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Demonstration of an Online Continuous Monitoring System for Partial Discharge on Critical HV Cables

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SUMMARY

INEOS is a major multi-national group of companies specialising in petro-chemical production. Its largest manufacturing site is based at Grangemouth, Scotland, which is home to its Olefins and Polymers (O&P UK) business, as well as a crude oil refinery that produces the bulk of Scotland's fuel. It owns and operates one of the largest private electricity distribution networks in Europe. EA Technology specialises in providing technical services and consultancy within the power industry worldwide. One of its key areas of expertise is the detection and measurement of Partial Discharge (PD) in High Voltage (HV) switch gear and equipment.

This paper describes a joint Pilot Study between the two companies to install an online Cable PD monitoring system on 18 critical 33kV XLPE cables that link the INEOS owned Combined Heat and Power (CHP) plant to the main distribution substation at INEOS' O&P UK manufacturing site at Grangemouth. The monitoring system, known as the CableData Monitor (CDM), detects PD on the cable by means of Radio Frequency Current Transformers (RFCTs) clipped non-intrusively around the earth screen terminations at one end of each of the cables. The system became operational in October 2016 and has since detected and recorded PD activity on three of the 18 cables being monitored. An analysis of the captured waveforms has located the PD sources to the vicinity of newly installed cable joints. This paper explains how the PD levels (which vary with time) are being monitored using trending and threshold alarms to manage the cables whilst they remain in operation. This monitoring may thus allow the replacement of the joints at the next planned maintenance outage rather than having to undertake an earlier intervention, avoiding unnecessary downtime of the CHP. Additionally, resources and personal safety measures have been put in place to manage an outage should one occur in the meantime.

The results from the CDM are also compared to conventional off-line VLF measurements that were performed on the same cables prior to energisation. The correlation was accurate enough to warrant not taking the cables out of service for further VLF testing (instead relying on the on-line measurements) which again has resulted in further financial saving by alleviating the CHP plant downtime required for traditional testing methods. As well as providing a unique opportunity to study the behaviour of the PD with time, if the cable joints can be replaced and subsequently forensically examined before failure occurs, this may provide valuable evidence (that might otherwise be destroyed during a failure) that could identify the cause of the PD - thus allowing corrective action to protect against it happening again in the future. In conclusion, the paper demonstrates how INEOS' pro-active approach to managing PD on its critical HV cables has helped to save money, whilst at the same time, enhance the reliability of its electricity distribution network at its site at Grangemouth.

KEYWORDS

Partial discharge, continuous on-line monitoring, cable condition assessment, PD measurement, detection, location, failure analysis, CableData Monitor, CableData Collector, CDM, CDC, 24/7

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1. INTRODUCTION

During August/September 2016 an on-line CDM pilot system was installed within one of the main 33kV Electricity Distribution Substations at INEOS's Olefins and Polymers manufacturing site at Grangemouth in Scotland. The purpose of the monitor was to detect the presence of PD on 18 critical Feeder Cables between the substation and the CHP plant. The 18 feeder cables are arranged as two ganged circuits, with each phase having three separate cables in parallel to carry the full output current of circa 2,300A from the CHP plant. Each of these cables are approximately 1km long and of XLPE construction. As constructed each contained a pair of joints - one close to the substation end, and one approximately 330m from the CHP plant end. Because there had been a history of problems associated with the joints nearest the CHP plant end, INEOS took the decision to replace all 18 joints during a planned maintenance shut down in September 2016. Each removed joint was replaced with a pair of new joints and a short length of XLPE cable to bridge the gap (36 new joints in total). At the same time, the CDM was installed in the 33kV Substation No3 to monitor the cables' condition when power was restored following the maintenance outage. Figure 1 shows the arrangement following the joint replacement.

