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The HVPD 4-Phase Partial Discharge Test and Monitoring Solution for Medium Voltage (MV) Electricity Distribution Networks

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Introduction to High Voltage Partial Discharge (HVPD) Ltd

HVPD Ltd is the new name for IPEC HV, specialists in the field of On-line Partial Discharge (PD) detection and monitoring of in-service mv and hv plant and cables. The HVPD Directors (Dr Lee Renforth and Dr Ross Mackinlay) have, collectively, over 50 years of experience in Partial Discharge testing of mv and hv plant. Over the past decade the focus of this work has been on the application of On-line PD testing of in-service cables and plant with the plant 'live'. This accumulated knowledge of PD testing and monitoring has been incorporated into the company's new *HVPD 4-Phase PD Test and Monitoring Solution* described herein.

Introduction to Partial Discharge (PD) Testing of MV and HV Cables

Medium voltage (mv) cable networks in the voltage range 6.6-45kV and high voltage (hv) cable networks (66kV+) are of critical importance for the reliable transmission and distribution of electrical power in both utility and private networks. As modern mv and hv XLPE cable insulation is particularly sensitive to the destructive effects of electrical partial discharge (PD) activity, it is imperative that the network operator strives to operate their polymeric cable network *discharge-free*. Partial discharge activity is known to result in deterioration and erosion of the primary insulation in cables and most particularly at cable accessories such as joints and terminations. If PD is not detected and the cause of the PD activity corrected, then PD activity will result in failures, unplanned power outages, equipment damage and/or injury to personnel.

Partial Discharge (PD) activity is produced by *incipient* faults in high voltage insulation and is widely regarded as the best early indicator of insulation degradation, providing an *'early warning'* against insulation faults which allows the high voltage plant owner to take corrective action before catastrophic failure/explosion occurs. For all cable systems, partial discharge will be damaging, and will result in slow damage to the insulating medium, which in turn will lead to failure. Perhaps the only exception to this is for outdoor insulation, where porcelain sealing ends do not degrade in general under PD activity (they can flash over, which is why they tend to be replaced by silicone materials in high pollution areas).

Background to HVPD Ltd and Our PD Test and Monitoring Technology

HVPD is a *knowledge-based* product supply and test services business, specialising in the supply of *On-line and Off-line Partial Discharge (PD) Test and Monitoring Solutions* and *On-line PD Training and Testing Services.* The company's PD test and monitoring products are used in the worldwide electricity supply industry to enable our customers to assess, monitor and manage the insulation condition of their in-service mv and hv plant.

We supply a complete range of PD Test equipment, complementary customer training courses and also PD Test Services to a *worldwide customer base* in Europe, North America, the Middle East, South East Asia and Australasia.

HVPD hold substantial experience in the *On-line PD 'Spot' Testing and Cable PD Mapping (pd site location) of 11kV & 33kV Cables and Switchgear*, with much of this experience having been developed in the UK from collaborative work with EDF Energy (formerly London Electricity) over the past 10 years. This work has focused on the PD testing and monitoring of older in-service, underground paper cables (PILC) and solid-insulated switchgear with a view to the reliable life-extension of these ageing assets beyond their 'design life'. By monitoring the condition of the insulation in it is possible to provide *reliable life extension* of their ageing assets.

In the UK utility distribution network, a large percentage of the in-service mv cables and plant was installed in the 1950's and 1960's, during the national electrification programmes of the time. In 2009, with the typical average asset age of in-service, mv cables and plant in UK DNO's (Distribution Network Operators) standing at around 45 to 50 years and with network replacement rates remaining low (in some cases less than 0.5% of the network per annum). Whilst the network has been ageing, it has remained generally reliable with high availability. An alternative to the wholesale cable & switchgear replacement programs of these ageing networks is required, which can be achieved through a condition-based asset management approach as per the HVPD 4-Phase PD Test and Monitoring Solution.

HVPD Research and Development

The PD-testing knowledge-base held by the HVPD directors (2), senior test and development engineers (4) and the HVPD associate design consultants (2) spans over one hundred and 50 years of combined experience in the application of on-line and off-line PD detection technology. This knowledge-base goes back to the early 1980's when the first on-line PD measurements of mv switchgear using the TEV method and the original VLF Off-line Power Supply were developed in the UK's Electricity Research Centre at Capenhurst, UK.

The foundations of the *knowledge-base* held by HVPD Ltd in the field of *on-line* and *off-line* partial discharge (PD) testing and monitoring has been built on the R&D work carried out by the HVPD Directors (Dr Lee Renforth and Dr Ross Mackinlay) over the past 30 years. This R&D activity includes pioneering work, which started in 1998 with developments in collaboration with London Electricity (now EDF Energy UK), in the field of *on-line* PD testing and monitoring of in-service, 11kV cable networks, tested with portable, PD detection sensors with the plant 'live'. This work has continued over the past 11 years.

The early work was carried out in conjunction with London Electricity (now EDF Energy UK) in their 11kV underground cable network in London, UK and included the world's first, *on-line* PD measurements of in-service, medium voltage (11kV) cables using high-frequency current transformers (HFCT's) in 1998. In these tests, *split-core HFCT sensors* were attached to earth connections of in-service, 11kV cables and wideband digital storage oscilloscopes (DSO) and fast analogue to digital data acquisition card were used to make high-resolution measurements of the PD activity detected.

These pioneering tests showed that reliable measurements of the PD activity in the cables and connected plant could be achieved using the new split-core HFCT sensor technique, without the need for an outage. This breakthrough was reported in a number of publications between 1999 and 2003 and has now led to this type of inductive, split-core HFCT sensor now becoming the sensor of choice for on-line PD measurements of both mv and hv cable installations.

The other sensor used throughout this 11-year period of research and development is the Transient Earth Voltage (TEV) capacitive coupler probe which is used in conjunction with the HFCT sensors. The TEV probe is seen as complementary to the HFCT as it detects high frequency PD pulses in the 'local' switchgear or plant whilst the HFCT is designed to detect lower frequency 'cable' PD's which have travelled some distance down a cable. By using a combination of the inductive HFCT and the capacitive TEV probes it is possible to test the entire cable and plant system including

"Our Knowledge is Your Power"

It has now been the long-term philosophy of the HVPD Directors (Dr Lee Renforth and Dr Ross Mackinlay), over the course of the past 11 years, to pass on as much of our contained knowledge of on-line PD testing and condition-based asset management of mv and hv networks to our customers as we possibly could. In fact, this knowledge-transfer process was *absolutely essential* during the early years of the application of the technology (1998-2003), initially simply in order to convince, what was a sceptical industry then, that these insulation condition tests could be carried out at all!

