DESIGN OF ULTRA HIGH FREQUENCY SENSORS FOR DETECTION OF PARTIAL DISCHARGES

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Abstract: Partial discharge (PD) measurement is an effective method to detect insulation deterioration. There are different ways that could be used to detect PDs, such as conventional PD measurements of the IEC60270, acoustic method and ultra high frequency (UHF) method. The UHF detection method has a number of advantages; the most dominant among these is a relatively lower level of noise and thus a better signal-to-noise ratio. This paper discusses the design of UHF sensors to detect PDs. Several types of sensor are investigated: monopole and conical sensors suitable for installation at transformer oil drain valves; bowtie, spiral and log spiral sensors for use at GIS dielectric windows. The sensors have ultra wideband (UWB) characteristic within frequency range of 300 MHz to 3 GHz. Experimental results show the conical sensor has higher gain response compared to the monopole, but the latter has a simpler construction. The disk sensor type with log spiral has a higher and smoother gain than the spiral and the bowtie, and its impedance characteristic is relatively more stable. Overall, results show the conical and log spiral antennas have the best response to PD signals.

1. INTRODUCTION

Partial discharge detection by ultra high frequency (UHF) method has some advantages compared to other approaches such as the conventional IEC60270 method [1,2,3]. This mainly arises from the impunity of UHF sensors from noise and interference. UHF sensors for PD monitoring can be inserted via oil drain valves as in transformers [4,5,6] or dielectric windows as in GIS [1,7,8,9]. The presence of the sensor itself can compromise the insulation integrity of the existing structure. Thus the type of sensor that can be used depends on the particular application which imposes constraints on its geometry and size.

This paper discusses two types of sensor for applications mentioned above. For mounting via transformer oil drain valves, the straight monopole and conical antennas are considered. For use via GIS dielectric windows, three disk (plane) sensors are investigated: bowtie, spiral and log spiral antennas.

2. EXPERIMENTAL SETUP

2.1. Sensor design

All sensors were designed and simulated first using the CST Microwave Studio software package. The design parameters taken into account are the impedance, S11 parameter, and realized gain. S11 is the input reflection coefficient with the output port terminated by a matched load. This parameter describes how much the portion of signal will pass through the port and the portion of signal that is rejected (loss). The realized gain gives information about the gain produced by sensor over the UHF range. A good antenna should have an S11 response as flat as possible and its gain as high as possible.

The monopole and conical antennas designed have an axial length of 10 cm and both were mounted on a single layer PCB of 4 cm in diameter. The monopole antenna was constructed using a straight copper rod with diameter of 2 mm. The opening mouth of the conical antenna has a diameter of 4 cm.

The bowtie, spiral and log spiral antennas were etched on single layer PCBs of 17 cm in size. They are balanced type antennas and thus can not be directly connected to the monitoring instrument (e.g. spectrum analyzer) with a coaxial cable. A tapered balun [10] is required.
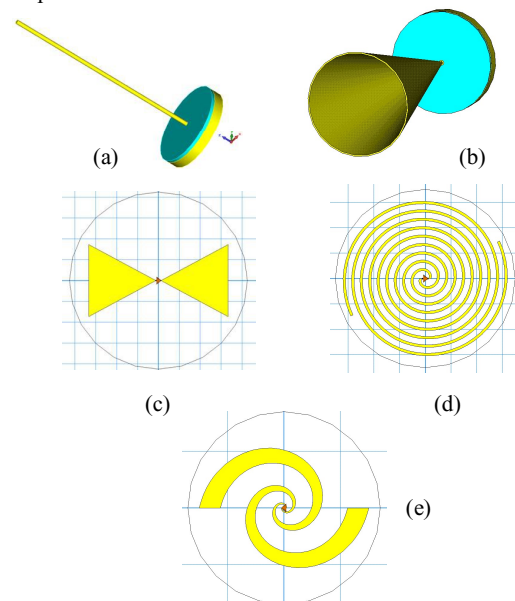

Figure 1. Five different UHF sensors: (a) monopole (b) conical (c) bowtie, (d) spiral and (e) log spiral

2.2. Experiment configuration

All sensors were tested using the same needle-plate electrode and plate-insulation-plate PD sources. The sensors are positioned at the same distance from the PD source and pointing directly at the source.