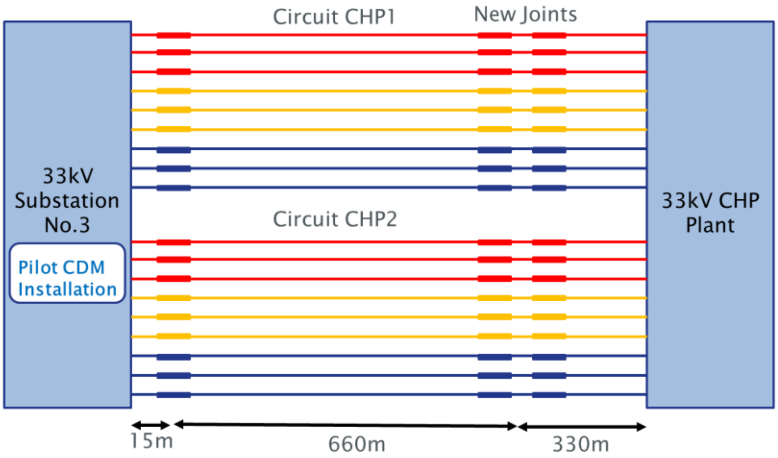

Figure 1 Substation/CHP Feeder Cable Arrangements Following Joint Replacement

2. CDM MONITORING SYSTEM INSTALLATION

The CDM is a distributed cable PD monitoring system consisting of a central Hub and numerous distributed Nodes and sensors. The Nodes detect and measure PD activity and then send the information back to the Hub where it is processed and stored. Recorded data can be viewed from the Hub, or a computer connected on the same network, through a web interface. The data stored on the CDM Hub can also be accessed remotely via 4G over the mobile phone communications network using a standard web browser on a personal computer. Figure 2 shows a block diagram of the CDM system installed at INEOS for the pilot study.

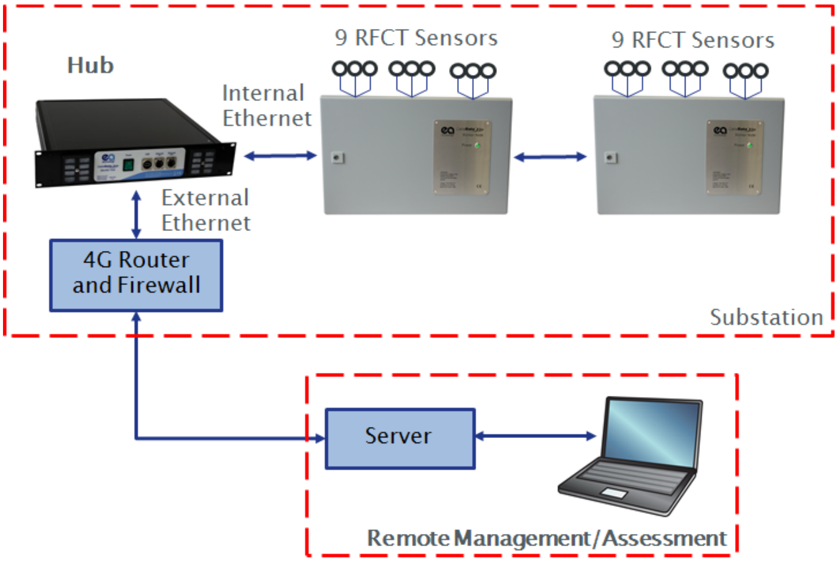

Figure 2 Block Diagram of the CDM Pilot System Installed in the 33kV Substation at INEOS

The CDM is an on-line monitoring system which means that it monitors for PD under normal cable operating conditions with system volts applied and, unlike some traditional methods, it does not require an outage for detecting PD. Detection is achieved by clipping Radio Frequency Current Transformer (RFCT) sensors around the cable earth screens at the cable terminations within the substation. The RFCTs can detect the minute high-frequency current pulses that are created when PD occurs inside cables [1]. Figure 3 shows the RFCTs clipped around the CHP cable earth screens. Figure 4 shows the CDM measurement Nodes mounted on the wall in the 33kV Substation. The Hub computer was mounted within an existing 19” SCADA rack in the substation. The system has been monitoring the PD activity on the CHP feeder cables since the beginning of October 2016 when the CHP plant was bought back on line following the maintenance shut down.

Figure 3 RFCTs Clipped Around the CHP Cable Screen Earth Terminations

Figure 4 CDM Measurement Nodes Mounted Within Substation

3. VLF TEST MEASUREMENTS

Following the replacement of the 18 original joints with 36 new joints, and prior to the cables being re-energised, a conventional VLF PD test was performed on the cables from the CHP end (i.e. at the opposite end to the CDM installation). VLF testing is an off-line method that requires the cables under test to be taken out of service and energised from a specialised Very Low Frequency (VLF) HV test source to perform the test. The results of the VLF test indicated that three out of the 18 cables had PD present and that the PD was located in the vicinity of the new joints. For logistical reasons, it was only possible to replace one pair of new joints on one of the cables before it was necessary to re-energise the CHP circuits.

3.1. Positive Cable Identification

Part of the VLF test sequence involves injecting a test pulse onto the individual cables. This is done to determine their length and to confirm the correct operation of the test equipment prior to performing the HV part of the PD test. When applied at the CHP end, these test pulses were detected by the CDM system at the far end of the cables. By correlating the time at which each pulse was applied, and from an analysis of the direction of travel of the detected current pulses, it was possible to identify which cable the pulses had been injected into. Whilst this proved a valuable method for confirming the correct operation of the CDM, it also unexpectedly revealed a number of discrepancies between the labelling of the individual cables at the 33kV Substation end and the labelling at the CHP end. It is thought that these discrepancies had arisen historically as a result of the cables being physically re-routed following cable termination failures. Due to the parallel connection of the cables, the discrepancy had not readily become apparent afterwards.

