A NOVEL SOLUTION FOR THE RELIABLE ONLINE PARTIAL DISCHARGE MONITORING (OLPD) OF VSD-OPERATED EX/ATEX HV MOTORS

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Abstract – The majority of the larger (> 7.5 MW) high voltage (> 3.3 kV) motors in the oil and gas industry are operated through variable speed drives (VSDs). In order to maintain the availability of these critical machines, on-line condition monitoring (CM) technology is required. This paper describes a novel solution for reliable, on-line partial discharge (OLPD) CM of the HV stator winding insulation condition of VSD-operated HV motors. Inductive, tri-band sensors were used to provide a power frequency synchronization signal alongside the OLPD measurement signal. This enables phase resolved partial discharge (PRPD) patterns across the power cycle to be constructed, at all of the VSDs operating frequencies. The data acquisition technology utilises a 24-channel smart multiplexer with 6-channel synchronous data acquisition to enable pulse precedence measurements to be made between distributed sensors. The new OLPD monitoring solution has been trialed in a pilot project with an oil and gas operator in Norway where a 5.9 kV, 40 MW twin-winding VSD-operated EX-P motor was successfully monitored on-line for partial discharge activity. This was made possible through the active discrimination of the electromagnetic (e/m) noise from the VSD power electronics. The large e/m noise pulses produced often dwarf any PD pulses as they can be up to 10x larger, thus making it difficult to extract the PD pulses from this continuously pulsed e/m noise. This paper describes the development and testing of a new CM system for the OLPD condition monitoring of the stator windings of VSD-operated HV motors located in an Ex/ATEX hazardous gas zones. The new technique utilises a combination of multiple inductive sensors, high speed data acquisition hardware and dedicated software to reliably perform both OLPD and Power Quality (PQ) measurements. The new technique employs the use of the synchronous detection (< 10 ns) of any 6 channels from a total of 18 sensors located at different points along the VSD and HV Motor circuit, as illustrated in Fig. 1. The solution was tested in a pilot project to monitor a twin-winding 5.9 kV, 40 MW VSD-fed synchronous motor in Norway. This motor was selected for continuous OLPD monitoring after OLPD ‘spot tests’ with a portable OLPD test unit had detected moderate levels of PD activity on one of the windings of this motor.

II. VARIABLE SPEED DRIVES (VSDs)

A. VSDs – Background and Principle of Operation

Direct fed, high voltage alternating current motors run at fixed speeds and are ideally suited to applications where a constant motor output speed is required. However, in the oil and gas industry, most of the larger HV AC motors as the ones that drive the production and refining process require some kind of varying demand.

Fig. 1 OLPD Monitor and 18-sensor solution for a twin-winding VSD-fed 5.9 kV, 40 MW EX-P Motor.
Historically, in applications requiring precise speed control, expensive direct current (DC) motors have been used in conjunction with hydraulic couplings to regulate the motor speed. In other applications the speed control process has been controlled by opening and closing dampers and valves, or changing the output speed with gears, pulleys, and similar devices with the HV AC motor speed remaining constant. In the 1980’s and 1990’s variable speed drive (VSD) operated HV AC motors started to appear on the market, offering an alternative method of motor speed control. The VSD, sometimes called frequency converter, adjustable speed drive (ASD) or inverter, is an electronic power controller that uses HV power switching devices to adjust the electrical supply to an AC motor with a corresponding change in the speed and torque output of the motor.

By implementing this type of control a very close match between motor speed and the process requirements can be achieved. Whilst there are a number of variations in VSDs design, they all offer the same basic functionality which is to convert the incoming electrical supply of fixed frequency and voltage into a variable frequency and variable voltage to the motor stator windings with a corresponding change in the motor speed and torque. An HV AC motor speed can be varied from zero rpm through to typically 100-120% of its full rated speed, whilst up to 150% rated torque can typically be achieved at reduced speeds, controllable in either direction [4].

