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Better Asset Management through:

On-line Partial Discharge Testing and Monitoring of MV and HV Networks

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Introduction to High Voltage Partial Discharge (HVPD) Ltd

HVPD Ltd is the new name for IPEC High Voltage Ltd, 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) and HVPD's Senior Test Engineers have built-up significant experience in the application of on-line PD testing, monitoring and cable PD mapping (location) over a period of 10+ years. 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 used in the preparation of this document.

Introduction to On-line Partial Discharge (PD) Testing

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 one of the most 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.

Diagnostics for MV and HV Plant as a Tool for Effective Asset Management

If carried out carefully, the introduction of diagnostics (such as on-line PD testing) into the maintenance and operation of medium voltage (MV) distribution networks (cables, switchgear and other plant) can provide cost benefits through more cost-effective asset management. Through the collection and processing of diagnostic test data, it is possible for asset managers to better understand the condition of their assets using a condition-based 'Criticality Index' measurement. By understanding the 'Criticality' of a cable and thus the consequential risks of failure, it is possible to implement more efficient and targeted replacement, repair and investment programs.

If each substation had a reliable alarm on the wall, which operated the day before a cable or switchgear failure, the impact on the number and length of interruptions would clearly be dramatic compared to the current position which is generally random failures. Similar improvements could be expected in investment targeting and customer satisfaction, particularly for "worst served customers".

In a modern electricity distribution business, condition-based asset management is one of the essential tools to enable the *reliable, cost-effective life extension* of existing plant and cables to be achieved. Timely location and the targeted, pinpointed replacement of specific cable sections and accessories of unsatisfactory circuits enables the effective service life of the whole network to be economically extended.

The large electricity network operator needs to consider how the required scale economies can be affected whilst at the same time delivering improving performance. This creates the driver towards the next generation of asset management tools to enable limited investment to be directed at those networks with the poorest performance, highest operational costs and the largest potential gains in terms of customer satisfaction.

The new generation of condition-based, asset management tools are aimed at directing limited investment to those networks with the poorest performance, the highest operational costs and the largest potential gains in terms of customer satisfaction. Condition-based maintenance techniques are, in fact, the *only* real alternative to wholesale renewal of aged underground cable networks. With replacement rates of in-service cables in UK and other European utilities remaining at very low levels (typically less than 0.5% per annum in many cases) the need for an alternative asset management solution is very clear to see!

HVPD's background in On-line PD Testing of MV (6.6-45kV) Cable Networks

HVPD have built-up significant experience in the application of *on-line PD testing and cable PD mapping (location)* over a period of 10+ years. The application of the new on-line PD test technology began in the UK in 1998 when the first series of on-line PD tests were carried out by the HVPD Directors on in-service, 11kV paper-insulated (PILC) cables in the London Power (now EDF Energy) Network.

These tests were *the world's first* on-line PD tests to be carried out on in-service MV cables using ferrite-based, inductive high frequency current transformers. This new on-line technique for insulation condition testing of in-service cables was made possible by the development of *inductive* PD sensors, the clip-on High Frequency Current Transformers (HFCT). The HFCT sensors are normally attached to the earth bar/strap of the cable termination under test, with no outage required.

The initial development work between 1998 and 2003 focused on the PD testing, PD mapping (PD site location) and PD monitoring of older (50-60 years old) in-service, underground paper-insulated cables (PILC). 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 it is possible to provide *reliable life extension* of these assets, providing huge savings to utilities which would otherwise have to carry out wholesale cable & switchgear replacement programs of their ageing networks at huge expense.

The business driver behind this decision was stated in the paper presented at the CIRED 2001 Conference by Cliff Walton of London Power Networks, as follows:

"Some 98% of the supply incidents that occur in London arise from cable systems and terminations (rather than transformer and switchgear failures). Network performance statistics also indicate that incidents on the 11kV (& 6.6kV) MV systems affect the most customers."

"LPN has recently commenced installing live line multi-functional monitoring equipment on 300 higher fault rate feeder circuits. Preliminary results of live line condition monitoring have shown very encouraging results in being able to detect and locate failure BEFORE it occurs."