This is the first time this combined technique of using the VLF test pulse and CDM has been used to aid cable identification. In this instance, where each circuit comprises three separate cables connected in parallel, this approach had the advantage that it was not necessary to disconnect each of the cables at the 33kV Substation distribution board to identify which one was which. This inherently safer, and saves both time and money by removing the need to disturb the HV connections and risk the possible introduction of further problems as a result.

4. CDM MEASUREMENT CAPABILITIES

The CDM has four main measurement modes:

- Phase Resolved Event Plots (using historic data)
- Live View (phase resolved event plots using live data)
- Waveform Capture
- Time-series

The time-series data records the following key parameters at every two-minute interval:

- Event Amplitude Mean
- Event Amplitude Max
- Overall Severity Mean
- Short Term Severity (STS) Max
- Pulses per Cycle Mean
- Pulses per Cycle Max
- Total Pulse Count

The monitoring system allows any of these parameters to be plotted over any time period as required, allowing trending of the data and the setting of alert thresholds that can be used to generate email and SMS notifications when they are exceeded. The Event Amplitude Mean is the average magnitude of all the PD events recorded in the two-minute interval. This has been found to be a useful way to monitor the variation in PD activity levels and will be used in the following illustrations in this paper.

5. PD MEASUREMENTS

5.1. Cable Energisation

Figure 5 shows the Event Amplitude Mean levels when the cables were first re-energised. It can be seen that there was a slight increase in the background noise levels but, other than the large spike the following day, the activity levels remained low. After further detailed analysis of the phase plot data and the CHP output SCADA data, it was established that the spike of activity, which lasted approximately 30 minutes and affected all the cables, corresponded to the use of the Static Frequency Converter (SFC) to start the CHP generators. The SFC was found to produce a characteristic Event Amplitude Mean and phase plot profile that was subsequently recognisable each time it was used. Figure 6 shows the Event Amplitude Mean profile over the 10 days following energisation. Other than the use of the SFC (as indicated by the spikes), there was no evidence of PD on any of the cables during this period.

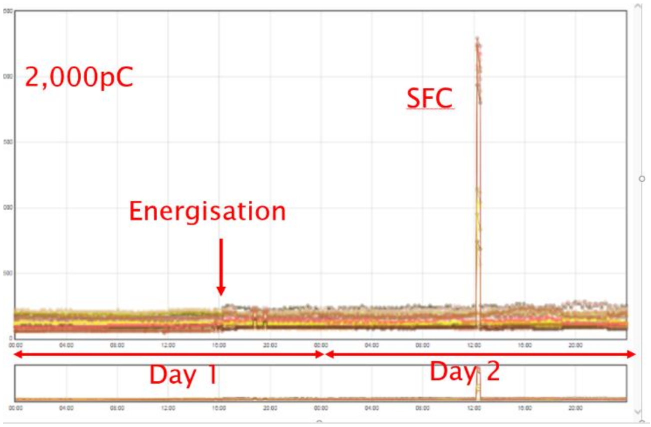

Figure 5 Event Amplitude Mean Levels (pC) for all Cables Immediately After Energisation

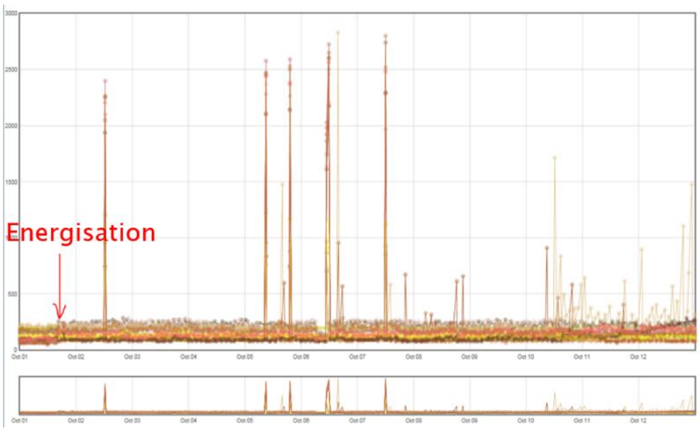

Figure 6 Event Amplitude Mean Levels (pC) for all Cables For 10 Days Following Energisation

