A NEW TECHNIQUE FOR THE REMOTE PARTIAL DISCHARGE MONITORING OF THE STATOR INSULATION OF HIGH-VOLTAGE MOTORS LOCATED IN “Ex” (HAZARDOUS) LOCATIONS

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Paper No. PCIC 2012-067

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Abstract — The authors present a paper on the application of a new technique for the remote on-line partial discharge monitoring of the stator insulation condition of in-service, high-voltage rotating machines. The technique applies wideband, ferrite-based high frequency current transformer sensors and high resolution measurement technology. This remote partial discharge monitoring technique has significant advantages when monitoring motors which are located in Ex hazardous gas zones in oil and gas and petrochemical facilities. The paper includes a technical review of published papers covering some of the history of the development of modern, on-line partial discharge sensors and measurement systems for rotating machines. This is followed by a comparison of the various partial discharge sensor options available and an introduction to the remote wideband partial discharge monitoring measurement technique employed by the authors. A case study from a recent pilot project (August 2011) where the new remote partial discharge monitoring measurement techniques were successfully trialed to measure partial discharge activity of in-service 10 kV motors in an oil processing facility is also presented.

Index Terms — Partial Discharge, On-line Partial Discharge, Phase Resolved Partial Discharge, PD wave shapes, PD Diagnostics, Ex and ATEX motors, rotating machines, hazardous gas zones.

I. INTRODUCTION

The on-line partial discharge (OLPD) assessment of in-service high voltage (HV) plant is now becoming more widespread in the oil and gas and petrochemical process industries. Particular focus is made on the condition assessment of the stator insulation of rotating high-voltage motors which drive the critical processes. The on-line partial discharge (PD) sensors, test and monitoring techniques described in this paper have been applied to a wide range of utility and industrial HV plant owners by the authors in test projects from around the world over the past 15 years. Many of these projects have been initiated following the experience of an in-service HV insulation failure which has resulted in loss of business revenue to the client. It can be noted that the partial discharge testing of HV rotating machine stator windings has been used to assess the condition of the stator insulation for over 50 years [1]. This paper includes a brief technical review of some selected published papers on this topic along with the sensor options available for PD monitoring of rotating HV machines.

The paper also includes a review of wideband high frequency current transformer (HFCT) sensors that can be located in the machine’s cable box or placed remotely from the machine under test (at the central switchgear lineup). This is made possible by the low-frequency response (down to around 100 kHz) of the HFCT sensor, providing a measurement range of up to around 1.0 km in polyvinyl chloride (PVC) insulated cables, 1.5 km in paper insulated lead covered (PILC) cables and up to around 2.5 km in cross linked polyethylene (XLPE) cables. These varying measurement ranges for different cable insulation types are due to the different dielectric properties, permittivity and geometry of these three main types of power cable [2].

II. DRIVERS FOR APPLYING ON-LINE PARTIAL DISCHARGE TESTING

The main benefits in applying the OLPD technology are:

- To improve the reliability of the networks by identifying sites of insulation degradation before they fail.
- To provide insulation condition data to provide an early warning against incipient insulation faults.
- To provide plant condition data to support reliable life extension programs of ageing networks.
- To avoid unplanned outages and minimise downtime.
- To provide qualitative information for a condition-based motor replacement and repair programmes.

Oil and gas supply chain operators worldwide are increasingly deploying OLPD technology to test, monitor and manage a wide range of HV plant including power cables, switchgear, transformers, and rotating HV machines [3]. The business drivers for carrying out OLPD testing and monitoring of the HV networks include:

- Health and Safety – most diagnostic OLPD test projects are carried out further to insulation faults and/or equipment component failures occurring within an HV network. In this case there is an immediate requirement
to carry out condition spot tests on sister plant to ensure there is no immediate risk of failure and thus danger to staff or the public.

- To support Reliable Life Extension projects – as many in-service HV machines are reaching the end of their ascribed design-life (typically of 20-25+ years) operators have important asset management decisions to make as to whether to extend the life of these existing assets (using condition-based maintenance (CBM) techniques) or to replace the machines with new units (time-based replacement).

- To Avoid Unplanned Outages and Downtime – generation, petrochemical and industrial process operators are focussed on the effect of any plant failure induced downtime on their generation capacity, process or service. This is the strongest financial driver for these production and process industries.

Studies on power generation, petrochemical and process customer networks show that the main cost driver which dominates is to avoid any unplanned outages. This is simply due the cost of an interruption to the process being normally much higher than the capital replacement/repair cost of any cable/plant/machine in the network.

Oil and gas and chemical processing facilities have HV networks which support critical processes with potentially large losses to business for unplanned outages. Such HV plant owners have little difficulty in justifying the cost of regular PD diagnostic measurements or complete-system, permanent PD monitoring installations.

