IMPROVED CONDITION MONITORING USING INTERNALLY MOUNTED PD SENSORS WITHIN NETWORK COMPONENTS AND SWITCHGEAR ENCLOSURES

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ABSTRACT

A key beneficial aspect of on-line partial discharge (PD) monitoring and testing is that it can be applied non-intrusively. Very often, PD sensors can be implemented quickly and at a low cost without the requirement for an outage.

PD sensors generally need to be mounted on earthed components externally. However, external mounting of on-line PD sensors can compromise the sensitivity and performance of the sensors, especially with modern switchgear design standards removing inspection windows, ventilation louvres, and sealing panel gaps for improved ingress protection.

This paper will demonstrate that internally mounted PD sensors, such as airborne acoustic (AA) ultrasonic sensors, outperform externally mounted options like contact acoustic emission (AE) sensors. This will not only be shown in theory but through experimentation, and a conducted study. Furthermore, this paper will show the necessity for increased collaboration between utilities, asset operators, and diagnostic system manufacturers to specify on-line PD monitoring to increase defect detection and extend asset lifetimes.

INTRODUCTION

Most permanent installations of on-line PD monitoring systems for air-insulated switchgear (AIS) are retrofitted externally onto assets that have been in operation for several years. The advantage of on-line monitoring is that generally no outage is required for testing and the installation of the sensors on to the assets.

Sensors like AA sensors can be easily installed externally, with the sensor head pointing through AIS panel gaps, ventilation louvres, and inspection windows.

Figure 1. *A photo of transient earth voltage (TEV) sensors installed on metallic switchgear panels and AA sensors installed with the sensor head pointing through a narrow panel gap.*

However, AIS switchgear is increasingly becoming fully enclosed due to the change in modern design standards. They often have no ventilation louvres and add rubber gaskets or silicone sealants to the panel gaps for increased ingress protection (IP). This change in design reduces the number of direct air paths for the ultrasonic emissions to escape the enclosure to be measured by the sensor.

For these switchgear asset types, some PD sensors require an internal installation to operate effectively. Whilst this means that utilities and asset operators must schedule downtime, the increase in PD sensor sensitivity is worth the added complexity and downtime.

This paper analyses and quantifies the benefits of internal sensor installation, the installation methodology, and a case study demonstrating the improvements in the sensitivity.

INTERNAL MOUNTING OF PD SENSORS

Several types of sensors can be deployed for on-line PD monitoring system for AIS switchgear.

Transient earth voltage (TEV) sensors are used to detect TEV signals that traverse the inner surface of earthed metallic enclosures en route to earth potential [1]. There is minimal benefit from installing TEV sensors internally, as TEV signals are equally detectable when externally mounted. The internal installation of TEV sensors is only convenient when installing other sensor types internally as the change in modern switchgear designs do not affect their performance.

High-frequency current transformer (HFCT) sensors detect PD in solid insulation, usually cable insulation. When a PD event occurs in insulation or a cable joint, a current pulse is induced on both the cable core and the sheath. This pulse propagates away from the defect site in both directions along the cable. HFCTs can detect the presence of these pulses where the cable core and earth are separated. For medium voltage (MV) cables, this is usually at the cable termination. On extreme high voltage (EHV), this is at the cable termination or cross-bond locations. HFCTs are installed around the cable earth or safely coupled around the cable core electrically above the cable earth.

Ultrasonic Sensors

Ultrasonic sensors detect acoustic emissions from PD, like surface tracking in switchgear. Contamination in combination with moisture on the surface of high-voltage insulators, is prone to a phenomenon known as surface tracking. Tracking creates carbon deposits which build up over time, this leads to flashovers and insulation failures. This is often catastrophic in switchgear as it can irreversibly damage the whole switchgear panel and potentially neighbouring panels. This discharge activity creates acoustic emissions that can be detected. The magnitude of the acoustic emission often indicates the degree and severity of the discharge activity.

There are two types of ultrasonic sensors used to detect PD:

- Airborne Acoustic (AA)
- Contact Acoustic Emission (AE)

AA sensors that have a direct air path between the transducer and the high-voltage stress points, where surface tracking is likely to occur, will be more sensitive to ultrasonic emissions.