B. VSDs - Main Components and Types

The basic design of an HV AC motor VSD consists of four main elements as shown in Fig. 2:
- The rectifier converts the incoming alternating current (AC) to direct current (DC).
- The rectified DC is then conditioned in the intermediate circuit.
- The inverter converts the rectified, conditioned DC back to AC of variable frequency and voltage.
- The control unit controls the operation of the VSD.

![VSD Functional Diagram](image)

The three (3) main VSD types used in the oil and gas industry based on their power switching topology are:
- The Current Source Inverter (CSI).
- The Load Commutated Inverter (LCI) – preferred for larger drives, as per the 40 MW drive in this project.
- The Voltage Source Inverter/ Converter (VSI/VSC).

C. VSDs – Main Benefits and Drawbacks

VSD systems typically have a high efficiency (of around 95% and above) with around 1% of the losses in the transformer, 2% in the converter and 2% in the motor.

The main benefits achieved by using a VSD are related to energy saving, reduction of the mechanical stresses (motor and pipe system) and improvement of the process:
- Energy savings:
  - With little phase-displacement between voltage and current there is a reduction of the reactive power required (this applies to VSI/VSC).
  - Soft start/stop can be achieved (reduced machines’ stresses and starting current).
  - Large energy-savings at reduced speed as the law of affinity applies; (see Eq. 1).

\[ P_1 = P_0 \left( \frac{\text{n}_1}{\text{n}_0} \right)^3 \]

Eq. 1 Law of affinity (P= power, n= motor speed)

- Acceleration/deceleration control:
  - Lessens mechanical/electrical stresses on motor.
  - Lessens the mechanical stress on pipe systems.
  - Reduces motor maintenance and repair costs.
  - Extends the life of the motor.

- Close match between motor speed and the process:
  - Optimal operating speeds for each process.
  - Compensates for changing process variables (due to a fast dynamic response).
  - Adjusts to the rate of production.
  - Avoidance of throttling devices to adjust flow.

Whilst there are a number of benefits to the application of VSDs to control HV AC motors as listed above, it is also known that VSDs can sometimes have a negative impact on the grid that they are connected to, as well as to the HV AC motor they are driving. Without sufficient voltage surge protection it is possible that the VSD output can result in the gradual aging of the HV motor stator winding insulation from over voltages caused by VSDs’ voltage pulses/surges. If these pulses are of a sufficiently high magnitude and with a sufficiently short rise time then they can produce an overvoltage of up to 2.5 Uo (working voltage) and above on the multi-turn HV motor stator winding. This high voltage will appear mainly over the first few turns of the stator winding and can initiate partial discharge (PD) if there is an air pocket or discontinuity in the HV motor stator winding insulation system. Once initiated and after a sufficient number of repetitive overvoltage surges, cumulative PD activity can then lead to insulation damage, tracking and eventually develop into a full turn-to-turn failure. Once a turn-to-turn failure occurs this can then rapidly progress to a full ground fault [5].

Some of the other potential drawbacks associated with VSDs are:
- Harmonic distortion:
  - Negative impact on AC supply on the same grid.
  - Increased heating losses in motor/transformer.
- Long lead effects:
  - Impedance mismatch between cable and motor winding can cause reflections of the VSD pulses resulting in overvoltages to 2.5 Uo – this is observed more in VSI/VSC but not in LCI.
  - Increased risk of HV insulation failure.
- Motor bearing currents:
  - Caused by common mode voltages and currents with inadequate grounding.
  - Electrical discharges across the bearings and bearings race can cause erosion.
III. THE MAIN CHALLENGES FOR OLPD MEASUREMENTS OF VSD-FED MOTORS

Each current pulse generated by the VSD has a voltage spike/pulse associated with it that is normally square in shape. This square pulse changes shape as it travels down the HV cable to the HV AC motor from the VSD and by the time it reaches the motor terminals it is then partly reflected due to the surge impedance mismatch between the cable and motor winding. This can alter the voltage pulse shape and cause a ‘voltage pile up’ onto the motor’s winding terminals due to the cumulative effect of repetitive pulsing [6]. Due to the way VSDs work and for other reasons associated with the hazardous gas environments in which they are often installed, the OLPD monitoring of VSD-operated HV motors has a number of main challenges associated, as follows:

- VSD power switching devices produce high levels of e/m interference that can obscure PD pulses.
- The supply frequency cannot be easily isolated because of the varying output frequency from VSD.
- Absence of clean (without harmonics) voltage reference source to carry out PRPD measurements.
- The location of the motor in the Ex/ATEX zone and the limited space for sensor installation in cable box.

