COMPARING ON-LINE PARTIAL DISCHARGE MONITORING SOLUTIONS FOR A CRITICAL 6.6 kV MOTOR

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Abstract – Medium Voltage (MV) and High Voltage (HV) asset criticality is increasingly at the forefront of plant operator's goals, with a view to preventing unplanned outages and maximizing uptime. Condition monitoring is integral to truly understanding asset condition and allowing remedial works to be scheduled and conducted at the most convenient times. In particular, on-line Partial Discharge (PD) monitoring of such motors and generators remains the best early warning indicator of stator winding insulation degradation. The authors present utilization of the latest On-Line PD monitoring technology, through a recent real-world pilot project conducted in South East Asia on a critical 6.6kV 9000HP Motor, whereby a combination of different sensors and locations were organized over an intensive 8-week period. The data from this pilot project is presented, including de-noising techniques and Phase Resolved Partial Discharge (PRPD) patterns for different sensor installations, concluded with a discussion as to the pros and cons of each solution. At the center of this pilot project is the goal to ensure technical performance of each sensor solution and improve the cost of ownership, particularly for installations where retrofitting sensors and providing communication can be challenging.

Index Terms — Partial Discharge, PD, Condition Monitoring, Motors, Stator Insulation, High Frequency Current Transformer, High Voltage Coupling Capacitor

I. INTRODUCTION

Maintaining a reliable high voltage network is critical to the smooth running of any operation within the chemical and oil and gas industry. Many tools are now available to operators for monitoring the condition of in-service assets as part of condition-based maintenance and to prompt interventions. Techniques such as Partial Discharge (PD) detection have been widely used for detecting degradation in machine stator windings with mention in various standards and guidance documents [1,2,3,4]. Advances in recent years in signal processing have led to many improvements in the ability of such systems to identify different PD sources and differentiate PD from noise [5, 6]. Likewise, in order to adapt to different site installations, there are various PD sensor options available, generally for installation in the machine terminal box or remotely at the switchgear as will be discussed in this paper.

II. PARTIAL DISCHARGE IN ROTATAING MACHINE STATOR INSULATION

PD can occur at various points in the stator insulation of rotating machines, such sources include but are not limited to: delamination, voids between stator core and slot insulation, phase-phase and phase-ground discharges at end windings. Whilst machine insulation may be able to tolerate some PD activity, it will over time degrade the insulation systems and can ultimately lead to stator insulation failure. Due the nature of PD sources in rotating machines, PD activity can be influenced by operating stresses on the machine such as thermal and mechanical stress [1, 2]. As a result of this there is benefit in PD monitoring to capture any such relations, even if just over a short period time to capture data during different running conditions.

Partial discharges are incepted when the high voltage applied to the stator windings causes these small voids to break down, resulting in a short duration (ns) current impulses. These pulses propagate away from the source towards to machine terminals where they can be detected. When machines are connected using power cables the pulses will couple onto the cables where they will continue to propagate into the network.

III. ON-LINE PD DETECTION METHODS

A. Sensors

On-line PD detection techniques primarily focused on capacitive or inductive coupling of current pulses. Capacitive coupling involves placing a high voltage coupling at the machine terminals, the capacitor is in series with a measurement impedance such that it forms a high pass filter. Capacitance values vary from 80 pF up to several nF. In general a higher capacitance leads to the sensor having better performance at lower frequencies allowing detection of more energy from PD pulses deeper into the machine windings. More noise can often be detected in the lower frequency bands it is thus crucial to have abilities to remove this as will be shown in Section IV. For inductive coupling, HFCT sensors or Rogowski coils may be used, both operate on a similar principle, with the ferrite core in the HFCT giving higher sensitivity. These sensors are used in cases where the machine is fed by power cables and are installed just below the cable terminations either at the machine or remotely at the switchgear. It is also possible to install on the ground link of surge capacitors when these are present at the machine terminals.

The sensor selection ultimately depends on several practicalities, notably:

If machine is cable or busbar fed. When machines are bus fed coupling capacitors are generally the preferred option. If there are surge capacitors it may be possible to attach HFCTs onto the connections to these.

Space inside machine terminal box. This is of particular concern when retrofitting to machines which are already in service. In order to retrofit sensors, there must be adequate space to mount the sensors whilst maintaining all high voltage clearances in the terminal box design.

