UHF SENSORS SENSITIVITY IN DETECTING PARTIAL DISCHARGE SOURCES IN A TRANSFORMER

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Abstract: Partial discharge (PD) detection in the ultra high frequency (UHF) range can offer better immunity against electromagnetic disturbances and higher signal-to-noise ratio. However, the UHF method cannot be calibrated as per IEC 60270 to determine the equivalent apparent charge from the output signal of the UHF sensors. As a substitution to the calibration, sensitivity verification is proposed by the CIGRE WC 15.03. The sensitivity of the UHF measuring method is very dependent on the type of PD source, the construction of the transformer and the sensor types. In this paper, 4 different sensors are applied to capture PD signals from two different types of PD source (void and floating metal) to check sensors sensitivity. The effect of a physical barrier between sensor and PD source is also investigated. The total energy and magnitude are extracted from the full-span and zero-span spectra. For similar PD level, the total energy of the full-span spectra, with the barrier at varying distance from the sensor, shows random values. The total energy and magnitude of zero-span spectra show linear correlation to the PD level if the barrier is kept at the same position.

1 INTRODUCTION

The transformer is one of the most important equipment items in electrical power system networks. Any failures that lead to transformer outage must be avoided. Transformer failure is mostly due to the failure in the insulation and this is usually started by the occurrence of partial discharge (PD).

The electromagnetic pulse emitted by the PD source has a very short duration, typically less than 1 ns of rise-time and few ns of pulse-width. Thus it is a broad band signal which contains frequency components well into the ultra high frequency (UHF) range (300 – 3000 MHz). Partial discharge detection at UHF has some advantages over the conventional IEC 60720 method, such as immunity against electromagnetic disturbances and higher Signal-to-Noise-Ratio. Due to these advantages, to date the UHF detection method is widely used to detect PDs in Gas Insulated Switchgear (GIS). Also, development for its application in transformer is being investigated by various researchers. However there is a drawback with the UHF method due to the problem with measurement calibration. The UHF method cannot be calibrated as per IEC 60270 to determine the apparent charge from the output of UHF sensors [1].

A PD can occur at almost any location inside the transformer tank. The path of the electromagnetic signals from the PD source to the sensor is affected by the structure inside the transformer. The PD signal propagation can be obstructed by some solid material parts inside the transformer. The active parts of the transformer also affect the attenuation of the electromagnetic signals which caused the attenuation not linear to the distance. Thus without knowing the exact location of the PD, it is difficult to convert the amount of PD detected by the UHF sensor to an equivalent pC level [2].

As a substitution to the calibration, CIGRÉ WC 15.03 [3] has recommended sensitivity verification which can be used to determine on-site the minimum sensitivity of this measuring method in GIS. The sensitivity of the UHF measuring method is very dependent on the type of the sensor, types of the PD source and the location of the PD source [2, 4, 5].

This paper investigates the sensors sensitivity to detect different PD sources. Four different sensor types were applied to detect PD signals generated by two different PD defect models (floating metal and void). To simulate the presence of a physical barrier, a bakelite plate was positioned between the sensors and PD source. The PD source was installed at a fixed location and at the same height level as the sensor. Both the sensor and the PD source are immersed in transformer oil insulation.

2 UHF DETECTION AND MEASUREMENT

The UHF sensors detect the PD signals by capturing the electromagnetic waves emitted by the PD source. The electromagnetic waves travel inside the transformer tank in every direction. Thus the signals might be refracted and reflected during the flights. All the signals including the direct and reflected signals will be captured by the sensor and transferred to the measuring unit such as an oscilloscope or a spectrum analyzer.

