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A NOVEL ELECTRICAL SENSOR FOR COMBINED ONLINE MEASUREMENT OF PARTIAL DISCHARGE (OLPD) AND POWER QUALITY (PQ)

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Abstract: A novel inductive sensor has been developed that can be used for both for online partial discharge (OLPD) monitoring and power quality (PQ) monitoring. The sensor has been designed for attachment onto power cables with 50/60 Hz currents up to 800 A. The sensor comprises a high frequency (HF) winding to detect partial discharge (PD) pulses between 200 kHz and 30 MHz with a flat frequency response within this range. A low frequency (LF) winding is aimed at monitoring the power frequency (50/60 Hz) and its harmonics up to the 63rd order; it can also be used for current signature analysis (CSA) in rotating machines. A passive low-pass filter is integrated inside the sensor casing to suppress the higher frequencies not relevant to power quality monitoring. The sensor has a split-core design, making it easy to install and allows for retrofit installations. The combined sensor is well suited to places where space is limited such as compact cable boxes where it would be difficult to install two separate sensors. The sensor is primarily used for high voltage (HV) rotating machines (direct or VSD fed) and can be used in a variety of other applications such as monitoring of onshore and offshore wind farms. The paper begins by reviewing the main types of sensors used for partial discharge monitoring followed by the development of the novel sensor. Finally, two case studies where the sensor has been successfully installed are presented.

1. INTRODUCTION

The continuous OLPD condition monitoring of high voltage cables and plant has been gaining traction in recent years as it provides valuable insight regarding in-service condition and can assist with the prevention of unplanned outages by detecting incipient insulation faults before they evolve into a failure.

There are several electrical detection methods being employed which focus on detection of current signals such as current signature analysis (CSA), power quality (PQ) and online partial discharge (OLPD) monitoring. Each method has its own advantages for detecting different failure mechanisms. However, by combining them into a holistic monitoring solution, more effective condition monitoring can be achieved [1], [2].

Traditionally, to implement each of the aforementioned monitoring methods a different sensor is required. An example is shown in Figure 1 where within the switchgear compartment, on each of the three phases, a 50 Hz measurement Current Transformer (CT) is installed to calculate load and assist with general day-to-day running of the plant together with a High Frequency Current Transformer (HFCT) for OLPD detection.

Installing multiple sensors inside the same compartment has several disadvantages. The MV/HV cable termination compartment needs to be manufactured to be large enough to accommodate the different sensors while maintaining the appropriate clearances between the live terminals and ground. If the sensors are being retrofitted into a pre-existing compartment their installation might not be possible. Furthermore, each sensor requires its individual signal cable which will need to be routed through the termination compartment to reach the associated monitoring system. Having different sensors for each monitoring method also increases the total cost of the monitoring solution.

To address the limitations described above and enable the easier implementation of a holistic

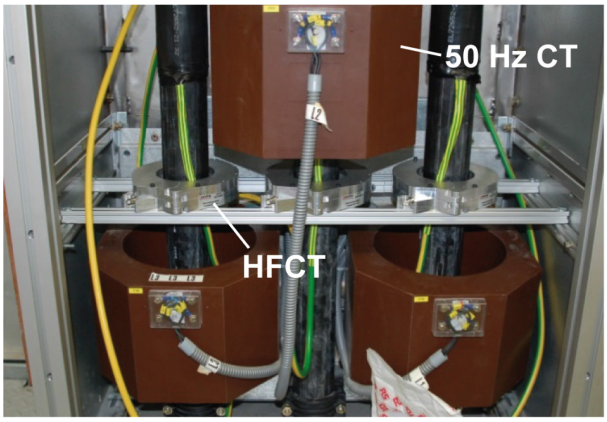

Figure 1: Permanent HFCT sensors installed above traditional CT for 50 Hz and power quality measurements.

condition monitoring method, a novel electrical sensor has been developed that can be used simultaneously for OLPD monitoring and PQ monitoring.