Space inside cable box at switchgear. Similar to installing sensors at the machine, if PD sensors are to be installed remotely at the switchgear, there must be adequate clearance at the cable terminations and cable terminations should be suitable for HFCT sensor attachment.

If machine is in hazardous gas zone. When machines are located in classified hazardous (e.g. ATEX) gas zones this adds another aspect to be considered with regards to PD sensor installation. If retrofitting sensors to an existing motor, recertification will need to be considered.

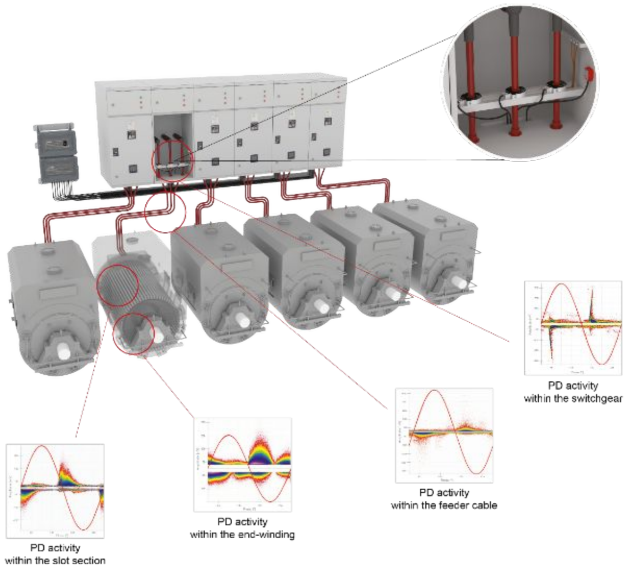


Fig. 1 Remote PD monitoring solution

B. *Measurement*

Most modern PD detection systems operate on a similar principle of digitizing signals from the PD sensors in sync with the 50/60 Hz high voltage frequency applied to the asset under test and subsequently plotting Phase Resolved Partial Discharge (PRPD) patterns. With the measurement bandwidth selected within the range of the sensor's bandwidth, if signals have been acquired with a high sampling rate (e.g. ≥100MS/s), it is possible to use characteristics of pulse wave shapes to differentiate PD and noise, some examples of this are shown in the next section of this paper.

C. *Deployment*

When it comes to deploying PD detection on in-service machines this can be done as spot testing, or continuous monitoring on a temporary or permanent basis. Spot testing is particularly suited to assessing a fleet of machines and may be used for trending. There are however limitations in that short-term variations in PD over time will not be observed, caution should thus be taken comparing measurements particularly if measurements are made under different running conditions. Short term monitoring gives a better assessment in that any stochastic variations in PD can be detected whilst permanent monitoring allows detection of any changes in the trend that would indicate any trends that may lead to failure. Permanent monitoring is also well suited for integration with SCADA systems, for immediate warnings of worsening condition and historian databases for trending alongside other operating parameters which may influence the occurrence and magnitude of PD.