After it was proven, and then generally accepted, that on-line PD measurements were both possible and reliable, there has been a further period of deliberation by the mv and hv plant owners, over the past 5 years or so, as to whether significant cost-benefits can be achieved in terms of reducing network operating costs through the application of the new PD test and monitoring technologies. Whilst this debate goes on, a number of studies by HVPD on a wide range of mv networks, from large, public utility networks to small, industrial process networks show that significant savings can be made in operating costs of running the networks through a careful, structured application of on-line PD test and monitoring technologies.

Now that on-line PD test and monitoring technology has now become widely accepted in the electricity supply industry, over a decade after the initial pioneering work was carried out, HVPD continue to apply our long-term philosophy of continual knowledge-transfer to our customers. This is now achieved via our dedicated, customer-focussed PD test training courses (both at our HQ in Manchester, UK and at our customer's sites around the world) and our customer engineering support services which include, databasing of test data, PD test data analysis services and asset management advice.

The knowledge transfer process from HVPD to our customers is best initiated through an ***On-line PD Test Pilot Project*** which is carried out on the customer's network by our highly-trained, in-house, specialist on-line PD test engineers. Typical pilot projects have a 1-week duration where on-line PD test surveys and diagnostic testing/monitoring are carried on a large number of cables and plant items in our customer's mv and hv networks. The results of the PD test survey and the recommendations to the client resulting from the survey are presented in an Interim powerpoint presentation at the end of the week which is followed by a detailed project report within 1 week, after review of the test results by HVPD Senior Engineers in the UK. This final report is reviewed and discussed in a follow-up teleconference with the client's engineers and managers to discuss any actions arising. Pilot projects are also combined with training of the client's staff in the use of the on-line PD test technology, whilst enabling HVPD to 'tailor' any testing method and filtering arrangements to any specific site conditions (such as in high RF noise environments!)..

Recent PD Test Technology Applications

Over the course of the past 6 years, HVPD have developed and applied the portable, 4-Channel *HVPD-Longshot™ PD Tester* which was brought to the market in 2003, with the v3.0 PDGold© Software. This test technology has since been upgraded through 2x Software upgrades (in 2005 and 2007) to the present v5.0 PDGold© software. Through PD testing and training contracts with our customers over the course of this 6-year period, HVPD have developed a wide range of *'PD Test Knowledge Rules'* for the On-line PD testing and monitoring of MV and HV Plant.

The purpose of the PD testing and monitoring technology is to be able to measure and record any *PD activity* within the cables, cable sealing ends/terminations and other HV plant to which the sensors are attached. This is achieved via the *synchronous detection* (to within less than 2ns) of signals on all 4x channels of the HVPD-Longshot™ unit. By synchronously recording high resolution data on all 4x measurement channels at once, it is possible to achieve the following benefits when making measurements:

- The differentiation of PD signals from electrical 'noise'
- The location of the source of the PD can be found using Time Of Arrival (TOA) measurement techniques using distributed TEV and HFCT PD probes.
- Measurement of both Phase-to-Earth PD and Phase-to-Phase PD

Why Carry Out On-line PD Testing?

There are three main reasons for carrying out the On-line PD Testing:

1. To get *baseline readings* for future condition assessment of cable condition.
2. To provide an *insulation quality check* on the cable termination and cable condition as part of the routine maintenance checks.
3. To *locate any PD activity along the length of the cable* as a pre-cursor to repair and/or replacement.

The testing method employed is based on HVPD's prior knowledge of On-line PD testing of MV and HV cables which spans 10 years. In order to get the highest resolution of PD test data, the cables and switchgear are tested with the HVPD Longshot™ Diagnostic Test Unit with a combination of Transient Earth Voltage (TEV) and High Frequency Current Transformer (HFCT) sensors to enable the simultaneous capture of the PD signals from both sensors. To identify dangerous discharges it is necessary to differentiate the internal PD signals in the cables/terminations from other discharges (such as those emanating from the switchgear and motors connected to the cables) and also any electrical 'noise' on the site (caused by switching, motor exciters etc).

HVPD's Recommended 4-Phase PD Test and Monitoring *Approach*

Over the past decade HVPD have worked in close collaboration with a number of electricity transmission and distribution utilities around the world (including close collaboration with EDF Energy. ScottishPower Systems and Scottish & Southern in the

UK) on the development of a range of on-line PD surveying, Diagnostic ‘spot-testing’ and PD monitoring technologies. These developments have included the handheld *PDSurveyor™ PD Surveying Tool* and the *HVPD-Longshot™ Diagnostic PD Spot Tester*, both of which have been used as portable units in the field for a number of years.

HVPD (and others) have proposed for many years that for the cost-effective, long-term condition-based management of medium voltage cables and plant, a 4-Phase PD Test and Asset Management Solution should be applied. This being as an alternative to the wholesale installation of permanent PD monitoring solutions which is presently not economically viable due to the very high cost.

The 4-phase, HVPD test and monitoring approach illustrated below in Figure 1 has been has now been presented at a number of International Conferences on MV and HV Plant Monitoring over the past 10 years, to widespread acclaim. The management approach provides for a *systematic and cost effective methodology* which can identify, locate and monitor PD activity within the customer’s network.

