. Differences in the attenuations result from the different measuring principles, which are compared here uncalibrated. Among other things, it is the different frequency ranges used that lead to a deviation in the signal power AP, as shown in the example of the oscilloscope. For a future comparability of UHF measurements with different equipment, a fixed frequency range should be defined and documented.

3 Recommendations for the Placement of UHF Sensors on Power Transformers

3.1 Comparison of Drain Valve Sensors and Window Sensors

Drain valve sensors (Fig. 5) for e.g. DN50 or DN80 gate valves (and other straight through oil drain valves) can be used for retrofit of transformers during operation. With these sensors, the insertion depth is crucial for the sensitivity. The positioning of the oil valves and thus the sensors is given by other conditions (usually one valve for oil filling in the upper part of the transformer, as well as one drain valve in the lower part).

Figure 5 UHF sensor for DN50/DN80 gate valves [16]

Due to the influence of the oil valve on the sensor sensitivity, these sensors are less sensitive than window sensors integrated into the tank wall. This influence is reflected in a resonance in the frequency range of a few 100 MHz, which is often used for UHF measurements, see Figure 6.

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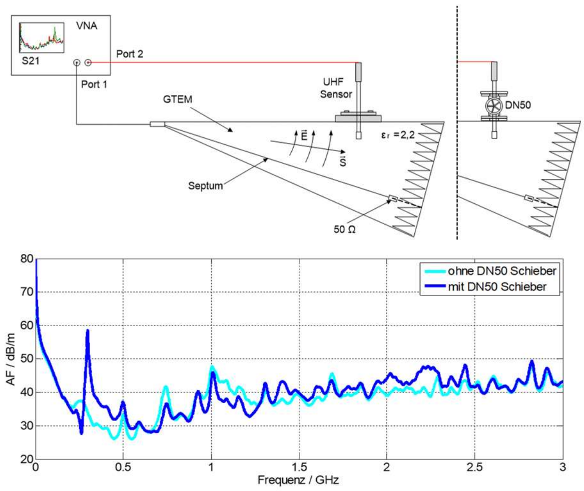

Figure 6 Setup for measuring the sensor sensitivity (oil-filled GTEM cell), and comparison of drain valve sensor directly mounted on cell and mounted on cell using a DN50 gate valve. [11]

Window sensors (Figure 7) can be directly integrated into the tank at new transformers through a dielectric window. The dielectric window serves as a gateway for electromagnetic PD signals to the UHF sensor and as an oil barrier. The sensor can be swapped later without oil handling.

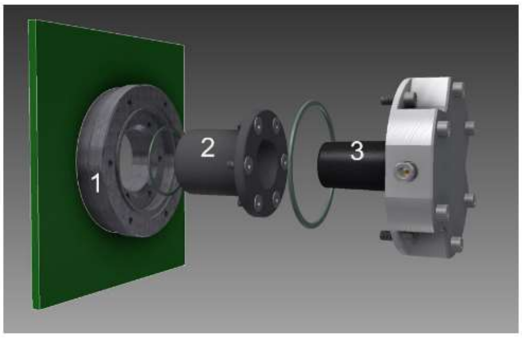

Figure 7 Window sensor according to the recommendations of the Cigré Brochure TB 662 consisting of (1) welding ring, (2) the dielectric window and (3) the actual UHF sensor. [16]

For new transformers, this type of sensor can be placed at nearly free positions on the tank. The window sensor has a better high-frequency grounding than the drain valve sensor, which leads to lower disturbances from the surrounding. In addition, it has no negative influence on the sensitivity from the pipe section of an oil valve, as at the drain valve sensor. Figure 8 shows a comparison of the sensor sensitivity between the drain valve sensor (here without the influence of the oil valve) and the window sensor (plate sensor). Furthermore, the UHF output of a combined PD sensor (combined UHF and acoustic in-oil PD sensor)[17] is compared.