As a result of the above, in order to provide effective and reliable OLPD measurements on VSD-fed HV motors, it was necessary to apply a number of innovative sensor and monitoring solutions, as described in the following sections.

IV. PILOT PROJECT - OLPD MONITORING OF A 5.9 kV, 40 MW VSD EX-P MOTOR

A. Project Overview

The main objective of the pilot project was to develop and test a reliable hardware and software OLPD monitoring technology for the electrical condition monitoring of a large VSD-fed HV AC motors. The OLPD monitoring solution developed was trialed over a 6-month period of monitoring on an in-service, 5.9 kV, 40 MW twin-winding synchronous motor.

B. Project Plan

The Pilot Project was scheduled in four main phases:
- Phase 1: Engineering survey and OLPD spot tests to select the motor for the 6-month monitoring trial.
- Phase 2: OLPD sensor installation.
- Phase 3: OLPD monitoring system installation.
- Phase 4a: Monitoring system training – 90 days.
- Phase 4b: Continuous OLPD monitoring – 90 days.

C. Project Success Criteria

The following four main criteria for success of the monitoring project were established by the partners:
1. To be able to perform effective OLPD measurements whilst differentiating real PD activity from all VSD switching e/m interference (noise).
2. To produce no ‘false alarms’ caused by e/m noise.
3. To measure & display the OLPD levels and trends across the entire VSD and motor circuit.
4. To carry out 90 days of continuous OLPD monitoring after a 90-day system training period.

D. Sensor Options, Selection and Installation

An engineering and test survey was carried out at the pilot project site in June 2014 during which a number of ‘sister’ 5.9 kV, 40 MW VSD-driven twin-winding HV AC motors were OLPD spot tested at the site. These short duration (30-minute) tests were made with a portable, high specification OLPD spot test unit (400 MHz, 250 MS/s). The suitability of the 5.9 kV cable terminations for the safe installation of the OLPD sensors at both the VSD cable terminal box and the EX-P motor cable box was also assessed and confirmed during this engineering survey. There were two (2) main sensor options available for OLPD monitoring of VSD-operated HV AC motors:
- High voltage coupling capacitor (HVCC) sensor.
- High frequency current transformer (HFCT) sensor.

Both of these types of sensor have been successfully applied to make pulse time of arrival measurements, in order to separate PD pulses from the stator windings of machines from external disturbances on the HV network. This technique uses two (2) geometrically separated (> 2 m apart) sensors per phase located along the bus or the cable connecting the motor or generator to the power system. This time of arrival established noise rejection approach is described in more detail in the referenced IEC standard [7]. The new technique described in this paper goes one step further than this by analyzing the data simultaneously on six (6) sensors selected from a total of eighteen (18) sensors located across a twin-winding VSD operated HV motor circuit. Analysis of these synchronized signals enables the measurement of PD activity across the complete VSD to HV motor circuit (and not just the HV motor stator windings).

Due to the requirement to collect wideband electrical signals (from DC up to 30 MHz) for combined OLPD, power quality (PQ) and transient event monitoring of the complete VSD-motor circuit, a new tri-band inductive sensor was developed. This sensor is a variant of the inductively coupled high frequency current transformer (HFCT – Band 3 in Fig. 3) but with an additional low frequency winding to provide Bands 1 and 2 outputs, as illustrated in Fig. 3 [8].

D. Sensor Options, Selection and Installation

- High voltage coupling capacitor (HVCC) sensor.
- High frequency current transformer (HFCT) sensor.