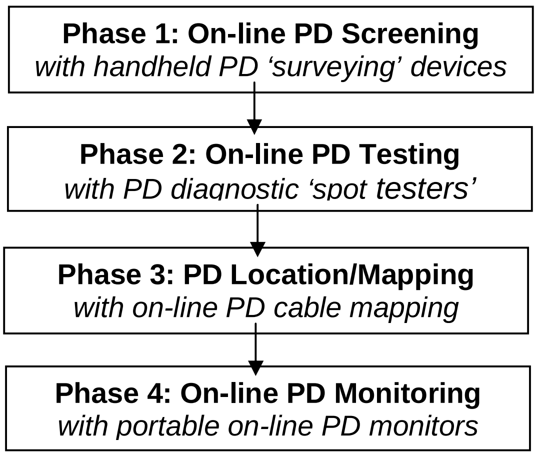

Figure 1: HVPD 4-Phase Approach for On-line PD Monitoring of MV Networks

The main benefit of this 4-phase solution is to provide the framework for a *more cost-effective* approach to PD testing and monitoring *as an alternative to the large-scale installation of permanent PD monitoring systems*. The approach is based on the on-line PD test and monitoring experience of the company’s Directors and Senior Engineers which has been attained over the past 11 years and is based on the fact that *only between 5 and 20% of mv assets in a network will have significant levels of PD activity*. The key to any approach here is to ensure that any test and monitoring resources (and ultimately maintenance activities) are directed to this small percentage of the network.

It is through the pre-screening of all assets for PD quickly and cheaply in Phase 1 which makes it possible for the mv plant owners to identify those assets as having some cause for concern. These assets are then taken onto the next stage of the asset management solution, Phase 2 comprehensive, diagnostic PD testing and, if the diagnostic tests show up some real PD, then onwards again onto PD location (Phase 3) and then contPD monitoring (Phase 4). If the PD activity in the cables or plant which are being monitored increase beyond acceptable, cumulative PD activity measurement guidelines then remedial action and repair is recommended.

The HVPD 4-Phase PD Test & Monitoring Technology *Solution*

In May 2009, HVPD launched our newly developed range of portable and permanent remote-access PD monitoring technology, including the *16-Channel HVPD-Multi™ Portable Monitor*, the *4-Channel HVPD-Mini™ Portable Monitor and the multiplexed, permanent versions of both technologies*. These technologies have been developed in conjunction with both utility and industrial electricity network operators and are available in both portable and permanent versions.

The portable PD monitors are for mobile use in the field and operate as stand-alone units with built-in 3G Modem Mobile Communications. The permanent monitoring systems have been designed with a base unit and multiplexed, add-on units with up to 64 monitoring channels available on the *HVPD-Multi™ Permanent Monitor*. The permanent monitors can also be integrated into the customer's LAN, ethernet or other plant communications systems (Modbus etc) via their standard communications interfaces.

With the addition of this new range of PD monitoring technologies to the HVPD's established PD surveying and PD 'spot-test' technology (including the *PDSurveyor™* and *HVPD-Longshot™ Diagnostic PD Spot Tester*) HVPD can now offer technology to provide a complete, 'holistic' solution for the PD screening, diagnostic testing, location and PD monitoring of medium voltage networks, as per the requirements of the 4-Phase Approach illustrated in Figure 1 above.

This HVPD technology range is summarised below in the table in Figure 2.

PD Test or Monitor Device	**No of channels** (typically one PD sensor is installed per item of plant tested)	**Typical Test or Installation Duration**	**Typical Test or Monitoring File Size**	**Onboard Data Storage Restriction**
PDSurveyor™	**3** (HFCT, TEV & Acoustic)	10-30 seconds per plant item	N/A	N/A
Longshot™ (with On-line Cable Mapping Expansion Kit)	**4** (synchronous acquisition to within 2ns on all channels)	5-10 minutes and up 1 day in 'monitor mode'	8MB for 5 min test, 50MB per day in monitor mode	30 GB hard drive
HVPD-Mini™	**4** (2x HFCT & 2x TEV, with precedence measure)	1 day (Portable unit) to Permanent installations	5kB per day 2MB for 1 year of data	1 year with data capture every 30 mins
HVPD-Multi™	**16** (multiplexed)	1 day (Portable unit) to Permanent installations	100kB to 16MB per day	one year of data

Figure 2: HVPD – 4-Phase On-line Partial Discharge Products Summary

With the newly launched *HVPD-Multi™ and HVPD-Mini™ monitor* technology, HVPD can now offer a complete range technology to provide a 'holistic' technology solution for the new application of on-line condition assessment of in-service mv networks.

This technology range includes a combination of PD screening, diagnostic testing, PD location and PD monitoring technologies for medium voltage networks which have been developed specifically for the cost-effective, *HVPD 4-Phase Asset Management Solution* which provides a process by which critical plant can be identified, located, monitored and managed. The technology and the HVPD 4-Phase test and monitoring solution is illustrated in Figure 3 below.

Figure 3 shows how low-cost PD surveying tests are used in Phase 1 to test the entire mv network (100%) which is then followed by diagnostic PD spot tests and pd site location of the top 20% of the network identified as having 'possible PD'. If significant levels of PD are confirmed in the diagnostic test, the plant is then monitored either temporarily (for 1 week to 3 months in Phase 3) and possibly more permanently in Phase 4 for periods of 3 months+.