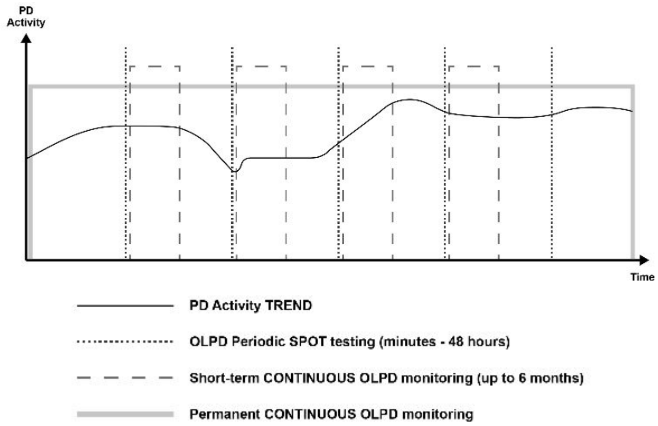


Fig. 2 PD activity trend vs solution duration

IV. PILOT PROJECT

D. *Background*

Condition monitoring of HV Motors using High Voltage Coupling Capacitors (HVCC) is a common practice for high reliability applications to monitor the quality of the stator insulation [7]. For over 20 years the use of 80pF HVCC has been the default method of measuring PD using standalone acquisition units with no connectivity. With the introduction of advanced real time signal processing, the use of larger HVCC up to 2nF has been possible, improving the acquisition resolution. Such a setup does require advanced signal processing to identify noise from PD. The use of HVCCs is most suited for installation in the motor terminal box or within the stator housing, which requires the acquisition unit to be installed near the motor, which in many cases is outdoors and in a potentially hazardous area. For many of the legacy plants, installing condition monitoring equipment with a communication link is challenging and CAPEX intensive. With the use of HFCT's, installation remote from the machine is possible, making it possible to install the sensors in the switchgear compartment, with the acquisition equipment in a weather controlled and non-hazardous environment. In addition, no modifications are needed to the high voltage parts of the installation. The added benefit to covering the complete circuit is that the HFCT will cover the cables, as well as the motor at no additional cost, albeit with the requirement for signal processing to define the source of the PD and to reject background noise. By screening pulse shapes it is possible to distinguish between the motor, cable and noise [5]. Installing the acquisition unit near the switchgear, communication links are more accessible and reduce installation cost by removing the need of field cabling. Installation of condition monitoring equipment without communication capability has proven to lead to poor results, where incidents were missed, or the acquisition unit was in a fault state, without operators being aware. Online data capturing allows real-time trending of PD and provides automated warnings when PD levels reach a certain threshold, or the rate of change has increased rapidly.

Given the advances in offsite signal analytics and condition-based risk analysis, condition monitoring devices connected to a networked solution, is a must. It provides for real-time continuous asset monitoring of critical parameters (rate of change, +Qm, -Qm, etc.) by an automated alarm system, which can inform a specialist that can perform further analytics to determine the criticality and any action required to be taken. As such, when existing PD acquisition units come to the end of their life, they will be replaced with a connected device based on using HFCTs installed in the switchgear compartment. The difficulty has been that in some scenarios for motors, the HVCCs are installed within the stator housing, which cannot easily be accessed without taking the equipment out of service restricting the change out to turn-arounds only. As a result of this limitation, some machines have been equipped with HFCTs and the HVCCs still being installed and connected. From an operator point of view, there was a need to ensure the 80pF HVCC would not significantly affect the PD measurements and most importantly not impair the ability to assess the criticality of the PDs. As such, it was needed to verify the impact of the HVCC on the HFCT measurements.

Using the operators fleet of machines a suitable test candidate was found at the Sakra site in Singapore. This machine has known PD activity and had easy access to the existing HVCC to support the testing of different configurations.

The machine is a 9000HP, 4-pole, 6.6kV induction motor built in 1996 and is used in the final step in the process in condensing nitrogen gas into liquid nitrogen. The motor has seen an approximate 3500 starts using a soft starter.

Fig. 3 9000HP, 4-pole, 6.6kV induction motor cable box

E. *Monitoring Session Set-ups*

An on-line PD monitoring system with synchronous acquisition on all sensors and sampling rate of 100 MS/s was utilized. Two primary monitoring session set-ups were conducted:

a) 'At machine with HVCCs' - conducted with pre-installed 80pF HVCCs via a sensor connection box at the motor terminals. For the remote HFCT monitoring, comparisons with the HVCC jumper cable connected and disconnected were also made, as shown in the photo below and data as per section E.

Fig. 4 Motor cable box – left; right; single phase with HVCC disconnected

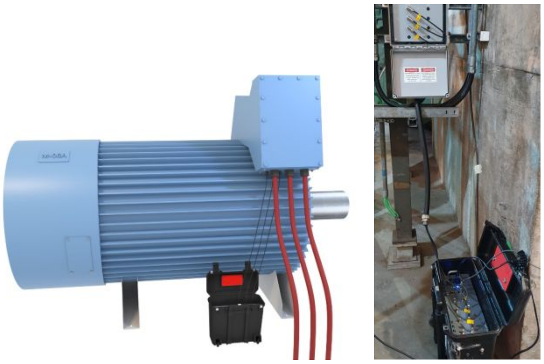


Fig. 5 At machine short-term monitoring using pre-installed HVCCs – left; CGI, right; real-world

b) 'Remote with HFCTs' - conducted with temporarily installed HFCTs installed at the switchgear end of the motor feeder cables, around the conductor cables and cancelled earth of one of the two conductors per phase.