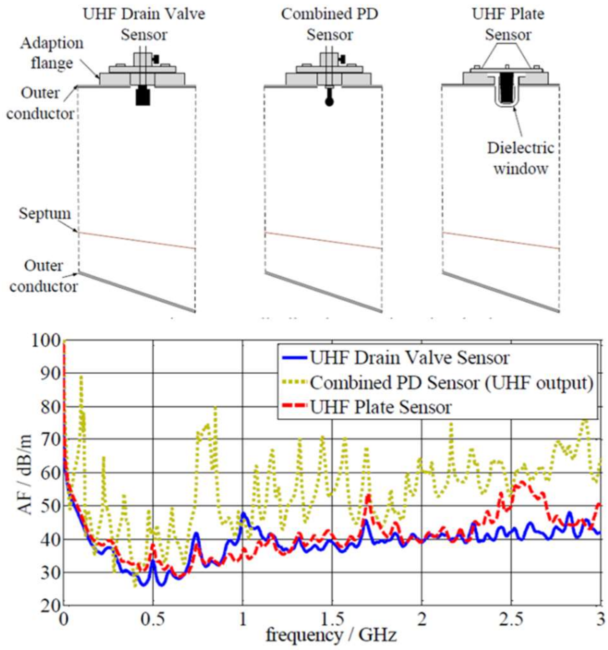

Figure 8 Comparison of the sensitivity between drain valve sensor at 50 mm insertion depth and window sensor. Both sensors show similar sensitivity. Here shown without the negative influence of the oil valve (see Fig. 6) [17]

3.2 Insertion Depth of Drain Valve Sensors

Various UHF performance check measurements on transformers (one exemplarily shown in Fig. 9), show that drain valve sensors, which are still in the pipe section of the oil valve (pos. 0-1) are still shielded against UHF signals from inside the transformer. In order to achieve sufficient sensitivity, the sensor must protrude into the transformer tank (pos. 2). Further insertion (pos. 3-6) does not significantly increase the sensitivity and can lead to safety risks.

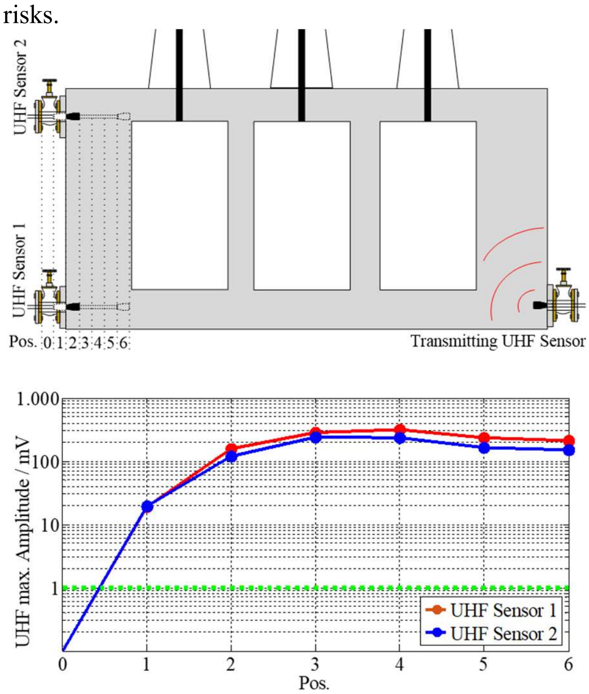

Figure 9 Dependency on the insertion depth [17]

The trade-off between safety and sensitivity leads to the general recommendation of 50 mm insertion depth for drain valve sensors. This insertion depth of the sensor is also achieved with the window sensors, which are manufactured according to the design specification of the Cigré brochure TB 662 [18].

3.3 Number of UHF Sensors

The execution of the performance check as described in chapter 2.2 is essential to receive meaningful and reproducible UHF PD measurements. Hence at least 2 UHF sensors should be available in a transformer tank. The most logical positions on the site walls may cause problems for the sensor placement as often the OLTC is installed on one side of the transformer tank. This could negatively influence the signal propagation.

Based on the measurements above and experience of the authors the recommendation is to place 4 UHF sensors on a transformer tank. Optional, additional sensors can be placed for bigger size transformers. See table 2.

Table 2: Recommended number of UHF sensors for power transformers

Minimal configuration:	2 sensors (minimum for performance check)
Recommended standard configuration:	4 sensors (minimum for localization purpose)
High-end configuration:	6 - 8 sensors (depending on size of transformer vessel and importance of transformer)

As per the presented results at chapter 2.7, the expected attenuation of the signal traveling in longitudinal direction of the transformer vessel is low (few dB only). That means, that the 4 sensors positioned according to the proposal as per figure 10 can be seen in this case as sufficient for an enough sensitive UHF PD measurement. This statement is limited by the fact of missing confirmation by the measurement of real PD sources for different failure types at different power transformers equipped with 4 UHF sensors.