5.2. PD Detection on Cable CHP2-R2

This situation changed 12 days after energisation. Figure 7 shows that there was a steady increase in the Event Amplitude Mean levels on cable CHP2-R2 from around 100pC to slightly above 300pC during the ensuing week. This was one of the cables reported as having PD during the VLF testing. Figure 8 shows a 2-minute phase plot for CHP2-R2 captured on the 13th day following energisation. A phase plot is used to display each of the high frequency current pulse events that was detected by the CDM during the selected time interval relative to the position where it occurred on the 50Hz mains cycle. Hence the x-axis shows the position of each event on the mains cycle (0-360°), whilst the y axis shows the relative magnitude of each event (pC). Because more than one event of the same magnitude can occur at the same position on the mains cycle (and they frequently do), the colour of the individual points on the plot is indicative of the number of events that occurred and effectively represents the event intensity around that point. Characteristic patterns produced within these plots can be used to recognise and classify PD. The events depicted in the phase plot in Figure 8 exhibit clustering on the positive and negative half cycles 180° apart that is characteristic of PD.

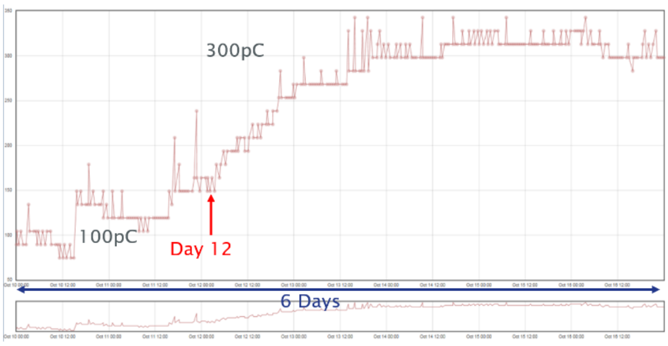

Figure 7 Event Amplitude Mean (pC) for Cable CHP2-R2 for a Period of 6 Days Commencing 10 Days After Energisation

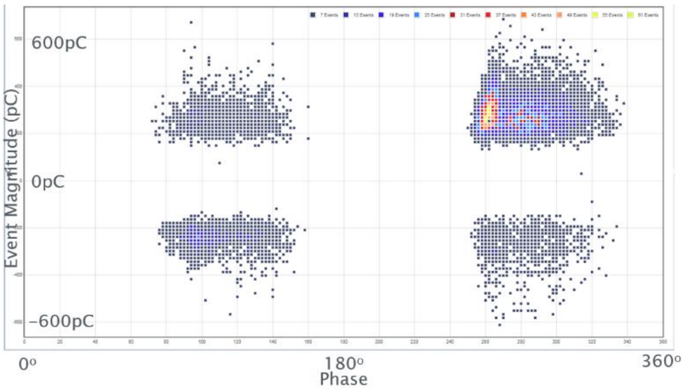

Figure 8 2-minute Phase Plot for CHP2-R2 Captured 13 Days After Energisation

There was no significant similar increase observed on any of the other cables although later, when the Event Amplitude Mean level reached higher magnitudes, there was evidence of matching (but lower level) activity at the same time on the other two cables in parallel with CHP2-R2, i.e. CHP2-R1 and CHP2-R3 on the same phase. This is shown in Figure 9. This is attributed to pickup from CHP2-R2, because the three cables are connected in parallel at both ends. This provides preferential earth paths at the terminations for the reflected PD pulse currents. It is also highly unlikely that three separate PD sources would start in all three cables at the same time, and mirror the activity levels. It can be seen that within a month the Event Amplitude Mean activity level for CHP2-R2 had risen from 300pC to around 1,000pC, although it is interesting to note the undulations in the measured levels as opposed to a steady increase.

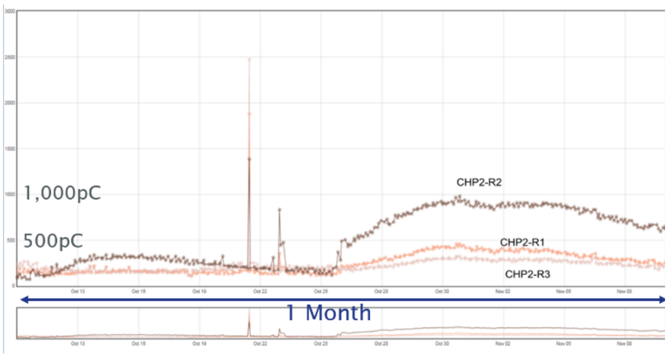

Figure 9 Event Amplitude Mean (pC) for Cable CHP2-R2 for a Period of 1 Month After the PD Started