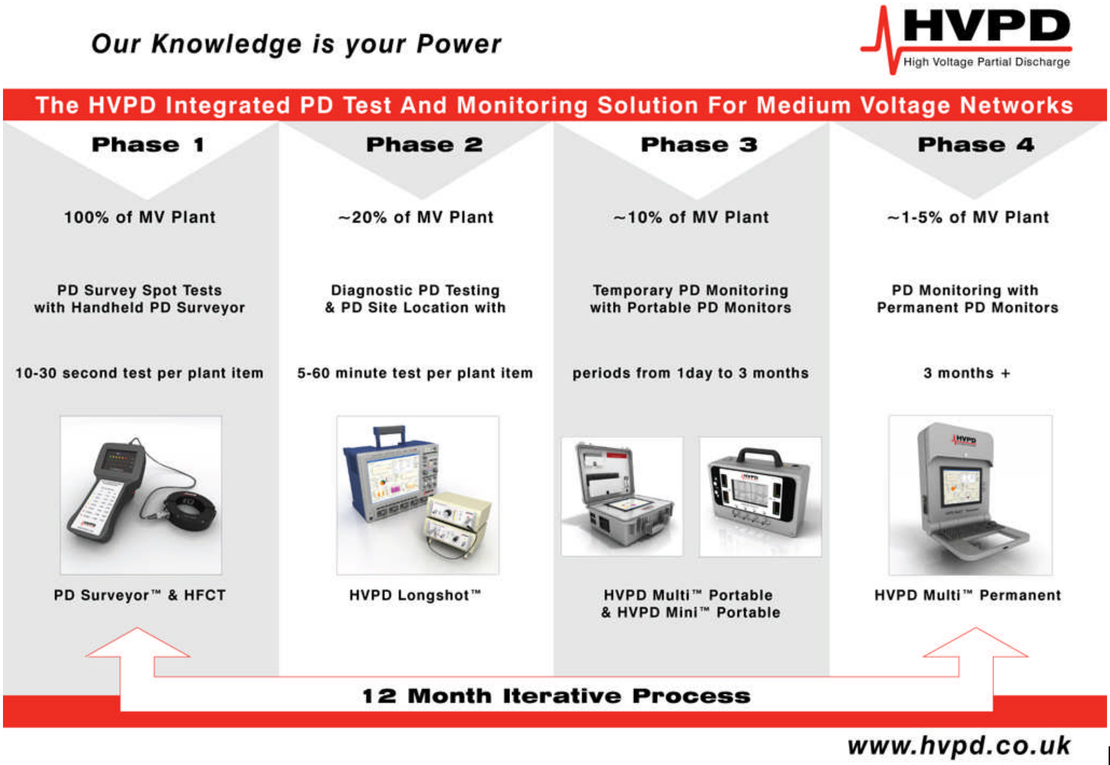

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Figure 3: HVPD Solution for 4-Phase Asset Management *Solution* for On-line PD Testing and Monitoring of Medium Voltage Networks

The PD Test continuously monitor cables and plant on a temporary or permanent basis, providing an 'early warning system' for incipient faults in this small percentage of 'critical' plant in the network which can cause a large percentage failures on the network.

Phase 1 - PD Surveying Tests* using the handheld *PDSurveyor™

The PDSurveyor™ is a simple, easy-to-use, handheld PD scanning device containing *three* built-in PD sensors (TEV/Acoustic for switchgear/'local' plant PD testing and a HFCT sensor for cable PD testing). The unit is suitable for the PD testing of a wide range of in-service, medium voltage (mv) plant in the voltage range 6.6kV to 36kV, including cables, switchgear, transformers and rotating machines.

The 4-Phase plan begins with the use of simple, quick PD 'screening' technology in Phase 1, followed by Diagnostic PD Spot Testing in Phase 2. This is achieved with the systematic application of portable PD 'spot test' and PD cable mapping equipment described below for Phases 1 & 2. Where significant levels of PD are detected, the plant is then taken onto Phases 3 & 4 which involve the use of On-Line PD Monitors to

Figure 4: The PDSurveyor™ Handheld PD Detector

The PDSurveyor™ is unique in that it is the *world's first* handheld PD test technology which combines *3x Types of PD Sensor Technology* (ultrasonic/acoustic, high frequency current transformer (HFCT) and transient earth voltage (TEV)) into one, simple-to-use test unit. The technology has been designed by HVPD to meet the specific requirements of both utility and industrial mv plant owner customers, further to their requests for a simple, portable and easy-to-use PD test device which can be used by *all* operational staff in mv substations.

The PDSurveyor™ is intended to be used as a *first-line* PD *'checker'* for mv plant, providing the user with the ability to test the insulation condition of the equipment in seconds. The unit's simple, 7-level, colour-coded PD level indications (displayed as a range of LEDs from green (OK) to yellow to orange to red (high PD)) allows the user to quickly identify potential insulation defects and incipient faults.

By using the PDSurveyor™, large numbers of mv plant items can be pre-screened for PD activity in a fraction of the time required for diagnostic PD test systems (such as the HVPD-Longshot™ test unit) thereby providing much higher levels of testing productivity. With the typical time required for a pre-screening survey on a mv plant item using the PDSurveyor™ at around *10 seconds per test*, compared with typically 5-10 minutes presently for a full diagnostic test, the benefits in terms of test time can be seen.

In the event of moderate-to-high PD activity (Yellow 2 LED or Orange 1 LED level and above) being detected by the PDSurveyor™, the plant under test should be moved to next stage of the insulation condition assessment process in Phase 2 – Diagnostic PD Testing. Phase 2 utilises the high-specification, diagnostic *HVPD-Longshot™ PD Test Unit* as described below.

It is recommended that the cables and plant in the top 20% of PD level measurements made during the Phase 1 PD screening tests are taken forward to the second stage.

Phase 2 – Diagnostic PD Testing with HVPD-Longshot™ PD Spot Tester

The HVPD-Longshot™ Diagnostic Spot Tester (Figure 5) is a portable, *4-Channel Synchronous* PD test device primarily used to perform short duration partial discharge tests (typically of 5-10 minutes, up to one hour in some cases) with HVPD's automated PDGold© v5.0 software. HVPD have successfully used the technology's *synchronous* data capture capability (to within less than 2ns across the 4-Channels) to carry out on-line PD tests on both medium voltage and high voltage cables and plant up to 500kV.

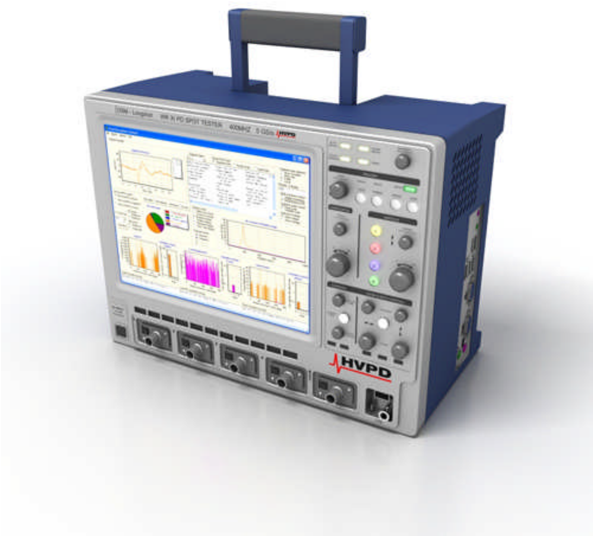

Figure 5: Synchronous, 4-Channel HVPD-Longshot™ Diagnostic PD Test Unit

The *HVPD-Longshot™* technology was originally brought to the market in 2003, with the v3.0 *PDGold©* Software and has since been upgraded through 2x Software upgrades (in 2005 and 2008) to the present v5.0 PDGold© software. The PDGold© software also includes a 'Monitor Mode' to allow extended PD monitoring tests to be carried out (typically of up to 24 hours) to enable 'PD soak testing' at commissioning as per IEC guidelines.