3.4 Placement of UHF Sensors

The placement of the UHF sensors should be decided under the consideration of the position of the active part or parts of a transformer inside the tank. Although especially on the side walls of the transformer tank, the positions of the magnetic yokes and the tap changer must be considered, which have the potential to screen UHF sensors and can lead to a reduction of their sensitivity. Furthermore, there are for example the leads to the tap changer at the front and/or the back side, which have the potential to lead to an unwanted screening the UHF sensors, too. The propagation paths of electromagnetic waves inside of a transformer from the signal source to the sensors are complex and usually multiple. By experience, transformers with special lead exits (turrets), need to be special taken care to achieve a sensitive signal decoupling in these areas, as these areas are often prone to PD activities [19].

As to low distances are reducing the sensitivity of the sensors, it has to be taken care in positioning in a way that the sensors have a fair distance to edges and corners of the tank (min 25 cm). Further, it needs to be avoided, that internal metallic parts like deflector plates are screening the sensor electromagnetically. Figure 10 shows exemplary a good distribution of the UHF sensors also considering later localization approaches.

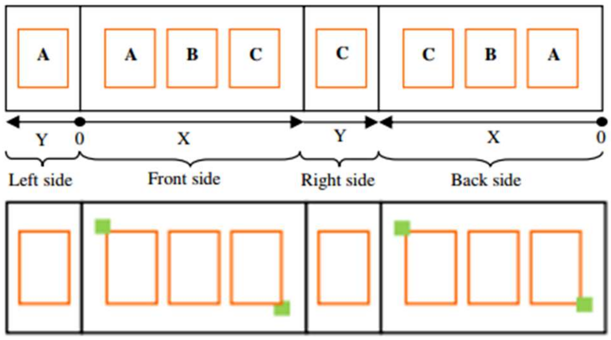

Figure 10 Geometric restoration view of a transformer with four positions for UHF sensors [20]

As shown in chapter 3.1, UHF window sensors providing pivotal advantages, like reproducible sensitivity which is independent from possible failure conditions, more linear sensitivity over the frequency range as well as easy and safe handling. Hence following the CIGRE recommendation [18] it is recommended to use UHF window sensors for new transformers. If no window sensors will be installed for new transformers, it makes sense to foresee dielectric windows (see CIGRE recommendation [21] and [18]), which will allow the cost-efficient retrofit of UHF sensors for monitoring or diagnostic purpose (e.g. PD localization) at a later point in time.

4 Conclusion

The findings gained during the comparative measurement on a large power transformer lead to the conclusion that UHF signals can be sensitively measured with different measuring systems. The experiment compared the qualitative results of time domain measurements by oscilloscope, frequency domain measurements by spectrum analyzer, and two commercial PD measurement systems. The qualitative results regarding the sensitivity of different sensors and the positioning of sensors are summarized as follows, independent of the measuring method:

- UHF signals experience a path-dependent attenuation, which increases with increasing distance.
- In the range of 400 – 800 MHz, a comparable coupling is possible regardless of the used pulse shape of the signal generator at the transformer considered in this publication.
- Compared to drain valve sensors, window sensors have the advantage of a better high-frequency grounding and therefore lower disturbances. Further the insertion depth is fixed, which leads to better reproducibility. Also the frequency response is more linear.

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- A minimum UHF sensor configuration consists of at least 2 UHF sensors to perform the performance check
- The recommended standard configuration consists of 4 sensors to assist in locating via UHF sensors.
- A high-end variant may consist of 6-8 sensors for very large tanks and / or critical assets.
- When positioning the UHF sensors, make sure there is sufficient clearance (at least 25 cm) to the corners and edges of the tank. It must be avoided that internal oil guidance structures or metallic structures shield the sensor electromagnetically from internal PD signals.

The comparability of different measurement methods will be the subject of further investigations in order to investigate and quantify the influence of measurement results as a function of the selected frequency range and the performance of narrowband or broadband measurements. In general, the qualitative statements of the measurement methods used are comparable, so that a general quantitative comparability (by calibration [22]) of the measurement methods seems possible. The UHF signal transmission properties are likely to be significantly different for different transformer types and tank sizes, which is why further experimental work is required to make more general and more specific statements on transformer types.

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