The inductive tri-band sensor is similar in design to the established inductive high frequency current transformer (HFCT) and has a split-core which makes it easy to install safely onto cables in OLPD sensor retrofit installations. The tri-band sensor was designed for attachment around HV cables (at the earthed section of their terminations) and to operate up to 800 A without any saturation of the sensor’s ferrite core. The sensor comprises two (2) windings covering three (3) measurement bands, a high frequency current transformer (HFCT) sensor.
frequency (HF) winding - Band 3 (0.1–30 MHz) and a low frequency (LF) winding – Bands 1 & 2 - DC up 200 kHz as shown in Fig. 3. A passive low-pass filter is integrated inside the tri-band sensor casing on the LF output to suppress the higher frequencies (> 200 kHz) not relevant to the harmonics, PQ and transient event monitoring. The sensor provides the following outputs:

- VSD operating frequency synchronization signal.
- A power quality (PQ) signal (to 63rd harmonic).
- Transient event detection (up to 200 kHz).
- An OLPD measurement signal (0.1 – 30 MHz).

The benefits of using these inductive split-core tri-band sensors in this project included the following:

- It was possible to safely retrofit the split-core HFCT sensors around the HV cable (below the cable earth take-off) in the space-limited EX-P motor cable box.
- The sensor is installed around the cable and cable earth return (below the cable earth take-off) on an insulated silicon collar as shown in Fig. 5 and is thus intrinsically electrically safe as it does not require galvanic connection to the HV conductor.
- The wideband frequency response of the sensor’s HF winding (from 100 kHz to 30 MHz) provides a noise reference signal to help suppress VSD e/m noise pulses in the sub 1 MHz frequency range.
- The LF winding provides a power cycle synchronisation signal for the VSD frequency, power quality (PQ) and transient events (DC to 200 kHz).
- With multiple sensors installed across the motor and VSD HV cable boxes, precedence timing measurements can be made to differentiate the PD signals originating from the HV motor stator windings, PD from the rest of the circuit and the e/m noise from the VSD power switching through pulse arrival timing.

In addition to the tri-band sensors, Transient Earth Voltage (TEV) sensors were also installed in the VSD and the HV motor cable boxes to identify any local PD within the cable terminations. Retrofit installation of the OLPD sensors was made during a planned maintenance outage inside the EX-P motor cable box on both HV cables to the twin-winding 5.9 kV, 40 MW EX-P motor. Tri-band sensors were installed, one per phase, on each of the two motor windings in the cable box. The sensors were installed below the cable earth take-off point on insulated silicone collars (to provide a tight fit for the sensor onto the power cable that provide a good anti-vibration mounting). The conductive casing of the sensor was grounded via a 16 mm² earth cable both between the sensors and the main earth bar as shown in Fig. 5.

RG223 double-screened, coaxial signal cables were fed to the outside of the HV motor cable box via a cable frame containing EX-P transit blocks to maintain the EX-P rating of the motor (see Fig. 6). The signal cables were then routed along the existing cable trays to outside the hazardous gas zone where they were terminated into a sensor point-of-attachment (POA) termination box that was then connected to the OLPD monitor.

The same combination of sensors was also installed in the VSD output HV cable box, as shown in Fig. 7. Additional tri-band sensors (one per circuit) were also installed on the combined cable earth connection in the VSD cable box in order to detect any PD along the HV feeder cable as this type of cable PD couples mainly to the HV cable sheaths. This combination of a total of eighteen (18) sensors located in the VSD cable terminal box (10 sensors) and the HV motor cable terminal box (8 sensors) ensures OLPD sensor monitoring coverage of the complete VSD HV motor circuit.
E. OLPD Monitoring System and Installation

A high specification OLPD monitoring system is required to carry out reliable OLPD monitoring of the VSD-fed HV motor circuits using this technique.

The system used in this project had the following specification:

- 6-channel synchronous (< 10 ns on 6 channels) data acquisition with a 24-ch. multipoint multiplexer.
- 18-sensor ‘distributed OLPD sensor’ timing and analysis for ‘pulse precedence’ measurements.
- A high analogue to digital sampling rate of 250 mega samples per second (MS/s) across the entire power cycle.
- Intelligent, knowledge-based software to analyze, classify and locate sites of PD whilst extricating PD pulses from high background e/m noise.

