Angle-DC

Circuit Condition Data Report

Future Networks

Index

Glossary of Terms

TERM	DEFINITION
AC	Alternating Current.
DC	Direct Current
HCCM	Holistic Circuit Condition Monitoring
HFCT	High Frequency Current Transformer
HV	High Voltage
MV	Medium Voltage
pC	Picocoulomb
PD	Partial Discharge.
PRPD	Phase Resolved Partial Discharge
TEV	Transient Earth Voltage

1. Executive Summary

ANGLE-DC aims to demonstrate a novel network reinforcement technique, by converting an existing 33kV AC circuit to DC operation. The existing distribution network is increasingly strained due to growing demand and a high penetration of distributed generation. The conventional AC network has limited controllability and flexibility, two fundamental attributes required as the network evolves and becomes increasingly complex. ANGLE-DC will utilise an existing 33kV AC circuit comprising cable and overhead line sections to establish a DC link. An AC/DC converter station will be installed at each end of the circuit and the condition of AC assets under DC stress will be monitored in real time using a Holistic Circuit Condition Monitoring (HCCM) System.

The circuit condition monitoring forms an important learning outcome of this demonstrator project. The project will demonstrate on-line Partial Discharge (PD) monitoring systems. These are now being used to give an indication of PD based degradation and trend in time with other operating stresses, which can influence PD including voltage ramp up/down, over voltages and ripple from power converters. Data has been analysed and benchmarked to inform SP Energy Networks and other DNOs about the way in which distribution circuits age. Pre- and post-DC operation monitoring is being used to validate of theories about how DC impacts on cable ageing

This report presents initial DC PD analysis for energisation of the Angle DC cable circuit from Bangor substation. Results from first DC energisation are included. Results from a period of AC energisation in 2018 (before conversion to DC) are also presented for comparison. The PD waveform signal analysis criteria from AC stress has been used for analysing the DC stress results. There was some low-moderate levels of PD under DC conditions and signals of similar magnitude have been observed under AC. It should be noted that longer duration measurements will be used to evaluate the severity and confirm the sources of such signals and this report will be updated periodically.

1.1 PARTIAL DISCHARGE TEST RESULTS

For the project, guideline PD levels were used for the condition assessment under AC stress, pre conversion and DC stress, post conversion. The insulation condition assessment bands are shown in Table 3.

Table 1. Supplier guidelines for OLPD Levels in MV Cables (3.3–36 kV).

INSULATION CONDITION ASSESSMENT	PD Peak Level (pC)
Average	0–500
Discharges within acceptable limits	500–1000
Some concern, monitoring recommended	1000–2500
Some concern, regular monitoring recommended	>2500

The peak PD levels from AC energisation are shown in Table 2, which show both poles were experiencing low to moderate levels of partial discharge over the monitoring period.

Table 2. AC partial discharge monitoring results.

Asset	Phase 1 PD Peak (pC)	Phase 2PD Peak (pC)	Phase 3 PD Peak (pC)
Positive Pole	536	1010	1510
Negative Pole	682	1400	1740

The peak PD levels from DC energisation are shown in Table 3, which show both poles are experiencing low to moderate levels of partial discharge through the monitoring period, but at lower values It should be noted these are interim results and data will continue to be gathered throughout the operational phase. Additional results will be added periodically through regular addendum reports.

Table 3. DC partial discharge monitoring results.

Asset	Phase 1 PD Peak (pC)	Phase 2PD Peak (pC)	Phase 3 PD Peak (pC)
Positive Pole	529	450	-
Negative Pole	622	803	564

2. Introduction to PD Monitoring on Power Cables

Partial Discharge (PD) is a degradation phenomenon occurring in the insulation of medium voltage (MV) and high voltage (HV) assets such as power cables, switchgears, transformers, and rotating machines. Detection of PD can thus give an indication of the health of the insulation. PD detection is performed with the MV and HV equipment in service allowing to use it as a valuable tool for condition monitoring (CM) of the assets and to support Condition Based Maintenance (CBM) strategies.

It is primarily the material properties of the insulation system that determine the PD behaviour under DC voltage when PD causing defects are present. The operating conditions, more precisely the temperature and temperature gradients, influence the DC PD activity. In general, the PD repetition rate increases with increasing temperature. The PD magnitude is usually influenced only slightly by the temperature.

The behaviour of insulation materials under DC voltage stress is extremely complex. While with AC loads the electrical field distribution is almost temperature-independent, the extreme temperature dependence of the conductivity with DC leads to electrical field distributions that are difficult to predict. There is obviously a non-trivial relationship between PD under DC and the risk of failure of the insulation system. There is no general evidence that the typically low PD rate is as damaging to insulation as AC PD. On the other hand, PD with AC or DC always indicates a local weak spot.

