Experiences from over 15 Years of On-line Partial Discharge (OLPD) Testing of In-Service MV and HV Cables, Switchgear, Transformers and Rotating Machines

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Abstract—The authors present a paper on the application of on-line partial discharge (PD) testing and monitoring technology for the insulation condition assessment of in service medium voltage (MV – 3.3kV to 45kV)) and high voltage (HV – 66kV to 750kV) cables and plant. The paper begins with a short summary of the different economic ‘DRIVERS’ which apply to both public utility and industrial HV networks. The paper presents some of the test techniques employed and the on-line PD sensor technology used to test in-service power cables, switchgear, transformers, rotating machines, CTs/VTs and other HV plant. The paper concludes with some case studies of past projects carried out by the authors from on-line PD test projects testing a wide range of MV & HV assets in electricity networks around the world.

Keywords - Partial Discharge, PD, On-line Partial Discharge, OLPD, Phase Resolved Partial Discharge, PRPD, PD Waveshapes, PD Diagnostics.

I. INTRODUCTION

The on-line partial discharge (OLPD) condition assessment of in-service MV and HV plant is now becoming more widespread in electricity transmission and distribution networks around the world. The main benefits in applying this OLPD technology are:

- To improve the reliability of the networks by identifying the ‘bad actors’ before they fail,
- To provide insulation condition data to provide an ‘early warning’ against ‘incipient’ insulation faults,
- To provide plant condition data to support reliable life extension of ageing networks,
- To avoid unplanned outages and minimise downtime.

MV & HV network owners worldwide are increasingly deploying OLPD technology to test, monitor and manage a wide range of medium voltage (MV) and high voltage (HV) plant including power cables, switchgear, transformers, instrument transformers and rotating machines.

This paper describes the experiences of the authors in the field of on-line PD testing over the past 15 years. These projects have been carried out wth a wide range of utility and private/industrial HV plant owners around the world including transmission & distribution utilities, power generators, renewables, cruise ship operators, oil & gas companies, railway and industrial processing clients. Many of the projects described in this paper have been initiated further to the failure of MV & HV plant which has led to PD test projects which have been carried out on ‘sister’ plant. Figures 1 and 2 below show some photos of the worst type of catastrophic failure and resultant damage which can result from insulation faults in 11kV switchgear in an indoor substation and the failure of a 132kV porcelain termination in an outdoor switchyard.

![Figure 1: Damage to an indoor substation after a 33kV solid insulated switchgear failure and explosion (UK). The explosion brought down the roof of this indoor substation which needed a complete replacement.](image1)

![Figure 2: The aftermath after an explosive failure of a 132kV outdoor cable sealing end (pothead termination) in the UK. The explosion resulted in ceramic ‘shrapnel’ being blasted up to 100m from the failure location.](image2)

II. WHAT ARE THE ‘DRIVERS’ FOR APPLYING OLPD?

The business ‘drivers’ for carrying out OLPD testing and monitoring of the HV network will depend on the type of electricity network (distribution, transmission, industrial, marine etc), where it is situated, what purpose it serves and the network owner’s operational and process requirements.
The following business ‘DRIVERS’ apply to all types of networks including utility, industrial & commercial customers:

- **Health & Safety** – this applies to all MV/HV plant owners. Most diagnostic PD test projects are carried out further to insulation faults and/or explosions occurring within an MV/HV network. In this case there is an immediate requirement to carry out ‘spot tests’ on ‘sister’ plant to ensure there is no risk of failure and thus danger to staff or the public and to minimise the risks of future failures.

- To support **Reliable Life Extension Projects**. As an example, the average asset age of in-service MV plant in the UK electricity distribution utility sector is around 55 years. With network replacement rates as low as 0.1% of the network per annum, this average age of the in-service plant is increasing by 1 year, every year. In order to support and justify the life extension of these ageing assets it is necessary to carry out condition assessment to support reliable life extension of the network components.

- To **Avoid Unplanned Outages and Downtime** – generation, industrial and commercial organisations are more focussed on the effect of any plant failure induced downtime on their generation capacity, process or service. This is the strongest driver for these production and process industries.

Studies on large, public electricity utility distribution networks have shown that the largest savings can be made by deferring and targeting capital replacement programs of the cable/plant population. This is simply due to the capital cost of replacement being so large compared to the other costs (such as CML penalties, outage costs etc), that saving even a small amount of this cost tends to dominate the other costs.

