

# The use of multiple sensors for the on-line partial discharge measurement of high voltage electrical equipment

Mr Lee Wai Meng describes the advantages of various detection systems, and suggests that they be used in combination, for the best results.

There are two important components in any on-line partial discharge measurement system. These are the sensors and the measurement system. The use of multiple sensors will greatly improve the detection of partial discharge because different sensors have their strengths and weaknesses. The various sensors commercially available include the transient earth voltage (TEV) type, the ultrasonic type, and the high frequency current transformer (HFCT) type. This article will provide an overview of the various sensors that can be connected to an oscilloscope-based measurement system for high voltage cables, high voltage switchgear, and transformers.

### Transient Earth Voltage (TEV) sensors

The TEV sensors are capacitive couplers placed on the surface of metal-clad switchgear, and which pick up the voltage pulses from partial discharge inside the switchgear. Bandwidth of around 100 Mhz are needed to capture this type of signal because the partial discharge tends to have pulse width of a few tens of a nanosecond. TEV sensors, from different manufacturers, used by the author, are shown in Figures 1 and 2.

### Ultrasonic sensors

Ultrasonic sensors are quartz elements that convert sound energy to electrical energy. The types of ultrasonic sensors that can be used to measure partial discharge are:

- Airborne ultrasonic sensor with output in the ultrasonic frequency range
- Airborne ultrasonic sensor with output in the audio frequency range
- Contact ultrasonic sensor with output in the ultrasonic frequency range
- Contact ultrasonic sensor with output in the audio frequency range

### Airborne ultrasonic sensors

These ultrasonic sensors will work best when there is a clear and direct air path from the sensor to the partial discharge site. The raw, ultrasonic electrical signal cannot be heard because it is outside the frequency range of the human ear. For the raw ultrasonic electrical signal to be audible to the human ear, the frequency of the signal must be shifted down to the audio frequency range. The partial discharge can then be detected and located by a headphone. Alternatively, the ultrasonic signal can be analysed in the frequency domain using commercial fast fourier transform software. The directional capability of airborne ultrasonic sensors makes them a powerful tool for the location



Figure 1: TEV Sensor from EA Technology of UK.



Figure 2: TEV Sensor from IPEC of UK.

of partial discharge. The advantage gained with the frequency shift from the ultrasonic frequency range to the audio frequency range, is not without drawbacks. It will not be possible to analyse the occurrence of partial discharge across the 360° phase angle of the AC line voltage. Neither can we analyse the partial discharge by waveform recognition.

Therefore there are commercially available, airborne ultrasonic sensors that provide output in the audio frequency range and in the raw ultrasonic frequency range. Airborne ultrasonic sensors are typically of narrow bandwidth, with 40 KHz centre frequency and 3 dB bandwidth of  $\pm 1$  KHz. Airborne ultrasonic sensors, from different manufacturers, used by the author, are shown in Figures 3 and 4.

### Contact ultrasonic sensors

When ultrasound is emitted from a partial discharge source



Figure 3: Airborne Ultrasonic Sensor with Output in the Ultrasonic Frequency Range.



Figure 5: Contact Ultrasonic Sensor with Output in the Ultrasonic Frequency Range.

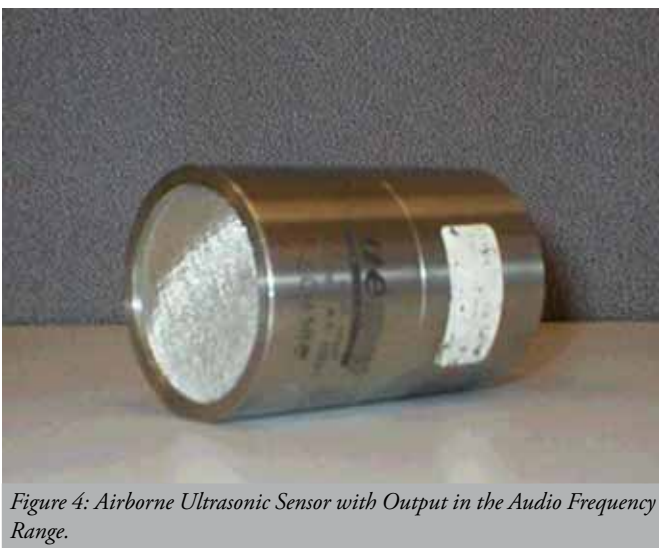


Figure 4: Airborne Ultrasonic Sensor with Output in the Audio Frequency Range.



Figure 6: Contact Ultrasonic Sensor with Output in the Audio Frequency Range.

towards a metal surface, most of the ultrasound will be reflected back and some will be transmitted through to the metal surface. The ultrasound that appears at the metal surface can be detected by a contact ultrasonic sensor placed at the metal surface. Therefore contact ultrasonic sensors can be used when there is completely no air path between the sensor and the partial discharge source.