III. THE HISTORY OF PD TESTING OF ROTATING HIGH VOLTAGE MACHINES

As stated in the introduction section of this paper, the condition assessment of stator insulation using PD testing has been used for over 50 years. Pioneering developments in Canada/USA (using HV coupling capacitors (HVCC) sensors, Resistive Temperature Detector (RTD) sensors and Stator Slot Couplers (SSC) sensors) and in the UK/Europe (using both HVCC and air-core, Rogowski Coil (RC) sensors) in the 1960s showed that it was possible to make effective measurements of PD activity in the HV stator windings of the machines [1]. Over the past 50 years, the PD testing and monitoring of rotating machines has been discussed by many authors as a key tool to understanding the causes of stator insulation failure. Today, the continuous monitoring of PD activity in rotating machines has now become widely accepted as an effective method to identify sites of localized damage or degradation ahead of scheduled preventative maintenance outages.

Historically, periodic (typically annual) PD spot testing of rotating machine stator insulation has been used to provide long-term trending of PD activity. Whilst useful for the detection of long-term insulation deterioration due to ageing, these annual spot tests can sometimes fail to diagnose certain load-related, environmental (temperature/humidity), machine duty-cycle or seasonal-related insulation problems. Permanent PD monitoring of rotating machines overcomes many of the limitations of the annual, PD spot-tests, by providing continuous monitoring of the PD activity under normal (and abnormal) operating conditions. As a result of this, on-line continuous diagnostic PD monitoring over time has now become accepted as the most effective means of providing the necessary condition data suitable for planning and scheduling of preventative maintenance activity to support CBM strategies.

The relevance of PD monitoring within rotating machines is discussed by Stone et al in [4] and [5] as an effective technique to determine the condition of the stator winding insulation. In particular cases the authors use pre-installed 80 pF, HVCC sensors, one or more per phase, to monitor both phase-to-phase and phase-to-earth PD activity. Interpretation of the severity of any PD activity has traditionally been carried out by considering the peak PD level (typically given in mV) and also the number of PD pulses across the 50/60 Hz power cycle.

Analysis of PD measurement severity by many authors [6] considers the energy density of the PD activity across the power cycle as the most effective way to measure the PD severity. A number of authors [1, 4, 5, 7] also refer to the effectiveness of comparing measured PD activity from similar types and voltage-classes of HV cables, plant and rotating machines through the use of databases and comparing measurements against other similar plant. The relevance of the rotating machines PD database and comparing PD measurements between similar classes of machine has been reported in [4, 5] where the authors reviewed peak PD level, PD energy density, winding age, and the voltage class of the rotating machine to analyse how these parameters affect PD levels and the reliability of the in-service rotating HV machines.

With regards to the application of the OLPD monitoring of HV motors located in Ex hazardous gas zones, a recent study by S. Haq et al in [3] discussed minimum discharge levels required to produce a possible spark risk. This study was made on rotating machines operating within different gas groups and reports that static charge within the stator winding should be kept below 10 nC for a machine operating in gas group B (Hydrogen) to minimise the risk of gas ignition (10 nC equates to a minimum ignition energy of approximately 0.019 mJ). This provides a benchmark, maximum level for static charge in such machines whilst also emphasizes the importance of monitoring partial discharge activity in this type of motor. It should be noted that whilst PD is not a purely static charge in this sense, it is known that PD activity can lead to active charge surface tracking of 100 nC+ (100,000pC) in extreme cases.

IV. MODERN ON-LINE PD TESTING AND MONITORING TECHNOLOGY

There are now a wide range of technologies available in the market for OLPD testing and monitoring of in-service HV cables, plant and rotating machines. These range from simple-to-use, handheld PD screening test units (for screening large numbers of HV assets quickly and easily) to
continuous PD monitoring technology. It is now becoming increasingly popular for rotating HV machine owners to install permanent PD sensors and monitoring systems at suitable points in the HV networks which drive their industrial processes, chemical processing and oil and gas refining. The OLPD technology is used to provide an early warning against insulation failure through the detection of incipient insulation faults i.e. faults yet to occur. PD detection is now commonly regarded as the best indicator of insulation degradation of in-service HV cables and plant. By combining PD screening tests (Phase 1), PD diagnostic spot-tests (Phase 2) and extended, continuous PD monitoring (Phase 3) technologies, it is possible to carry out:

- Routine, regular walkby assessments of HV cables and rotating plant using simple, handheld PD test units.
- Diagnostic PD testing and location of the PD site(s) using portable diagnostic spot-test technology.
- Permanent monitoring of key substations, circuits and rotating machines on the network to trend PD activities with time/load cycle changes.

