ON-LINE PARTIAL DISCHARGE CONDITION MONITORING OF COMPLETE NETWORKS FOR THE PULP AND PAPER INDUSTRY: CHALLENGES AND SOLUTIONS EXPLAINED THROUGH CASE STUDIES

Lewis Dodd	Riccardo Giussani	Aaron McPhee	Andrew Burgess
Member, IEEE	Member, IEEE	Member, IEEE	Member, IEEE
HVPD Ltd	HVPD Ltd	International Paper	PDMSGlobal LLC
Manchester, UK	Manchester, UK	Augusta, GA, USA	Houston, TX, USA

Abstract - Outages within the paper industry lead to significant costs to operators. To reduce unplanned outage and losses condition monitoring (CM) techniques can be implemented to determine asset health and help target maintenance where it is most required. The challenges faced by the paper industry to implement condition based maintenance (CBM) on their medium voltage (MV) and high voltage (HV) networks and solutions for on-line partial discharge (OLPD) monitoring are due to the range and number of assets present and geographical spread coupled with problems of retrofitting the technology on pre-existing plants. The implementation of OLPD testing and/or monitoring can vary based on several factors: network topology, connected assets, switchboard type, owner budget and owner's desired local engineer involvement. This paper discusses different approaches to implementing an OLPD test program, ranging from simple handheld survey units to complete network monitoring. This paper focuses on case studies of the deployment of OLPD testing and monitoring solutions at several paper sites within the U.S. The case studies will present diagnostic testing of unshielded MV cable at one paper mill up to full permanent OLPD monitoring systems at two others.

Index Terms – Complete Network Monitoring, HFCT, HV Assets, HV motor, HV generator, HV transformer, Pulp and Paper, OLPD, On-line Partial Discharge, Remote OLPD Monitoring

I. NOMENCLATURE

AA	ultrasonic Airborne Acoustic, a PD sensor.
CBM	Condition Based Maintenance.
CM	Condition Monitoring.
CT	Measurement Current Transformer.
HFCT	High Frequency Current Transformer, a PD Sensor.
HV	High Voltage.
MCSA	Motor current Signature analysis.
MV	Medium Voltage.
OLPD	On-line Partial Discharge.
PD	Partial Discharge.
PDMS	Partial Discharge Monitoring Server.
SCADA	Supervisory Control and Data Acquisition.
TOF	Time of Flight.
TEV	Transient Earth Voltage, a PD Sensor.
XLPE	Cross-Linked Polyethylene Insulation.

II. THE PULP AND PAPER INDUSTRY

The pulp and paper industry is the fourth largest industrial energy consumer globally, after iron and steel, chemicals, and non-metallic minerals [1], [2]. Pulp and paper production requires heat and electricity as the primary source of energy input with energy costs making up, on average, 16% of production costs [3]. Therefore, rising energy costs are a concern for the industry and the need to maintain the production assists free of electrical/mechanical failures is of primary significance to maximize the plant efficiency.

North America continues to remain the largest world region for paper consumption and enjoys significant fiber resources to support this. The main inputs for paper and paperboard are different forms of pulp, which in turn are made from wood or other raw materials containing cellulose fibers.

If a pulp and paper mill produces the pulp on-site for use in the production of paper products it is considered to be an integrated mill. Conversely, if the pulp is dried and pressed before transportation to the paper mill for production it is considered to be a separated mill. The following sections will explore the different methods of producing the pulp required for the paper industry.

A. Mechanical Pulping

Mechanical pulping is principally used in integrated pulp and paper mills rather than separated mills. This process uses mechanical energy to separate the fibers. The efficiency of this process can vary from 1 – 45% with respect to the raw materials used, however, the process is considered both simple and efficient with the primary disadvantage being that the wood fibers are often damaged [4]. Mechanical pulping is mainly used for weaker paper such as newspaper, printing paper, toweling, tissue, or paperboard. Where additional strength is required, chemical pulp is occasionally mixed in to the process. Electricity is the main source of power for mechanical pulping [5] and mechanical pulp production yields substantial amounts of heat as side product, which can be used for district heating [6], [7].

B. Chemical Pulping

Both integrated and non-integrated pulp and paper mills can make use of chemical pulping. Chemical pulping involves removing the cellulose wood components from the pulp whilst leaving the cellulose fibers intact [8]. Leaving the cellulose fibers intact makes chemical pulping a more suitable method when higher quality paper is required [4]. There are mainly two different processes for chemical pulping: Kraft (sulphate) and Sulphite. Energy rich byproducts, black and red liquor, are generated by the chemical pulping process which can then be burned in recovery boilers to produce combined heat and power.

C. Recycled Pulp

Paper can also be made from recycled pulp, where scrap paper is recovered, shredded, heated, cleaned and de-inked. The resulting product is recycled pulp that can be processed into paper products.