Compared to airborne ultrasonic sensors, the frequency response of the contact ultrasonic sensors has a higher centre frequency and wider bandwidth. The typical frequency response will be 100 KHz centre frequency and 3 dB bandwidth of  $\pm 20$  KHz. Contact ultrasonic sensors, used by the author, are shown in Figures 5 and 6.

### HFCT sensors (High Frequency Current Transformer)

Partial discharge in high voltage cables will induce high frequency current pulses in the earth screen of the cable. Such earth screens will be connected to earth and the connection of a HFCT at the earth screen will pick up the high frequency current pulses associated with the partial discharge in the cable. The HFCT, used by the author, will not respond to 50 hertz current and has a frequency response (Figure 7) that is constant over 300 KHz to 20 MHz. The HFCT must have a flat frequency response across the full frequency range of interest, when measuring partial

discharge. The HFCT is of split core construction (Figure 8), so that it can be easily connected around the earth screen of the high voltage cable. Therefore partial discharge measurement of high voltage cables can be done online, with no interruption to the customer. In the event that the earth screen is not accessible, the earth cable of the high voltage switchgear may be used.

The secondary of the HFCT has 10 turns and a small air gap at the soft ferrite core. The air gap is to prevent saturation of the HFCT due to the high magnitude of the 50 hertz current in the earth screen, which will be high for long lengths of single core cable and solid connection to earth for the earth screen at both ends of the cable. The 50 hertz circulating current in the earth screen is directly proportional to the length of the cable and the load current of the cable.

### Comparison of sensors

The airborne ultrasonic sensor is most sensitive for the measurement of partial discharge in air insulation. For this sensor to work best, there must be a clear air path between the sensor and the partial discharge site. This means that fully enclosed switchgear with no grills or air vents, will not be suitable for partial discharge measurement using airborne ultrasonic sensors. Contact ultrasonic sensors may be used in such situations but

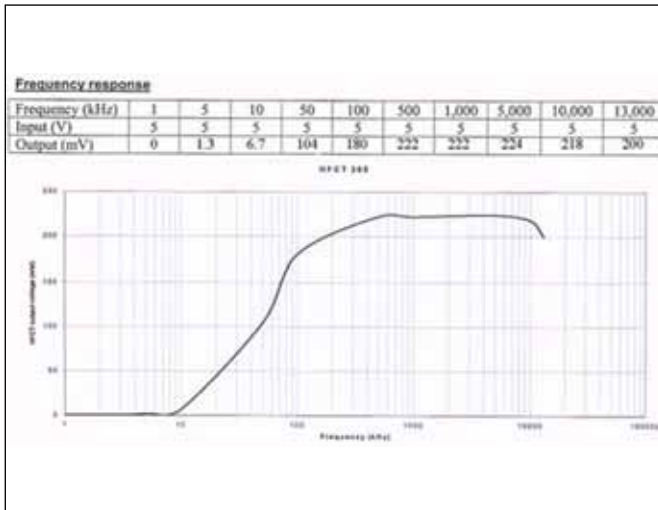


Figure 7: Frequency Response of HFCT.



Figure 8: Split Core HFCT Sensor.

with much less sensitivity.

For partial discharge that occurs inside an insulation, ultrasonic signals will be produced, but this will generally not be picked up using ultrasonic sensors (both airborne and contact type) because of the attenuation in the insulation and poor coupling of the air/solid interface. TEV sensors will be more suitable in such situations.

The HFCT sensor is most suitable for the partial discharge measurement of high voltage cables. The HFCT sensor is also suitable for the measurement of partial discharge in switchgear, when the sensor is inserted around the earth cables of the switchgear.

### Measurement system

The measurement system is based on an oscilloscope with 100 MHz bandwidth and a sampling rate of 1 Giga sample per second. The oscilloscope has four channels and is therefore suitable for simultaneous measurement of partial discharge for three-phase systems. The oscilloscope is interfaced to a partial discharge software using a standard GPIB (General Purpose Interface Bus). The software will display, in real time, the partial discharge information across the phase of the 50 hertz AC line voltage. The measurement can be recorded (in typically 5 minutes) for post analysis in the office. The input impedance of most standard

oscilloscopes is about 1 megaohm, as this provides for the largest voltage it has to withstand, in the event of flashover at the input to the oscilloscope.

However, most sensors are designed to drive a 50 ohm impedance, and so a 50 ohm through connector must be used, in front of the oscilloscope to obtain accurate results. Figure 9 illustrates the measurement system. The GPIB will set up the oscilloscope to the following settings:

- The trigger source is set to the AC line voltage to the oscilloscope. This is very important because of the need to analyse the occurrence of the partial discharge across the 360° phase angle of the AC line voltage. At the zero crossing of the AC line voltage, there will be no voltage, and partial discharge cannot occur when there is no voltage. Partial discharge will occur at either the rising positive AC line voltage or rising negative AC line voltage.
- The oscilloscope is set to peak detection. This means that in every measurement cycle, the largest magnitude of partial discharge will be recorded.
- The input channel is set to consider only the AC component. The DC component will be ignored.