The HVPD-Longshot™ unit is able to measure and record any *PD activity* within the cables, cable sealing ends/terminations and other hv plant to which the sensors are attached. This is achieved via *multi-channel*, *synchronous detection* of the signals on all 4x channels of the HVPD-Longshot™ unit. By synchronously recording very high resolution data on all 4x measurement channels at once, it is possible to achieve the following benefits when making measurements:

- The differentiation of PD signals from electrical 'noise' using wavelet denoising, waveshape analysis and 'precedence' detection ('which pulse came first?').
- The location of the source of the PD can be found using Time Of Arrival (TOA) measurement techniques using distributed TEV and HFCT PD probes.

- Measurement of both Phase-to-Earth PD and Phase-to-Phase PD

This synchronous, multi-channel detection technique is recommended by HVPD when testing all types of high voltage plant in the voltage range of 66kV+.

The device has four channels which can be used for various different PD sensors for testing up to four items of plant in a single test. Plant which can be tested includes medium and high voltage cables, medium voltage switchgear, motors and generators. The device is based around a Windows PC and has an onboard LAN port, however as the device's primary use is for short duration tests this is rarely utilised.

Depending on the results obtained from this Phase 2 of PD diagnostic tests, typically around one-half of the cables and plant tested (around 10% of the total network) will be taken onto Phase 3, short-term PD monitoring using portable PD monitors, as described below.

Phase 3 – Short-Term PD Monitoring with HVPD Portable Monitors

HVPD recommend the use of a combination of portable PD monitoring technology in Phase 3 for a large utility or industrial medium voltage distribution networks (6.6kV-45kV). For wide-area distribution network PD monitoring, a combination of the portable, 16-Channel HVPD-Multi™ Monitor and the portable 4-Channel HVPD-Mini™ Monitor provides a 'holistic' solution for continuous, *on-line* PD monitoring of mv cables and switchgear in wide-area networks.

The HVPD portable monitors are installed temporarily, typically for 1 or 2 weeks to monitor any PD activity diagnosed in Phase 2. These units are stand-alone and are suitable for installation in electricity distribution substations for extended periods of time to log and trend PD data on the MV cables and switchgear to which the on-line PD sensors are attached. The PD monitoring data is stored locally in the portable monitor's memory (hard disk and 'flash') which can be viewed at any time by the Field Engineer. This data is also remotely downloaded using the portable monitors built-in communications *modem module (GPRS and HSDPA)*. Data files are automatically downloaded to the HVPD server in Manchester, UK and access to these data files is provided to the customer via a password-protected, secure link to the IPEC HV server.

The HVPD-Multi™ Monitor technology (shown in Figure 6 below) has been designed for use in primary substations and is supplied in a portable, 16-Channel form for temporary installations (to monitor up to 16x cable feeders using 16x HFCT sensors). For primary substations with less than 16x feeders it is recommended that TEV sensors are also used in conjunction with the HFCT sensors to detect any 'local' PD in the switchgear.

Figure 6: 16-Channel HVPD-Multi™ Portable Monitor – Multiplexed Unit

The HVPD-Mini ™ Monitor (Figure 7) is designed for use in *either* primary or secondary substations and can be supplied in a portable form for temporary installations (to monitor 2x cable feeders and 2x switchgear panels using 2x HFCT and 2x TEV sensors) or as a permanent monitor (for integration into the customer's plant management systems).

Figure 7: 4-Channel HVPD-Mini™ Monitor – with Synchronous Detection

For wide-area distribution network PD monitoring, a combination of the portable, 16-Channel HVPD-Multi™ Monitor and the portable 4-Channel HVPD-Mini™ Monitor provides a 'holistic' solution for continuous, *on-line* PD monitoring of mv cables and switchgear in wide-area networks. This requires the use of both the HVPD Multi™ Monitor (positioned at the primary substation) and multiple HVPD Mini**™** Monitor Units distributed at RMU's and secondary switchgear around the network, as is illustrated below in Figure 8.