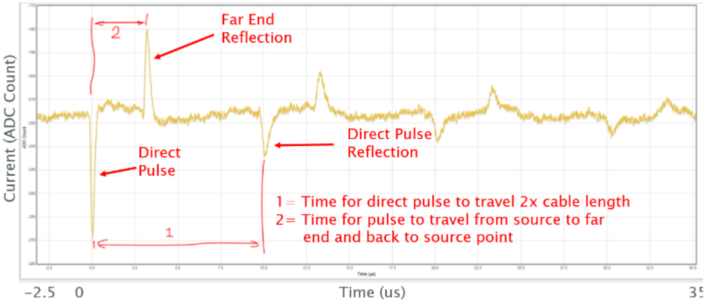

Figure 10 PD Pulse Current Waveform for CHP2-R2 Captured 13 Days After Energisation

An example of a single PD current pulse waveform captured at the same time as the phase plot shortly after the PD had started is depicted in Figure 10. The waveform is characteristic of cable PD (sharp unipolar pulse with a fast rise time) with multiple reflections of the transient PD current pulse from the far end of the cable evident. Although the y-axis represents current (A), at present the CDM system displays the value as ADC (Analogue to Digital Converter) Counts. These are proportional to the current. At least three reflections of the first direct pulse can be seen. The distance travelled by the third one is 6km as the cable is 1km long and the pulse has travelled up and down it three times within the given capture window.

5.3. Cable PD Source Location on Cable CHP2-R2

In Figure 10, the interval between the first and second negative pulse “Time 1” (about 10us) represents the time taken for the first direct pulse to be reflected from the near end termination, travel to the far end of the cable, be reflected again, and return to the near end. Hence this time represents twice the cable length and equates to 2km as the pulse propagation speed in this XLPE cable is known to be around 200m/us. This correlates well with the documented cable length which is 1km long. Similarly, “Time 2” (about 3us) represents twice the distance of the PD source to the far end of the cable. About 3us represents 600m making the source about 300m from the far end. More exact results obtained by calculation using more accurate values extracted off the pulse waveform are represented in Table 1. These are compared to the VLF test results and INEOS’ cable records.

Table 1 Location of PD Source in CHP2-R2 from CDM Waveform

CDM Waveform		VLF Test		INEOS Cable Information	
Route Length	**PD Source Distance From CHP End**	**Route Length**	**PD Source Distance From CHP End**	**Route Length**	**CHP2-R2 original joint Distance From CHP End**
997m	315m	980m	308m (31.5%)	1000m	330m

It can be seen that there is excellent agreement between the CDM and VLF results in relation to the documented cable information, and the location of the PD source at the position of the new joints. However, because each pair of joints are only separated by a short length (few metres) of new cable, they are too close to each other to be able to determine which of the two joints in the pair is discharging using either PD detection method.

5.4. PD Detection on Cables CHP2-B3 and CHP2-Y1

The Event Amplitude Mean plot of Figure 11 shows that PD started on cable CHP2-B3 18 days after energisation. This was the second cable identified to have PD by the VLF test. Unlike CHP2-R2, the start was much more abrupt and within one day it had exceeded 1,000pC. There was matching (but lower level) activity attributed to pick up that commenced at the same time on the other two cables in parallel with CHP2-B3, i.e. CHP2-B1 and CHP2-B2, which is not shown. A 2-minute phase plot in Figure 12, taken 3 days after the PD started, shows classic PD activity with some events as large as 3,000pC.

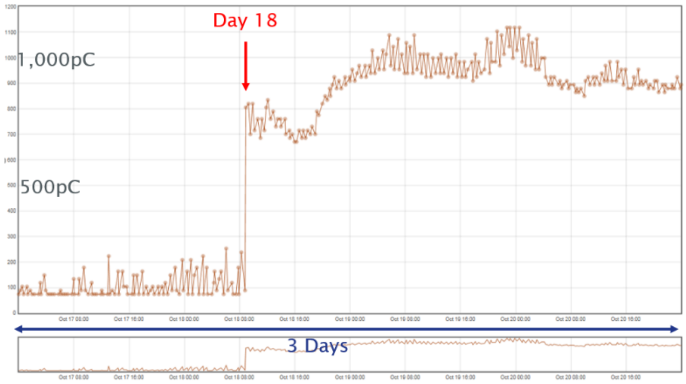

Figure 11 Event Amplitude Mean (pC) for Cable CHP2-B3 for a Period of 3 Days Commencing 17 Days After Energisation