3. PD under AC and DC Voltage Stress

Under AC electric fields (e.g. 50 or 60 Hz), PD generally occurs in every half cycle of the applied voltage. In contrast, under DC stress PD tends to occur infrequently (or not at all) but is more likely to become evident during voltage changes, particularly when the voltage is initially applied or removed. In DC systems, it is expected that nearly all the measured pulses will be negative on increasing the voltage and the pulses became positive when the voltage is decreased and continue to occur after the voltage is decreased. However, PD activity usually stalls once the applied voltage stabilises, see example in Figure 1.

Analysis of AC PD activity is normally based on the PD magnitude and phase (i.e., phase-resolved PD patterns). With DC, the basic PD parameters from testing are the PD magnitude and the pulse occurrence time of PD (or the time interval between consecutive PD pulses). In addition, the likelihood of wide scattering in both the PD repetition rate and magnitude is usually noticed in DC cables. The repetition rate of PD under DC conditions is influenced considerably by the energising time, temperature, applied stress and ripple components superposed on DC voltages.

However, individual PD pulses are essentially the same as those that occur with AC voltages so similar detection techniques can be utilised for DC monitoring applications. Since the frequency of PD occurrence with DC is usually several orders of magnitude lower than with AC, correspondingly longer recording times are employed (for example, 30 – 60 minutes is not unusual). Consequently, interference that might be regarded as relatively sparse and therefore tolerable in the context of an AC PD measurement can dominate the captured data for DC PD. Anti-interference measures therefore become more important in PD testing at DC to distinguish PD pulses from interference pulses.