V. PARTIAL DISCHARGE SENSOR OPTIONS

There are a number of sensor options available for the online detection of PD activity in cables, switchgear, transformers plant and rotating machines. These sensors include SSC, RTD, HVCC, HFCT, RC, and Transient Earth Voltage (TEV) sensors. The four main types of on-line PD sensors used are shown in Table I. The wideband frequency response of the three sensor types used to test rotating HV machines is shown in Fig. 1.

It can be noted from Table I that at 10 MHz, the HVCC sensor is the most sensitive, followed by the HFCT sensor, the TEV sensor and then the RC sensor. Fig. 1 shows the frequency response along with the approximate spectra of PD activity occurrence from 10 kHz to 100 MHz. The most suitable sensor solution for any application will depend on the cable/plant/machine to be tested and the most suitable point of attachment (POA) for the sensor on the network.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>PD Sensor Options</th>
<th>Relative Sensitivity at 10 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Voltage Coupling Capacitor</td>
<td>Capacitive</td>
<td>100</td>
</tr>
<tr>
<td>Ferrite-cored High Frequency Current Transformer</td>
<td>Inductive</td>
<td>30</td>
</tr>
<tr>
<td>Transient Earth Voltage</td>
<td>Capacitive</td>
<td>5</td>
</tr>
<tr>
<td>Rogowski Coil</td>
<td>Inductive</td>
<td>1</td>
</tr>
</tbody>
</table>

With reference to Fig. 1, the center frequency and wide bandwidth of the new HFCT sensor ensures that lower frequency PD signals, which have been attenuated by dispersion within the power cable and propagation through the machine stator windings, can still be detected with sufficient sensitivity to make reliable measurements. The HFCT sensor can also detect higher (> 10 MHz) frequency components of the PD signal which appear closer to the point of origin of the PD activity such as in the switchgear cable box or machine terminal box. This wideband frequency response of the HFCT means that the sensor can be located remotely from the rotating machine under test whilst still being able to detect sufficient PD pulse energy to ensure that the PD pulse is represented accurately in the time and frequency domains. This allows for the discrimination between PD types based on location and pulse wave-shape.

It should be noted that, as discussed in the IEEE and IEC standards [8] and [9] (sections 11 and 5 respectively), the risk of misinterpreting PD signals always exists due to interference exhibiting similar characteristics as the PD signals. These IEEE and IEC standards discuss time and frequency domain methods of noise separation, types of interference that can be expected in OLPD testing, and the importance of distinguishing between the origins of the PD activity. The remote monitoring technique developed by the authors has been built on PD classification knowledge rules described in [6] and [7] that use time and frequency domain parameters to distinguish between PD types and interference. This new, remote PD monitoring technique with HFCT sensors located at the central switchboard can also reduce the risk of Variable Speed Drive (VSD) and inverter drive pulses at the machine being classified as noise, as such pulses are attenuated by the low-pass filtering effect of the power cable from the machines under test.

A brief description of the four main types of sensor used for the OLPD detection of in-service HV cables, switchgear, bus duct, transformers and rotating machines is given below.

Fig. 1 Normalised Frequency Response of four types of PD Sensor with PD Pulse Spectrum
A. High Voltage Coupling Capacitor Sensors

A typical installation of three HVCC sensors, one per phase in a generator terminal box is shown in Fig. 2. These sensors require a galvanic connection to the HV terminals of the machine and provide the greatest measurement sensitivity of all the PD sensor options when installed here. HVCC sensors of different voltage and capacitances are available in the marketplace ranging from 6.6 kV to 36 kV in voltage with typical capacitance ratings available of 80 pF, 500 pF, 1 nF and 2 nF. High voltage coupling capacitor sensors are recommended for PD monitoring of larger rotating machines (e.g. 20 MW+ at 11 kV) and are now widely employed to monitor PD activity in HV generators and larger HV motors. A limitation in the use of these sensors is sometimes seen with smaller motors (<5 MW) supplied with concentric neutral, 3-core triplex cables as it is sometimes difficult to fit the HVCC sensor in the smaller cable boxes on these machines. In such cases HFCT sensors are preferred as they require less space to fit.

![Fig. 2 Permanent On-line High Voltage Coupling Capacitor installation in an large 11 kV Generator Terminal Box](image)

B. High Frequency Current Transformer Sensors

Split-core, ferrite HFCT sensors have now become the de facto sensor of choice for the on-line PD testing of in-service HV cables. The HFCT works inductively to detect PD currents in the either the HV cable earth/drain wire or in the HV cable’s conductor. Permanent HFCT sensor installations such as those shown in Fig. 3 are also now becoming more popular with HV plant owners for the application of PD monitoring of smaller rotating machines (sub 10 MW) due to their ease of installation and lower cost compared to the more conventional HVCC sensors. The HFCT sensors are installed inside the terminal box and are installed to intercept the PD current on the conductor of each phase (i+) or the PD current on the earth drain/electrostatic shield (i-). Another advantage of the HFCT sensor, as discussed in the previous section of this paper, is that they have a suitable low frequency response (down to approximately 100 kHz, as shown in Fig. 1) whilst also being capable of detecting high frequency PD signals (up to approximately 30 MHz+). Due to this wideband frequency response (from 100 kHz to 30 MHz), the HFCT sensors are suitable for permanent installation within either the machine terminal box or switchgear cable box. Installation of these sensors at the switchgear cable end enables remote PD monitoring of rotating HV machines to be made as they are able to detect the lower frequency PD pulses that have travelled down the HV cable from the machine.