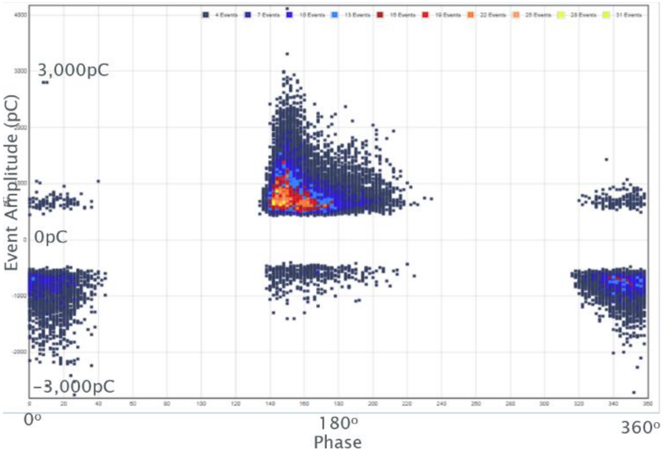

Figure 12 2-minute Phase Plot for CHP2-B3 Captured 20 Days After Energisation

Similarly, PD started on cable CHP2-Y1 28 days after energisation as shown in Figure 13. Like CHP2-R2, the start was fairly abrupt reaching 1,000pC within hours and accompanied by matching (but lower level) activity attributed to pick up seen on the other two cables in parallel with CHP2-Y1, i.e. CHP2-Y2 and CHP2-Y3. Again, a 2-minute phase plot taken 3 days after the PD started shows classic PD activity with events up to 2,500pC (Figure 14). Unlike the previous two cables, this cable had not exhibited PD when spot tested with the VLF.

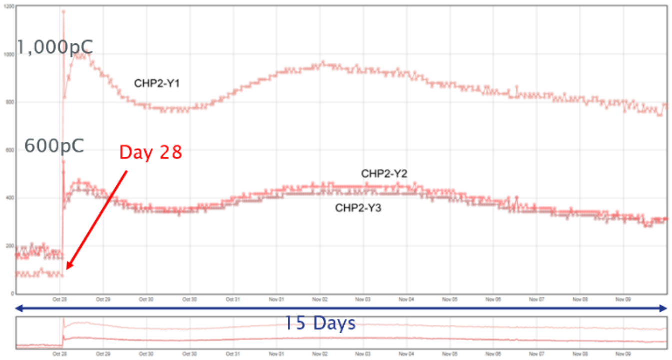

Figure 13 Event Amplitude Mean (pC) for Cable CHP2-Y1 for a Period of 15 Days Commencing 27 Days After Energisation

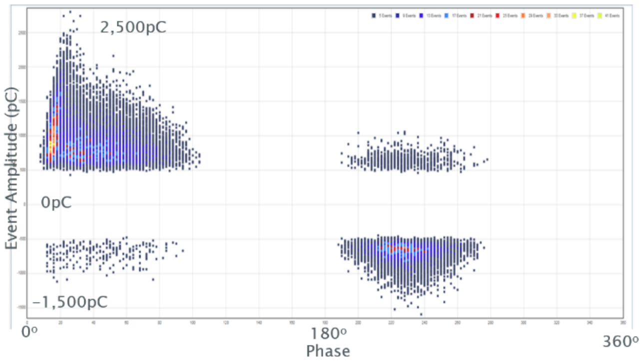

Figure 14 2-minute Phase Plot for CHP2-Y1 Captured 30 Days After Energisation

Waveform captures for both CHP2-B3 and CHP2-Y1 virtually replicated those shown in Figure 10 above for cable CHP2-R2. Using the reflected pulse timings from these waveforms, the location of both PD sources was calculated to be approximately 320m from the CHP end of the cable. This corresponds to the position of the new joints and provides good correlation with the results of the VLF tests.

6. LONG TERM PD TRENDS

Figure 15 shows how the Event Amplitude Mean PD activity has changed for the three discharging cables CHP2-R2, CHP2 B3 and CHP2-Y1 since they started discharging in October 2016 through to the end of June 2017 [The very narrow spikes on the plot should be ignored as these correspond to SFC operation events]. It is interesting to note that there are both similarities and differences in their respective profiles. Although their behaviour was different at the start (two abrupt, one more gentle), in general in each case the PD level has reached a maximum within a month or two of starting, and has then reduced. In the case of cable CHP2-Y1, the activity stopped altogether in December 2016. The PD levels on the other two cables have fluctuated up and down mainly between 400-800pC but have not exceeded their maximum values that occurred nearer the start (1,000-1,200pC). In the last two months, there has been a noticeable "saw tooth" pattern that has emerged in the behaviour of cable CHP2-R2, that can be seen in Figure 15 by the "noisier" appearance of the plot. Whilst the explanation for this behaviour and its implications are not yet fully understood, it is hoped that in the fullness of time, this information will provide a further insight as to the nature of the PD source itself, as well as an indication of the probability of failure.