Figure 2. *A photo of an AA sensor installed on VMX AIS with the transducer pointing through a large gap at the breaker spouts.*

AIS switchgear is often enclosed within a metallic body to allow human-safe operation when said components are on-line. This means there is no direct air path between the high-voltage stress points and the transducer. When an AA sensor is installed externally, and the transducer needs to be aimed through a narrow panel gap, such as the sensor pictured in figure 1. Figure 2 shows an ideal external installation with a short air path and a large panel gap between the transducer in the sensor head and the high-voltage stress point.

Contact AE sensors are seeing an increase in deployment on modern switchgear enclosures due to this trend towards higher IP ratings. However, installed contact AE sensors are significantly less likely to detect ultrasonic PD signals within AIS switchgear as almost all of the discharge energy is reflected internally and, therefore, cannot be detected outside the steel enclosure.

Calculating the acoustic sensitivity of the contact AE sensor

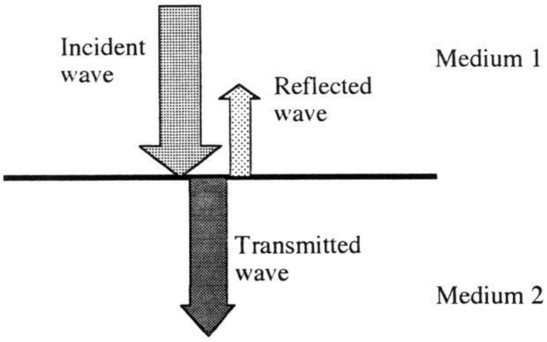

Figure 3. *Diagram of transmission and reflection at a plane boundary.*

The following equation is used to calculate the characteristic acoustic impedance of the insulating air within AIS switchgear, the insulating mineral oil within transformers, and the steel enclosures used for both AIS and oil-filled transformers [2]:

$$Z = \rho \cdot c$$

Where:

Z = Acoustic Impedance (Rayl or $kg \cdot s^{-1} \cdot m^{-2}$)
ρ = density of the medium ($kg \cdot m^{-3}$)
c = speed of sound in the medium ($m \cdot s^{-1}$)

For medium 1, if we assume a temperature of 20°C for the air inside of an AIS switchgear asset, a sea-level atmospheric pressure of 1 atm, and the following values for density and speed of sound:

$\rho_1 = 1.204\ kg \cdot m^{-3}$
$c_1 = 344\ m \cdot s^{-1}$

We get a characteristic acoustic impedance of:

$Z_1 = 414.18$ Rayl

For medium 2, if we assume a temperature of 20°C for the steel enclosure of an AIS switchgear asset and the following values for density and speed of sound:

$\rho_2 = 7750\ kg \cdot m^{-3}$
$c_2 = 5100\ m \cdot s^{-1}$

We get a characteristic acoustic impedance of:

$Z_2 = 3.9525x10^7$ Rayl

And for medium 3, if we assume a temperature of 20°C for the mineral oil used within the transformers, a sea-level atmospheric pressure of 1 atm, and the following values for density and speed of sound:

$\rho_3 = 870\ kg \cdot m^{-3}$
$c_3 = 1450\ m \cdot s^{-1}$

We get a characteristic acoustic impedance of:

$Z_3 = 1.2615x10^6$ Rayl

When the ultrasound energy meets a plane boundary separating two media, some energy is transmitted forward, and the remainder is reflected, as shown in figure 3.