After six (6) months of testing and development in a test laboratory on a specially designed VSD motor test rig, the trial OLPD monitoring system was installed in the control room of the facility in October 2014 as shown in Fig. 8. The sensor cables from the cables installed in the VSD HV motor circuits were routed back to the control room via a cable termination box. The monitoring system was connected via Ethernet cable to a dedicated partial discharge monitoring server (PDMS) which then performed data storage, post processing, databasing and visualization of the results. The PDMS was connected to the local area network (LAN) at the facility so the system could accessed by the reliability engineers at the facility, whilst also being remotely accessible (via a secure internet connection) by expert OLPD diagnostic engineers to facilitate remote data retrieval, analysis, alarm level setting, reporting and software upgrades.

V. RESULTS

A. Measurement of Power Frequency

The monitoring system recorded the VSD varying power frequency using the LF signal from the tri-band sensor. A plot of the power frequency measurement from the 17th March up to 9th of April 2015 is shown in Fig. 9. The frequency fluctuated between 42.4 Hz and 58.7 Hz during the measurement period. It can be noted that between the 1st and 4th of April 2015 the monitoring system was not able to synchronize to a valid frequency signal and as a result reverted to the monitor’s triggering default frequency of 50 Hz. The loss of the external triggering signal for this 3-day period can also be seen in the OLPD activity trend presented in the following sections of this paper. The VSD power frequency measurements made by the LF winding of the sensor were compared to the frequencies reported by the VSD controller and were found to be the same (to ± 0.1%).

B. Power Quality Analysis

Alongside OLPD monitoring, the tri-band sensor can also measure the power quality (PQ) parameters of the HV circuit. The LF signal from one of the sensors installed at the VSD end was used to acquire the voltage reference waveform and the frequency spectrum of the waveform was calculated using a power quality software module in the monitoring system using a Fast Fourier Transform (FFT) with a flattop window. Fig. 10 shows the PQ frequency spectrum with a fundamental component of 55.019 Hz. Using this the harmonic components were extracted, up to the 63rd harmonic (3.465 kHz).

C. OLPD Activity Trending Data

The monitoring system was installed and set-up to collect training data continuously for a period of ninety (90) days, prior to carrying out the 90-day continuous OLPD monitoring trial. The continuous trending of the OLPD data over time is considered to be a much better diagnostic for HV insulation condition than periodic OLPD
spot testing since it also shows the variation of PD activity in response to load cycle variations, environmental changes as well as other external factors. An example of a 6-day continuous OLPD activity trend plot from the VSD motor is shown in Fig. 11 (data from 12.03.15 to 17.03.2015 for Winding 1, Phase-V). Whilst there is some variation in OLPD activity over this 6-day period, the average trend remains flat with an average low level average PD pulse count of around two (2) per cycle for the monitoring period. In other words, the OLPD activity remained at both a low intensity and also remained constant i.e. in a stable state.

The synchronous data acquisition capability of the monitoring system allowed for pulse waveforms from of up to six (6) sensor readings to be recorded and compared simultaneously (to within 10 ns) with the motor on-line and in-service. The data for a 10-day continuous OLPD monitoring period (between 30.03.2015 and 09.04.2015) for Winding 1 is shown in Fig. 12. It can be noted that the Peak PD level of Phase-V (28 mV) was around twice that of the other two phases (15 and 14 mV) which is a first-stage indicator that there is PD activity on this phase. The PD on all three phases also showed a flat trend line over this short monitoring period.

Fig. 11 OLPD activity trend for the period 12.03.15 to 17.03.2015 – HV Motor Winding 1, Phase-V

The PD activity on Phase-V of Winding 1 was analysed further by looking at the phase-resolved partial discharge (PRPD) heat map for each phase of Winding 1. The (varying) phase reference signal for these PRPD plots was provided by the voltage reference signal from the LF winding of the tri-band sensor. Fig. 13 shows a comparison between Phase-U and Phase-V of Winding 1 before and after the data has been passed through the monitoring system's de-noising software. The heat map of Phase-V clearly shows OLPD activity clusters that are not present on the heat map of Phase-U (no PD). This corroborates the results presented in Fig. 12 where Phase-V has higher Peak PD levels.