![Fig. 3 Permanent HFCT sensor inside cable boxes Left: HFCT sensor around Cable + Earth/Drain. Right: HFCT sensor on Earth Drain Wire](image)

Effective Measurement Range:
- Up to 1.0 km for PVC
- Up to 1.5 km for PILC
- Up to 2.5 km for XLPE

![Fig. 4 Measurement range for an HFCT sensor connected at the switchboard cable end for the three main cable insulation types (PVC, PILC, XLPE)](image)

C. Rogowski Coil Sensors

Air-cored, RC inductive sensors have been used in the UK power generation, oil and gas and petro-chemical industries to monitor PD in rotating machines for many years. They were originally adapted for the application of monitoring PD activity in large generators by scientists at the UK’s Central Electricity Generating Board (CEGB) in the 1960s. These RC sensors have also been used in the UK North Sea offshore oil and gas industry and a number of designs have become Atmosphere Explosive (ATEX) approved for installation within hazardous gas zones. They are normally permanently installed in the cable boxes of the motor or generator and are located on each phase, around the HV cable cores. Whilst proven to have a very low spark-risk, the main drawback to the RC sensor is that it has a low
sensitivity to PD signals, typically around 30 to 100 times less than the HFCT and HVCC sensors respectively. This means that only very significant levels of PD activity are detectable by the RC sensor with the early stage detection of PD activity more difficult due to the poor signal-to-noise ratio of this sensor.

Fig. 5 A handheld PD test unit with TEV sensor shown testing a switchgear panel from the outside

D. Transient Earth Voltage Sensors

Transient Earth Voltage sensors are used on the outside of the metal-clad plant under test and are used predominantly to test HV switchgear for internal PD activity. The occurrence of PD within the HV insulation system induces a high frequency voltage pulse (the so-called transient earth voltage) on the inner surface of the earthed housing. These electromagnetic signals emerge onto the outer skin of the switchgear through breaks in housing such as vents, joints or seams. The TEV sensors are thus placed on the outside of the switchgear panel to capacitively couple to these induced PD signals originating from inside.

There are a number of handheld PD screening devices in the market which incorporate TEV sensors which have been shown to be very useful in identifying and locating PD activity in HV switchgear panels and bus ducting (example shown in Fig. 5). Handheld PD test technologies for this type of simple look-see PD screening test are now becoming more popular and can now also be used for the testing rotating HV machines which are equipped with built-in permanent PD sensors (HVCC, HFCT or RC sensors).

V. PD LEVEL GUIDELINES FOR HV ROTATING MACHINES

Table II gives guidelines for condition assessment vs PD levels for measurements on rotating machines using both HFCT sensors (PD levels in pico-coulombs (pC)) and HVCC sensors (PD levels in mV) for rotating machines in the 10-12 kV voltage class. The PD level guidelines in Table II are based on the authors’ own experience and also information published in the IEEE Transactions on Industry Applications, see [3, 4].

<table>
<thead>
<tr>
<th>Assessment</th>
<th>PD Level (pC) HFCT sensors</th>
<th>PD Level (mV) HVCC sensors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excellent</td>
<td>&lt; 2000</td>
<td>&lt; 20</td>
</tr>
<tr>
<td>Good</td>
<td>2000 – 4000</td>
<td>20 – 40</td>
</tr>
<tr>
<td>Average</td>
<td>4000 – 10000</td>
<td>40 – 1000</td>
</tr>
<tr>
<td>Still Acceptable</td>
<td>10000 – 15000</td>
<td>100 – 250</td>
</tr>
<tr>
<td>Inspection Recommended</td>
<td>15000 – 25000</td>
<td>250 – 600</td>
</tr>
<tr>
<td>Unreliable</td>
<td>&gt; 25000</td>
<td>&gt; 600</td>
</tr>
</tbody>
</table>

Whilst the guideline PD levels given in Table II provide a good basis for the initial assessment of the condition of the machine’s stator insulation, it should be noted that the PD condition assessment of rotating machine stator insulation should not be based on PD magnitude levels alone. It is the trend in the PD activity which is generally considered as more important.