Similar studies on power generation, industrial and commercial customer networks show that a different cost driver dominates to that of the public utility distribution companies. The major cost driver here is to avoid any unplanned outages as the cost of an interruption to the process is normally much higher than the capital cost of any cable/plant. Generating stations, offshore oil platforms, processing plants, cruise ships, nuclear reactors, wind farms and internet data centres all fit into this category as they all have high profile or sensitive power supplies with potentially very large ‘loss of business costs’ for unplanned outages. Such customers have little difficulty in justifying the cost of PD diagnostic measurements or complete system PD monitoring.

### III ON-LINE PD TEST & MONITORING TECHNOLOGY

There are a wide range of technologies available for OLPD testing of in-service cables and plant which range from simple-to-use, handheld PD screening test units (for screening large numbers of MV and HV assets quickly and easily) to diagnostic PD ‘spot-test’ units (to diagnose and locate PD activity within the plant and cables) to continuous PD monitoring technology. It is now becoming increasingly popular to install permanent PD monitor systems into ‘critical’ substations within distribution and transmission networks and this is also being seen in industrial and commercial local area networks such as an oil & gas platforms and datacentres.

The technology is used to provide an ‘early warning’ against insulation failure through the detection of ‘incipient insulation faults’ i.e. faults yet to occur. PD detection is commonly regarded as the best indicator of insulation degradation of in-service HV cables and plant.

This paper introduces some of the technical aspects of on-line PD measurements including the PD sensor options and the measurement techniques which are employed to detect, diagnose, locate and monitor PD activity in cables, plant and rotating machines. All on-line PD measurements of in-service HV plant requires an effective way to differentiate any PD activity from the often high electromagnetic (E/M) interferences (‘noise’) which can be observed in the field. These noise sources can include switching noise from frequency converters, noise from variable speed drive (VSD) motors, interference from surface discharges on the outside of outdoor insulation and also ‘cross-talk’ of signals from neighbouring plant and equipment.

By combining PD ‘screening’ (Phase 1), PD diagnostic ‘spot-testing’ (Phase 2) and extended, continuous PD monitoring (Phase 3) technologies, it is possible to:

- make routine, walkby assessments of cables and plant using simple, handheld PD test technology,
- carry out diagnostic PD testing and location of the PD site using portable diagnostic PD ‘spot-test’ technology,
- permanently monitor key substations and circuits on the network to trend PD activities vs time/load cycle changes.

### IV. PD SENSOR OPTIONS FOR CABLES AND MACHINES

There are a number of sensor options available for the on-line detection of PD activity in cables, switchgear, transformers plant and rotating machines as shown below in Table I.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>PD Sensor Options</th>
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<tbody>
<tr>
<td><strong>High Voltage Coupling Capacitor</strong></td>
<td>Capacitive 80</td>
</tr>
<tr>
<td><strong>Ferrite-cored High Frequency Current Transformer</strong></td>
<td>Inductive 20</td>
</tr>
<tr>
<td><strong>Transient Earth Voltage</strong></td>
<td>Capacitive 5</td>
</tr>
<tr>
<td><strong>Rogowski Coil</strong></td>
<td>Inductive 1</td>
</tr>
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The OLPD sensor options include HV Coupling Capacitors (PDA’s), ferrite-based High Frequency Current Transformers (HFCT’s), Rogoswki Coil (RC) Sensors and Transient Earth Voltage (TEV) sensors. The best sensor solution for any application will depend on the cable/plant/machines to be tested and the voltage rating.

Alongside the sensors’ sensitivity, it is important also to know frequency response of the sensor across the wideband frequency range of 100 kHz to 50 MHz. Figure 3 shows the frequency response of 3x types of sensor used to test HV rotating machines. It can be noted that the HVCC is most sensitive followed by the HFCT and then the Rogoswki Coil.

A. High Voltage Coupling Capacitors (PDA’s)

A typical Installation of a set of 3x High Voltage Coupling Capacitors (1 per phase) in a generator cable box is shown below in Figure 4. It can be noted that these sensors require a physical (galvanic) connection to the HV terminals of the machine. Such a sensor provides a high sensitivity and the ability to ‘look’ for PD deep within the machine windings.