The signal spectrum can be readily obtained using a spectrum analyzer. One of its standard features is that the frequency range can be set up to measure the spectrum over the full frequency range of the analyzer (9 kHz to 1.5 MHz for the instrument used in this work) or over a narrower range or even at a single frequency with the zero span function. Applying the full frequency span, the spectra of the PD can be recorded to show the magnitude of the PD at each frequency over the full frequency range. The zero-span mode is applied to record the phase resolved partial discharge (PRPD) patterns with respect to the 50Hz power frequency cycle. Thus by using a spectrum analyzer for measurement, PD activities can be quantified in terms of the magnitudes of the spectra recorded in the two recording modes aforementioned. The disadvantage of using such an instrument is that, due to its measurement principle, a relatively long integration time is needed to build up the spectrum display.

2.1 Experiment Set-up

Two PD defect models were constructed to simulate discharges due to a void and floating metal. The PD defect models were built using three layers of solid insulation sandwiched between two flat copper electrodes: 2 layers of pressboard and a layer of Kraft paper on top. For both void and floating metal, the middle layer of the pressboard was punctured to create a hole with diameter of 0.5 mm. For floating metal sample, a metal plate was fitted into the hole. All samples were immersed in oil inside a fully covered distribution transformer tank in the laboratory. The PD sources were positioned 70 cm from the sensor. Between the sensor and PD source, a solid barrier is placed in varying distance to investigate its effect on the signal propagation.

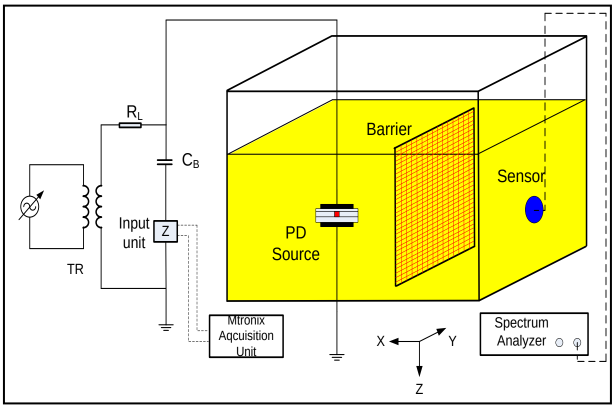


Figure 1. Experiment setup

The applied voltage was increased until the inception voltage was reached and then increased further to produce larger PD levels. The PD signals were recorded using a conventional IEC60270 measurement system and a spectrum analyzer for each PD level. The experiment setup is illustrated in Figure 1.

2.2 Sensor

The presence of defects such as a cavity or metal particle trapped in insulation is undesirable. These defects will enhance the local electric stress and if it is excessive, local breakdown will occur. Electromagnetic pulses will be emitted as a result. These pulses have a very short duration, typically less than 1 ns in rise time and a few ns of pulse width. Their spectra cover a wide frequency range, typically from some kHz to a few GHz.

Unlike the IEC60270 conventional method which records the apparent charge by electrical means, the UHF method utilizes antennas to capture the electromagnetic waves generated by the PD sources. For monitoring purposes, such sensors can be either inserted via the oil drain valve [6] or dielectric windows [7]. In the experiment, 4 sensors were tested and used to capture the electromagnetic signals emitted by PD sources. They are log-spiral, conical, short monopole and spiral as shown in Figure 2.

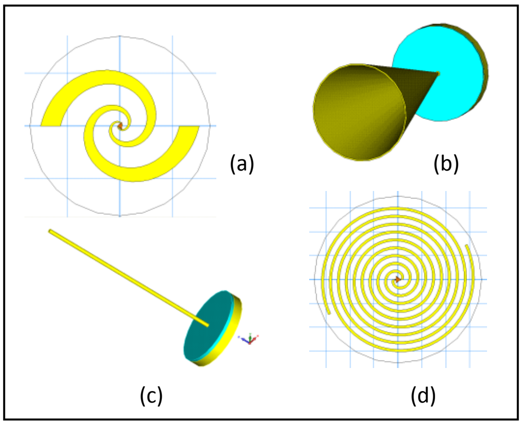


Figure 2. The types of sensor in use, (a) Log-spiral, (b) conical,(c) monopole, and (d) spiral

2.3 PD Signal Spectrum

The occurrences of the PD can be observed from the full span spectrum, by comparing the full span spectrum measuring results which are obtained with and without PD signals. Figure 3 shows typical full span measurements of the 4 sensors without PD. The sensors were placed inside a fully covered transformer tank and connected to the spectrum analyzer using 10m coaxial cables. External interference from known sources such as digital radio/television broadcast and mobile telecommunication can be noticed at frequency below 300 MHz and at around 900 MHz.