D. Paper Products

The process in which pulp is made into paper can be roughly divided in to the following steps:

- Stock preparation. Raw stock is converted into finished stock for the paper machine. This includes blending of different pulps, dilution and addition of chemicals.
- Paper processing. In the paper machine, water is removed and the papers' properties are developed.
- Finishing and coating. The paper is coated, depending on the desired end product.

Paper products can be split into two broad categories: paper and paperboard. Paper products are either coated with a compound or polymer to deliver a certain quality (weight, gloss, etc.) or are uncoated such as copy (graphic) paper, newsprint, or tissue/sanitation products. Paperboard is similarly treated or processed to deliver specific qualities and is used in case materials, as cartons for consumer products or packaging. Often, a combination of different kinds of pulps are used in the process and a certain product may be produced through different processes.

III. CONDITION MONITORING: OVERVIEW

Outages, within the paper industry, lead to significant costs associated with lost production, lost material, start-up delay and manpower requirements to re-start the production cycle [9]. To reduce unplanned outages condition monitoring (CM) techniques can be implemented to determine asset health and help target maintenance where it is most required. There are several CM technologies available for assessing equipment in MV/HV networks such as on-line partial discharge (OLPD) monitoring, vibration monitoring, motor current signature analysis (MCSA) and thermography among others. They all look at difference aspects of an asset health and are considered complementary to one another [10]–[12].

Partial discharge (PD) is a degradation phenomenon occurring in the insulation of MV and HV assets such as power cables, switchgear, transformers and rotating machines. PD activity is indicative of a degradation of the insulation and detection of PD can give an indication of the health of the insulation system. In particular on-line PD (OLPD) detection is performed with the MV and HV equipment in normal service allowing it to be used as a valuable tool for assessing in service assets and to support a CBM regime [13], [14]. This paper will focus on the OLPD detection and monitoring options for MV and HV network that support asset managers in implementing effective CBM solutions. The technology available varies from simple handheld screening and diagnostic testing up to permanent continuous monitoring system of the complete network as shown in Fig. 1. For process critical plant such as that in the pulp and paper industry continuous monitoring is often deployed to give immediate notification on any incipient faults. Real world case studies of implementation of OLPD diagnostic testing and continuous monitoring are reported and explained in the paper. For the reader interested in more information on solutions for OLPD testing and monitoring, OLPD sensors and PD in general, the authors suggest to consult [11], [13], [14].

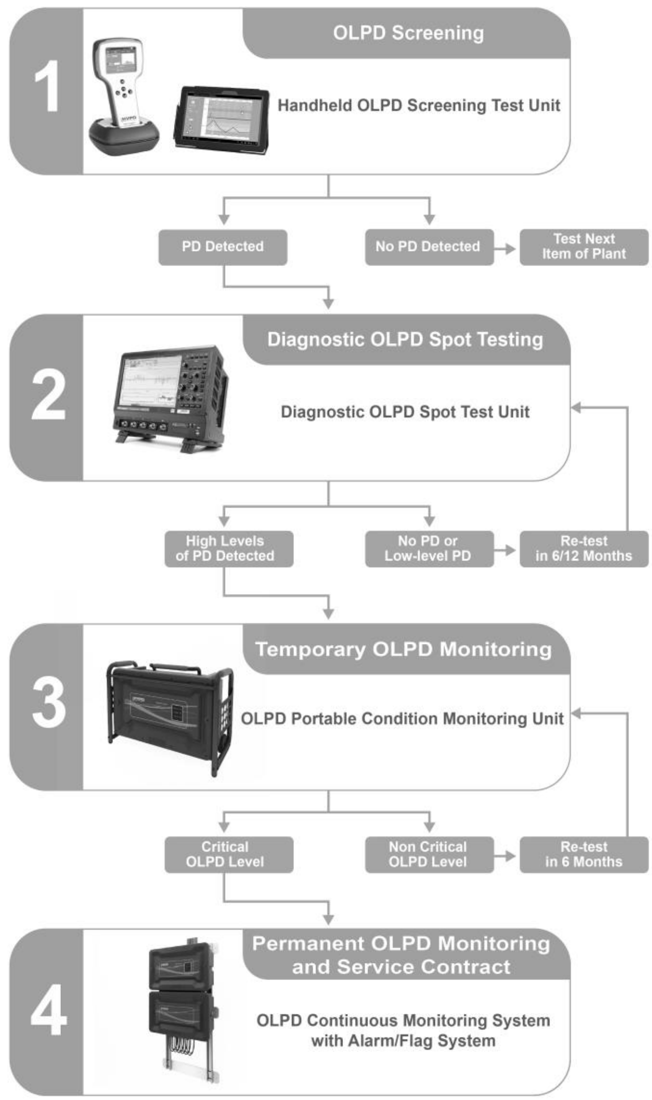


Fig. 1 Four levels of OLPD CM testing technology [14].