The signal from the sensor output is fed to a spectrum analyzer via a 50Ω coaxial cable. The analyzer has a maximum span of 1500 MHz. The PD is also measured concurrently using the traditional IEC60270 method with a digital PD detector. The PD magnitude is ~7000pC and ~2000pC for needle-plate and plate-plate electrode respectively, and at this level the raw signal captured by the UHF sensors does not need to be amplified.
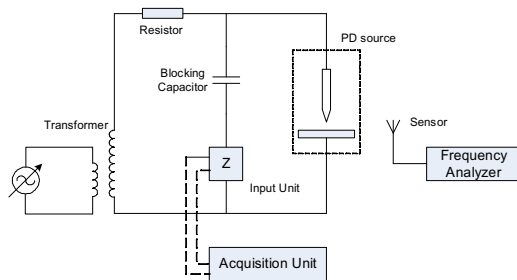
Figure 2. Experiment setup diagram

3. RESULTS

3.1. Simulation Results

The simulation results are shown in Figures 3-5. Comparing the S11 characteristics (Figure 3), the spiral sensor has the most consistent response: mostly flat although uneven at frequency below 700 MHz. Thus this sensor would be suitable for use in wide band measurement. The bowtie sensor also has a relatively flat response from 700 to 3000 MHz except at around 2400 MHz. Meanwhile, the conical and monopole have a very high S11 parameter for some short frequency intervals. The log spiral also has a very flat response with a high S11 value. Thus overall, this sensor appears to have the best S11 parameter characteristic.
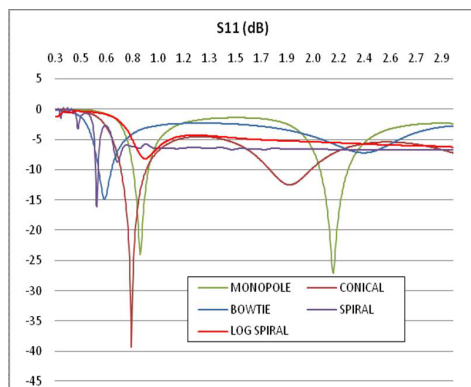
Figure 3. Sensors S11 Parameter.

The monopole has two significant dips in S11 value at around 900 MHz and 2.1 GHz. On this basis, the monopole sensor not a wideband antenna. A similar dip was observed with the conical sensor at around 700 – 900 MHz. For the bowtie and spiral, there are also fluctuations in the range 500 – 700 MHz.

Figure 4 shows the sensor realized gain responses. The conical has higher gain at lower frequency but decreasing rapidly after about 1900 MHz. The monopole also has a similar response, decreasing sharply after around 2 GHz. Thus these two sensors are not suitable for wide band measurement or for detection at the higher end of the UHF band.

The bowtie sensor has the worst realized gain, which is below – 40 db up to around 1.7 GHz. The spiral and log spiral sensors yield similar gain, but the log spiral has a smoother gain.
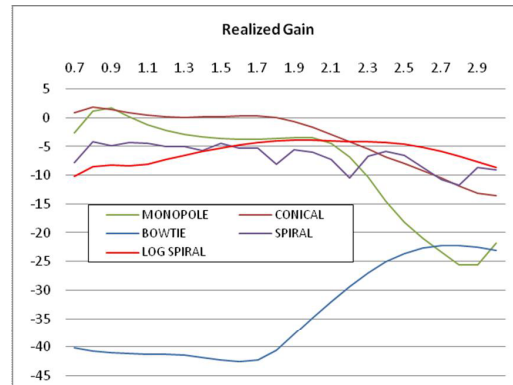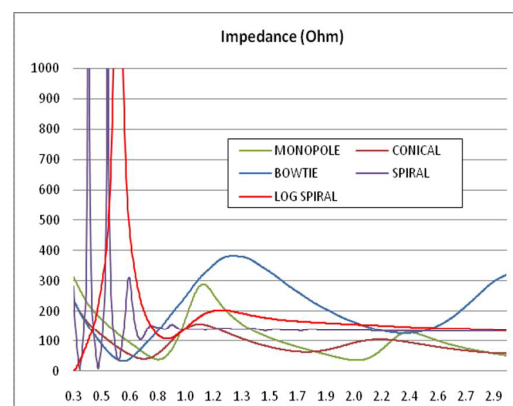
Figure 4. Sensors Realized Gain Parameter

Figure 5. Sensors Impedance

The monopole and conical antennas can be connected directly to a coaxial cable. For the bowtie, spiral and log spiral antennas, the connection is made via a balun. From Figure 5, the spiral sensor has a flat impedance response of around 160 ohms (Qinggo Chen et. al result is 164 ohms). The impedance of the log spiral

antenna is around 180 ohms and the bowtie has a fluctuating response with a mean value around 220 ohms. Using those impedance values, matching baluns were designed using the tapered balun method [10]. The baluns hava a length of 48 cm and tapered near sensor side at 320^0, 330^0 and 340^0 for spiral, log spiral and bowtie respectively.