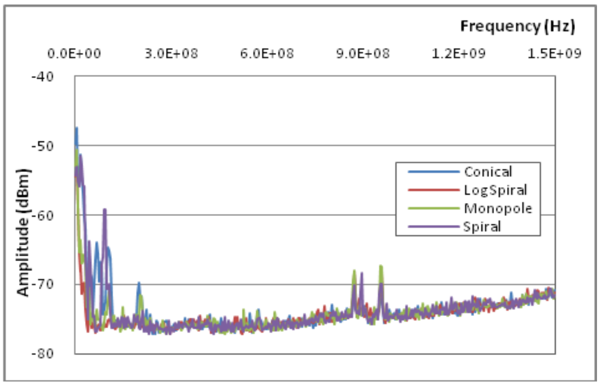


Figure 3. The background noise spectrum recorded by 4 different sensors.

Figure 4 shows the PD spectrum captured by the sensors when the void defect generated PD at 60 pC. By comparing Figures 3 and 4, the occurrence of the PD can be identified. The PD appears in the frequency range 200 MHz to 300 MHz. This can be confirmed by setting the spectrum analyzer to zero span mode and set the frequency to a specific value in this frequency range. In the experiment, after trial of several values, the frequency setting at 270 MHz gives the highest magnitude response. The zero span measured results show the phase resolved partial discharge (PRPD) pattern which is very similar to the result recorded by the IEC60270 method (Figure 5).

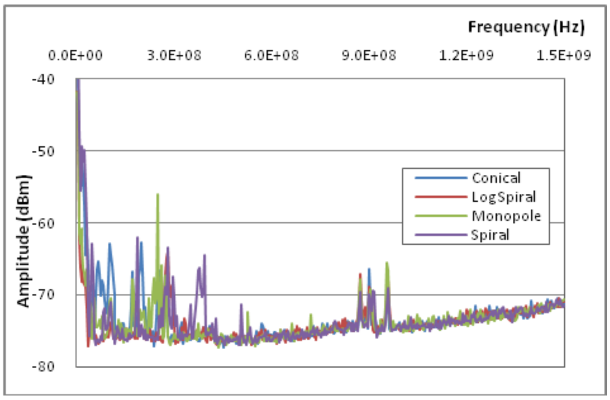


Figure 4. Full-span of void PD spectrum captured by 4 different sensors at 60 pC.

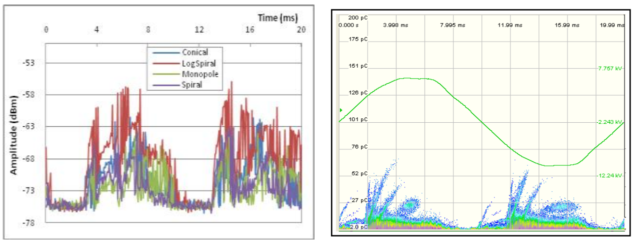


Figure 5. PD spectrum of zero-span at 270 MHz of void PD at 60 pC

Higher PD levels appear to generate spectrum in higher frequency for both PD sources. At lower PD levels, both samples produce quite similar frequency ranges, but at higher level (at around 150 pC) the void generates frequency components in the same range (200 MHz to 500 MHz) while the floating metal defect emits electromagnetic signals up to 750 MHz. These frequency ranges are obviously far lower than that for GIS which can be up to 6 GHz [8]. This could be because the oil attenuates the higher frequency components of the PD signals.