IV. LEVEL 2 – OLPD DIAGNOSTIC TESTING

Level 2 technology is referred to as Diagnostic OLPD Spot Testing technology. This is typically performed with a 4-6 channel test unit with synchronous data acquisition on all channels. Level 2 technology allows for detailed testing to be undertaken where OLPD data is collected from all three phases at once and/or from multiple PD sensors installed on the same phase. This enables discharge type i.e. phase-to-phase or phase-to-ground to be ascertained along with using time-of-flight (TOF) analysis to locate any PD source(s).

Typical diagnostic spot test times range from around ten minutes to one hour per asset with detailed data analysis and reports often required upon completion of the tests. If OLPD activity is detected, then the diagnostic testing is extended to locate the source of the PD site(s) within the circuit under test.

In the case of cables, OLPD cable mapping is carried out to locate the source(s) of PD activity along the cable circuit. These sources can be within the cable and can also include PD activity from the end of the cable and from the remotely connected plant. Fig. 2 shows an example of mapping the location of PD in a 33 kV XLPE cables. The source of the high levels of discharge was located to a single joint (Jt 2) in the circuit. The joint could then be repaired/replaced. For the reader interested in how PD location in cables can be performed, the authors suggest [15], in this paper the theoretical principles are explained.

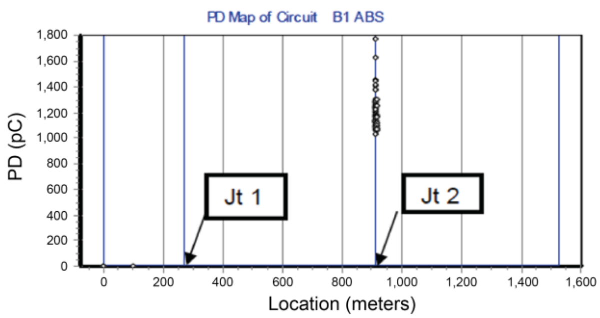


Fig. 2 OLPD mapping result for a 1600 m 33 kV XLPE cable showing the location of the PD sources at Joint 2.

A typical output from a OLPD spot test unit is shown in Fig. 3. The output highlights one of the main advantages that Level 2 technology has over Level 1 technology, higher resolution phase resolved partial discharge (PRPD) patterns.

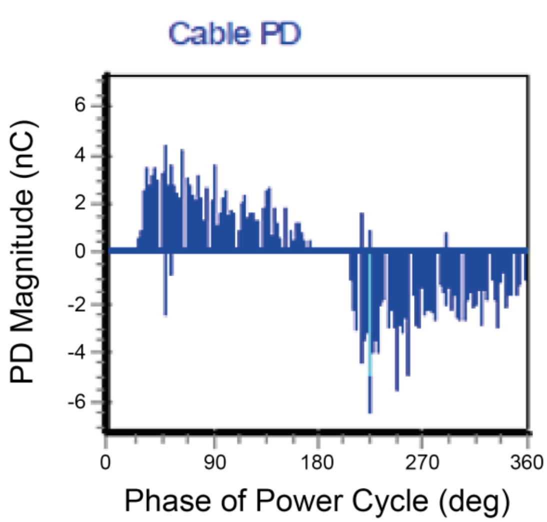


Fig. 3 Example of PRPD pattern for an OLPD spot test on a 33 kV XLPE cable.

The high resolution PRPD patterns, alongside the ability to observe the wave shapes of the signal recorded (see Fig. 4), can be used to further investigate PD and can assist in determining the cause and/or source of the fault.

TOF analysis using the high-speed data acquisition system in a Level 2 spot test unit is another key advantage. Using matched length signal cables precise measurements can be taken allowing an accurate PD source to be located. This type of analysis is particularly useful when testing switchgear lineups and can determine which panel is worth further investigation. A typical time of flight analysis, from four TEV sensors output, is shown in Fig. 4 and Fig. 5 show the test set up.

The capability to interrogate the pulse shapes and frequency content is another crucial factor when diagnosing PD results. Relying only on an amplitude figure can result in innocuous electromagnetic noise being reported as PD. It is critical that the nature of any result be investigated before maintenance actions (or lack thereof) are followed.

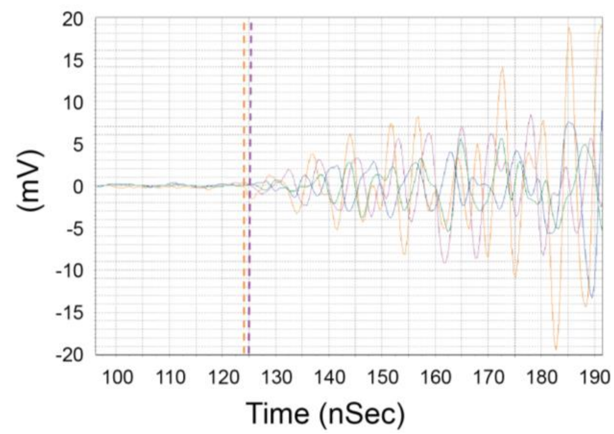


Fig. 4 TOF analysis between OLPD detection from four TEV sensors.