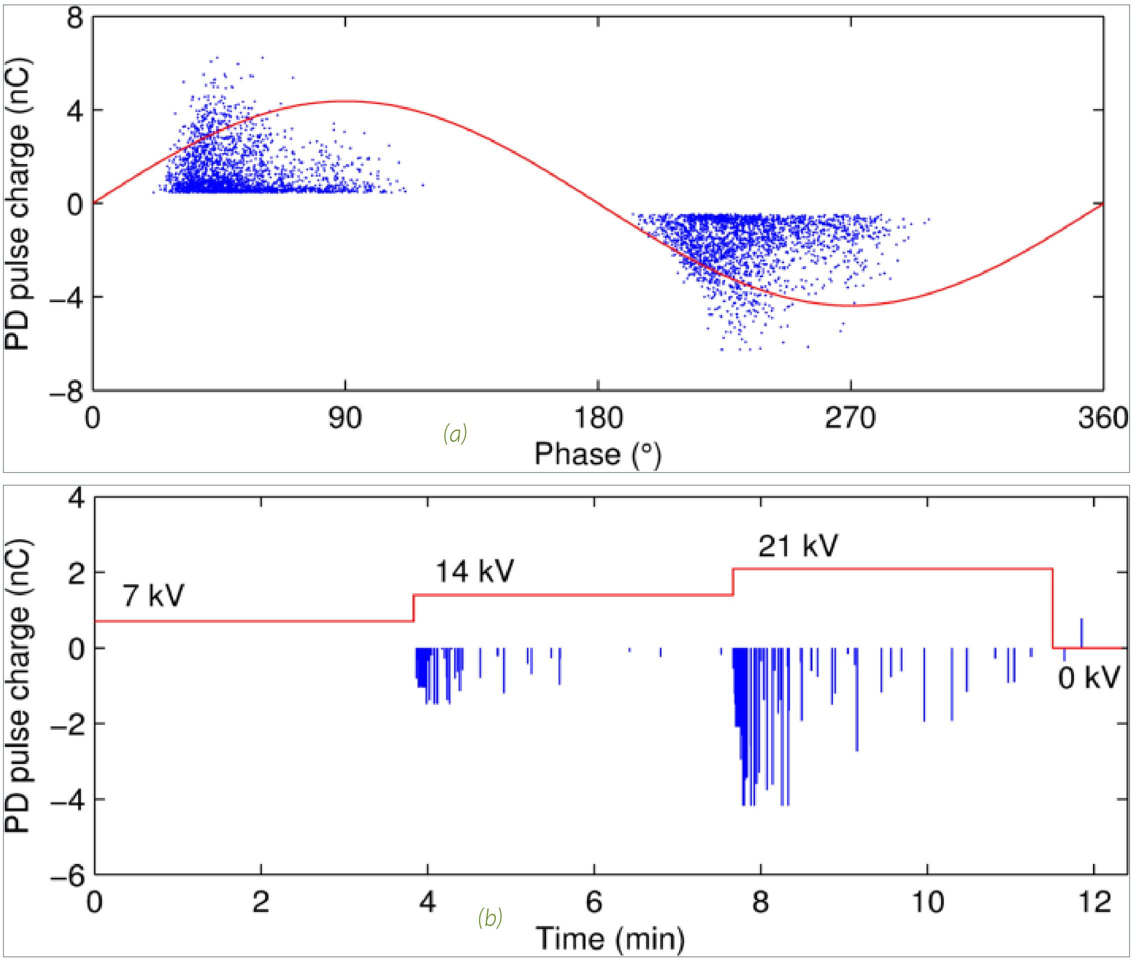

Figure 1. Comparison of AC and DC PD on defect in laboratory[1].

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[1] *Seltzer-Grant M, Giussani R, Siew W H, Corr E, Hu X, Zhu M, Judd M, Reid A, Neumann A and Awodola J 2015 Laboratory and field partial discharge measurement in HVDC power cables Proc. 9th Int. Conf. Insulated Power Cables (Jicable'15) (Versailles)*

4. DC On-line PD Monitoring Equipment and Sensor Connections

4.1 OVERVIEW

High Frequency Current Transformer (HFCT) sensors have been installed on each phase conductor of the positive and negative poles. The sensors are then connected to a HVPD Kronos unit which is used to acquire and analyse the data. The measurement system schematic is shown in Figure 2.

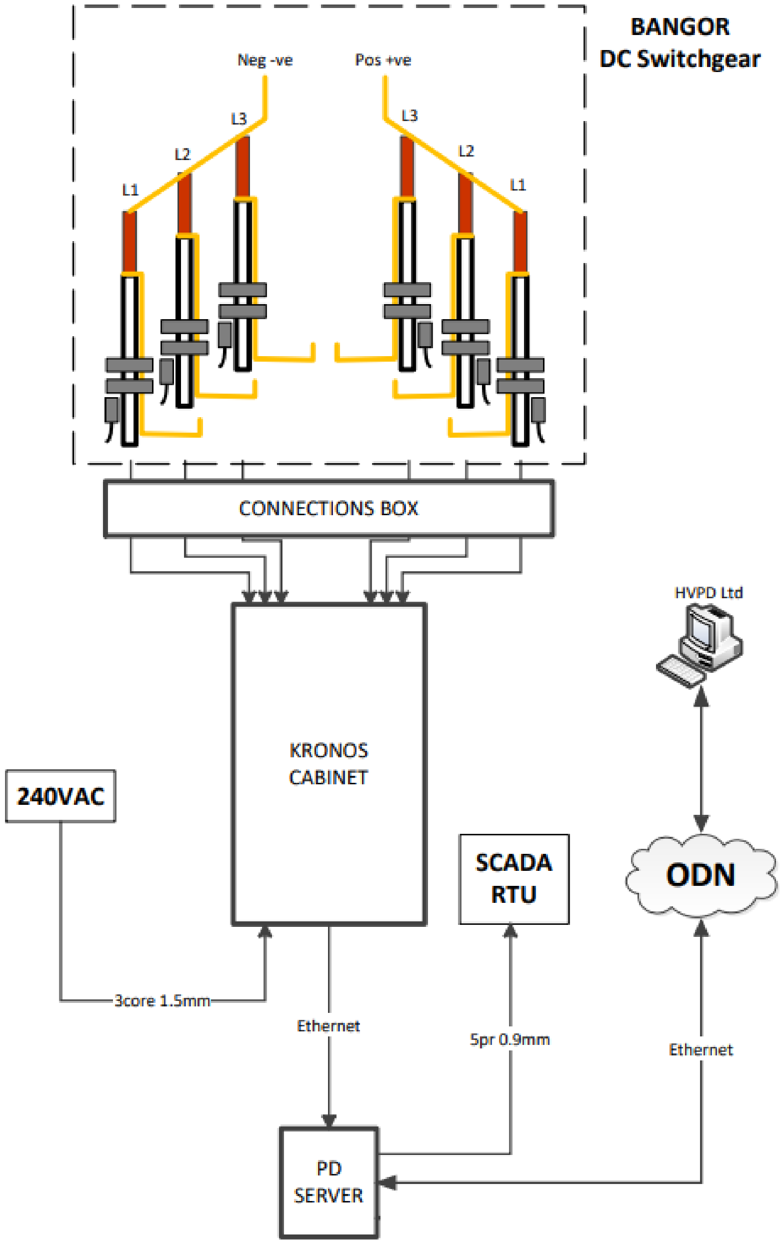


Figure 2. Online PD Monitoring System Schematic.