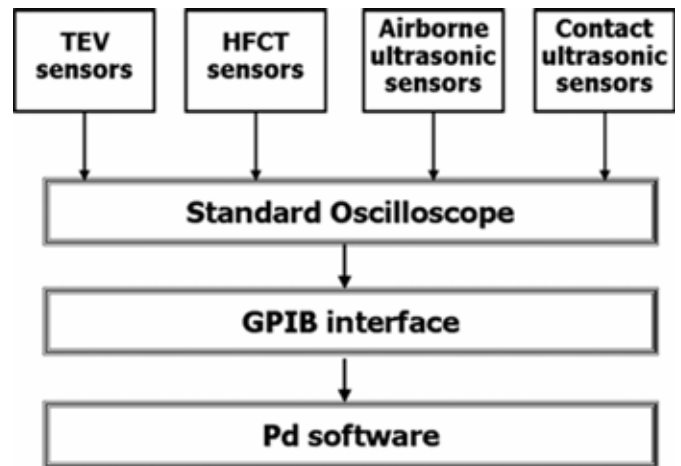


Figure 9: Measurement System

### Background noise

The greatest difficulty in all on-line partial discharge measurement, is background noise. If the background noise is low, any large magnitude partial discharge will appear above the background noise and will be easily detected. However if the background noise is high, the partial discharge may be masked out and will escape detection. One inexpensive and hence common technique to reduce background noise, is noise gating. This will require the selection of a source that contains only noise but not the partial discharge activity. For example, if the noise is airborne interference, then an aerial antenna will provide a good noise source with no partial discharge activity. The noise source will be connected to Channel 4 of the oscilloscope and the partial discharge sensors will be connected to Channel 1, 2 and 3 of the oscilloscope. The noise and partial discharge activity will be simultaneously measured and recorded via the oscilloscope. In this manner, only partial discharge activity that occurs simultaneously with the noise, will be removed. In consequence, noise gating will work best for pulsed noise and will not be suitable for continuous noise. Using the noise gating method with continuous noise, will

unfortunately delete a large number of true partial discharge activities that may occur simultaneously with the continuous noise. Figure 10 is a picture of the oscilloscope connected to the noise gating aerial antenna and partial discharge sensors. The activity to de-noise the measurement Channels 1, 2 and 3 is usually done off-site after the completion of the measurement. The software used by the author has the option to either use or not use noise gating.



Figure 10: Oscilloscope Connected to the Noise Gating Aerial Antenna and Partial Discharge Sensors.

### Case history and interpretation

A 22 kV air insulated switchgear with vacuum circuit breakers, was measured for partial discharge activity by the simultaneous use of four different types of partial discharge sensors. A TEV sensor and contact ultrasonic sensor were connected to the external back panel of the switchgear. An airborne ultrasonic sensor was placed inside the front door of the switchgear with the front door closed. The HFCT sensor was installed at the earth cable of each individual power cable to the switchgear. The partial discharge measurement, in average values of millivolts, are summarised in Table 1.

The interpretation of the amplitude of the partial discharge is not useful or meaningful. For example, the amplitude of partial discharge from the HFCT sensor is typically much larger than from the TEV, contact ultrasonic and airborne ultrasonic sensors, but it is incorrect to conclude that there is deterioration in the insulation. It is the trending of the amplitude of each sensor over time, that is useful. A rising trend over time, is an accurate indication of deterioration of the insulation.

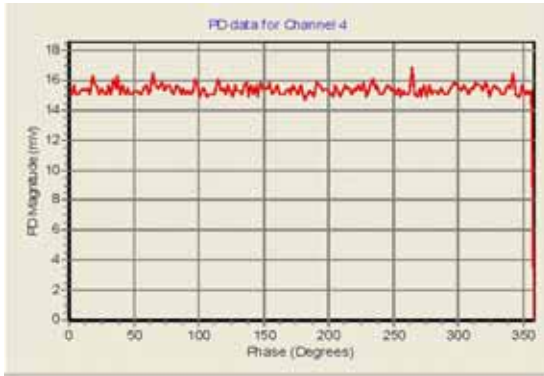
In addition to the trending of the amplitude of the partial discharge over time, another useful indicator of insulation deterioration, is to view the amplitude of partial discharge across the 360° phase angle of the AC line voltage. Partial discharge cannot occur when there is no voltage or at the zero crossings of the AC line voltage. High amplitude of partial discharge which occurs throughout the 360° phase angle of the AC line voltage, is very likely continuous noise. Figure 11 shows the measurement for the four sensors, and indicates the absence of severe insulation deterioration. Further investigation is recommended when the measured partial discharge has a waveform as shown in Figure 12. Partial discharge is observed above the background noise, at the rising positive voltage and rising negative voltage. The same waveform is observed at both the peak values and average values of partial discharge.