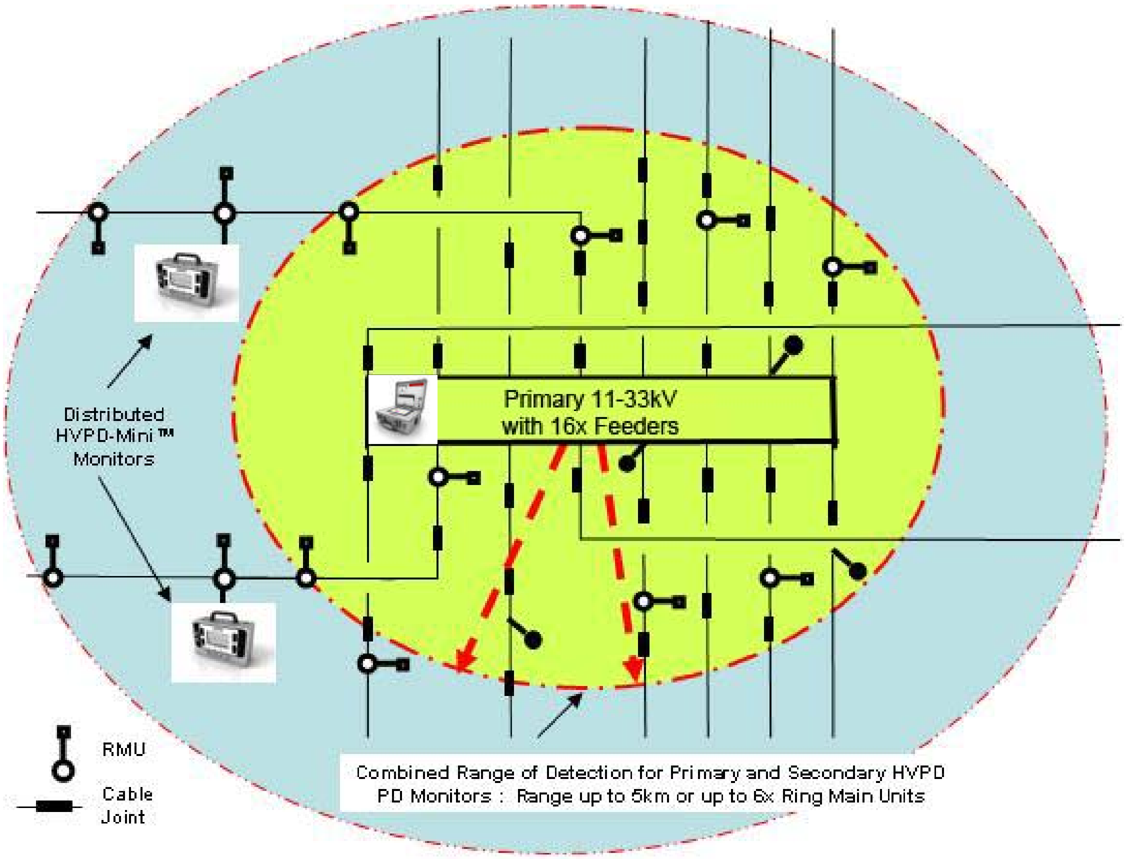

Figure 8: **Wide Area PD Monitoring Solution with the HVPD-Multi Monitor at the Primary Substation and at Distributed Mini Monitors at RMUs**

Depending on the results obtained from this Phase 3 of short-term PD monitoring, a decision is then made as to whether to proceed to Phase 4 of the PD Test and Monitoring Solution, the long-term PD monitoring using permanent PD monitors, as described below.

Phase 4 – Long-Term PD Monitoring with HVPD Permanent Monitors

The final phase of the HVPD 4-Phase PD Test and Monitoring Solution involves the installation of permanent PD monitor technology (the HVPD-Multi^{TM} Permanent Monitor) in substations where significant levels of PD have been detected during the first 3 phases. For large utility medium voltage distribution networks this will typically entail monitors being installed in around 5% (or less) of the network.

For industrial mv networks supporting critical processes this percentage may be much higher as the plant owner may see the benefit in continuously monitoring PD in more of their 'mission-critical' network. The base unit of the HVPD-Multi™ Permanent Monitoring system is shown below in Figure 9. This system is expandable, up to 64 channels, using up to three 16-channel, 'slave' units which are connected through the main unit.

The device is based around a Linux PC and has an onboard 10/100 Ethernet LAN port for connection to the internet and other communication and plant management systems (such as Modbus) where there is no LAN available.

Figure 9: HVPD-Multi™ Permanent Monitor – Base Unit

When wide-area distribution network, continuous PD monitoring systems are required then a combination of the HVPD-Multi™ Permanent Monitor and permanently installed HVPD-Mini™ Monitors can provide a 'holistic' solution for continuous, *on-line* PD monitoring of mv cables and switchgear in wide-area networks in the same way as shown previously for the portable technology in Figure 8.

Examples of HVPD Recent On-line PD Projects

The project scope for HVPD On-line PD Testing Pilot Projects can range from the *PD spot testing of individual items of plant* (typically after failures – see below) up to carrying out *complete, wide-area network PD testing and monitoring* projects on utility customer's large distribution networks.

Past HVPD test projects include testing a wide range of mv and hv plant including cables, switchgear, transformers, motors/generators, ct's, vt's etc) of both in-service medium voltage (MV - 6.6kV to 45kV) and high voltage (HV - 66kV to 500kV) cables and plant.

Project to Test for a Specific Incipient Faults – HV Cable Sealing Ends

A number of recent test projects carried out by HVPD have involved the On-line PD testing of MV and HV cable sealing ends further to explosive failures of customer cable sealing ends of voltages of up to 275kV. This test and development work has shown that internal PD activity can be measured several months in advance of subsequent failure using the HVPD on-line PD test technique, thereby allowing repair of the termination to be made ahead of failure.

HVPD have carried out a number of test projects on hv cable sealing ends and terminations and this appears to be a growing problem in the utility transmission business in Europe, The Gulf and South East Asia. The purpose of these testing projects is to check the insulation condition inside the cable termination by measuring and recording any *internal PD activity within the MV & HV cables and terminations* and also the switchgear and transformers to which the cables are connected. In order to differentiate between dangerous internal PD and relatively benign external PD signals, this testing requires synchronous, multi-channel signal acquisition which is provided by the portable HVPD Longshot™ 4-Channel Spot Tester.

The source of any PD activity is located using the technique of *On-line Cable Mapping* (cables and accessories) and Time Of Arrival measurements with distributed HFCT sensors and TEV probes (switchgear and transformers). On-line Cable PD Mapping will be carried out on cables which have measurable PD activity on them. This will be done with the OSM-Longshot™, the Portable Transponder Type PTT 2000-CT and PDMap© Software.

Pilot Projects to Test a Wide-Area Distribution Networks

These involve PD 'spot-testing' and analysis of the customer's power networks in detail in order to establish optimised, network-wide methods for deployment of non-invasive, permanent HFCT PD sensors and/or PD monitors at strategic positions. Projects typically include a complete 'sweep' of PD surveying (with the PDSurveyor™ Unit) and diagnostic PD spot-testing (with the HVPD-Longshot™ Unit) of *all* of the mv and hv plant and cables on the customers network.

Past projects have included surveys of utility transmission and distribution cable networks, medium-scale industrial electricity networks and contained, small networks such as those on ships or oil platforms.

The PD data from the different HV components within the networks are analysed, along with circuit usage data in order to determine how much PD activity can be tolerated, where to deploy any non-invasive, permanent PD sensors or monitors at strategic positions and how to use on-line PD test data in a client's condition-based asset management programs.

The Pilot Project involves analysing the different PD detection methods (spot testing and monitoring) and determines at which strategic positions permanent HFCT PD sensors should be installed. Permanent HFCT PD sensors are installed when there is no access to the cable earth or core outside a switchgear/cable box and the permanent HFCT sensor is connected around the earth of the cable inside the switchgear/cable box (during an outage) and the signal BNC cables 'brought out' to be mounted on the outside of the metalclad plant.