4.2 SENSORS

The sensors installed at the cable terminations can be seen in Figure 3.

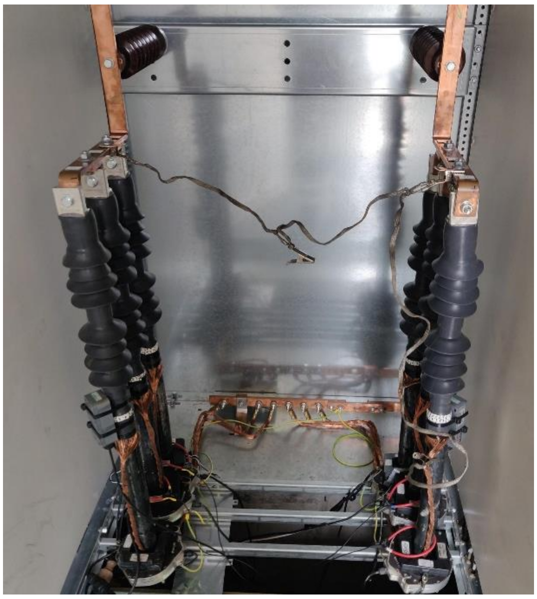


Figure 3 HFCT sensors installed on core of the pole cables. Transient Earth Voltage (TEV) sensors attached to cable termination (Note this picture is from the installation hence cables were temporarily shorted and grounded for safety.)

4.1 PD MONITORING EQUIPMENT

PD monitoring was conducted using HVPD Kronos® Monitor. This is a continuous monitoring unit for detection of PD in all types of in-service plant, including cables, switchgear, transformers, and rotating machines operating at 3.3 kV and above.

The HVPD Kronos® Monitor is a continuous PD monitoring device for MV and HV assets. It comprises modern data acquisition and data processing capabilities. It has 24 multiplexed input channels and acquires data synchronously on six channels. Data is acquired at a high sampling rate (100 MS/s) with software that processes the data to remove noise and identify PD signals using pulse wave shape analysis. The system is available for permanent and temporary installation.

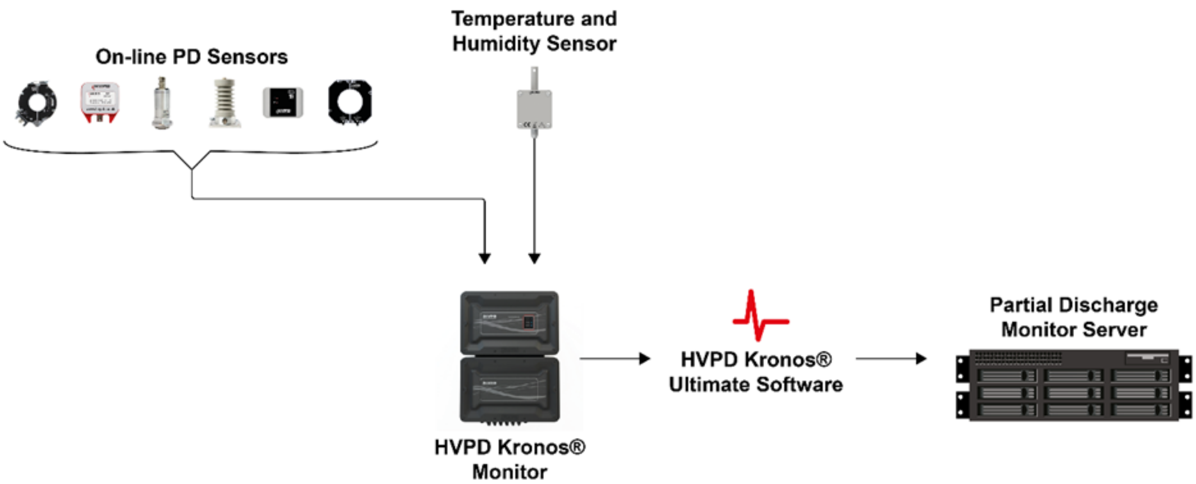


Figure 4. HVPD Kronos® Monitor 24-Channel Diagnostic PD Test Unit.

The HVPD Kronos® Monitor unit records any internal PD activity within the cables, cable sealing ends/terminations and other MV/HV plant to which the unit's TEV probes and HFCT sensors are attached. By synchronously recording high resolution data on all 6x measurement channels at once and through automatic data processing, it is possible to achieve the following benefits when making measurements:

- Identifying PD signals from electrical noise; and
- Measurement of both Phase-to-Earth PD and Phase-to-Phase PD

PD must be identified using a fully diagnostic PD test system to differentiate the dangerous internal PD signals in the MV/HV plant to those, less dangerous, signals from typically bad earth connections benign or, for outdoor insulation systems, from external surface discharges and corona (neither of which are harmful to outdoor HV plant). Any high levels of electrical, radio-frequency noise detected on the site must be removed using a combination of hardware and software high-pass and band-pass filters along with automatic signal interpretation.