2. REVIEW OF OLPD SENSORS

The six (6) main OLPD sensor options available for the online detection of PD in MV/HV networks are shown in Table 1. The OLPD sensor used depends on the application. HFCTs, due to their low-profile design and split core, are now the preferred sensor of choice for the OLPD testing of in-service MV and HV cables and rotating HV machines. For rotating machines the sensors can be installed at the machine or remotely at the connected switchgear [3]. Further information on the development of a high current (1000 A) high frequency current transformer (HFCT) sensor suitable for the OLPD monitoring of HV motor circuits is provided in [4].

3. THE SMART-TB3™ SENSOR

On the base of the HFCT a novel electrical sensor has been developed which can be used for OLPD, PQ and ‘transient events’ monitoring (Figure 2). The high frequency (HF) winding detects PD in the range 200 kHz – 30MHz. The low frequency (LF) winding is aimed at monitoring the power frequency (50 – 60 Hz) and its harmonics up to the 63rd order, and the bandwidth 3.5 kHz – 200 kHz. Figure 3 shows the frequency range covered by the three bands. The LF winding and its filter have been designed to provide an adjustable output and hence can be connected to a multitude of industry standard PQ monitoring systems.

The split-core design of the sensor makes it easy to install and also allows for retrofit sensor installations even while the system is energised provided that the cable termination is accessible and it is safe to do so.

Table 1: The six main OLPD sensor Options [5]

Sensor	Picture	Coupling Method	Primary Application(s)
High Voltage Coupling Capacitor		Capacitive	Rotating Machines
High Frequency Current Transformers (Ferrite-Cored)		Inductive	Rotating Machines / Power Cables / Transformers
Transient Earth Voltage		Capacitive	Switchgear / Cable Terminations
Airborne Acoustic		Acoustic	Switchgear / Cable Terminations
Rogowski Coil (Air-Cored)		Inductive	Rotating Machines
Ultra High Frequency (UHF) Coupler		Capacitive	Gas Insulated Switchgear (GIS)

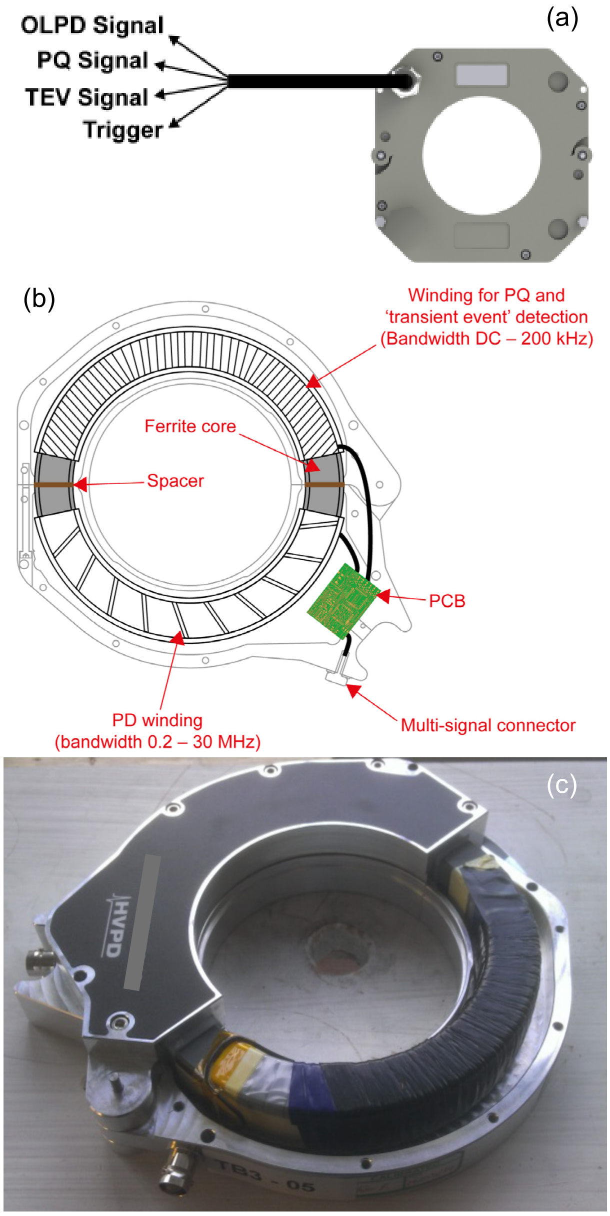

Figure 2: Function overview (a), construction schematic (b) and a prototype (c) of the SMART-TB3™ sensor.