HV coupling capacitors of different voltage and capacitances are available in the marketplace ranging from 3.3kV to 28kV in voltage with capacitance ratings available of 80pF, 150pF, 500pF, 1000pF/1nF and 2nF. HVCC sensors are recommended for PD monitoring of larger rotating machines (10MW+) and are used widely to monitor PD in generators and large motors. A limitation in the use of these sensors is seen with smaller rotating machines (<10MW) as it is often difficult to fit the coupling capacitors in the smaller cable boxes on these machines. In such cases HFCT sensors (see B below) are preferred as they require less space to fit.

B. HFCT Sensors

Split-core, ferrite-based High Frequency Current Transformer (HFCT) sensors have become very popular in the marketplace in the past 5 years or so and are now the de facto sensor for the on-line PD testing of in-service MV and HV cables.

The HFCT is a highly versatile sensor and works inductively to detect the PD currents in the cable earth (drain) wire or around the core of the cable. In many cases the split-core HFCT sensor can be attached onto the cable sheath of in-service cable at the terminations outside cable box. 2x HFCT attachment options (A & B) at an 11kV switchgear panel is shown below in Figure 5.

If it is not possible to connect the HFCT sensor outside the cable box (due to the cable earth take-off point being inside) then permanent HFCT sensors are used. These sensors are installed inside air insulated/dry type cable boxes with connections to an external termination box via a BNC cable. Whilst the HFCT sensor can be installed inside the cable box safely (through connection around the cable earths) an outage is required to install these sensors safely. Two examples of permanent HFCT sensor installations are shown in Figure 6. Permanent HFCT sensors installed inside the cable box allow on-line PD testing of an in-service cables to be carried out at any time.
One of the big advantages of the HFCT sensor is that it has a wideband frequency response from 200kHz up to 30MHz (refer to Figure 3). This means that the HFCT sensor is capable of detecting high frequency PD signals (of 5MHz+) from ‘local’ PD activity (in switchgear, transformers and rotating machines) whilst also being able to detect lower frequency PD pulses which have travelled some way down cables.

HFCT sensors have a measurement range of up to 5km in polymeric XLPE cables and around 2.5km in PILC (paper-insulated lead covered) cables. This difference is due to the greater signal attenuation observed with PD pulses travelling along mass-impregnated PILC cables compared to XLPE.

With their low frequency response and wide measurement range, HFCT sensors can be used to monitor PD activity in the stator windings of rotating machines by connecting the sensor at the central switchboard at up to 2km away from the rotating machine (in XLPE cable), as is illustrated below in Figure 7.

C. Rogowski Coils (RC)

These air-cored, inductive sensors have been used in the petrochemical industry to monitor PD in motors which are located in hazardous environments. The sensors are Ex-approved for use in hazardous gas such as oil, off-shore oil platforms and onshore processing plants. The Rogowski Coils are normally permanently installed and their main advantage is that they do not saturate under heavy load currents. However, there is a significant drawback to the RC sensor in that they have a very low sensitivity to PD signals of Around 20-50x less than the HVCC and HFCT sensors (refer to Table 1). This means that only very significant PD activity is detectable by this sensor.

D. Transient Earth Voltage (TEV) Sensors

TEV sensors are capacitively coupled to the plant under test and are used predominantly to test medium voltage, metal-clad solid-insulated switchgear (SIS) and air-insulated switchgear (AIS) for PD. The occurrence of PD within the equipment induces a high frequency voltage pulse on the inner surface of the earthed housing. The pulse will emerge on the outer surface through breaks in housing such as vents, joints or seams. The TEV sensors are attached to the inside or outside of the switchgear panel to capacitively couple these signals. There are a number of handheld PD ‘screening’ devices in the market which incorporate TEV sensors which are very useful for identifying and locating PD activity in metalclad MV switchgear panels (example shown below in Figure 8).

V. ON-LINE PD TEST & MONITORING TECHNOLOGY

In order to meet the exacting requirements of the OLPD testing in the field, the authors have applied a wideband PD test technique to carry out short-duration, diagnostic tests. The measurement system is based around the wideband (0-400 MHz) test unit with a high-speed Digital Storage Oscilloscope (DSO) front-end to make high-resolution A to D measurements of the PD signals.