5. Data Analysis

5.1 SUMMARY

Under AC stress, the data analysis of PD signals concentrates firstly on identifying pulse waveforms which bear characteristics expected from PD signals and secondly evaluating the phase resolved pattern, (plotting said pulses against the power cycle). As the position of PD pulses in power cycle is not relevant under DC stress, analysis focusses mainly on the pulse waveforms.

To analyse PD activity, under DC stress, the AC PD monitoring results were taken as a point of reference to establish the likely waveform characteristics of the PD which could be observed. In addition, as the positive and negative poles contain three cables in parallel it is of note to compare results from the three sensors on each pole. In summary, if there is PD on one cable, opposite polarity and lower magnitude pulses are expected on the other cables on the DC same pole.

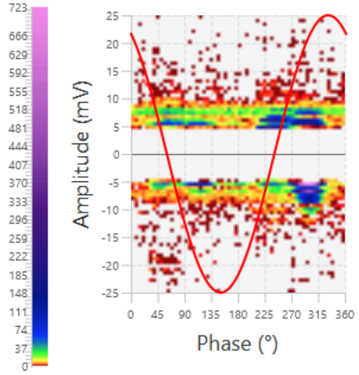
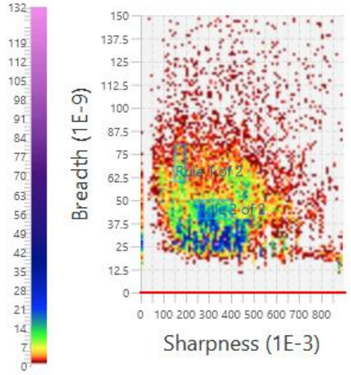
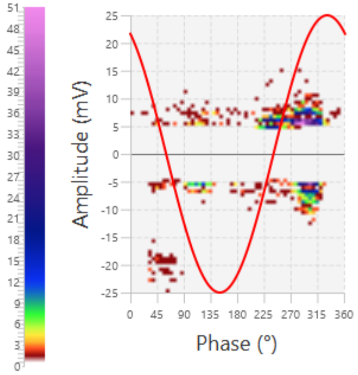
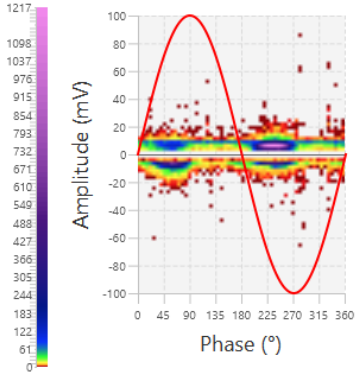
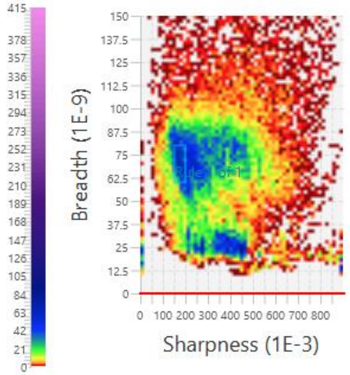
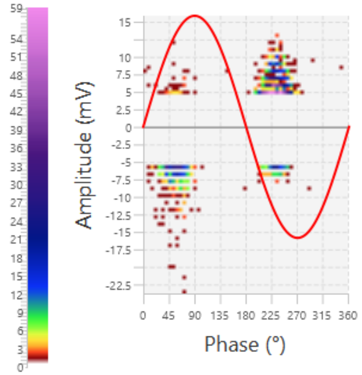
5.2 HEATMAP DATA ANALYSIS