Fig. 6 Remote short term monitoring using temporarily installed HFCTs – left top; real-world sensors in Switchgear cable box, right top; HFCT attachment, bottom; multiple circuits

Data was compared from each monitoring session set-up, as detailed in Section D.

F. Data De-noising

As is often the case, a combination of both PD and noise interference was detected. The ability to differentiate noise sources is particularly crucial when monitoring PD with sensors at the switchgear due to the closer proximity to multiple signal sources both PD and noise. An example of the remote HFCT data pre-denoising is shown below, the data acquired over several power cycles has been processed to extract transient events in the ns - µs range, the peaks of these events with reference to their phase position has been plotted in the heatmap style plot. Other wave shape characteristics of the transient events are also measured, such as pulse rise time, fall time and peak in frequency spectrum.

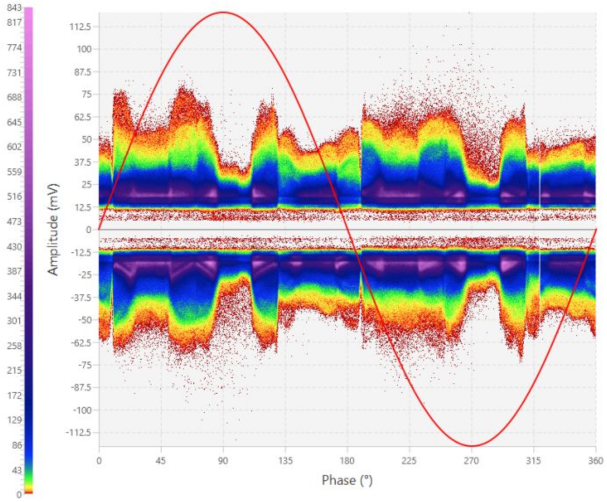
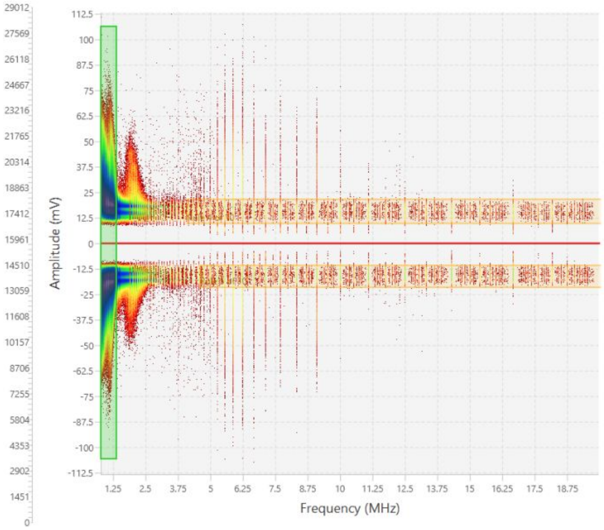
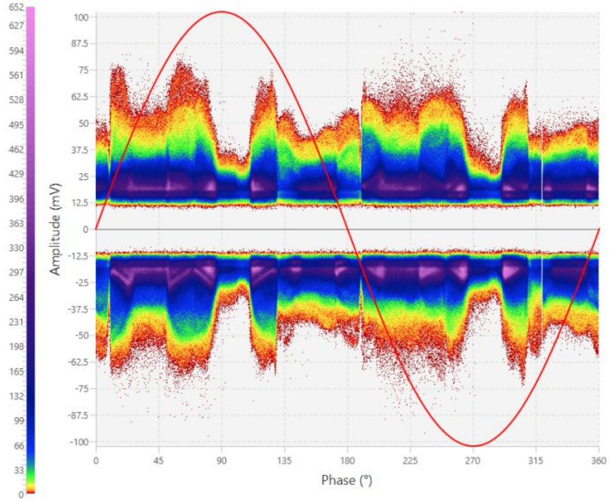