The hardware allows for entire 50/60 Hz power cycles to be sampled synchronously on four channels at up to 500 MS/s (or one sample every 2ns). This detection system is used predominantly for short-term, PD ‘spot-tests’ of around 10 to 30 minutes and short-term PD monitoring over a period of up to around 24 hours.

After collection of the PD signals a range of analysis software is then used to categorise and analyse the data collected. This software uses a signal extraction technique based on pulse shape analysis algorithms to separate and analyse the real PD pulses from noise and other interferences.

If extended, continuous PD monitoring is required for periods longer than 24 hours, the authors apply PD Monitoring technology. This consists of a PD acquisition unit which houses a computer, user display, signal digitiser and a 16-channel multiplexer. Multiplexing is utilised in order to maximise the number of cables/plant items which may be tested in a single monitoring session and to keep acquisition hardware costs down. The unit has an on-board web interface which can be accessed on the unit or remotely via LAN or a GPRS/HSDPA modem. As with PD ‘spot-test’ measurements, data is captured in power cycle duration blocks. After processing of the data, summary statistics are generated and saved. Notably the peak: magnitude of largest pulse detected.
(pC for cable PD, dB/mV for local PD/noise); count: number of pulses of each category detected and cumulative PD activity: integrated sum of all pulses of that category (pC/cycle for cable PD, mV/cycle for local PD/noise).

By trending this summary data, changes in the PD activity during the monitoring session can be observed. For example increases in PD peak indicate the defect is getting bigger and increases in PD count indicate defects discharging more rapidly. The system installation with PD sensors is shown in Figure 9.

The monitor in Figure 1 is designed for installation at indoor primary distribution substations where up to 16x cables or switchgear panels can be monitored in a single session.

VI. CASE STUDY 1: PD MONITORING OF 6.6 kV PVC CABLE
Figure 10a shows PD levels of 6000 pC peak and 130 nC/cycle cumulative PD measured for 1 week in April 2010. In Dec 2010, 8 months later the cumulative activity had doubled during a 3 week monitoring period whilst the peak had increased by only around 20% as shown in Figure 10b.

The critical PD level was verified to be 7000 pC (peak) with the offline damped AC test (OWTS) at rated voltage Uo. The level increased to 50 nC if phase-to-phase voltage 1.7Uo was applied to the cable

VII. CASE STUDY 2: 110kV XLPE TRANSFORMER CABLE TERMINATION
An on-line spot test on a 110 kV transformer cable termination in May 2009 revealed a suspect PD signature on the L2 phase (no PD on other phases). The extracted phase patterns of the PD and noise data and characteristic pulses are shown in Figure 11 and Figure 12 respectively.

Due to the criticality of the cable to the network and the recent experience of a failure of similar cable termination of the same vintage, remedial action was deemed necessary. The suspect termination was subsequently removed from service. Photographs of the PD damage are shown overleaf in Figure 13.

It can be seen that the termination is severely degraded through surface tracking which is thought to be due to incorrect installation of the stress cone. From the extent of the extensive tracking damage this cable termination was probably very close to failure when it was removed.

It should also be noted that the termination was not removed from service until August 2010 which was fourteen months after the initial PD measurement was made. It is expected the magnitude and recurrence of the PD immediately before removal of the termination would have been very much higher than at the time of spot test. Nevertheless, this result is encouraging due to the very long length of time (14 months) between detection and subsequent repair i.e. this test provided a long ‘early warning’ against an incipient fault.
established based on the PD pulse waveshapes. These are mainly separated into phase/phase PD events (in the end windings) and phase/ground PD events (in the slot sections) of the machine. Phase-resolved Partial Discharge (PRPD) analysis methods are combined with the pulse waveshape analysis to diagnose to the nature of the discharge type and the location of the PD. Two examples of different PD pulses are shown in Figure 15 and Figure 16.

Figure 13. Degradation to a 110kV termination by PD

VIII. CASE STUDY 3: PD TESTING A 13.8kV, 100MVA HYDROGENERATOR

A. Multi Channel Comparison Methods

Multi-channel data across the 60Hz Power Cycle is shown below in Figure 14 from a single power cycle of PD data from an on-line PD test on a large hydro generator. The measurements here were made using permanently installed high voltage coupling capacitors (PDA’s).