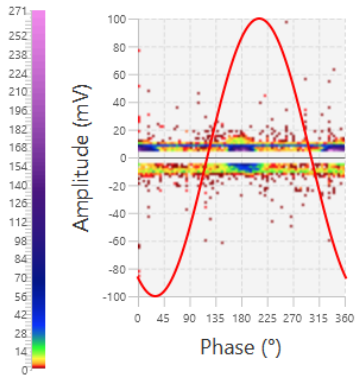
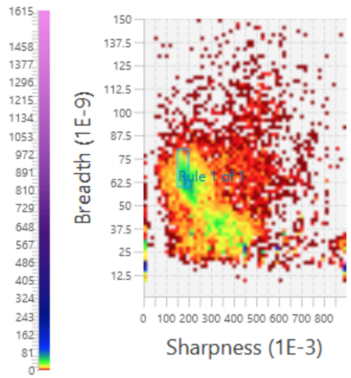
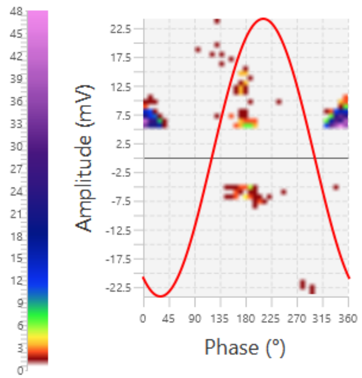
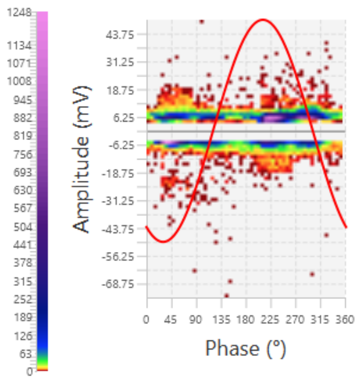
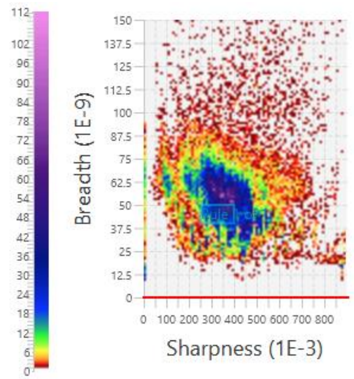
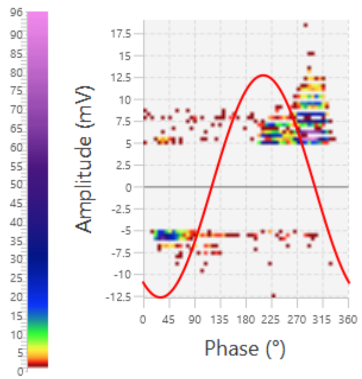
To scan the recorded data for PD events, the data has been analysed by clustering different pulse waveform characteristics. With reference to Table 4, the raw data is shown in the left column, the PD rule heatmap plot for different pulse parameters is in the centre column and the PRPD pattern in the right column for the pulses within the blue box of heatmap plot.

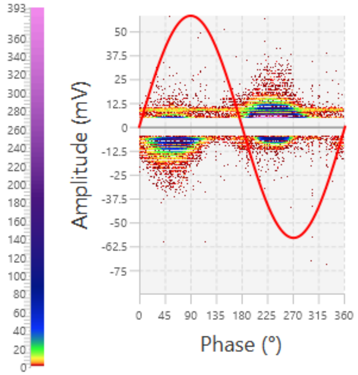
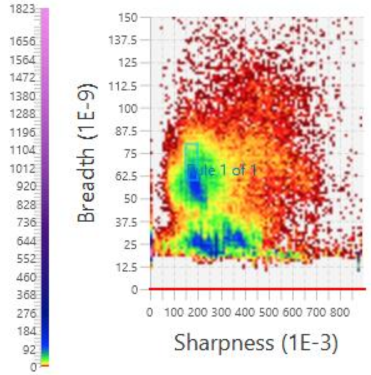
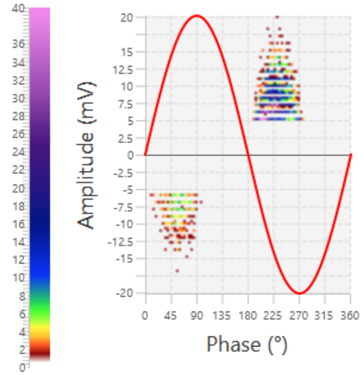
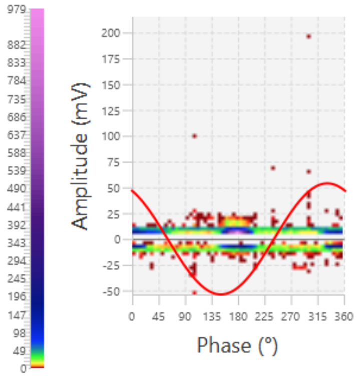
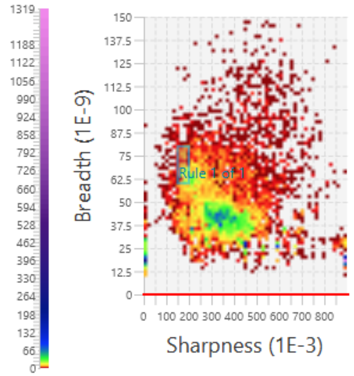
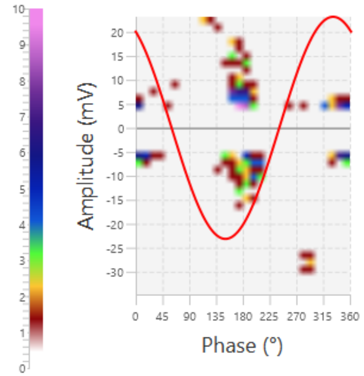
Pulse sharpness and breadth were found to give good clustering of data. In the first instance this was carried out for the AC test results, the areas where PD was detected were then used in the DC PD analysis.