Over the 8 year period since the above was reported LPN/EDF Energy have presented a number of papers at CIRED (in 2003, 2005, 2007 and now 2009) on the further development of this on-line PD monitoring technology and methodology. Today, EDF Energy have over 1,000 of their 11kV cable feeders being monitored using the latest web-enabled, remote-access PD monitors. The data from these monitoring systems is being used to support a condition-based asset management decisions by the company.

In recent years the authors have also worked in close collaboration with other UK utilities (Scottish Power Systems and Scottish & Southern) on the development of portable, remote-access PD monitoring technology. This new technology is in the form of *portable*, remote-access PD monitors which can be moved around large, utility distribution networks to carry out short-term monitoring of PD activity (typically for periods of 1 week). Through the use of portable PD monitors, moved around the network and positioned at both primary and secondary substations (for 1 week per sub), it is possible for *PD monitoring* to be achieved at a fraction of the cost of permanent systems.

HVPD propose that for effective long-term management of medium voltage and high voltage cables and plant a 4-Phase Condition-Based Asset Management Solution should be applied, as illustrated in **Error! Reference source not found.**. The idea behind this 4-phase solution is to provide a cost-effective approach to PD testing and monitoring as an alternative to the large-scale installation of permanent PD monitoring systems.

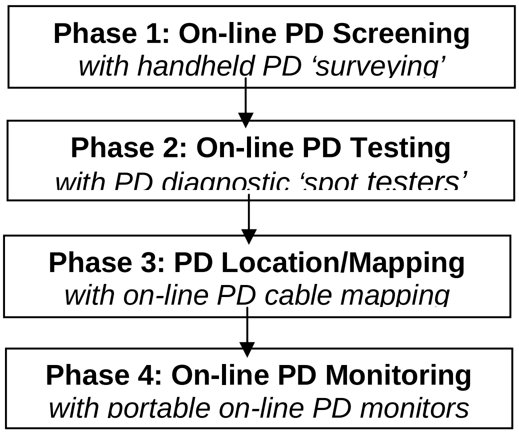


Figure 1: HVPD 4-Phase Approach for On-line PD Monitoring of MV networks

The 4-phase Condition-based, Asset Management approach recommended by HVPD illustrated above in Figure 1 has been presented at a number of International Conferences on MV and HV Plant Monitoring in 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.

HVPD have recently completed the development of a new range of portable and permanent remote-access PD monitoring technology, the *16-Channel HVPD-Multi™ Monitor* and *4-Channel HVPD-Mini Monitor*. These technologies have been developed in conjunction with both utility and industrial electricity network operators and are available in portable and permanent versions. The portable 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 can be integrated into the customer's LAN, Ethernet or other plant communications systems (Modbus etc).

With the addition of this new range of PD monitoring technologies to the HVPD's established PD surveying and PD 'spot-test' technology, HVPD can now offer 'holistic' technology to provide a complete solution for the PD screening, diagnostic testing and monitoring of medium voltage networks. This PD technology range has been incorporated into the cost-effective, *HVPD 4-Phase Asset Management Solution* which is illustrated in Figure 2 below.

Figure 2: HVPD Solution for 4-Phase Asset Management Approach for On-line PD Testing and Monitoring of MV networks

HVPD's background in On-line PD Testing of HV (66kV+) Cables and Plant

Over the course of the past 6 years, HVPD Ltd have developed and applied the portable, 4-Channel *HVPD Longshot™ Synchronous PD Tester* to test both MV and HV plant of voltages up to 500kV. The Longshot™ unit was 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 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* (to within less than 2ns) 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 i.e. *"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.

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

Example of an HVPD Project – On-line PD Testing-of HV Cable Sealing Ends

A successful application of the HVPD-Longshot™ unit's synchronous, multi-channel PD detection technique is the on-line PD spot testing and monitoring of in-service, energized *high voltage outdoor cable sealing ends* (terminations). The technique was developed by HVPD further to the occurrence of several explosive failures of 132kV and 220kV porcelain cable sealing ends by electricity transmission utility clients of HVPD in Europe, South East Asia and the Gulf.