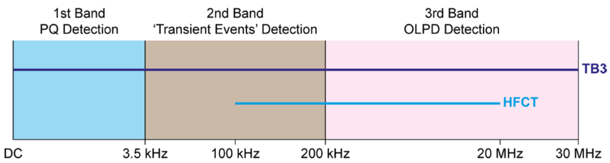

Figure 3: The three (3) bands monitored by the SMART-TB3™ sensor in comparison with the bandwidth of HFCT.

4. SENSOR PROTOTYPING & LAB TESTING

4.1. Integrated low-pass filter

For the PQ winding of the SMART-TB3™ sensor a low-pass (LP) filter incorporating a voltage divider was designed. The low-pass filter allows the detection of signals having frequency up to 200 kHz while the voltage divider limits the voltage output of the sensor to harmonise the sensor output with industry standards and allows integration with existing PQ monitoring systems. The filter is integrated within the sensor casing. The filter bay is fully screened and depending on customer requirements, different filter/divider combinations can be manufactured and integrated with the sensor.

4.2. PQ winding linearity

The output of the PQ winding was tested to check whether it saturates or not when high currents are present. The RMS voltage output was plotted against the primary current and the results are shown in Figure 4. For this particular case a divider with a ratio of 333 mV / 800 A was used. The regression coefficient (R^2) shows the linear output of the PQ winding, with no evidence of saturation.

4.3. PD winding transfer impedance

To check that the PD detection capability of the sensor is not hampered by the inclusion of the PQ winding, the transfer impedance of the HF winding of the SMART-TB3™ sensor was measured. The results are shown in Figure 5. The sensor has a flat frequency response between 1 and 30 MHz with a transfer impedance Z_{Tr} = 2.8 Ω. This value of transfer impedance is similar to the transfer impedance of the standard HFCT upon which the design of the SMART-TB3™ sensor was based.

4.4. Thermal testing

Because the PQ winding of the SMART-TB3™ sensor is mainly used to monitor the power frequency and its harmonics, the continuous current flowing through the winding can be substantial (up to approximately 220 mA using the

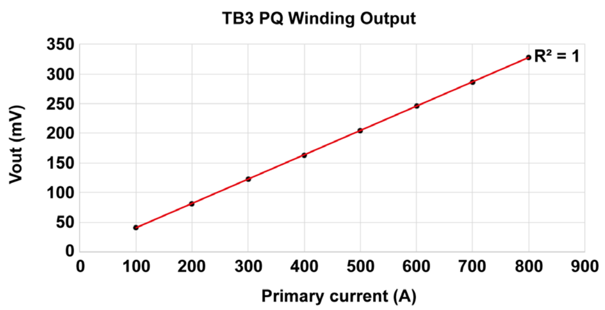

Figure 4: The regression coefficient (R^2) shows the linear output of the PQ winding.

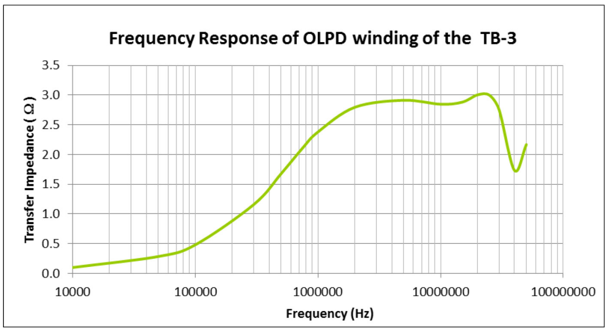

Figure 5: The third band of the SMART-TB3™ sensor used to detect OLPD parameters (0.2 – 30 MHz).

filter/divider described in the previous section).

To make sure that the sensor does not overheat, a test was performed to examine the temperature rise inside the sensor casing. The senor was clamped around a cable able to provide the equivalent of 800 A of primary current. A thermocouple probe was inserted inside the sensor casing, touching the PQ winding. A digital thermometer was used to log the temperature.