Alongside PD levels, it is thus also important to measure the PD magnitude trend over time including trends in:

- Average PD Pulse Charge Content, Q (in pC or mV).
- Total PD Activity across the power cycle i.e. the Energy Density measurement (nC/cycle or mV levels multiplied by N - number of pulses, the NQN factor).

VI. WIDEBAND ON-LINE PD TEST TECHNIQUE

In order to carry out fully diagnostic PD testing in the field it is necessary to apply wideband PD diagnostic test and continuous PD monitoring technology. This requires PD measurements based around wideband (0 - 400 MHz) test units, 4-channel synchronous data acquisition which can also provide high high-resolution Analogue-to-Digital conversion of a minimum of 100 Mega-Samples per second (MS/s) for monitoring and up to 500 MS/s for diagnostic testing and PD site location. Such high resolution A to D hardware allows for entire 50/60 Hz power cycles to be sampled synchronously on all three phases of the HV machine at once to an accuracy of 1 sample per 2 ns with all channels synchronous to within 2 ns.

High resolution capture of the PD signals in this way can then be followed by data analysis using software algorithms to categorise and analyse the PD pulse data collected. Software data analysis techniques employed can use pattern recognition techniques including the well-established Phase-Resolved Partial Discharge (PRPD) plots across the 50/60 Hz power cycle.

More advanced PD signal extraction techniques are now also being employed which utilise pulse waveshape analysis to separate and analyse the PD pulses from noise and other interferences whilst also differentiating phase-to-earth and phase-to-phase discharge activity.
VII. CASE STUDY EXAMPLE

A crude oil producing field and treatment facility in Kazakhstan began operation in 1993, and has grown significantly since. There are approximately 100 HV motors at the plant rated 10 kV presently in operation, with about half of these now nearing an in-service age of 20 years. The site conditions are severe, with the ambient air temperature ranging from -30°C to +45°C. Additionally, almost all of the motors are Ex-rated for continuous operation in hazardous gas zones (refer to [3] for definitions of Class, Group, Division and Zones related to hazardous environments). The motors are critical to production operations with limited spares maintained at the site. As the motors are reaching an in-service age of 20 years, a decision was made by the operator to employ on-line partial discharge analysis PD diagnostic testing to measure the condition of the stator windings to ensure that the motors will continue to work reliably.

The HVCC type of sensor, mounted within the terminal box, has been used at the facility for a number of years to monitor the stator condition of the gas-turbine generators on the site. This conventional approach has been applied as the gas turbines are located in a non-hazardous location. However, as most of the HV motors at the facility are located in Ex (hazardous gas) locations, an alternative PD monitoring solution was sought. A solution using wideband HFCT sensors was thus proposed, since this allowed the PD sensors to be located at the switchgear end of the cable, in a non-hazardous area. A large part of this work involved the measurement of the PD pulses at each end of the PVC motor cable feeders (which were around 350 m in length) to take into account the attenuation of the high-frequency partial discharge signals as they passed along the cables. It is known from previous on-line PD tests that these PVC-insulated cables significantly attenuate PD pulses (far more than XLPE cables for instance) and it was therefore important to evaluate whether the PD pulses could be measured reliably at the switchgear end of the cable.

A pilot test was carried out on two motors: Motor 1: a 10 kV, 800 kW four-pole induction motor driving a pump, and Motor 2: a 10 kV, 2400 kW two-pole induction motor driving an air blower. The first tests carried out involved injecting calibration pulses at the motor terminal boxes to calibrate the pulse propagation time along the cable and the pulse attenuation coefficients of the cables. Secondly, on-line PD data was collected from both the switchgear end and motor terminal end of the cables with the motors running using clamp-on HFCT sensors. The PRPD plots from the measurements made at the switchgear end of the cable tests are shown below in Fig. 6. The plots are referenced to the blue phase 60 Hz power cycle voltage (a sine wave from 0 to 360 degrees).

The results presented in Fig. 6 showed that it was possible to reliably measure the PD pulses at the switchgear end of the motor feeder cables using the wideband HFCT sensors. Comparison of the measurements made at each end of the cable gave an average PD Pulse Retention Factor (PPRF) of the pC content of the pulses of around 0.50 (this being the ratio of the switchgear end PD to the motor end PD). The PPRD plot for Motor 1 on the top of Fig. 6 shows predominant phase-to-earth PD activity which indicates slot section discharge activity on the blue phase of motor. This is characterized by there being predominant signals on this blue phase, which are not seen on the other two phases at the same point in time. Conversely, the PPRP plot for Motor 2 on the bottom of Fig. 6 shows predominant phase-to-phase PD activity which indicates end winding PD activity in this motor. This is characterized by there being equal and opposite signals observed on two phases at once.