Fig. 7 HFCT PRPD pre de-noising

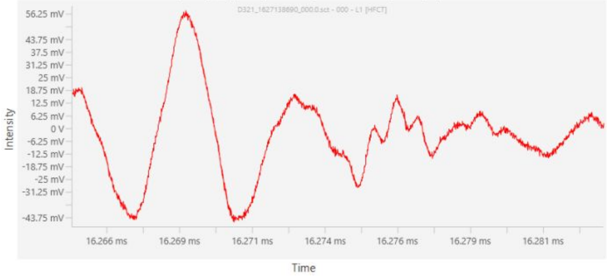
Using these other parameters the data can be plotted in different ways and clusters of similar events selected in order to separate noise and PD activity. An example of de-noising methods is shown below in Fig. 8 and Fig. 9 based on Amplitude vs Frequency. In this, the data from Fig. 7 has been re-plotted based on the event amplitude with reference to its peak of the frequency spectrum. Different bands have been identified which contain PD and noise signals.



(a) Pulse amplitude vs frequency

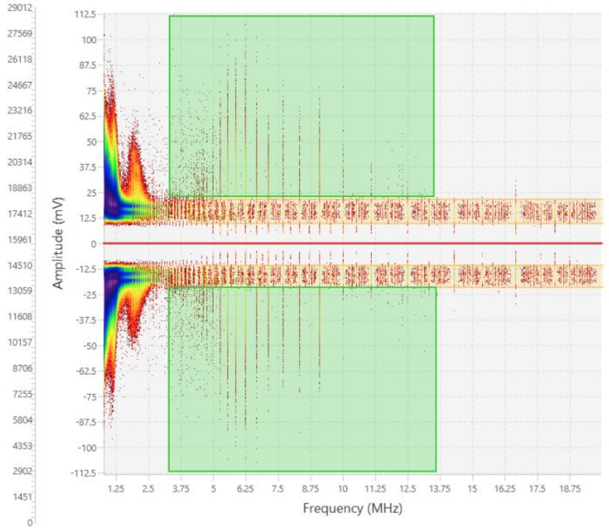


(b) Amplitude vs phase for box selection in (a)

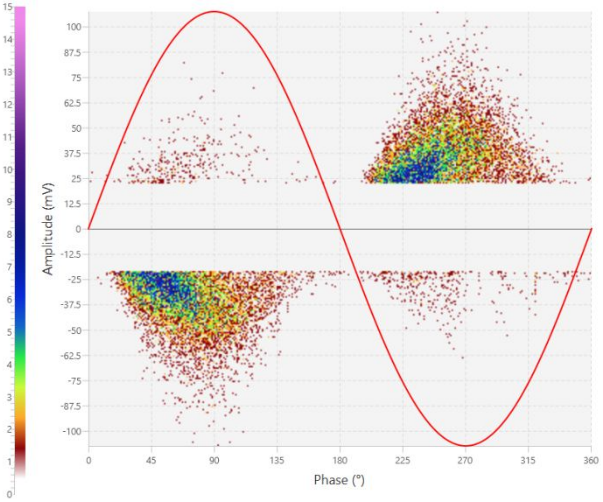


(c) Typical pulse waveform for box selection in (a)

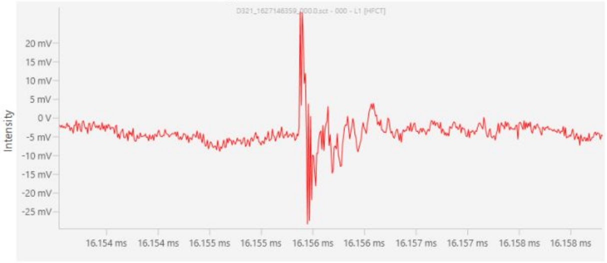
Fig. 8 Separated noise signals



(a) Pulse amplitude vs frequency



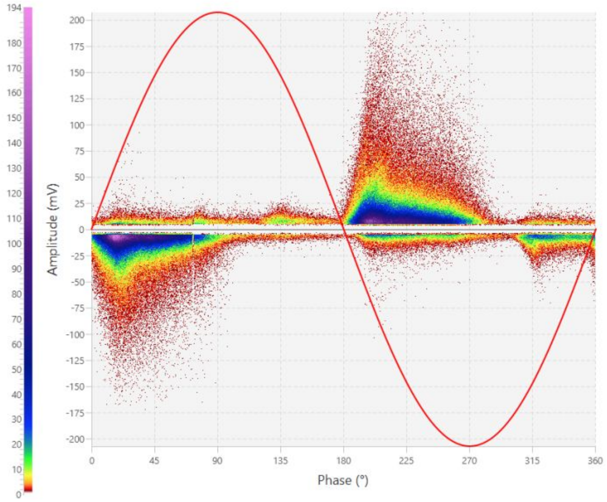
(b) Amplitude vs phase for box selection in (a)