The ambient temperature at the beginning of the test was measured to be 25 °C. The results from the test that lasted for 4 hours can be seen in Figure 6. After approximately three hours the temperature inside the sensor casing reached 45 °C and stayed at the same level for the remainder of the test. The maximum temperature rise above ambient was therefore determined to be 20 °C. The voltage output of the sensor was monitored throughout the test. There were no observable changes to the sensor output after the conclusion of the test.

4.5. Functional test

The operation of the SMART-TB3™ sensor as a complete unit (i.e both windings at the same time) was tested by using the sensor with approximately 400 A flowing in the primary while pulses were injected by a signal generator. The output of the PQ winding was also compared to the output of a

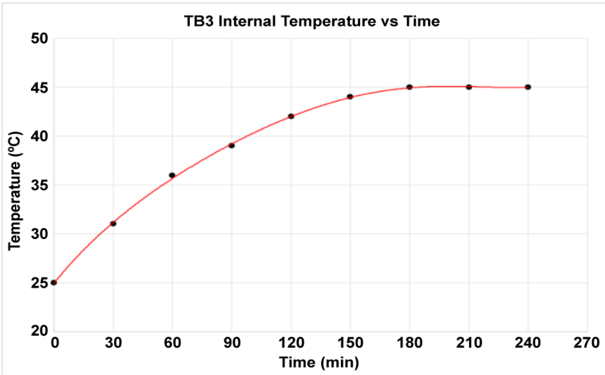

Figure 6: SMART-TB3™ thermal test. The sensor temperature stabilises at 20 °C above the ambient.

commercial power frequency CT. The waveforms can be seen in Figure 7. The PQ winding can detect the power frequency component while rejecting the HF pulses while the opposite is true for the PD winding. The phase shift present in the PQ winding output is because of the use of the low-pass filter and can be compensated by the acquisition instrument.

5. APPLICATIONS AND CASE STUDIES

5.1. SMART-TB3™ application for offshore wind farms

The generator of each turbine within an offshore wind farm (OWF) operates at different speed depending on the wind speed. The generators are connected to the inter-array cables (typically 33kV) through a power converter to regulate the frequency at which the energy is supplied to the network. As a consequence, each power converter introduces harmonic pollution into the system; the higher the number of turbines, the higher the total harmonic distortion present within the system. The high level of harmonics can create several problems to the generator, the protection system and other components. Moreover, harmonics can increase the build-up of sheath currents within the subsea cables resulting in the reduction of the lifetime of the cable insulation. It is therefore important to monitor OLPD and PQ parameters.

The SMART-TB3™ sensor was initially developed to perform CM of distributed cable networks, specifically for OWF. Figure 8 shows a schematic of a turbine at which SMART-TB3™ sensors were installed as part of a permanent CM system specifically developed for OWF [6].

Preliminary testing revealed intermittent PD activity (Figure 9). Subsequent OLPD 'spot' tests were performed to pinpoint the source of the PD and inform remedial action. Figure 10 shows the waveform of the PD pulses detected. The reflection of the PD is clearly visible as is the crosstalk of the PD on the blue phase. By analysing the return time of the PD and the PRPD pattern (Figure 11) it was possible to pinpoint the source of the PD in one of the gas insulated switchgears installed in the nearby turbine.

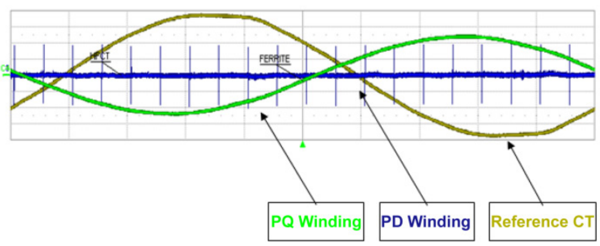

Figure 7: The LF and HF output of the SMART-TB3™ and a reference CT; in this case the LF phase shift was not compensated.

The sensors were also used to record PQ parameters. Figure 12 shows an example of measured harmonic parameters.