Fig. 5 Time of flight testing using 4x TEV sensors and Level 2 diagnostic test unit.

A. LEVEL 2 OLPD - CASE STUDY
Testing at a U.S. Paper Mill

This case study presents the results of Level 2 Diagnostic OLPD Spot Testing technology that took place after an annual outage at a paper mill located in the U.S.

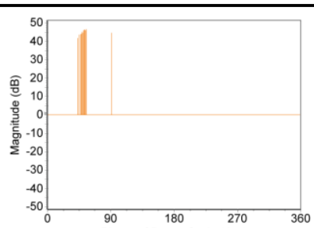
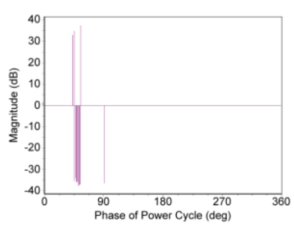
The asset present comprised of an outdoor 13.8 kV transformer switch being fed from the central switchboard.

An HFCT OLPD sensor was permanently installed around the common cable earth during the annual outage with an external TEV sensor installed on the cubicle. Fig. 6 shows the HFCT being installed within the transformer switch. The transformer switch was comprised on shielded MV cables being terminated onto phase bars followed by unshielded MV cable being fed through measurement current transformers (CTs) and routed through to the transformer bushings. As part of the commissioning process, OLPD tests were undertaken on the network at the end of the annual outage.

The results of the OLPD testing for this transformer showed very high levels, up to 47 dBmV, of Local PD being recorded at the transformer switch. The results of the OLPD spot test are shown in TABLE I

These levels were high enough to warrant an immediate investigation into the switch cubicle. The circuit was taken off-line and isolated and a visual inspection was carried out. The inspection of the transformer cable terminations showed evidence of poor installation of an unshielded MV cable. As shown in Fig. 7, the cable was found to be in very close proximity to earthed components at two locations within the cable box. The first was at a bolt connected to the earthed housing and the second being inadequate clearance to the LV terminations and cables connected to the 60 Hz measurement CT.

TABLE I

<table>
<tr><th colspan="3">TRANSFORMER SWITCH OLPD TEST RESULTS
PRE-MAINTENANCE</th></tr>
<tr><td colspan="3">Individual PRPD</td></tr>
<tr><td>HFCT SENSOR</td><td colspan="2">TEV SENSOR</td></tr>
<tr><td>
</td><td colspan="2">
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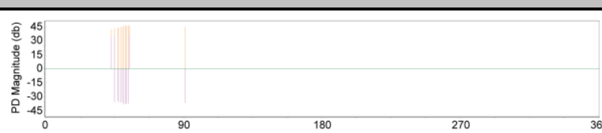
<tr><td colspan="3">Synchronous PRPD</td></tr>
<tr><td colspan="3">
</td></tr>
<tr><td colspan="3">PD Test Results</td></tr>
<tr><td></td><td>HFCT Sensor</td><td>TEV Sensor</td></tr>
<tr><td>Local PD [dB]</td><td>46</td><td>37</td></tr>
<tr><td>OLPD Activity [mV/Cycle]</td><td>242</td><td>69</td></tr>
</table>

The 60 Hz measurement CT was rotated and the MV unshielded cable was repositioned to increase the clearance between the cable and the earth bolt. The circuit was re-energized and retested and no PD was detected.

This case study demonstrates the implementation of an OLPD spot test carried out during an annual routine and how the maintenance cycle has helped to avoid a possible costly outage.

The circuit is part of a complete OLPD network monitoring system and regularly tested as part of the site CBM program. The program can be extended to incorporate more of the site network and improve reliability and reduce downtime.

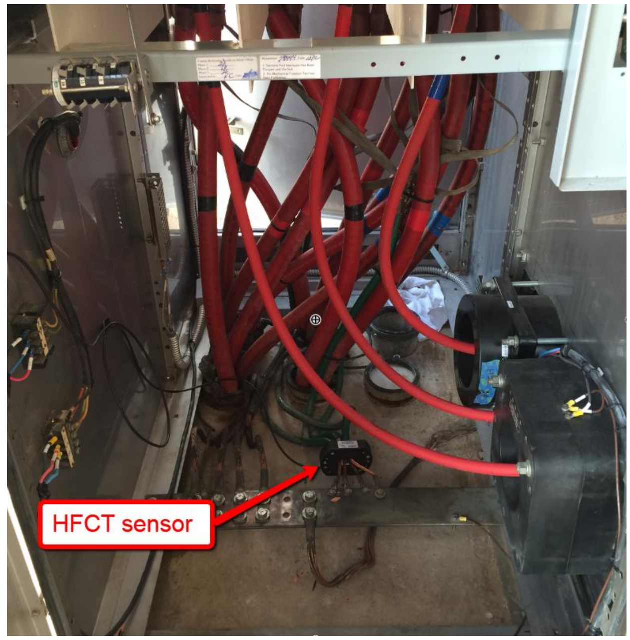


Fig. 6 OLPD permanent sensor installation within the transformer switch cubicle.