The relative amounts of reflected and transmitted acoustic emissions are given by the reflection coefficient (R_a) and the transmission coefficient (T_a). These are amplitude coefficients and can be shown as:

$$R_a = \frac{Intensity\ of\ reflected\ wave}{Intensity\ of\ incident\ wave} = \frac{Z_2 - Z_1}{Z_2 - Z_1}$$

And,

$$T_a = \frac{Intensity\ of\ transmitted\ wave}{Intensity\ of\ incident\ wave} = \frac{2Z_2}{Z_2 + Z_1}$$

The equivalent intensity coefficients, R_i and T_i, are as follows:

$$R_i = \frac{(Z_2 - Z_1)^2}{(Z_2 + Z_1)^2}$$

And,

$$T_i = \frac{4Z_2Z_1}{(Z_2 + Z_1)^2}$$

Expansion of these equations shows that the conservation of energy is satisfied as;

$$R_i + T_i = 1$$

Calculating the energy reflected using the above equations and the assumed values for density and speed of sound for both mediums; **at the boundary plane between air and steel, 99.996% of the sound energy is reflected**. For comparison, at the boundary plane between mineral oil and steel, 88.011% is reflected.

Contact sensors are therefore best suited to oil or resin-filled assets where the ultrasonic emissions can propagate through the solid or liquid medium with significantly less reflection at the boundary plane between the two media.

Internal Mounting Methodology

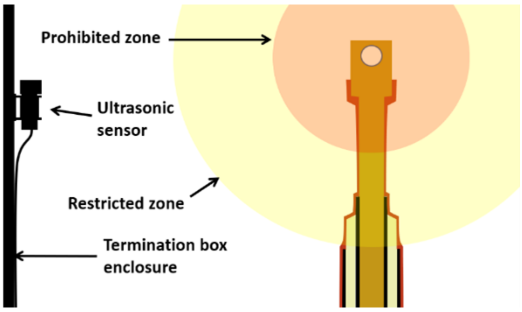

Figure 4. *A side view of the ultrasonic AA sensor mounted on a termination box enclosure.*

The sensors are mounted on the walls of the switchgear enclosure to ensure that the flashover risk does not increase. In addition, the sensor is placed well outside the restricted zone, defined as 1.5x the asset operator's safe distance.

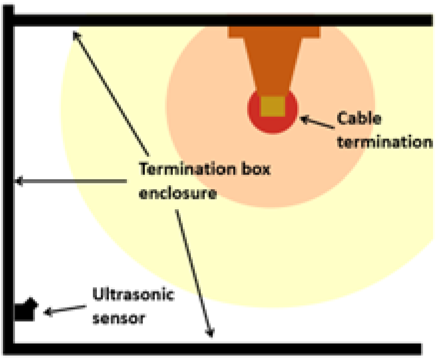

Figure 5. *A plan view of the ultrasonic AA sensor mounted on a cable termination box enclosure.*

Figure 6. *A photo of a transformer termination enclosure with a UHF sensor and an AA sensor mounted internally.*

Internal installations of AA, UHF, HFCT and TEV sensors were conducted in approximately 3,500 switchgear terminations as part of an extensive permanent monitoring programme with a large national distributor in the Middle East, using the internal mounting method outlined.

INTERNAL VS EXTERNAL ULTRASONIC SENSORS CASE STUDY

A study was conducted on a switchgear panel with known PD to demonstrate the difference in the performance of internally & externally mounted sensors. The data was simultaneously recorded with the internal AA ultrasonic sensor and two additional temporarily installed sensors:

- An external ultrasonic AA sensor with the sensor head pointing through a gap between the panels.
- An external contact AE ultrasonic sensor.

Figure 7. *The external ultrasonic AA sensor is installed on the asset of interest, with the sensor head pointing through a gap between the panels.*

Figure 8. *The contact AE sensor is installed externally on the asset of interest with ultrasonic gel between the contact sensor and the asset enclosure.*

Internal AA sensor vs external AA sensor

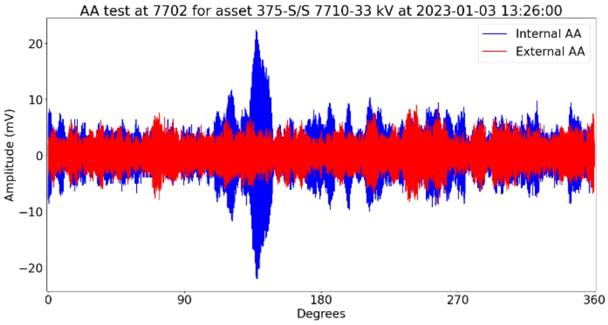

Figure 9. *Graphs of the internal AA vs external AA sensor readings for a single power cycle on a live asset.*

The results from simultaneous recordings of the internal and external ultrasonic AA sensors in figure 9 show that the internal AA sensor is seeing an indication of phase-resolved PD (PRPD) patterns with a peak of 20mV. The external airborne acoustic (AA) sensor is not showing any discernible PRPD patterns.