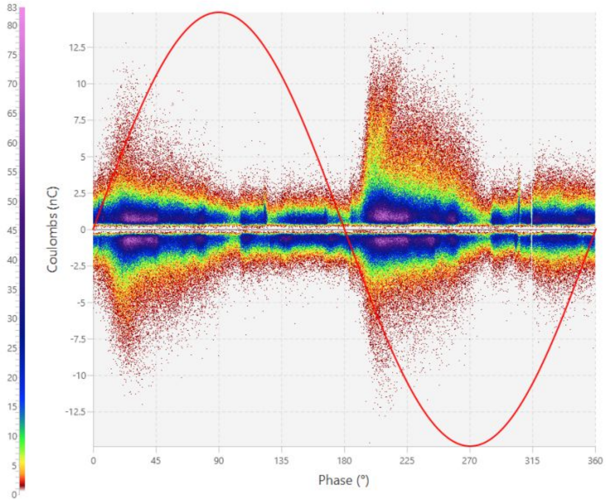
(c) Typical pulse waveform for box selection in (a)
Fig. 9 Separated PD signals

G. *Remote and at-machine comparison*

Comparing remote HFCT and at machine HVCC data sets shows clear correlation between the PRPDs, confirming the same PD types and sources being measured. Some distortion(s) due to different propagation paths and bandwidths of the PD sensors is expected and present, it should also be noted the HVCC data is measuring pulse peaks in millivolts (mV), whilst HFCT data is measuring pulse areas in nanocoulombs (nC).



(a) HVCC



(b) HFCT with HVCC connected
Fig. 10 Post de-noising PRPDs – HVCC Vs remote HFCT (with HVCC connected)

Both PRPD patterns in Fig. 10 show slot section, phase-to-earth, PD. Analyzing the PRPD patters and comparing against relevant standards, they allude to either; delamination in the main stator coil insulation, or slot PDs generated in air or gas-filled pockets, inside the stator core, between the surface of a bar and the stator core, often caused when the electrical contact between the semi-conductive coating of the bar and the slot is lost or too high [1].

H. *Comparison of remote HFCT Data with and without HVCC jumper cable connected*

Comparing both sets of remote HFCT data, shows the effect of disconnecting the HVCC jumper cables. The data for each test set-up were acquired consecutively with similar motor loads (at ~600-700A) and winding temperature (at ~175-200°F taken from the RTD), equating to ~90% full load. The HFCT PRPD pattern with HVCC jumper connections disconnected is shown below. Strong similarities to PRPD from the HVCC sensor and HFCT sensor with the HVCC connected can be observed. Trendlines of peak PD level from the HFCT data with and without the HVCC connected are shown in *Fig. 13* and *Fig. 14*, relatively stable trends were observed during both monitoring periods.

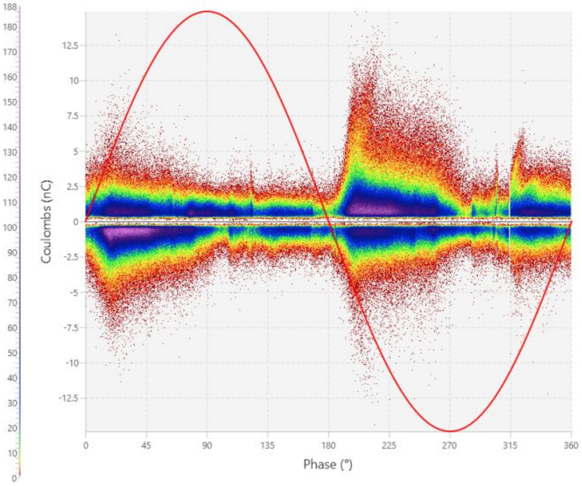


Fig. 11 Post de-noising PRPD – HFCT (with HVCC disconnected)