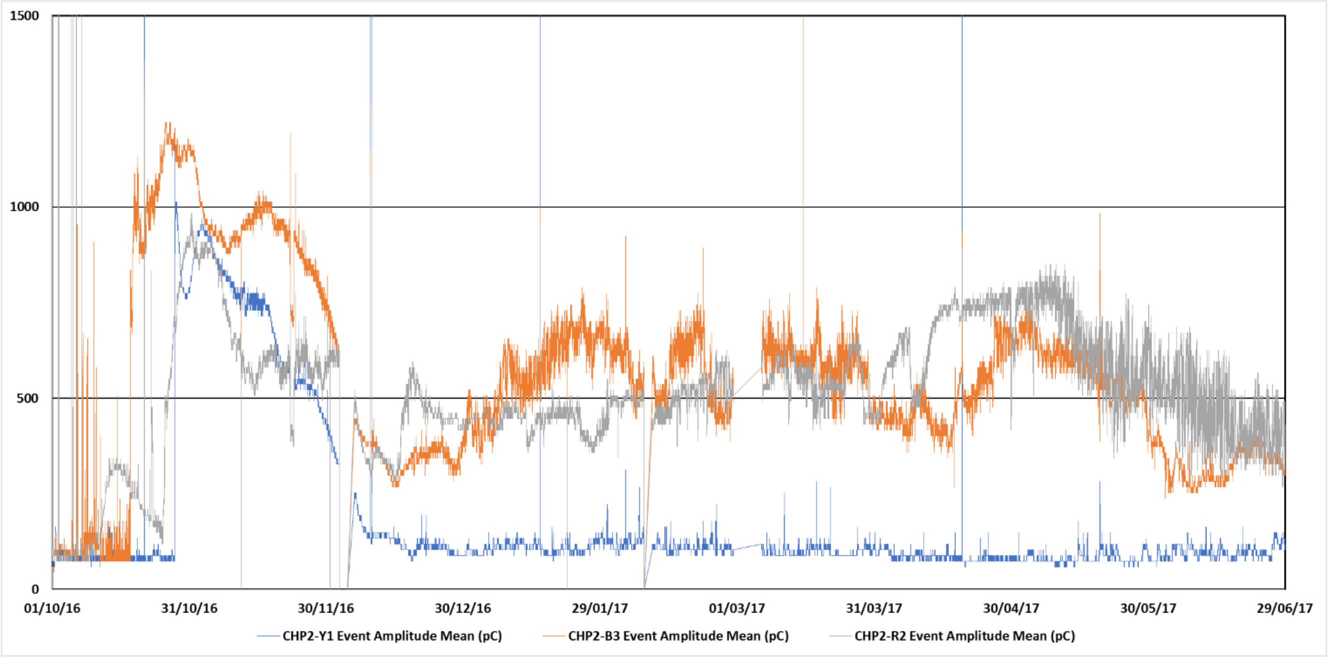

Figure 15 PD Activity Trend for the Three Discharging Cables Since the Onset of Discharge Activity (October 2016 to June 2017)

6.1. Alerts and Notifications

The CDM system has the facility to set alert thresholds on many of the measured parameters that can be used to trigger remote notification messages when the thresholds are exceeded. In this instance, a two-tier alert level system was employed. Amber level alerts were set to produce email notifications when exceeded. Red alerts were set at a higher level, and set to produce both email and SMS text messages when exceeded. This regime has proved particularly effective in managing the PD on these cables as described in Section 7. The alerts can also be used to trigger the capture and storage of waveforms, which can be useful to diagnose events that occur out of hours.

7. CABLE MANAGEMENT IMPLICATIONS

The information provided by the on-line cable monitoring system has been particularly helpful to INEOS in terms of managing their critical CHP feeder cables. Returning the cables to service with the CDM system in place has ensured that the known PD can be continuously monitored, and any deterioration promptly identified. Without this, there would have been a necessity to take the CHP out of service periodically to repeat the off-line VLF tests. This is a time-consuming activity as well as being inconvenient and very costly in terms of lost production. In contrast, the CDM has saved the cost of the CHP down-time as well as providing a much more detailed picture of the PD behaviour. The pilot study has also highlighted the benefits of on-line continuous monitoring over spot measurements in that it was able to detect PD activity on cable CHP2-Y1 that was not detected with the VLF test. As the PD source has only been active on this cable for a couple of months so far, spot testing may have missed this activity unless the testing was performed fairly frequently. In effect, the CDM has provided an earlier warning of PD than might otherwise have been possible; i.e. until the PD source deteriorated to the point that the activity became continuous.