Internal AA sensor vs contact AE sensor

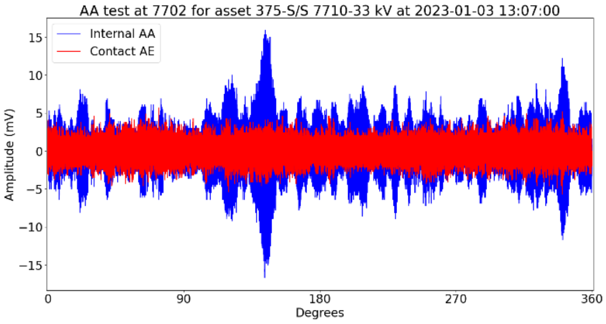

Figure 10. *Graph of the internal AA vs contact AE sensors readings for a single power cycle on a live asset.*

The results from simultaneous recordings of the internal AA sensor and the contact AE sensor in figure 10 shows that the internal AA sensor is again seeing distinct PRPD patterns with a peak of 15mV. The contact AE sensor is not showing any PRPD patterns.

The results from this study show that the internally mounted AA sensor outperforms both the contact AE sensor and the externally mounted AA sensor pointing through the narrow panel gap.

CONTACT AE SENSOR VS INTERNAL AA SENSOR EXPERIMENT

An experiment was conducted to quantify the relative performance of an externally mounted contact AE sensor versus an internally mounted AA sensor.

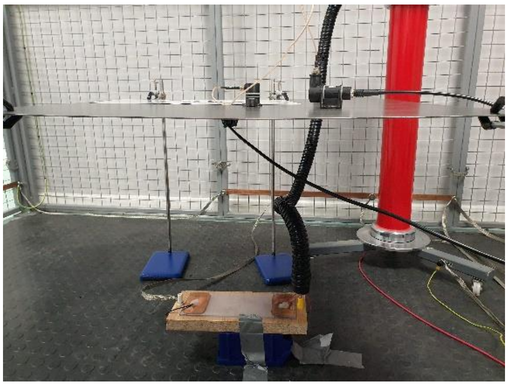

Figure 11. *A photo of the experimental setup in the high-voltage test area. Which consists of the contact AE sensor on the top and the AA sensor on the bottom of a 2mm thick steel plate above a surface tracking PD sample.*

As shown in figure 11, a 2mm thick steel sheet was suspended 45cm above a surface tracking producing sample. The sample was primed with a spray of a 1tps/100ml salt-water mixture which was then energised in a high-voltage test area. The AA sensor was mounted above the surface tracking sample on the underside of the steel sheet. The contact AE sensor was mounted above the surface tracking sample on top of the steel sheet with ultrasonic gel between the contact AE sensor and the steel sheet. The voltage was controlled to create three levels of surface tracking PD activity:

- low (20-30pC at 14kV),
- medium (40-50pC at 17kV)
- high (70-90pC at 22kV).

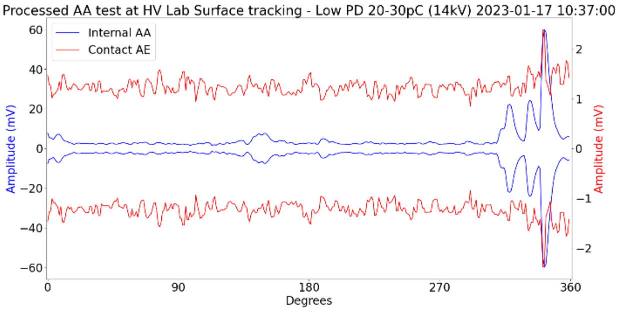

Figure 12. *A graph of the sensor readings for the AA and AE sensors at a low PD activity.*