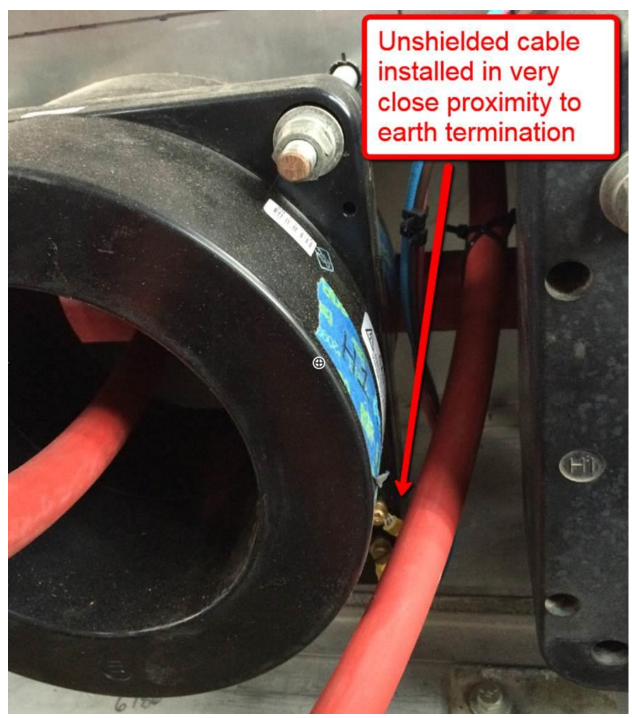


Fig. 7 Unshielded MV cable touching LV terminations/cables of 60 Hz measurement CT.

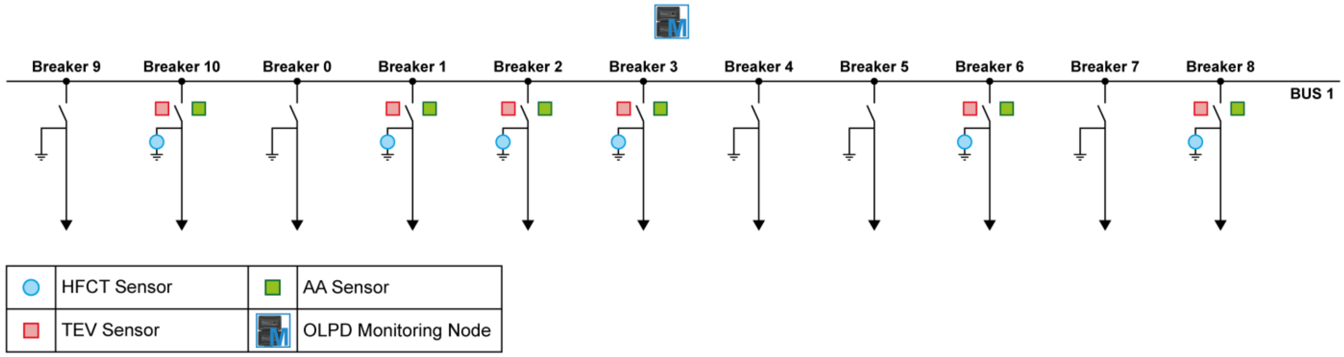


Fig. 8 OLPD monitoring of a 13.8 kV switchboard using permanently installed PD sensors

V. LEVEL 4 – PERMANENT CONTINUOUS OLPD MONITORING

Permanent, continuous OLPD monitoring technology is becoming more widely accepted within the pulp and paper industry as an effective CM tool to provide an early warning against insulation failure through developing insulation faults. By undertaking preventative maintenance interventions and repairs of the assets where PD is detected, it is possible for operators to avoid costly, unplanned network outages that can be caused by an insulation fault [16].

Examples of other CM technologies that can be combined with the OLPD technology to provide a holistic monitoring solutions include: vibration analysis, current signature analysis (CSA), power quality (PQ) analysis, distributed temperature sensing (DTS), thermography and dissolved gas analysis (DGA). Such systems are now becoming more commonplace as operators begin to see the interdependence of the various CM data streams they receive.

With the ever-increasing demands on assets to operate at the highest level of availability, the continuous trending of OLPD data from continuous monitoring systems is considered to be the most effective way to provide the necessary data to identify trends and any rise in PD levels over time. Continuous OLPD monitoring systems detect operational and environmental variation in PD. Such variations, in the case of rotating machine, can be summarized by the T.E.A.M stresses:

- **Thermal** – Loading/duty related thermal cycles/ stresses.
- **Electrical** – Localized electrical stresses
- **Ambient** – Temperature and relative humidity.
- **Mechanical** – Vibrations, loose bar, short circuit fault forces.