Fig. 12 HVCCs with jumper cables disconnected

TABLE I
PD measurements with HVCC connected and disconnected

Phase L1	OLPD Activity (nC/cycle)	Peak PD (nC)
HVCC Connected	64.0	6.2
HVCC Disconnected	83.5	5.5
Percentage Change (%)	+30	-11

Remote HFCT L1 – Peak PD & OLPD Activity Comparison

Fig. 13 HFCT with HVCC connected PD peak trend

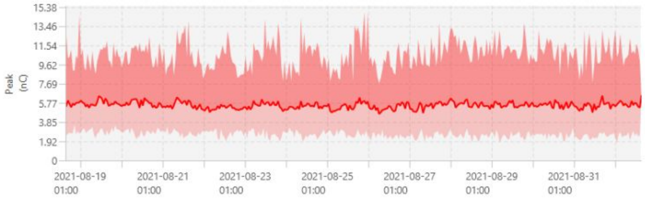


Fig. 14 HFCT with HVCC disconnected PD peak trend

Comparing the recorded signal levels using the HFCT with HVCC connected and disconnected, there are slight differences in the PD peak levels which are in the same range of what could be normal variations between tests due to the stochastic nature of PD. It can be noted there is a more significant reduction between HVCC jumper cables connected and disconnected, as seen in the averaged PD activity levels on all phases, the PD activity value is the cumulative sum of all recorded PD pulses in a power cycle. Increases averaging 30% across the phases were observed when the HVCC jumper cable was disconnected. Typically, it would be recommended to disconnect the HVCC jumper cables in order to provide the most accurate remote HFCT PD monitoring. However, this data also confirms that remote monitoring with HFCTs, with the HVCCs still connected is possible, and although there's an effect it's not detrimental to the ability to monitor remotely, providing sufficient signals for PD analysis and trending.

V. CONCLUSIONS

PD technology continues to considerably improve, especially in pulse shape recognition and noise rejection, with larger and more detailed data sets being able to be acquired in shorter time durations. Such detailed data allows for in-depth analysis, not only providing PD levels and ranked asset league tables, but also allowing good suggestions to be made on PD types, such as the following for rotating machines; delamination, surface tracking, voids, etc. and if the PD is from the end winding or slot section. This additional detailed information enables plant operators to maximise uptimes, through making more informed and prioritised decisions on any necessary remedial works, such as motor stator re-winds, prior to, often costly, unplanned outages.

Use of pre-installed PD sensors can be beneficial and cost-effective, removing the requirement for further outages and testing/monitoring under the assets normal working conditions. In addition, new non-intrusive PD sensors can be installed during scheduled outages, shutdowns or turnarounds (TAR), with a wide range of installation options possible for machine and switchgear cable boxes.

Time and date stamped PD data can be successfully correlated with both operational and ambient parameters, such as load, temperature, humidity, etc. This often proves useful to confirm any possible cross-coupling between circuits – i.e. when the PD incepts on a specific motor's energisation/start-up, in addition to assisting operations with recommendations to limit PD damage, with a view to extending insulation condition as best possible. Variations and cycling in both the PD trends over time and motor load/RTD temperature were present however no clear correlation exists in this data set.

Further to the temporary on-line PD monitoring conducted during this project, this motor is now being considered for continuous monitoring with a view to flagging any high or increasing PD levels. Such permanent, long term, monitoring will also enable PD levels to be compared to operational fluctuations, such as load, as this was relatively stable during the short term monitoring sessions reported on within this paper.

When conducting remote monitoring with HFCTs, the ideal scenario is to disconnect the HVCC jumper cables at the motor terminal box, however for installations where this is difficult, running with HVCCs connected and remote HFCTs installed will provide sufficient coverage of the machine. This data also confirms that remote monitoring with HFCTs, whilst the HVCCs are still connected, is possible, however it is prudent for the operator to recognise that some of the sensitivity is lost. The same PRPD patterns, and therefore PD type(s), can be observed with each method, with the HVCC connected or disconnected, in addition to confirming a similar good motor insulation condition, providing high confidence in both solutions.

VI. REFERENCES

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VII. VITAE

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