5.3 AC MONITORING SESSIONS

Table 4 AC PRPD Patterns Showing De-noising.

Channel	Raw Data	PD Rule	After
Cable 1 R Phase HFCT			
Cable 1 Y Phase HFCT			

Channel	Raw Data	PD Rule	After
Cable 1 B Phase HFCT			
Cable 2 R Phase HFCT			

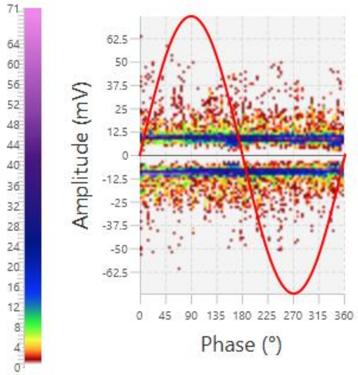
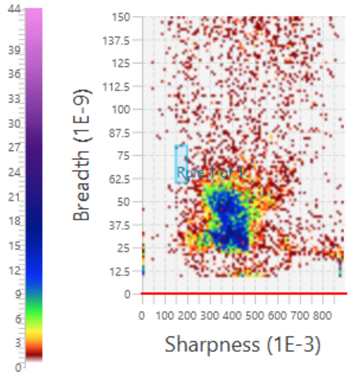
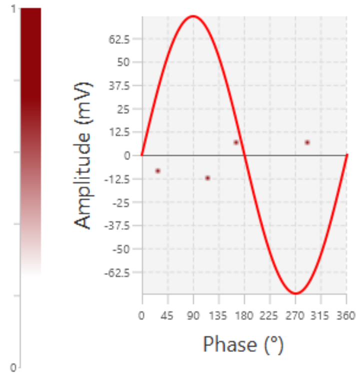
Channel	Raw Data	PD Rule	After
Cable 2 Y Phase HFCT			
Cable 2 B Phase HFCT			

5.4 DC MONITORING SESSION

Two general rules where used which took into consideration the rules created for the AC monitoring session. The two rules where very consistent in AC monitoring, but for the DC tests it looked like Rule-2 was very broad and so it was ignored. Although the phase position is not relevant to DC PD, some noise sources from the power converter may occur synchronous to the AC waveform and thus results are shown against phase for reference.

RULE -1	SHARPNESS	150-200	BREADTH	60-80
~~Rule -2~~	~~Sharpness~~	~~250-450~~	~~Breadth~~	~~20-40~~

Table 5. DC PRPD Patterns Showing De-noising.

CHANNEL	RAW DATA	PD RULE	AFTER
Postive Pole Cable 1 (Cable 1 R Phase HFCT)			