Trending of data over time is one of the primary advantages of Level 4 CM technology. Fig. 9 shows an example of a typical output of a Level 4 continuous monitoring system. The trend displayed shows a load-related variation in OLPD activity over time. Conducting spot tests at different times would yield different results and trending these spot test results could result in an incorrect insulation condition diagnosis.

Fig. 10 shows an example of a temperature and humidity-related variations in OLPD activity. The levels of Local PD are lower during the day when the temperature is higher and the level of humidity is lower than during the night.

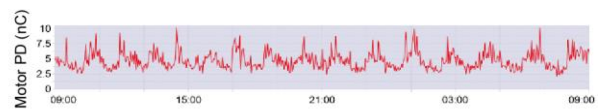


Fig. 9 Example of load related variation of Peak PD (nC) on a motor, over a 24-hour period [13].

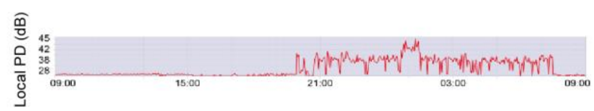


Fig. 10 Example of variation of Local PD (dB) on the switchgear, over a 24-hour period [13].

A. LEVEL 4 OLPD - CASE STUDY 1

Permanent Continuous Monitoring at a U.S. Paper Mill

This case study presents the results from a permanent OLPD monitoring system installed at a U.S. paper mill. The monitoring system consists of five OLPD monitoring units connected to distributed OLPD sensors to perform continuous OLPD CM of four 13.8 kV switchboards, Fig. 8 shows one of the switchboards and the PD sensors utilized. The complete monitoring system is linked together on an internal local area network (LAN) allowing a central user to view all results from one centralized location.

During the monitoring session one circuit, Breaker 10, showed high levels of Local PD that were then investigated using the monitoring system software tools.

Fig. 11 shows a Local PD data trend of the TEV sensor installed within Breaker 10.

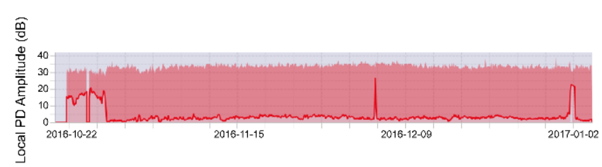


Fig. 11 Breaker 10 Local PD trendline.

Advanced monitoring systems feature the ability to look at the PRPD pattern of the saved monitoring data. This results in a greater understanding of the signals that are being recorded by the system and can allow the network operator to determine the validity of the raw data. The discharge within Breaker 10 can also be heard during periods of heavy load. Local engineers at the mill have noted that audible discharge is apparent from outside the cubicle and have been using portable ultrasonic equipment to record the discharge.

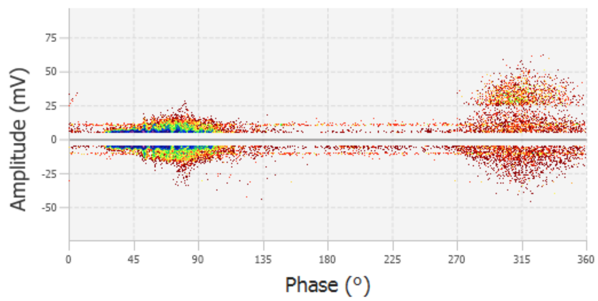


Fig. 12 PRPD pattern for Breaker 10 circuit, recorded by the TEV sensor.

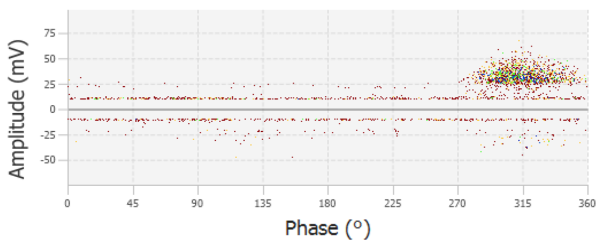


Fig. 13 PRPD pattern for Breaker 10 circuit, recorded by the HFCT sensor.

Fig. 12 and Fig. 13 show the PRPD patterns for the TEV and HFCT sensors installed in Breaker 10. The PRPD pattern reveals the presence of Local PD discharging within the breaker cabinet, with levels up to 35 dBmV. These levels place the cubicle breaker within the "Red" (critical) condition.

The neighboring breakers also recorded evidence of Local PD discharging. These are likely to be cross-coupled from Breaker 10 due to the lowering in amplitude and OLPD intensity as shown in Fig. 14 (PRPD pattern recorded by the TEV, compared to the pattern shown in Fig. 12)

On the basis of these results, the operator currently has plans to conduct a visual investigation of Breaker 10 during the next available outage. The operator can now implement CBM on the circuit and track the Local PD level and plan maintenance when possible.