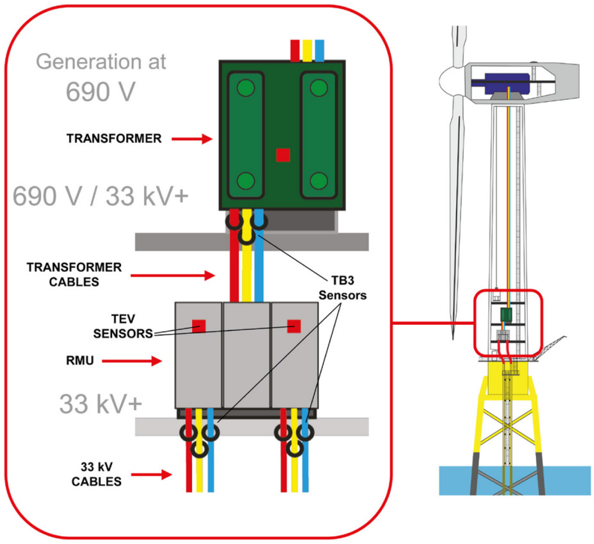

Figure 8: Installation of SMART-TB3™ sensors in an OWF.

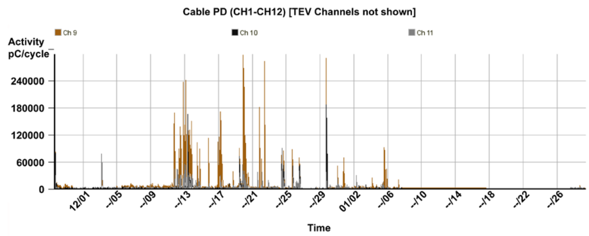

Figure 9: Intermittent PD activity (pC/cycle) detected over a 2-month period. Ch9: R Phase, Ch10: Y Phase, Ch11: B Phase.

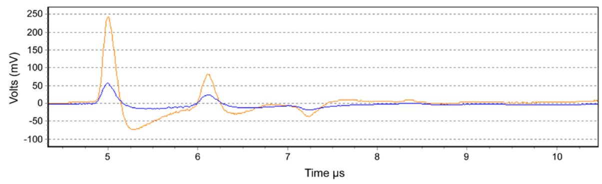

Figure 10: Partial Discharge pulse and the PD reflection (yellow phase) and the crosstalk on the blue phase.

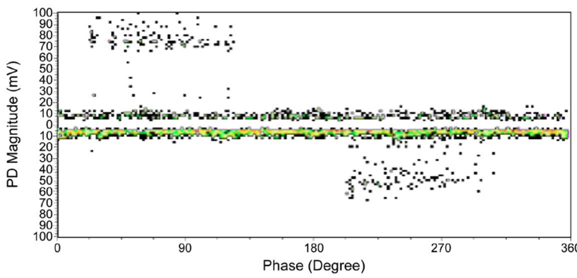

Figure 11: the PRPD pattern of the PD activity measured.

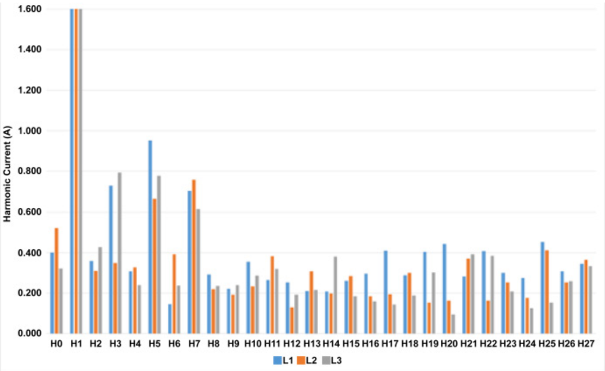

Figure 12: An example of harmonics measurements recorded using the SMART-TB3™.

The case study has demonstrated how the use of the SMART-TB3™ sensors in conjunction with a permanent CM system has helped to detect PD activity that may had led to degradation of the insulation and eventually to an unplanned outage.

5.2. SMART-TB3™ application for VSD-fed HV rotating machines

In the 1980s and 1990s VSD operated HVAC motors started to appear on the market, offering an alternative method of speed control. VSDs (sometimes called frequency converters or adjustable speed drives) control the power delivered to the machine using high voltage power electronic converters to adjust the electrical supply to the HVAC motor with a corresponding change in the motor's speed and torque output. The HVAC motor speed can be varied from zero (0) rpm through to typically 100-120% of full rated speed, whilst up to 150% rated torque can be achieved at reduced speeds.