The motors were tested with a high-specification, digital discharge detector based around a fast digital storage oscilloscope (DSO) with a wide bandwidth (0-400 MHz) and high-resolution data capture (100 MS/s). This made it possible to analyse the PD activity based on individual pulse wave-shape analyses of the high resolution measurements of all of the individual PD pulses detected.
The basis for this pulse wave-shape analysis was first developed in 2005 [11] and is illustrated in Fig. 7 which shows the time-domain pulse parameters measured for an individual PD pulse. The pulse wave-shape analysis uses measurements of the pulse rise-time (measured between 10 – 90% of the rising edge of the pulse), the pulse width (time between 50 – 50% of the rising and falling edges) and the pulse fall-time (90 – 10% on the falling edge). These measurements, combined with the frequency measurement of the pulse are fed through the knowledge-rule based analysis algorithm which is based around the PD pulse analysis of the shark-fin shape as it passes through the HV network from its source.

Using the parameters from the pulse as shown in Fig. 7 it is possible to incorporate the Transfer Impedance of the HFCT sensor and some basic calculus to derive the charge content \( q \) of the pulse using (1).

\[
q = \frac{1}{Z_{Tr}} \int_{t_0}^{t_1} i(t) \, dt
\]

(1)

Where the limits of integration; \( t_0 \) and \( t_1 \) define the time of the PD event waveform. The charge content is effectively the area underneath the PD pulse waveform. The PD pulses shown in Fig. 8 and Fig. 9 below are from measurements made with HFCT sensors on the two 10 kV motors where the PD pulses have been measured at both the motor and switchgear ends of the 350 m, PVC insulated motor feeder cables.

The three different lines in Fig. 8 and Fig. 9 represent the three phases of the motor/cable circuit with the PD signals for each phase detected using a split-core, HFCT sensor connected around each phase cable. The PD pulse parameters for a phase-to-earth PD signal measured at each end of the cable (from Motor 1) are shown in Fig. 8 and for a phase-to-phase PD signal (from Motor 2) in Fig. 9.

By comparing the pulse wave-shape measurements made at each the cable, the effects of attenuation and dispersion of the pulses as they travel along the cable feeder can be assessed. In this case it can be noted that this leads to a general broadening of the pulses.

The PD pulse parameters for the individual PD pulses shown in Fig. 8 and Fig. 9 above are provided in Table III and Table IV respectively. The measurements of the shark-fin PD pulses have been made using the measurement parameters shown in Fig. 7. The characteristics of the individual PD pulses illustrate how the PD pulse emanating from the motor stator attenuates in magnitude and disperses (pulse broadening) as it travels down the cable to the switchgear end. The measurements made at each end of the cable agreed with previous PD measurements on cable-fed HV plant carried out by the authors and also with the data reported in [12].

<table>
<thead>
<tr>
<th>Parameter of PD Pulse</th>
<th>Motor-End PD Measurements</th>
<th>Switchgear-End PD Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Phase</td>
<td>Phase</td>
</tr>
<tr>
<td>L1</td>
<td>29.4</td>
<td>150.5</td>
</tr>
<tr>
<td>L2</td>
<td>49.2</td>
<td>122.4</td>
</tr>
<tr>
<td>L3</td>
<td>58.3</td>
<td>166.9</td>
</tr>
<tr>
<td>Rise Time (ns)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L1</td>
<td>59.6</td>
<td>192.2</td>
</tr>
<tr>
<td>L2</td>
<td>54.8</td>
<td>322.3</td>
</tr>
<tr>
<td>L3</td>
<td>47.7</td>
<td>306.7</td>
</tr>
<tr>
<td>Fall Time (ns)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L1</td>
<td>100</td>
<td>340</td>
</tr>
<tr>
<td>L2</td>
<td>100</td>
<td>470</td>
</tr>
<tr>
<td>L3</td>
<td>100</td>
<td>480</td>
</tr>
<tr>
<td>Pulse Width (ns)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L1</td>
<td>3.84</td>
<td>2.56</td>
</tr>
<tr>
<td>L2</td>
<td>5.18</td>
<td>3.79</td>
</tr>
<tr>
<td>L3</td>
<td>10.93</td>
<td>5.03</td>
</tr>
<tr>
<td>Charge (nC)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L1</td>
<td>55.6</td>
<td>26.9</td>
</tr>
<tr>
<td>L2</td>
<td>57.6</td>
<td>24.6</td>
</tr>
<tr>
<td>L3</td>
<td>409.6</td>
<td>54.4</td>
</tr>
<tr>
<td>Amplitude (mV)</td>
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</tbody>
</table>

TABLE III

PHASE-TO-EARTH PD PULSE PARAMETERS MEASURED AT THE HV MOTOR AND SWITCHGEAR END OF THE FEEDER
A PPRF for the cable/motor was used to take into account signal attenuation along the cable feeder and thus convert the remote PD measurements to the at machine-end equivalent. As stated previously, the PPRF for any cable feeder depends on length of the cable, its geometry and the type of cable insulation used (PVC cables produce the greatest pulse attenuation followed by paper-insulated cables whilst XLPE cables produce the least attenuation).