3.2.   Experiment Results

3.2.1.   Sensors response to background noise

Before using the sensors to detect PDs, their responses to the background noise/interference were tested. All sensors showed similar response patterns. There are three distinct frequency bands where significant interference is present: below 350 MHz, in the range 400 to 500 MHz, and 870 to 950 MHz. For the monopole and conical sensors, the signals captured in the range 870 – 950 MHz are higher than the other sensors. This agrees with the S11 parameter (Figure 2) that indicates the monopole and conical antennas have a higher value at around 800-900 MHz.
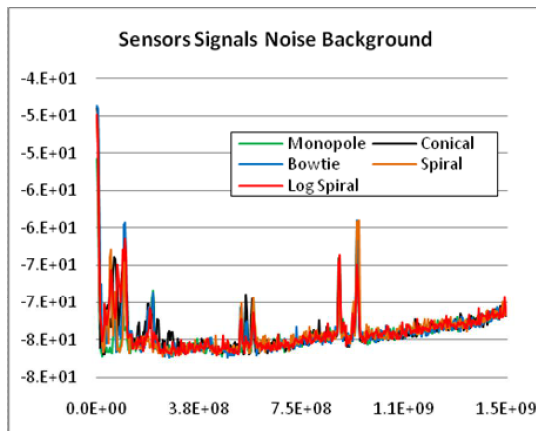

Figure 6: Sensors response to background noise

By comparing the signals captured by the sensors without PD and with PD occurring, it was concluded that the noise level in the frequency ranges below 200 MHz, 400–500 MHz and 870-950 MHz is significant relative to the PD signal. In the first frequency range, the interference comes from radio and television transmissions. The second is associated with television, and the last from mobile phone.

3.2.2.   Partial Discharge detection

PD signals were generated using a needle to plate electrode setup and each sensor was used to detect the PD. All sensors give similar response (Figure 7). Evidence of PDs emitted can be observed in three

frequency groups: below 150 MHz, 200-250 MHz and 300-400 MHz. The conical and log spiral show higher PD signal than the other sensors. For the conical, the three groups of signal can be easily distinguished from the noise, while the log spiral has a weaker response in the range 200-250 MHz.
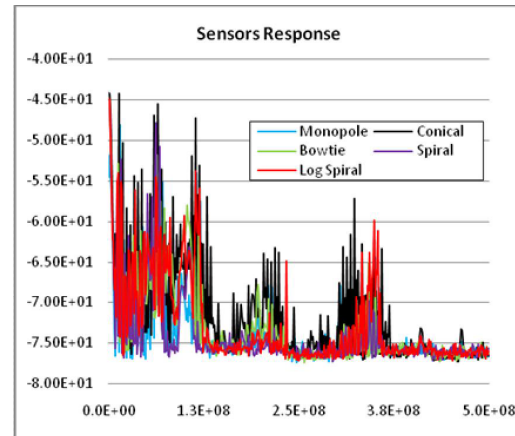
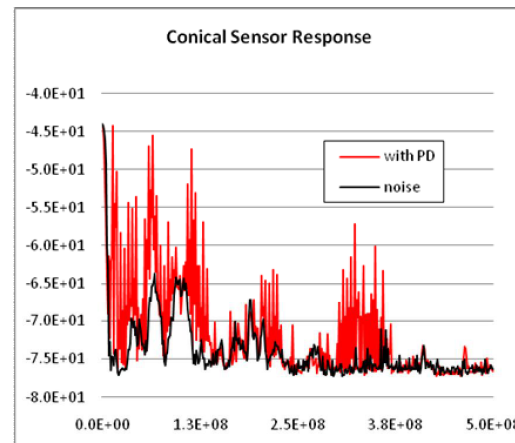

Figure 7: Sensors response to PDs (up to 500 MHz)

Figure 8: Typical conical sensor response

The conical sensor has the highest sensitivity to PD (Figure 8). However, it should be noted that since this sensor should be installed via the transformer oil drain valve, its sensitivity would depend on its depth of insertion. Obviously, the deeper the insertion the higher the sensitivity.