Furthermore VSDs have high efficiency of typically around 98% [7]. However, it is known that if they are not designed and installed correctly, VSDs can have a negative impact on the local HV network that they are connected to, as well as serious, damaging effects on the HV stator winding of the motor they are driving. The main drawbacks associated with VSDs can be summarised as follows:

- Can produce harmonic distortions on the network
- Increased thermal losses in motors & transformers
- Too short (or too long) HV connection cables from the VSD to the motor can lead to fast voltage transients (of up to 2-3 U0+) appearing on the circuit leading to an increased risk of high voltage (HV) insulation failure [8] [9]
- Induced motor bearing currents can cause sparking erosion of bearings due to common mode voltages and currents and/or poor grounding.

There are a number of challenges to achieving reliable OLPD data detection and analysis on VSD motors, as follows:

- The VSD switching devices can produce high levels of interference (noise) that can obscure PD.
- The supply frequency cannot be easily isolated due to the continuously varying output frequency from the VSD and so a 'clean' (without harmonics) voltage reference source is difficult to obtain.

The first challenge can be overcome through a recently developed OLPD monitoring solution for VSD-fed HV motors based on 6 channel synchronous acquisition [10]. This method uses a 'twin OLPD sensor' measurement approach that enables the monitor to make 'pulse precedence' measurements by comparing synchronous pulse arrival times, between sensors of the same phase installed at the motor and VSD ends, (Figure 13). The pulse precedence measurement technique is illustrated in Figure 14 for the case of using twin sets of SMART-TB3™ sensors, one set in the VSD output terminal box and one set in the HV motor terminal box. Additionally, the SMART-TB3™ sensor is used to ensure that phase-resolved plots

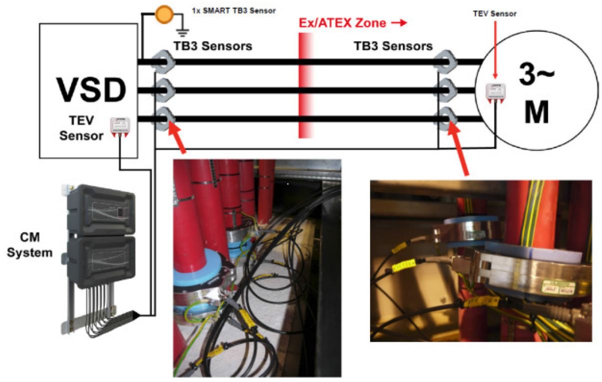

Figure 13: Installation of twin OLPD SMART-TB3™ sensors on a VSD-fed HV motor.

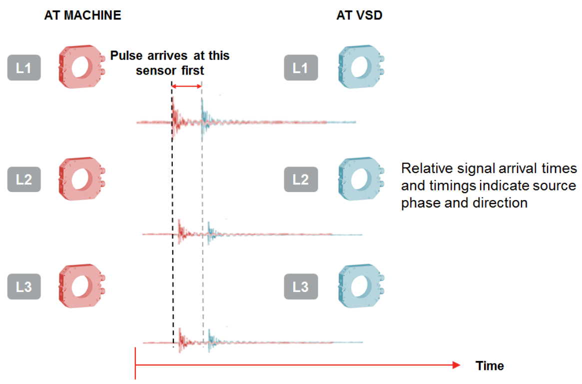

Figure 14: Pulse precedence measurements with SMART-TB3™ sensors.

of the PD activity can be provided at all frequencies across the range of operation of the VSD (typically in the range 40 - 70 Hz).

6. CONCLUSION

This paper has summarised the development of a new tri-band sensor for condition monitoring of in-service high voltage cables and plant. The incorporation of multiple bandwidth measurements allows one sensor to target several condition monitoring parameters, notably OLPD, PQ, CSA and other transient events on the system.

The sensor has been designed for easy installation and can be retrofitted into operating networks. It can be used for VSD-fed motor and off-shore wind farm applications together with monitoring instruments to provide a holistic view of the insulation condition of the monitored assets.

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