3 RELATIONSHIP BETWEEN THE UHF AND IEC 60270

CIGRÉ WC 15.03 recommended sensor sensitivity verification as an alternative to overcome the calibration problem of the UHF method. An approximation of the measured PD using the UHF method comparable to the magnitude of pC as recorded by the IEC60270 can be done. To be able to make comparison, what is needed is a quantity extracted from the UHF measurement results such as the energy and magnitude of the PD spectrum [5,9,10]. The UHF measurement itself can be carried out in two modes, i.e. full-span and zero span. In this paper, both full-span and zero-span are investigated.

3.1 Quantifying the PD spectrum

Direct comparison of the PD spectra in order to determine the difference between them or to observe the effects of the barrier on the propagation of the PD signals can be difficult. For example, the spectra recorded by using different sensors in Figure 4 show quite similar patterns. Thus it would be difficult to detect differences if any between them. Therefore, it is useful if some parameter can be extracted from the spectra [4,7,9] to be used as a comparator. For the analysis purpose, the total energy is extracted from both the full-span and zero-span measuring results. As an addition for zero-span, the magnitude of the spectrum is also included as an indicator to analyze different sensors.

Due to its nature, background noise is always present in the measurement results. Different sensors have different noise background level as shown in Figure 3. To eliminate the noise, the spectrum without PD, i.e. noise background is subtracted from the spectrum with PD.

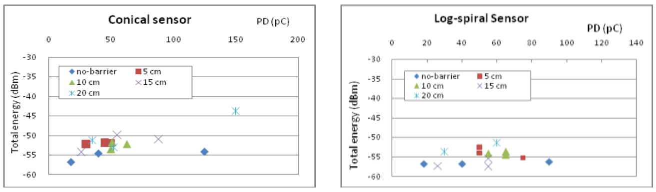
Table 1. The total energy of the full-span spectrum of different sensors

	Spiral (dBm)	Monopole (dBm)	Log Spiral (dBm)	Conical (dBm)
Background Noise	-48.1273	-48.5799	-48.9069	-47.8877
Void (20 pC)	-47.8890	-48.1198	-48.2564	-47.3635
FM (30 pC)	-47.6589	-47.0977	-48.1293	-47.0395

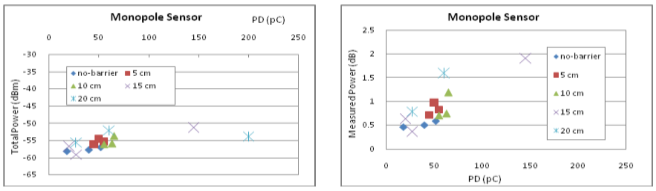
3.2 Void PD

The PD level at the inception voltage is ~20 pC. At this PD level, the total energy of the full span spectra increases slightly from the total energy of the noise background. Table 1 shows the total energy of the noise background and the inception of full-span for both void and floating metal PDs.

Figure 6 shows the total energy graphs of full span for all sensors with varying barrier distance (the background noise has been subtracted). All sensors are able to capture PDs as low as 20 pC. As the PD level increases, the total energy is also increased. The presence of the barrier has a random effect to the total energy and almost un-correlated to its position. All sensors produce similar results.

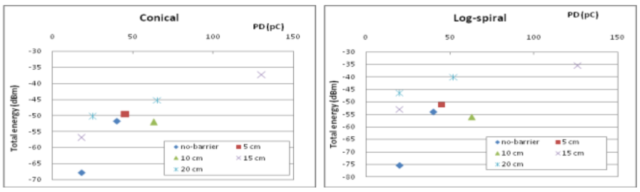


(a) (b)



(c) (d)

Figure 6. Total energy of full-span spectra with varying barrier position, void PD source