In this project it was possible to carry out calibration pulse injection tests to compare against the PD pulse analysis summarized in Tables III and IV. This was possible to do with the motor de-energized with low-amplitude (60 mV) phase-to-earth and phase-to-phase calibration pulses injected onto the stator windings of the motors at their terminal box. The charge content of the injected calibration pulses were measured at each end of the cable and the results from the calibration testing of Motor 1 are shown in Fig. 10. This shows the pulse injected onto the motor terminals in the top trace and the same pulse measured at the switchgear end of the cable in the bottom trace. The feature observed at approximately 6 µs on the timebase is the reflection of the pulse from the end of cable. It can be noted that inversion of the reflected pulse is due the impedance of the stator winding being less than that of the feeder cable, and hence the reflection coefficient (Γ) being negative.

The parameters of the calibration pulse injections on Motor 1 for both phase-to-earth and phase-to-phase pulses are summarised below in Table V. The same calibration tests were also carried out on Motor 2.

<table>
<thead>
<tr>
<th>Parameter of PD Pulse</th>
<th>Machine-End PD Measurements</th>
<th>Switchgear-End PD Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Phase</td>
<td>Phase</td>
</tr>
<tr>
<td>Rise Time (ns)</td>
<td>L1  88.2</td>
<td>L3  50.4</td>
</tr>
<tr>
<td></td>
<td>L2  24.9</td>
<td>L2  192.5</td>
</tr>
<tr>
<td></td>
<td>L3  50.4</td>
<td>L3  192.5</td>
</tr>
<tr>
<td>Fall Time (ns)</td>
<td>L1  95.6</td>
<td>L3  88.2</td>
</tr>
<tr>
<td></td>
<td>L2  74.6</td>
<td>L2  214.8</td>
</tr>
<tr>
<td></td>
<td>L3  88.2</td>
<td>L3  214.8</td>
</tr>
<tr>
<td>Pulse Width (ns)</td>
<td>L1  190</td>
<td>L3  580</td>
</tr>
<tr>
<td></td>
<td>L2  100</td>
<td>L2  278.3</td>
</tr>
<tr>
<td></td>
<td>L3  150</td>
<td>L3  278.3</td>
</tr>
<tr>
<td>Charge (nC)</td>
<td>L1  20.48</td>
<td>L3  10.05</td>
</tr>
<tr>
<td></td>
<td>L2  3.97</td>
<td>L2  19.65</td>
</tr>
<tr>
<td></td>
<td>L3  19.65</td>
<td>L3  88.2</td>
</tr>
<tr>
<td>Amplitude (mV)</td>
<td>L1  415.98</td>
<td>L3  543.98</td>
</tr>
<tr>
<td></td>
<td>L2  160.0</td>
<td>L2  73.0</td>
</tr>
<tr>
<td></td>
<td>L3  543.98</td>
<td>L3  11.52</td>
</tr>
</tbody>
</table>

The calibration tests on Motor 1 shown above in Table V yielded a PPRF for phase-to-earth pulses of 0.45 and a PPRF of 0.58 for phase-to-phase pulses along 350m of PVC motor cable feeder.

Calibration test results on Motor 1 and Motor 2 were compared with the results from the OLPD measurements made at each end of the motor feeder cables these are summarized in Table VI. It can be noted from Table VI that there is a good correlation between the average PPRF values obtained by direct calibration pulse injection and the PPRF values calculated from the on-line PD measurements.

Calibration tests confirmed that it was possible to monitor PD activity reliably using wideband HFCT sensors located at the switchgear end of the motor feeder cable. The results also confirmed the importance of using the PPRF factor as without it the remote measurements would be out by a factor of two. It is thus recommended that calibration pulse injections are made on the cable to measure the PPRF for...
each motor feeder cable as part of any remote HFCT sensor and PD monitor commissioning tests.

Further to the success of the remote PD monitoring trial project described above, a new project has been initiated to install HFCT sensors within the switchgear motor feeders for all of the 10 kV motors at the processing facility to enable continuous PD monitoring of the motors. Since most of the motors are of similar ratings, this is expected to lead to a program where replacement candidates can be prioritized and spares or replacements procured. This new project will provide continuous PD monitoring to identify variations related to operational, environmental and seasonal variations to provide trends in data. The results of this continuous monitoring program of a large population of motors, using HFCT sensors mounted at the switchgear end of the cable, may be a future topic of another technical paper on this application into the future.