Appendix 1: PD Testing of MV Cables & Switchgear – PD Levels for Diagnostics

Through work carried out by IPEC HV over the past 10 years with HV Power Plant Owners in the UK, Europe and the Rest of the World a large database of results has been generated. From this database it has been possible to produce Cable and Switchgear Insulation Condition 'Knowledge Rules' which allow the plant owner to assess the condition of their MV Cables and Cable Accessories through the on-line PD Test results. These Knowledge Rules can be used in conjunction with the IPEC HV range of On-line PD test equipment for the insulation condition assessment of both paper and polymeric-insulated MV cables and solid and air-insulated MV switchgear.

In order to place PD Test results obtained from PD testing of MV cables and switchgear into some context Figures A1 and A3 below provide *Guideline**, PD threshold levels for Medium Voltage Cables and Switchgear.

* N.B. It should be noted that these PD levels are based on IPEC HV's own experience of PD testing (mainly in the UK) and are not definitive figures. The levels given are meant as a guideline only and could be considered in some cases to be conservative. They do nevertheless provide a basis for developing a 'League Table' of in-service MV Cable and Switchgear Insulation Asset Condition from which to make Asset Management Decisions.

It is recommended that the user/customer develop their own 'at risk' MV Cable and Switchgear PD levels as part of IPEC's Diagnostic Consultancy and Training course on PD Diagnostics. In this way the PD levels for different levels of concern or action can be developed in line with the general condition of the plant owner's equipment and their maintenance schedules and budgets.

PILC Cables	**0pC – 3000 pC**	Discharge within acceptable limits
	3000 pC – 6500 pC	Some concern, monitoring recommended
	6,500 pC – 10000 pC	Some concern, regular monitoring recommended
	> 10000 pC	Major concern, repair or replace

XLPE Cables	**0pC – 250 pC**	Discharge within acceptable limits
	250pC – 350 pC	Some concern, monitoring recommended
	350pC – 500 pC	Some concern, regular monitoring recommended
	> 500pC	Major concern, repair or replace

PD Level for MV Cable Joints and Terminations

PILC Cable Accessories	XLPE Cable Accessories
0-4000 pC	**0 – 500 pC**
4000 pC – 6000 pC	**500 pC – 1000 pC**
6000 pC – 10000 pC	**1000 pC – 2500 pC**
>10000 pC	**>2500 pC**

Figure A1: MV Cables & Cable Accessories
- *Guideline* PD Levels vs Recommended Action

Guidelines for On-line TEV PD Measurements for MV Switchgear

Background

The measurement of PD magnitudes and rates can be enormously variable when measurements on power systems are made. The nature of the system makes a large difference in the interpretation of the results. What is very bad in one type of equipment may just be acceptable in another. Hence the interpretation of PD activity must take into account all the factors which can influence the outcome. The largest influence comes with the detailed location of the PD activity. Hence for example, if the PD originates between two metal structures one of which is not grounded, then this may be benign for the life of the equipment. However, if the PD originates in a cavity in a high stress part of the insulation, then this is very serious, and has to be treated to avoid failure. Hence it is mostly *the position of the PD site* which determines the 'badness' of the measured PD activity. Lists of the factors which influence the weighting of the PD measurements are given below for guidance purposes.

The PD Level Guide vs Condition given below is really for medium voltage systems (typically 11kV to 33kV) as any plant at higher voltages should always be run discharge-free. The advice that all power systems should be operated discharge-free is a very good one although in practice this is not normally practicable due to limited maintenance and operational budgets. In addition it is known that some insulation types in MV plant are more resilient to PD activity than others (see Insulation Materials) below. For example the mica-based insulation in MV Motors is known to be able to withstand PD activity of tens and sometimes hundreds of thousands of picoCoulombs (10,000 to 100,000pC) whilst PD of a few hundred pC's in polymeric cables is likely to cause insulation failure over a short period of time.

Most polymer based insulation now has standards which set by IEC guidelines (at least in the factory/type test) to have a PD level of better than 10pC. It is difficult to see that properly installed plant which is discharging less than this level is going to fail by insulation failure. All other failure modes can be sorted with maintenance programs and hence the aim should be to run any new system discharge-free (this can be tested at commissioning stage to provide a 'base-line, at-installation' PD level).

Operating Voltage

As the voltage increases, the same size of PD activity becomes more serious. This is partly because the stresses tend to increase in larger voltage plant, partly because there are simply more volts available and partly due to the geometry. Probably a rough rule would be to weight the voltage level linearly. Hence a discharge of 50pC in a 33kV system would be three times more damaging than the same size discharge in an 11kV system. Again this depends on geometry, type of PD event, location etc, but the rough scaling is there. Notice that at transmission voltages, PD events are significant at a small level, and tend to be more difficult to measure. Measurements at medium voltage (e.g. 11kV) are probably the easiest to make as the signal to noise ratio tends to be smaller.

Type of discharge

These can be cavities bounded by dielectric, or bounded by metal, surface discharges, PD in layered media, corona in air etc. Internal PD events in dielectric cavities tend to be the most damaging. The daughter products from the PD events remain within the cavity (these can be acids, corrosive chemicals, or simply active elements from the gases in the discharge). No ventilation is possible, and cavities like this almost always end up in failure. The time scale is the only variable. The important part here is the damage the PD events do to the surrounding insulation.

Insulation materials

The materials of the insulation are critical. Hence old switchgear with porcelain and metal parts, were virtually indestructible unless nests of mice shorted out the porcelain insulators. In this case, PD activity had almost no effect. With polymers, paper, oil, bitumen etc, this is no longer true, and the rate of deterioration will depend on the nature of the degradation of the insulation material. The route of deterioration will also depend on the material. For example, in air insulated switchgear, surface discharges will damage the hydrophobicity of the materials, with the result that the surfaces will wet out distorting the fields, and causing a tracking/erosion failure.