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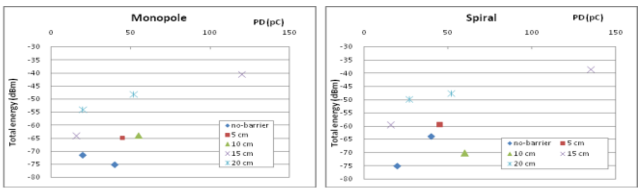
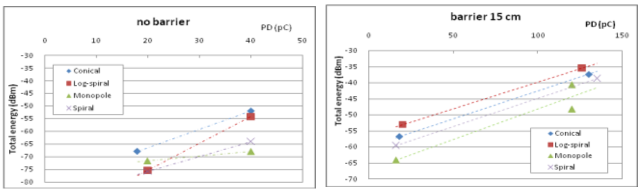


(c) (d)

Figure 7. Total energy of zero-span spectra with varying barrier position, void PD source

In the experiment, measurement was done in both full-span and zero-span modes as aforementioned. Similar to the full-span method, the zero-span measurement results can also be used to determine the sensitivity of the sensors. Figure 7 shows the magnitude of the measured power as a function of PD level without and with the presence of the barrier. Similar to the full-span result, the presence of the barrier on zero-span mode has random effect to the total energy.

Figure 8 shows graphs of the total energy and magnitude of the zero-span spectra for all sensors with the PD level. The total energy and magnitude of the PD spectra show linear correlation with the PD level. This linear correlation occurs for both cases (with and without barrier). Thus, it suggests the zero-span method can be used to calibrate or at least to check the sensitivity of the sensors. The graphs also show the conical and log-spiral sensors have higher sensitivity (in dBm/pC) than the spiral and monopole sensors.



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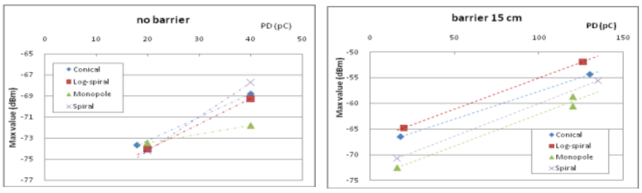


(c) (d)

Figure 8. Total energy and magnitude of the zero-span spectra of void PD.

3.3 Floating Metal PD

Figure 9 shows the full span spectra of the floating metal PDs. The PD level is ~30 pC at the inception voltage. Similar to the void, the spectra reveal occurrence of the PD over a similar frequency range from 200 MHz to 300 MHz. The 270 MHz is chosen as the frequency of the zero span mode, to make it comparable to the void zero-span spectra.

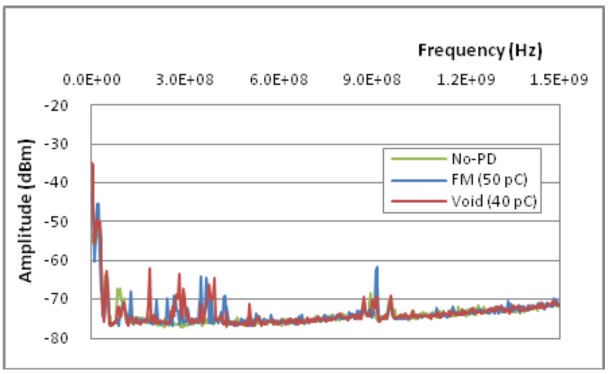


Figure 9. The full-span spectrum of floating metal and void, measured using spiral sensor.

All sensors demonstrate capability to detect the PD at inception level. The powers of the PD spectra at 30 pC are shown in Table 1, slightly higher than the total energy of the inception of void PD. This is due the higher PD inception level of the floating metal defect.

The full-span spectrum of the floating metal is similar to that of the void. As mentioned before, the frequency range of both void and floating metal is mainly in the range 200 MHz to 500 MHz. Figure 9 shows the full-span of the void and floating metal.