### Conclusion

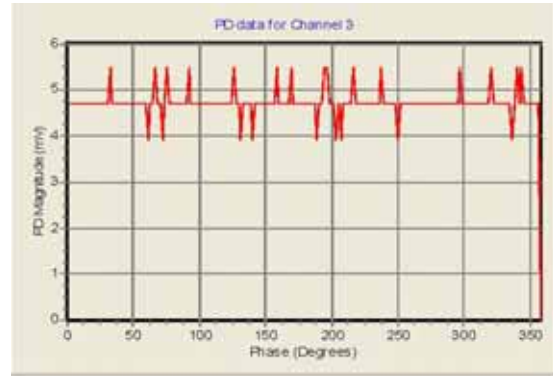
The simultaneous use of multiple sensors will greatly improve the reliability and sensitivity in the detection of partial discharge. The connection of the sensors to a standard oscilloscope will provide an inexpensive tool for real time analysis of the measured signal, to immediately detect large magnitude partial discharge. The use of the oscilloscope will not require the purchase of expensive and proprietary hardware for the connection of the various sensors. The oscilloscope is an inexpensive and open hardware that can be connected to any type of sensor. While the oscilloscope system shows the real time partial discharge events, it is recommended that partial discharge measurements made in the field be recorded and stored over a period of time, say 5 minutes, to provide statistical post analysis of the partial discharge data using commercially available software.

Sensor type	Average mV									
	Panel 1	Panel 2	Panel 3	Panel 4	Panel 5	Panel 6	Panel 7	Panel 8	Panel 9	Panel 10
HFCT	40	45	105	40	110	300	15	110	3	5
TEV	2	2	2	2	2	1	2	1	1	1
Contact Ultrasonic	3	4	3	3	3	3	3	4	4	4
Airborne Ultrasonic	7	7	12	15	10	14	14	7	7	7

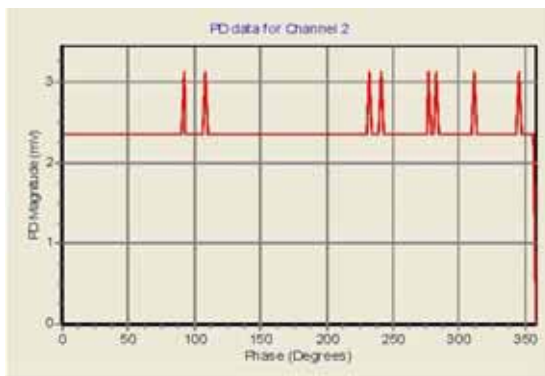
Table 1: Summary of PD Measurement.



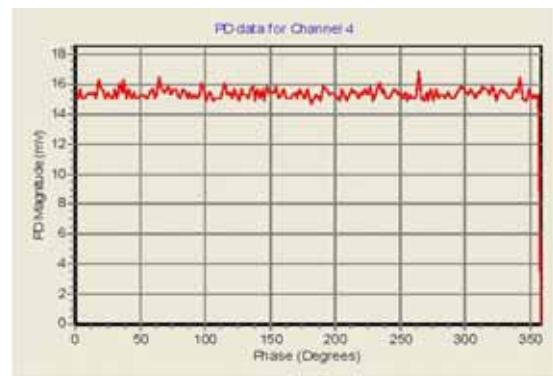
HFCT Sensor



Contact Ultrasonic Sensor



TEV Sensor



Airborne Ultrasonic Sensor

Figure 11: Measurement of Four Sensor.

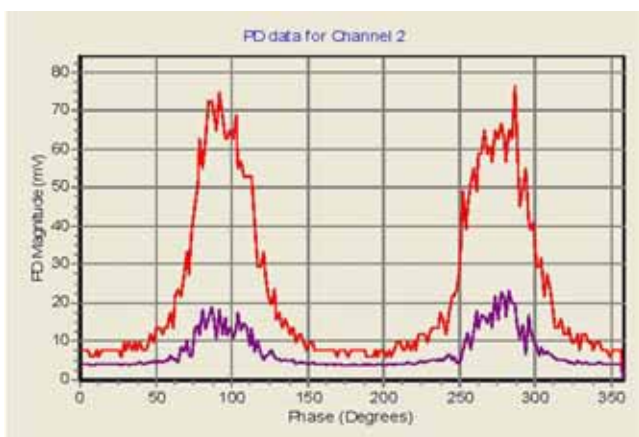


Figure 12: Measured Partial Discharge.

Box Story: To be added later.

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