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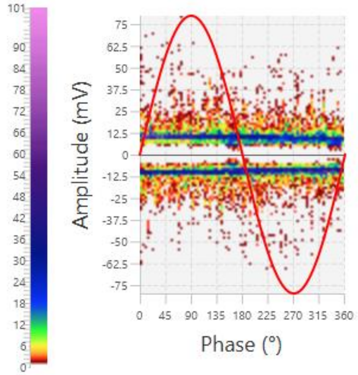
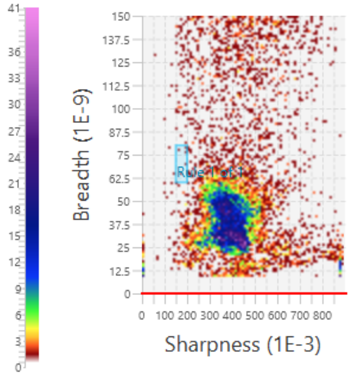
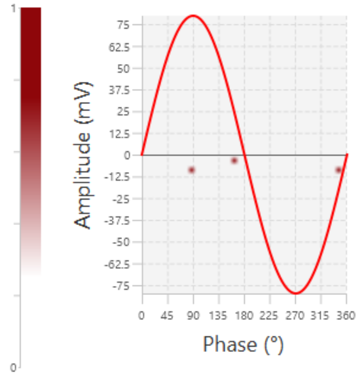
<tr><td>Postive Pole Cable 3 (Cable 1 B Phase HFCT)</td><td>
</td><td>
</td><td>
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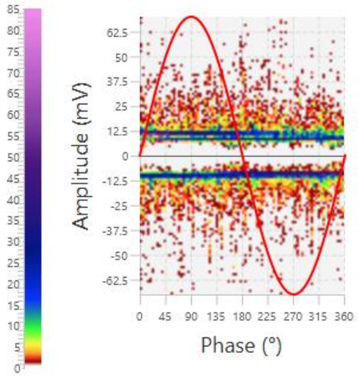
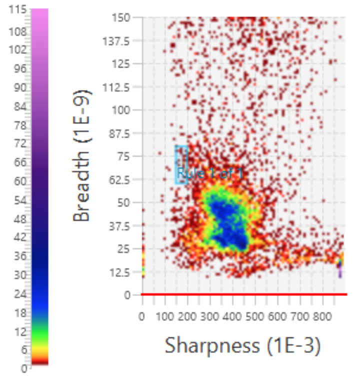
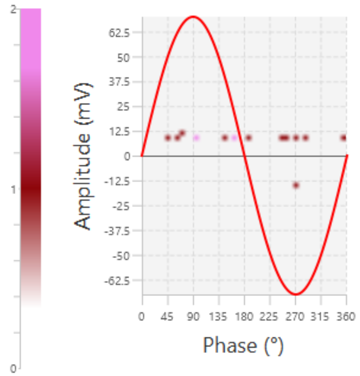
<tr><td>Negative Pole Cable 1 (Cable 2 R Phase HFCT)</td><td>
</td><td>
</td><td>
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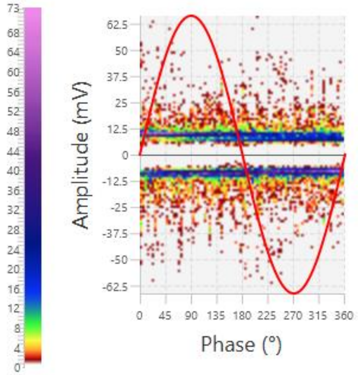
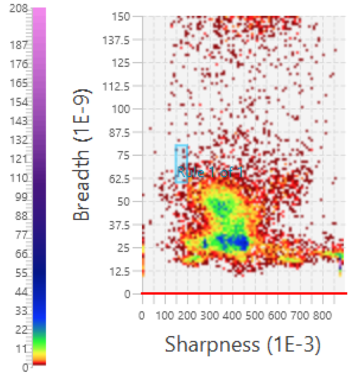
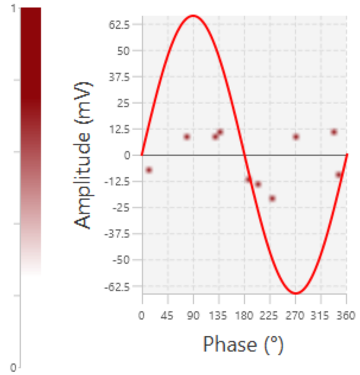
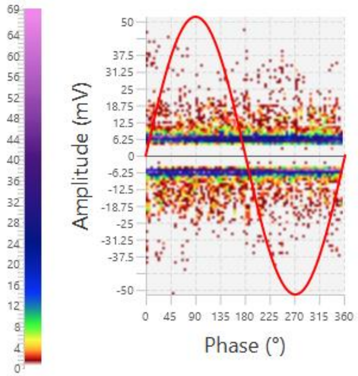
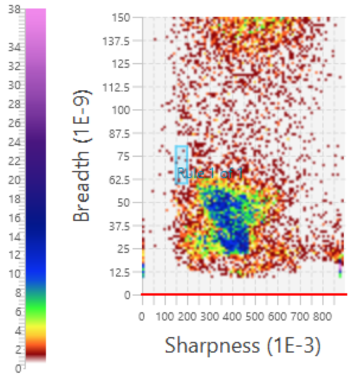
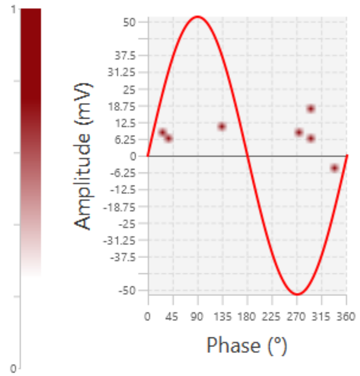
Negative Pole Cable 2 (Cable 2 Y Phase HFCT)			
Negative Pole Cable 3 (Cable 2 B Phase HFCT)			

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