IV. CONCLUSION

The project has shown that it is possible to reliably detect the PD signals emanating from the stator windings of the motors located in the Ex zone using remotely located HFCT sensors at the central switchboard. It is also proposed that the individual pulse wave-shape analysis method described in this paper allows for a much more detailed analysis of the PD pulses emanating from the machines’ windings to be made. Most crucially, this type of waveshape-based, diagnostic measurement provides the ability to discriminate between phase-to-phase PD (from the end windings of the machine) and phase-to-earth PD (from the slot sections of the machine). This has a significant bearing on the level of maintenance required as the repair of slot insulation requires removal of the rotor (a big job) whilst end-winding discharges can be repaired in many cases with only having to remove the motor end caps to clean and touch-up the end winding insulation with stress-grading paint.

Partial Discharge diagnosis algorithms developed by the authors over 15 years ago for PD testing cables, transformers and switchgear, allowed a similar analysis to be made for HV rotating machines. To better understand pulse propagation, retention of energy and multiple reflections of PD signals in rotating machines, the authors will continue to carry out pulse injection tests and remote-end PD testing of in-service HV motors and generators. Such tests provide an understanding of how the machine construction and cable geometry and affects pulse attenuation and distortion from source to sensor. The accurate location of PD sites within a rotating machine will be dependent upon the combined knowledge of the propagation paths throughout the windings and the application of suitable differential equations to describe the pulse propagation process and ultimately locate the source(s) of PD.

Developing relationships between the different sites of PD activity within rotating machines, and the PD pulse signals at different locations, is dependent upon having knowledge of the frequency response of the PD sensor, and an understanding of certain types of differential equations which permit so-called travelling wave solutions. Such equations help in describing the PD pulse propagation process as they allow decaying modes of solution that model how a wave travels in a dispersive medium. Further work is planned to examine the validity of using differential equations to predict PD pulse attenuation, dispersion and reflections as a function of distance travelled through the windings.

REFERENCES

Lee A. Renforth studied Electrical and Electronic Engineering at the University of Manchester in the UK between 1986 and 1990. He was sponsored throughout this 4-year industrially-linked course by BICC cables where he received his first training in the testing of HV cables. He graduated with a BSc, MEng degree in 1990 and went on to study for a PhD in the field of high voltage insulation breakdown under sponsorship by the National Grid Company, the transmission network operator for the UK. He was awarded his PhD in 1993 when his thesis on the topic of the breakdown of high voltage insulation was published, also at Manchester University. In 1994 he set-up a new technology start-up company, IPEC Ltd, with other members of Manchester University’s Power Systems Group. He was Managing Director at IPEC Ltd for 10 years from the company’s start-up before leaving to set-up HVPD Ltd in 2004. He is currently Managing Director of High Voltage Partial Discharge (HVPD) Ltd, Manchester, England, UK which has now established itself as one of the market leaders in the growing field of on-line partial discharge test and monitoring technology for high voltage plant, cables and rotating machines. He oversees the relationships with HVPD’s customers and partners in more than 80 countries worldwide whilst remaining involved in the company’s R&D activities in conjunction with Manchester University, UK.

Steven Goodfellow received an HND in Electrical & Electronic Engineering in 2003 from Tameside College in Manchester, achieving a distinction level in his final year project, the study of HV full-bridge resonant power supply. With 8 years electronics manufacture and field experience working as a HV test engineer, previous projects have ranged from LASER power supplies to HV Marx Generators. Prior to joining HVPD in Jan 2009, he worked as an electrical test engineer at AMTAC laboratories and since joining HVPD, he has been focused on field trials of the HVPD’s range of PD monitoring technology. With over 1000 hours of at-site field test experience with HVPD, Steven carried out the on-line test trials reported in this paper. He is an offshore certified engineer and is a member of the HVPD online field test team providing PD test services to industrial customers worldwide.

David Clark was born in Canterbury, Kent, UK, on 4th October 1980. He received the B.Sc. degree in Mathematics from the University of Kent in 2009, and the M.Sc. degree in Electrical Power Engineering from the University of Greenwich in 2010. At present he is pursuing a Ph.D. degree at the University of Manchester with sponsorship from HVPD Ltd. His research interests include partial discharge pulse propagation in machines, applications of solution theory and travelling wave solutions to partial discharge interpretation and the development of knowledge-based rules for partial discharge (PD) classification.

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Russell Armstrong is the E&I Reliability Supervisor at Tengizchevroil (TCO), Tengiz, Kazakhstan. He worked on the project described in this paper in conjunction with HVPD and Chevron, applying his knowledge of the 10 kV network under test to identify the most suitable points and attachment (POA’s) for connection of the HFCT sensors and supervising access and switching of the network to allow for the installation of temporary sensors and off-line tests.