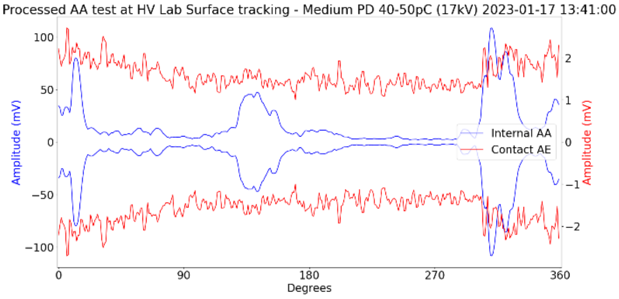

Figure 13. *A graph of the AA and AE sensor readings at a medium PD activity level.*

The raw data recorded was averaged and enveloped to remove intermittent and transient noise seen by both sensors resulting in the graphs in figures 12, 13, and 14.

As shown in the results in figures 12 and 13, the AA sensor detected a PRPD pattern consistent with PD characteristics with peak amplitudes of 60mV and 100mV, respectively. The AE sensor detected peak values of 2mV and 2.5mV but no discernible PRPD pattern as it was below the noise floor of the sensor aside from a single spike in figure 12.

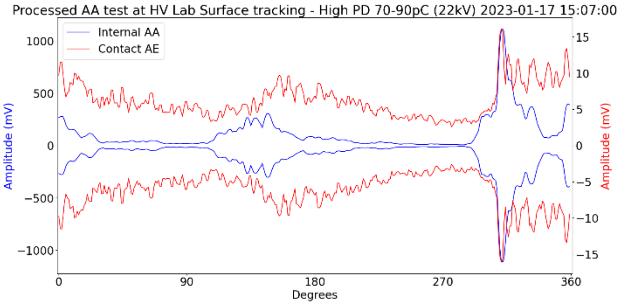

Figure 14. *A graph of the sensor readings for the AA sensor and the AE sensor at a high PD activity.*

As shown in the results in figure 14, the AA sensor detected a PRPD pattern consistent with PD characteristics with a peak amplitude of 1000mV and the AE sensor saw a peak value of 15mV with a clear PRPD pattern. The ratio of peak amplitudes is 1.5%.

The difference in theoretical ultrasonic transmission (0.004%) and experimental transmission (1.5%) could be attributed to several factors. First, the contact AE sensor has a much wider bandwidth of 55kHz with a sensing range from 15kHz to 70kHz within a 3dB level. In contrast, the AA sensor has a central frequency of 40kHz with a ±1kHz bandwidth within a 3dB level. Therefore, the contact AE sensor can detect a broader range of ultrasonic emissions than the AA sensor and thus produced a higher electrical signal than expected.

A possible second reason is that ultrasonic energy is being transmitted along and through the steel providing a larger area for the emissions to be detected by the AE sensor when compared with the AA sensor.

Aside from the difference between theoretically calculated and experimentally detected ultrasonic transmissions, the contact AE sensor performed poorly compared to the internal AA sensor. As seen in figures 12 and 13, the internal AA showed clear PRPD patterns where any patterns detected by the contact AE were hidden below the noise threshold.

CONCLUSION

The case study and the experimental data show an improvement in sensitivity of about two orders of magnitude by mounting the PD sensors internally. It has been shown in this paper that, internal airborne acoustic (AA) sensors vastly outperform contact acoustic emission (AE) sensors in detecting the onset of surface tracking and other defects that release ultrasound energy from partial discharges.

If utilities and asset operators specify on-line PD sensors to be mounted inside new switchgear and distribution network installations, defect detection could be improved. This when effectively managed, will reduce failure rates and increase asset life. Additionally, commissioning errors can be discovered and rectified when the asset is taken off-line to check and survey the asset condition.

The work covered in this paper demonstrates that internally mounted PD sensor outperform external ones. This drives a need for dialogue between utilities, asset OEMs, & diagnostic system/sensor manufacturers to discuss the internal installation of PD sensors at the manufacturing or commissioning stages. This could extend asset life, reduce failure rates, and reduce costly outages.

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