A similar analysis was performed for Winding 2. All three phases of Winding 2 exhibited low levels of Peak PD over the monitoring period at approximately 18 mV on each phase. As with Winding 1, the PD activity trend for all three phases of Winding 2 was flat.

Fig. 12 Peak PD trend data on Phase-U (a), Phase-V (b) and Phase-W (c) of Winding 1. 10-day monitoring plot.

D. Discharge Origin Determination - Pulse Precedence

As mentioned earlier, the main method employed by the monitoring system to distinguish between VSD noise pulses and PD pulses is to apply pulse precedence measurements using very fast pulse timing techniques. In this case, with a set of sensors installed both in the VSD output cable box and in the HV motor cable box at either end of the HV feeder cable, it is possible to detect PD from three possible sources: motor, feeder cable and VSD, whilst discriminating against VSD switching interference.

This is achieved by detecting the same pulse at both ends of the cable and measuring ‘which pulse came first?’: As the signal cable lengths from the sensors to the monitor are carefully measured physically and through time domain reflectometry (TDR) testing (to measure pulse propagation speeds) it is possible to program the exact signal cable delay times into the OLPD monitor to align the signals synchronously in time.

In this way it is possible to identify the location of any PD sources originating across the entire VSD to motor HV circuit, including the HV cable feeder. Fig. 4 shows an example of PD pulse from Phase-V of Winding 1 detected by the tri-band sensors installed at either end of the cable feeder. The sensor at the motor end (blue trace) detects
the PD pulses first. After approximately 0.24 μs of delay, the pulses arrive at the sensor located at the VSD end (red trace), somewhat attenuated as they have travelled down the HV cable feeder. In this case, it can be concluded that the PD pulse originates from the motor.

E. Discharge Type – Pulse Wave Shape Analysis

Using the synchronous acquisition capabilities of the monitoring system, the PD pulse detected on a particular phase can also be analysed and compared with the simultaneous OLPD detection on the other two phases. This analysis allows the software to differentiate between phase-to-ground and phase-to-phase PD originating in the circuit. An example is shown in Fig. 14 where a PD pulse was detected on Phase-V of Winding 1 but it does not appear on any of the other two phases of the same winding, indicating a phase-to-ground discharge.

![Fig. 14 PD type determination - Phase-V, Winding 1: the discharge is a phase-to-ground discharge (no coupling)](image)

F. Summary of results

The OLPD monitoring results for Windings 1 and 2 of the motor from the 90-day monitoring trial are summarised in Table I. It can be noted that OLPD activity was only detected on one (1) phase out of the six (6) across the two HV windings. OLPD was detected on Phase-V of Winding 1 with a Peak PD Level of 22.1 nC but a low Cumulative OLPD Activity of only 7.1 nC/cycle that indicates the PD site is relatively inactive. The OLPD activity trend was flat with no sign of increase during the 90-day monitoring period. As a result, the condition of both windings of the HV motor was classified as ‘Excellent’ based on the Guideline OLPD Levels for rotating HV machines provided Table II. Continuous OLPD monitoring will detect any increasing PD activity trends, which might occur over time, if the condition of the HV insulation system worsens.

![TABLE I](image)

![TABLE II](image)

The developed solution was made compatible with a condition monitoring database and user interface (UI) as shown in Fig. 15. This UI displays the condition criticality of individual plant items in a mimic of the operator’s single line diagram (SLD) of the network. The User Interface uses superimposed, colour-coded plant condition criticality data (rating from 0–100%).

![Fig. 15 Visualization of OLPD monitoring data from two VSD-fed HV motors from a CM Database User Interface](image)

Fig. 16 shows the final solution for the installation of sensors to perform OLPD monitoring on the twin-winding VSD-fed HV Motor:

- Twin sets of tri-band sensors are located in the VSD and Motor cable boxes and are used for detection over the frequency range of DC to 30 MHz. The attachment of sensors at both ends of the VSD-motor cable allows precedence measurements to be made to identify PD signals originating in the motor stator winding.
- The TEV sensors in each cable box enable the detection of local PD from within the termination boxes.
- Tri-band sensors are installed on the combined earths of the cable at the VSD end to detect PD from along the cable (these couple mainly to the cable sheaths).