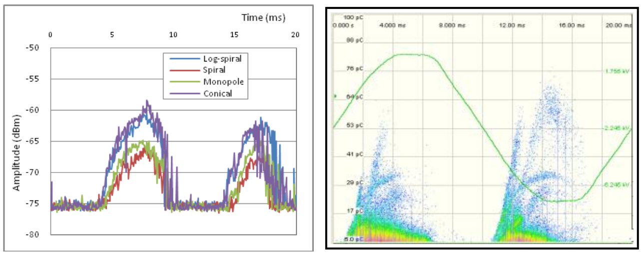
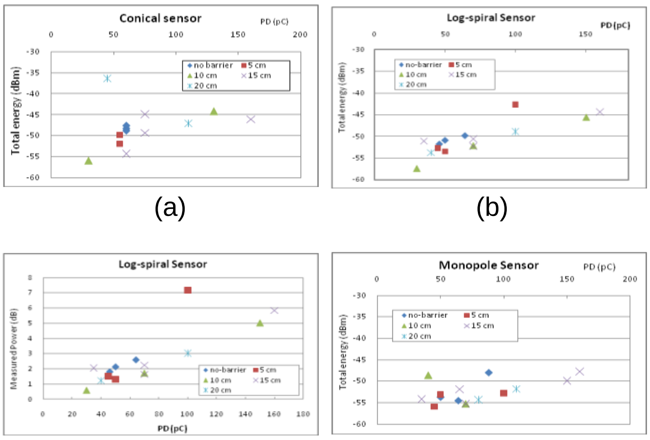


Figure 10. Zero-span spectrum at 270 MHz of the floating metal and comparison to the IEC60270

The presence of a solid insulating barrier at different location has no significant correlation to the total energy of the full-span and zero span mode results. For similar PD levels, the total energy of the full-span spectra shows random values. This result suggests that knowing the location alone is not enough to enable converting the total energy to an equivalent pC value. One needs to know the detailed structure of the transformer as parts of the transformer may block the travelling path of the PD signals to the sensors.

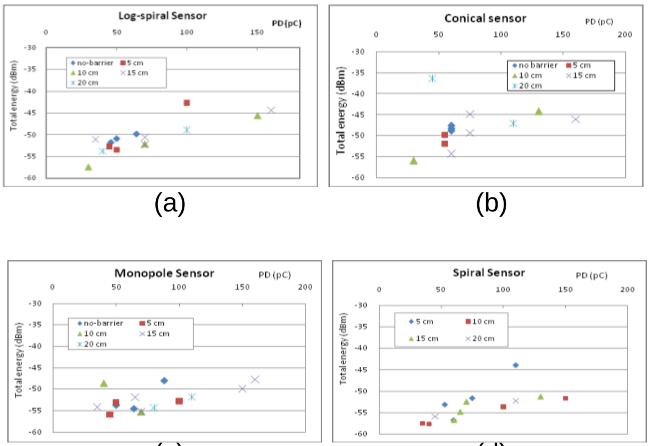


(a) (b)

(c) (d)

Figure 11. Full-span total energy of sensors with varying barrier position, floating metal PD source

The total energy of the full-span and zero span spectra of PDs from the void and floating metal shows similar trend. All sensors can detect both PD sources with a PD inception of 20 pC. For similar condition, i.e. barrier at same position, the total energy and magnitude of zero-span spectra show linear correlation to the PD level. Similar results are observed for all sensors.



(a) (b)

(c) (d)

Figure 12. Total energy of zero-span with varying barrier position, floating metal PD source

4 CONCLUSION

Four different UHF sensors are used to capture electromagnetic signals emitted from PD sources. These sensors are connected to a spectrum analyzer which is used to record the spectra of PDs from void and floating metal. All sensors show ability to capture electromagnetic signals emitted by both PD sources and sensitive enough to detect the PD inception from both sources.

Two indicators are extracted from the PD spectra, i.e. total energy and the magnitude. Result show that the presence of a solid insulating barrier has no significant correlation to the total energy value. For similar PD level the total energy, with the barrier at varying distance from the sensor, shows random values.

The total energy and magnitude of the zero-span spectra show linear correlation to the amount of PD for same position of the barrier. All sensors show similar results.

5 REFERENCES

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