One of the main challenges encountered when testing HV cable sealing ends is to differentiate between the *highly dangerous internal PD activi*ty within the sealing ends from the large number of external, high frequency impulsive interferences originating from other nearby items of plant. Sources of such interference include corona and the (*relatively)* benign external discharges on the surfaces of ceramic insulators related to atmospheric pollution and weather.

The HVPD technique developed to test in-service, energized high voltage outdoor cable sealing ends involves the synchronous capture of data (to within 2ns on all four channels) and comparing the signals in order to identify internal PD activity in the cable sealing end. The PDGold© v5.0 software utilizes *three* software modules to make these measurements including the *'EventRecogniser©'*, *'RF Noise Filter'* and the *'Precedence Detector©'* time-of-flight software module. By using this unique combination of software modules, HVPD-Longshot ™ can be used as a tool for commissioning new cable sealing ends and also assessing the insulation condition of aged ones**.** For further information on this application refer to HVPD Technical Document: *"HVPD Ltd – Technical Document for HV & EHV Cable Sealing On-line PD Testing April 2009".*

Case Study Example – PD surveying of an 11kV utility cable network

Figure 3 below shows the results of an On-line PD test survey of over 629 11kV cable feeders in EDF Energy's 11kV distribution network where the peak and count PD data was measured. The graph is a cumulative chart of the PD magnitude data from all 629 feeders tested. It can be noted that around 5% of the sample (30 out 629) were recommended for further 'Action' as the PD levels on these cables were measured at above 200MV.