This case study has shown the successful implementation of a OLPD monitoring system in the pulp and paper industry. The system detected and trended a Local PD source within one breaker cubicle.

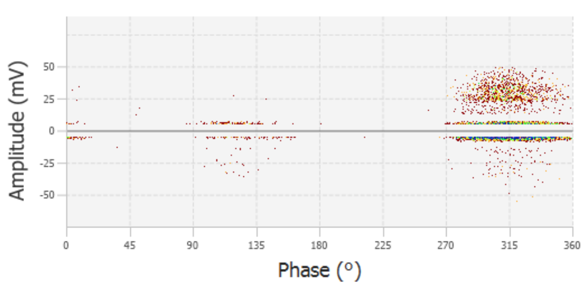


Fig. 14 PRPD pattern for Breaker 2 circuit, recorded by the TEV sensor.

B. LEVEL 4 OLPD - CASE STUDY 2
Permanent Continuous Monitoring and SCADA Integration at a U.S. Paper Mill

This case study presents a complete OLPD network monitoring system installed at a U.S. paper mill. The OLPD system has also been integrated into the mill's SCADA system creating a holistic system wide monitoring overview to include PD measurements viewable to the network engineers.

The main MV network at this paper mill consists of three centralized busses, each installed with a OLPD CM system. The CM systems are then connected to a central PDMS that collates the data into one place, viewable from the LAN.

HFCT, TEV and ultrasonic sensors are used to monitor the network. Each bus cubicle contains one of each sensor that is routed back to the respective monitor. Fig. 15 and show an example of HFCT installation within a cubicle

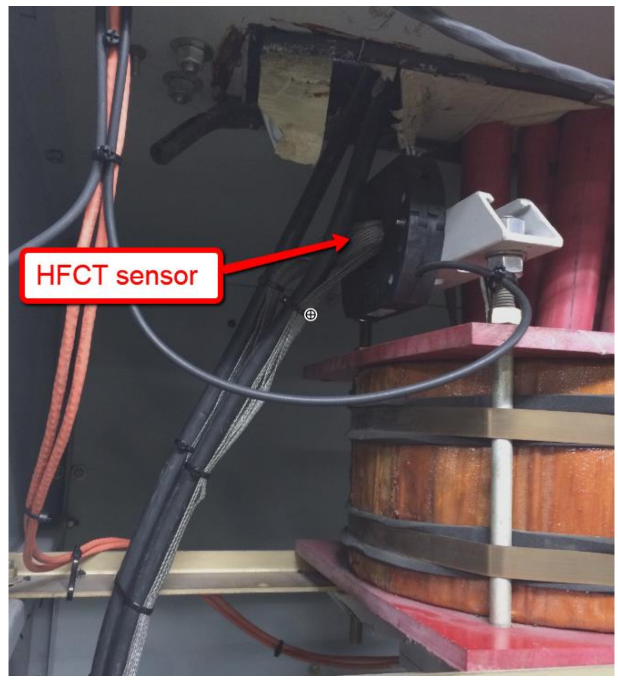


Fig. 15 Permanent HFCT installation on the circuit cable common earth wire.

Moderate levels of PD were detected on one of the circuits, SWGR23, and an investigation was undertaken to determine the nature and possible source of the PD. Fig. 16 shows the Cable PD trendline for SWGR23.

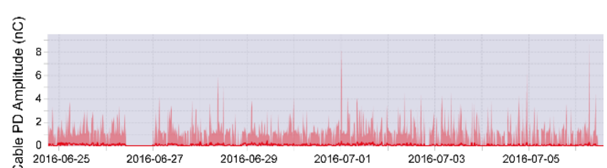


Fig. 16 Cable PD trendline for the SWGR23 circuit.

Using the software tools to analyses the trend, a PRPD pattern was found that confirmed the existence of PD on the circuit. Fig. 17 shows the PRPD pattern for SWGR 23.
The cable mapping capabilities of Level 2 diagnostic testing can be used to locate the possible insulation fault and source of PD. This can then be fed into the plant maintenance schedule to plan for a cable section replacement/repair.

Data from the monitoring system is also integrated into the mill's local SCADA system. This allows the mill engineers to use their SCADA system and see the whole network health and status including PD activity on MV assets.

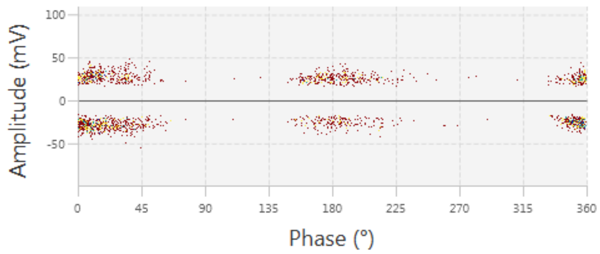


Fig. 17 PRPD pattern for SWGR 23 circuit, recorded by the HFCT sensor.