Over the 90-day training period the OLPD monitoring system’s software was adjusted to improve its ability to make reliable, noise-free OLPD measurements. The fundamental problem here was to differentiate real PD activity from VSD switching interference that typically dwarfs the PD signal by several orders of magnitude.

VI. SOLUTION FOR THE ON-LINE PARTIAL DISCHARGE CM OF VSD-FED HV MOTORS

This VSD Pilot Project has helped to further the knowledge on how to perform effective on-line partial discharge (OLPD) CM of complete VSD-fed HV motor circuits.
The effect of all the data analysis solutions implemented in the VSD Pilot Project are illustrated in Fig. 17 and can be summarized as follows:

- **Phase 1** - The raw data acquired is shown (2,802,722 pulses from over 36,073 acquisitions). The data collected is dominated by noise from the VSD and this raw data cannot be analysed by an automated alarm/flag monitoring system as it would produce an incorrect RED-Concern alarm/flag.

- **Phase 2** - Shows the first step of the de-noising process where an automatic event recogniser pulse analysis module identifies 56,977 pulses (2%) as possible PD with 98% of noise pulses removed.

- **Phase 3** - Shows the effect of the additional ‘expert de-noising rules’ implemented into the system as part of the system’s 90-day training program.

- **Phase 4** - Shows the correctly de-noised OLPD data. From a total of 2,802,722 pulses detected, the monitoring system correctly classified 3,692 PD pulses (only 0.1% of the pulses captured).

As a result of the 4-phase de-noising process described above and illustrated in Fig. 17, the true condition of the motor’s HV insulation system and that of the complete circuit can now be observed. In this case a GREEN flag (Excellent condition) is indicated as opposed to the original RED flag i.e. the potential false alarm here has been avoided through effective de-noising.

In practice, the (Green-Yellow-Orange-Red) flag/alarm setting thresholds vary between different installations and can only be configured after the 90-day training period.

**VII. CONCLUSIONS**

A novel solution has been developed for the condition monitoring of a large twin-winding VSD-operated EX-P HV motor. The solution in this case employed a total of 18 sensors across the VSD motor circuit including 14x tri-band inductive sensors and 4x TEV sensors. A 24-channel, 6-channel synchronous monitoring system was used along with a range of software tools to perform reliable OLPD, PQ and transient event measurements.

This solution has been shown to provide reliable, noise-free continuous OLPD monitoring measurements of an in-service VSD-fed motor in this pilot project where the condition of an in-service 5.9 kV, 40 MW twin-winding VSD-fed synchronous motor in Norway was continuously monitored successfully for a period of 6 months. The project has helped to further the knowledge on how to perform effective OLPD CM on VSD/converter fed HV AC motor circuits. This includes the importance of carrying out an initial 90-day training period to develop additional ‘expert de-noising rules’ and to avoid false alarms that would have occurred without this. It is only through the
development of such tailored, circuit-by-circuit-specific expert de-noising rules (and their implementation into software) that reliable OLPD monitoring of VSD-fed HV motors can be achieved in practice. The avoidance of false alarms is crucial in order for the OLPD monitoring technology to become fully accepted as an effective and reliable CM technology in the oil and gas industry.

VIII. REFERENCES


IX. VITAE

Lee Andrew Renforth studied Electrical and Electronic Engineering at the University of Manchester between 1986 and 1993 where he received a BSc, MEng and finally a PhD in 1993, in the field of HV insulation breakdown under sponsorship by the National Grid Company, UK. In 1994 he set-up IPEC Ltd where he was Managing Director for 10 years before leaving to set-up HVPD Ltd Manchester, UK in 2004. Over the past 12 years, HVPD have become one of the market leaders in the growing field of OLPD monitoring technology. Lee oversees the relationships with HVPD's customers and partners in more than 100 countries worldwide whilst remaining actively involved in the company’s R&D activities with end-users and manufacturers.

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