If left unattended, it is generally accepted that the presence of PD will ultimately result in the failure of the cable/joint [2]. PD sources can often be intermittent, unpredictable, and the discharge levels go up and down with time. However, once present, PD will not cure itself. To the Author’s knowledge, there is no direct and reliable relationship between cable PD level and time to failure. Hence, at present it must be accepted that it is not usually possible to accurately predict when a discharging cable or joint might fail, and in some instances failures could occur with little or no warning. Despite this, it is probably fair to say that in general the larger the PD magnitude and the more frequent the occurrence, the more likely the cable is to fail. This basis can be used now for making more informed decisions and for prioritisation when considering what remedial action to take, if any. In the future, greater understanding and experience gained from the use of on-line cable PD monitoring may lead to more accurate failure forecasting.

In the case of the three discharging CHP cables at INEOS, given the magnitude of the recorded PD levels, the trend patterns to-date, and the knowledge that the PD is coming from a joint which will normally tolerate higher levels of PD over longer periods of time compared to cables (particularly XLPE cables), the decision was taken not to replace the joints immediately. Weighing up the risk of failure against the consequences of failure, and taking into account precautionary measures put into place, it was decided to leave the discharging joints in service until the next planned maintenance outage scheduled for August 2017 (provided the monitored PD levels do not change significantly). If this can be successfully achieved, it will avoid significant CHP down-time costs associated with taking the CHP out of service purely to replace the defective joints.

Using the information from the CDM, INEOS have been able to put in place a number of precautions to pro-actively minimise any adverse effects should one of the cables fail without warning prior to the scheduled maintenance outage in August 2017. These precautions include:

- Ensuring resources (manpower, expertise, and materials) are immediately available to repair a sudden failure,
- Making alternative provision for electricity and steam supply on the plant in the event of sudden CHP loss,
- Ensuring personnel safety by preventing access to the joints whilst energised due to the risk of failure,
- Continue monitoring the state of the joints with the CDM using pre-set alerts and notifications allowing immediate reaction should the situation change.

8. FORENSIC EXAMINATION OF DISCHARGING JOINTS

It is planned to replace the three pairs of joints on the discharging cables in August 2017 during scheduled maintenance shut down. The intention is to forensically examine each of the joints to look for evidence of PD activity and try and establish the cause of the PD. Examining defective joints after they have failed (as is normally the case when trying to establish the cause of failure) is often difficult because the evidence sought has been destroyed in the failure. This rare opportunity to examine the joints internally in the absence of damage caused by catastrophic failure may provide valuable evidence to establish the cause of the PD. This would enable preventative action to protect against the same thing happening again in the future. A more detailed understanding of the PD breakdown mechanism itself may also enhance the understanding of the trend behaviour monitored by the CDM, thereby improving future diagnostic capability.

9. CONCLUSIONS

1. A pilot on-line cable PD monitoring system has been installed in the main 33kV electricity distribution substation at INEOS' Olefins and Polymers plant and oil refinery in Grangemouth, Scotland. It has been successfully monitoring PD activity on 18 critical CHP feeder cables since October 2016.

2. Initially, when the cables were first energised, no PD was detected. However, over a period of one month, three separate cables started to exhibit PD. Two of these cables had previously been identified as exhibiting PD during VLF testing prior to energisation. The third cable, which stopped discharging in December 2016, was not identified as having PD during VLF testing.

3. An analysis of the data captured by the CDM has shown that in all cases the source of the PD appears to be located within a set of joints approximately 320m from the CHP end of the cable.

4. The results from the on-line CDM measurements have been compared to the off-line VLF measurements and shown to exhibit good correlation, giving confidence in the on-line measurement system.

5. Information from the CDM is now being used to pro-actively manage the cables until they can be replaced. Already significant savings have been achieved by not having to take the plant off-line to repeat VLF tests to check on the cables' condition. If the replacement of the joints can be deferred until the next scheduled maintenance outage due in August 2017, then significant costs associated with the unscheduled CHP downtime (many times greater than the cost of the CDM system) may also be avoided.

6. It is hoped that a forensic examination of the affected joints, after they have been removed intact from service, will reveal the cause of the PD. Once the cause is established, action can be taken so that it can be prevented in future, as well as further aiding the interpretation of the data captured by the CDM by providing feedback on the real-life observations made.

7. With the advent of online cable PD measurement, it is now possible to measure and record PD activity in more detail and over longer periods than has previously been possible. Given the unstable behaviour of PD, this makes it more probable that "worst case" activity will be captured by the CDM than might be expected using traditional spot measurements. As an expanding database of on-line reference measurements become available, it is hoped that this will allow the technique to be improved further, providing greater certainty about the cause of the PD and the likely time to failure.

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