Figure 14. PRPD data from three phases of a hydro generator

With reference to Figure 14, it is clear that some pulses exist singularly on one phase/channel and others exist on several or all phases/channels simultaneously. If the pulse propagation path through the generator windings can be established, then simple locations (or at least categories) of PD can be

The Type 1 event shown in Figure 15 is a phase-to-phase event as the signal is seen on all three PDA couplers at once. Notice the oscillatory nature of this Type 1 PD event in the above case. This is typical of a surface discharge/tracking PD event in the end winding of the machine. Figure 16 below shows a Type 2 PD event detected on Ch 1 from the same test data on the hydro generator. This type of PD is a phase-to-earth discharge as it is largely mono-polar in shape with predominance on Ch1 (with a small amount of ‘cross-talk’ on the other two phases) and is more typical of internal PD originating within the winding insulation of defined impedance i.e. in the groundwall insulation in the slot section.

Figure 15. Type 1 PD: ‘Surface’ type, Phase-to-Phase PD event

The two graphs shown in Figures 15 and 16 illustrate the different waveshapes which can be captured in the detection method. It can also be noted that there is a very large disparity in the magnitudes of the 2x types of PD activity (surface discharges up to 4.0V+, internal discharges = 80mV).

B. High Resolution Data Analysis of PD Signals

Over the past ten years the authors have developed new measurement methods for high-resolution data capture (in the data acquisition range of 100MS/s up to 500MS/s) which now
make it possible to consider a new type of analysis of PD activity. This is based on *individual pulse shape analysis* in which the analysis of high resolution ‘waveforms’ of individual PD pulses is made. It is proposed that this method allows for a much more detailed analysis of the PD pulses emanating from the machines’ windings to be made. This detailed recording of the waveshapes of individual PD pulses allows for different PD pulses, from different defects in the machine insulation, to be separated and analysed.

The authors have developed robust algorithms for diagnosing PD in power cables, switchgear and machines over the past 10 years which uses the wave shapes and pulse timing between phases to get useful diagnostic data in the form of ‘Event Recognisers’ for different types of PD which was not available before.

It is seen as a natural extension to allow the same type of data analysis to be made for rotating HV plant, thereby greatly improving the potential for on-line diagnostic testing, particularly when diagnosing multiple discharging sites in stator windings.

**IX. Future Work**

In an attempt to understand the concepts of pulse propagation and reflections of PD signals in MV and HV networks better, the authors are carrying out a series of pulse injection experiments on HV cables, switchboards, transformers and rotating machine stator windings. Carrying out such tests will allow a better understanding of how the HV plants’ geometry and construction affects pulse attenuation and distortion from source to sensor. The accurate location of PD sites within an MV network will be dependent upon the combined knowledge of the propagation paths throughout that network, and the correct application of suitable differential equations to describe the pulse propagation process.

Developing a relationship between the sites of PD activity within the MV/HV network, and the pulse shapes of the signal at different locations, will be dependent upon the frequency response of the PD sensor, and understanding certain types of differential equations which permit so-called traveling wave solutions. Such equations help in describing the PD pulse propagation process as they exhibit decaying modes of solution that model how a wave in a dispersive medium travels.

Further work will be carried out to examine the validity of using differential equations to predict PD pulse attenuation, dispersion and reflections as a function of distance travelled through the windings.

**X. Conclusion**

This paper describes some of the experiences of the authors in the field of on-line partial discharge (OLPD) testing over the past 15 years. These projects have been carried out with a wide range of utility and private/industrial MV and HV plant owners around the world who are increasingly deploying OLPD technology to test, monitor and manage a wide range of plant including power cables, switchgear, transformers and rotating machines.

The paper describes the PD sensor options available and provides some summary information on the PD test and monitoring technology which can be employed to carry OLPD testing out.

The paper also includes a discussion about some of the business ‘DRIVERS’ behind the adoption of the OLPD technology by HV network owners and summarises some of the benefits this adoption can bring. Studies on large, *public electricity utility distribution* networks have shown that the largest savings can be made by *deferring and targeting capital replacement programs* of the cable/plant population. Similar studies on *power generation, industrial and commercial customer networks* show that a different cost driver dominates to that of the public utility distribution companies. The major cost driver here is to avoid any unplanned outages as the *cost of an interruption to the process* is normally much higher than the capital cost of any cable/plant.

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