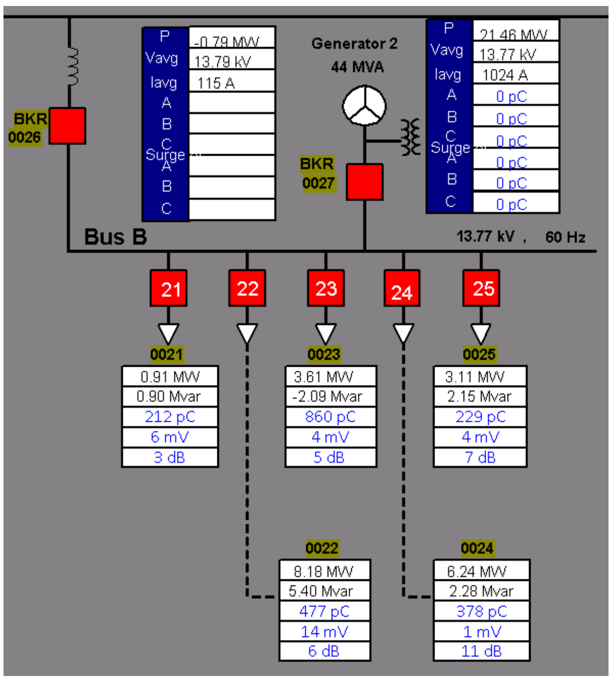


Fig. 18 OLPD monitoring system integration into mill SCADA system.

Fig. 18 shows an example of the monitoring system SCADA integration for one of the busses at this paper mill. The system independently trends the PD data giving the mill an easily accessible trend in their SCADA system.

This case study demonstrates the successful deployment of a OLPD monitoring system into a paper mill environment and the integration of the system in the mill SCADA system.

VI. CONCLUSIONS

This paper has given an overview of OLPD condition monitoring technology for complete HV and MV networks in the pulp and paper industry. This paper has described how it is possible to carry out reliable and effective OLPD testing and monitoring of HV networks to support condition based maintenance regimes.

Different approaches to implementing a CBM regime have been presented, at-asset testing using a diagnostic device and centralized monitoring from a central switchboard, each with their own advantages. Examples of key requirements for effective OLPD testing and monitoring have been described including using PRPD patterns, time of flight measurements and PD source mapping.

The case studies, finally, have shown the real advantage to have OLPD sensors permanently installed and how outages can be avoided through CM campaigns.

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VITAE

Lewis Dodd received a BEng (Hons) Degree from the University of York in 2011 in Electronic and Communication Engineering followed by an MSc from Brunel University, London in 2012 in Sustainable Electrical Power. Lewis is member of both the IEEE and IET. Over the past 4 years since joining HVPD he has carried out a wide variety of PD test and monitoring projects for the utility, industrial and marine sectors whilst also being an active member of the HVPD R&D team. He also regularly contributes to HVPD technical conference papers.
lewis.dodd@hvpd.co.uk

Riccardo Giussani (StM'10, M'13) was born in Legnano, Italy and graduated as an Electrical Engineer from Politecnico di Milano, Italy and went on to complete a PhD in Electrical and Electronic Engineering at The University of Manchester, United Kingdom. Since joining HVPD in 2013 he has been an active member of the HVPD R&D team, taking the lead on a number of projects and also contributed to a variety of published work and papers. Dr Giussani is a member of Institution of Engineering and Technology (IET) and the IEEE Dielectrics and Electrical Insulation Society (DEIS).
riccardo.giussani@hvpd.co.uk

Aaron McPhee is currently Sr. Electrical Reliability Engineer, International Paper Corporation, Augusta, Georgia. He is responsible for all aspects of EPD (Electrical Power Distribution) throughout the Augusta Mill. He serves as the bleach board division electrical engineer assigned to International Paper's Enterprize wide EPD Steering Committee, as well as on numerous company electrical and reliability committees. He is also responsible for conducting EPD courses within the company and has also received several awards and recognitions for his practical approach to EPD. Mr. McPhee attended the Georgia Institute of Technology' Atlanta Ga, Augusta Technical College; Augusta Ga. and Brenau University, Gainesville Ga, receiving both an ASEE and BS degrees.
aaron.mcphee@ipaper.com

Andrew Burgess received a B.Eng (Hons.) degree in Electrical and Electronic Engineering from The University of Manchester in 2010. Andrew joined HVPD in June 2010 to focus on field demonstrations of HVPD's technology and has worked with plant managers and owners across HVPD's global customer base. He is a certified HVPD PD Senior Test Engineer providing PD test services and training courses to both utility and industrial customers worldwide.
In 2014, Andrew left his role as USA Director of Operations for HVPD to set up PDMS LLC to serve the North America region providing HV engineering consultancy, MV switchgear services alongside his continued relationship with HVPD.
Andrew.burgess@pdmsglobal.com