Among the three disk sensors for dielectric windows, the log spiral has the best simulation characteristic and this was verified by experimental result. Figure 9 shows its response to PDs. The pattern is similar to other sensors, with smaller signal in the frequency range 200-250 MHz.
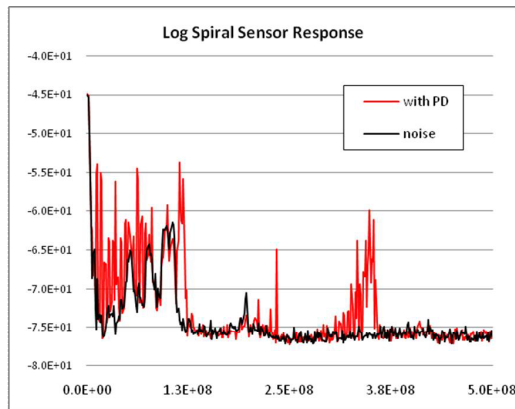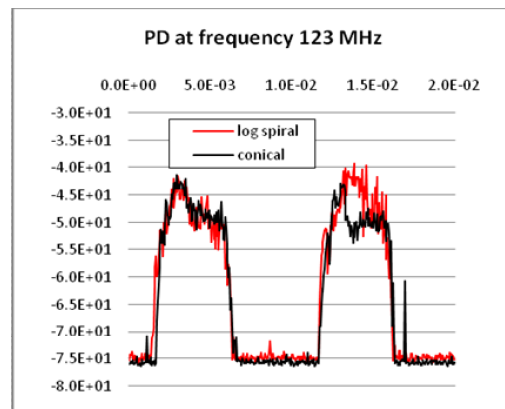
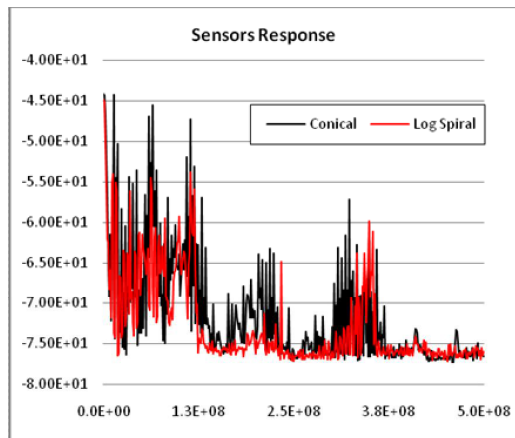Figure 9: Typical log spiral sensor response

Figure 10: Comparison between conical and log spiral sensors.

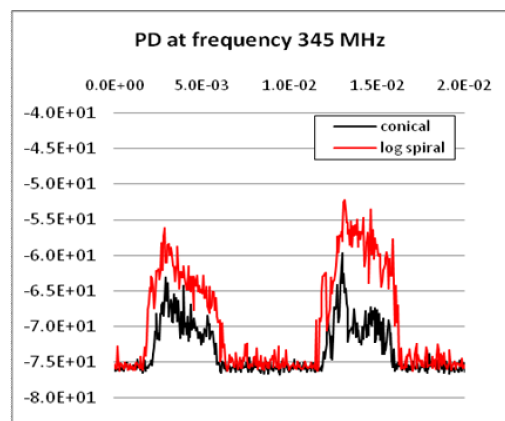

Figure 11: Phase-resolved response at 123 MHz

Figure 12: Phase-resolved response at 345 MHz

Figure 10 gives a comparison of the PD signal captured by the conical and log spiral sensors. By and large, the conical response is relatively higher. This could be because the conical realized gain is higher at lower frequency (below 2 GHz). For narrow-band detection, which sensor gives a better sensitivity varies with the choice of the detection frequency. Figures 11 and 12 show the phase-resolved patterns of the PDs captured by operating the spectrum analyzer with a 20ms sweep (power frequency cycle) at two different center frequencies using plate-plate electrode. The patterns obtained are typical discharge finger-prints, i.e. the PD activity occurs at specific phase windows on the AC cycle. At the lower frequency of 123 MHz, the response seems similar for both sensors. However at the higher frequency (345 MHz), the log spiral appears to be more sensitive.

4.   CONCLUSION

Five different UHF sensors suitable for mounting via transformer oil valve holes and GIS dielectric windows were investigated. CST software was used to simulate and obtain the sensor responses over the frequency range from 300 MHz to 3 GHz. Results show the conical sensor has higher gain compared to the monopole, but the latter has a simpler construction. Among the disk sensors, the log spiral has higher and smoother gain than the spiral and the bowtie. Its impedance characteristic is also relatively more stable.

All the sensors tested can detect UHF signals. However, it can be concluded that the best choice is the conical sensor for insertion via transformer oil drain valve and the log spiral for insertion via GIS dielectric window.

5.   REFERENCES

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