Thermo-mechanical variations

The effect of load (i.e. temperature) is vital in the development of discharges. The variation will temperature can come simply because the insulation is hotter. Polymers (both thermoset and thermoplastic) will become softer and less resistant to PD as they heat up. Whereas mass impregnated non draining (MIND) impregnated paper cables tend to improve with temperature, as the wax based oils flows more easily into any cavities. Temperature variations can produce a large change in the mechanical movements of the equipment as the components expand. Movement at terminations and joints are a good example of this. These movements can make a large change in the PD activity, depending on which parts of the high voltage region they move or distort.

Mechanical movement

Clearly the movement of parts in the high voltage system can cause PD to appear, increase or decrease. Tap changer selectors, switchgear circuit breaker trolleys, earthing arms, knife blade switches etc, can all cause changes in the equipment which can affect the PD activity. With cables, external damage is probably the most common cause of failures of all.

Environmental conditions

Other than temperature, there are some environmental conditions, which can affect the performance of high voltage plant. For air insulated switchgear, the effect of temperature and humidity is a vital component of damage due to PD activity. Water condensation is the vital part of the induction of PD on surfaces in air insulated switchgear. In fact water condensation should be avoided for all high voltage plant. Only outdoor insulators are designed for operation in wet condition, and only in a fully ventilated state. All other plant should be operated dry.

On-line PD Testing Method for MV Switchgear

The On-line Partial Discharge (PD) Testing of Medium Voltage (MV) Switchgear (voltage range of 6.6kV to 33kV) originated in the UK in the 1980's through the use of **Transient Earth Voltage (TEV)** / External Capacitive Coupler sensors attached to the outer casing of the switchgear at strategic positions. These sensors pick-up the high frequency (radio-frequency) pulses (in the frequency range of 4MHz to 100MHz) which emanate from discharges occurring within the insulation of the metal clad switchgear. This phenomenon is illustrated in Figure A2 below:

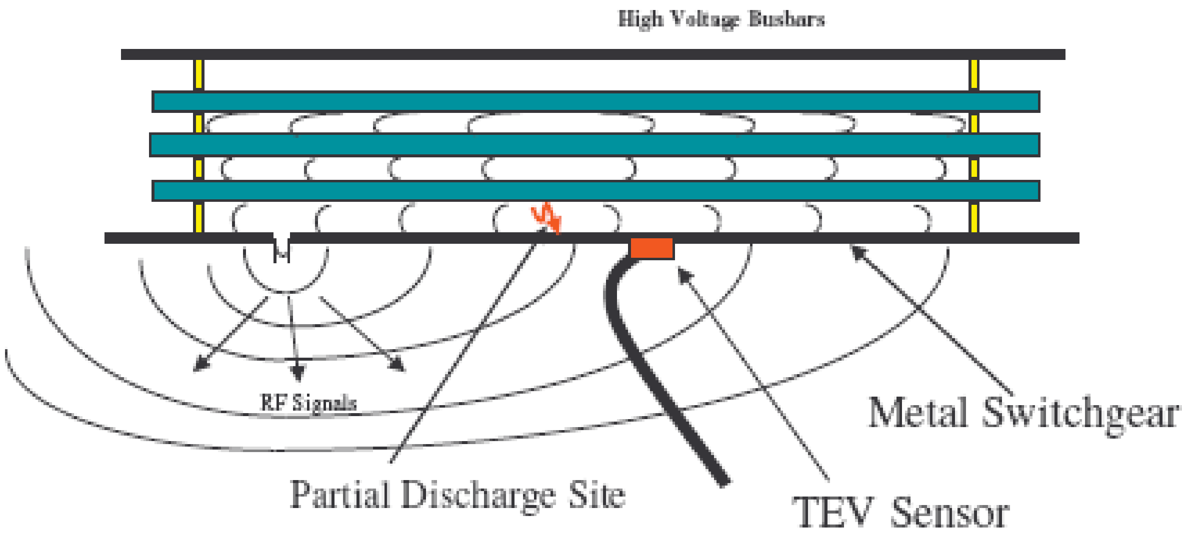

Figure A2: TEV Signals emanating from within Metalclad Switchgear

Through work carried out by the UK Electricity Association in conjunction with UK Electricity Distribution Customers, a large database of results has been generated which *compares* off-line PD testing of MV Switchgear (measurements in pico Coulombs, pC's) with those made on-line using the TEV Sensor (measurements in decibels, dB). From these results it has been possible to produce Plant Condition 'Knowledge Rules' which allow the plant owner to assess the condition of their MV Switchgear through the on-line PD Test results.

These TEV Knowledge Rules are given in this Appendix and can be used in conjunction with the IPEC HV On-line PD test technology to provide quick and simple on-line PD Spot Testing and condition assessment of solid-insulated, air-insulated and gas-insulated MV switchgear of operating voltage up to 33kV. The technology utilises TEV sensors which act as capacitive couplers when placed against metalclad HV plant to detect PD pulses flowing out of the HV plant onto the earthed metal surfaces. The bandwidth of these TEV sensors is >100MHz and is designed to pick-up PD pulses in the frequency range of 4 to 100MHz. The TEV sensor is suitable for testing both the older type of in-service, Solid Insulated Switchgear (SIS) and the newer type of 'dry' Air-Insulated Switchgear (AIS). The techniques have also been applied with good success for the on-line PD testing of the internal insulation of mV Gas Insulated Switchgear (GIS).

Solid Insulated Switchgear (SIS)		
dB Level	**mV Level**	**Condition & Action**
0dB – 15dB	1 mV – 6mV	Discharge within acceptable limits
15dB – 25dB	6mV – 18mV	Some concern, monitoring recommended
25dB – 35dB	18mV – 60mV	Some concern, regular monitoring recommended
>35dB	> 60mV	Major concern, locate PD and then repair or replace

Air Insulated Switchgear (AIS)		
dB Level	**mV Level**	**Condition & Action**
< 0dB	< 1mV	Discharge within acceptable limits
0dB – 15dB	1 mV – 6mV	Some concern, monitoring recommended
15dB – 30dB	6mV – 32mV	Some concern, regular monitoring recommended
>30dB	> 32mV	Major concern, , locate PD and then repair or replace

Figure A2: MV Switchgear - *Guideline* PD Levels vs Recommended Action

*******End of Document********

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