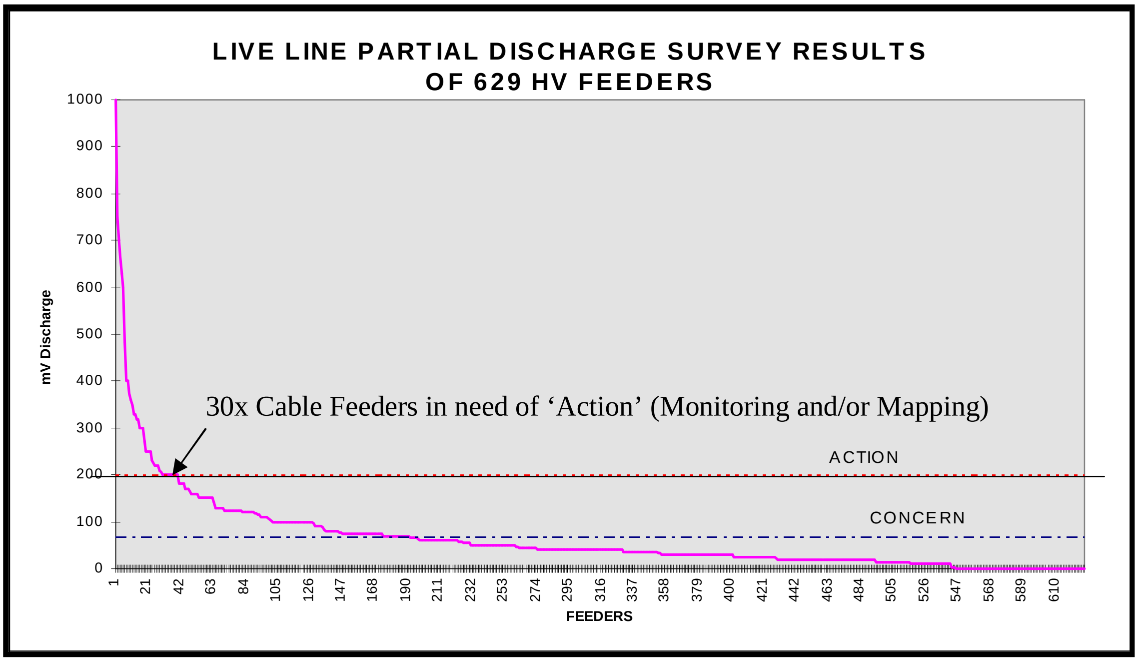
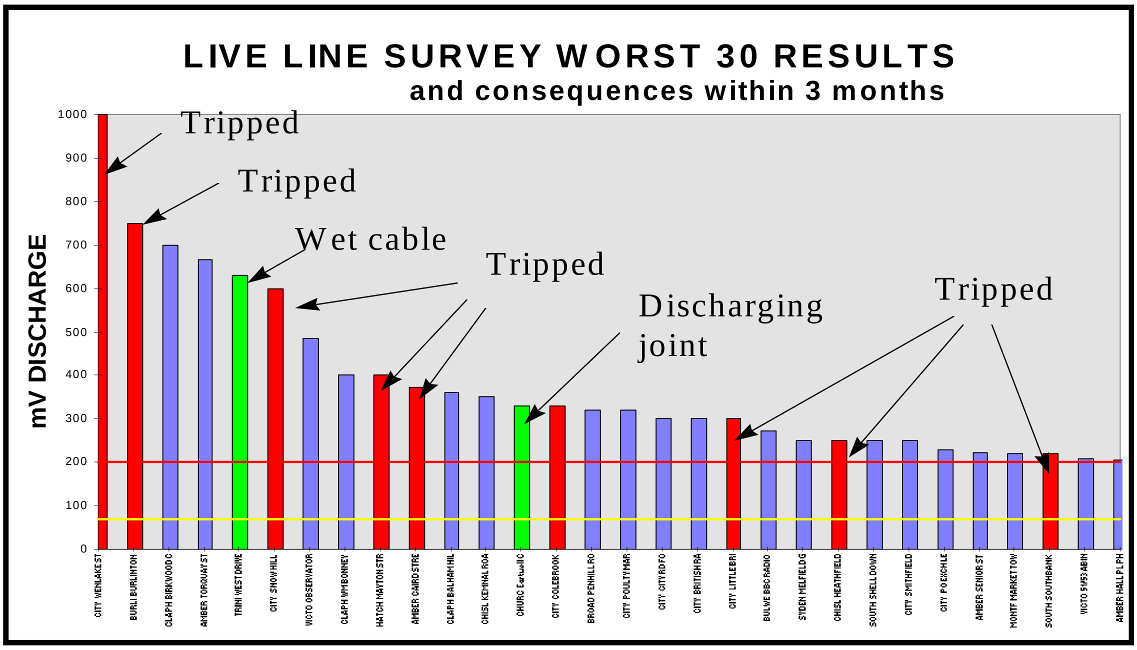


Figure 3: On-line PD Test Survey results from 629x 11kV cable feeders

Whilst these simple measurements will have included some noise, not withstanding this, the graph in Figure 3 shows that very few cables (typically between 5-10% of the population) are responsible for the high values of PD. It is postulated that it is this small percentage of cables which will largely contribute to the system performance failures and therefore it is this 5% or so of cable feeders where diagnostic PD testing, cable PD mapping (PD site location) and PD monitoring resources and any resulting preventative maintenance and repair actions should be targeted.

The above statement was reviewed as part of this project with the decision being made to observe the performance of the 30 'critical' cables from the test survey (where the PD levels were measured at above 200MV) for a period of 3 months after the survey was completed. Out of this top 5% of the PD survey sample (30 out 629) the service performance over the resulting 3 months is illustrated overleaf in Figure 4.



11 Circuits out of 30 (37%) failed within ***3 months of Survey***

Figure 4: On-line PD Test Survey – Performance of the 'Worst 30' Cables

Discussion

It can be noted from the pilot project results shown above in Figures 3 and 4 that it is possible through the use of the On-line PD test technology to identify the cables most likely to fail in advance of failure. In this case it can be noted that out of the 30 cables identified in the PD survey as having high levels of PD, 11 of these (37%) failed within 3 months of the survey being completed. This result confirmed that the PD testing is effective in identifying the cables most in danger of suffering faults, thereby providing an 'early-warning' of any incipient faults, ahead of failure.

HVPD's Customers

HVPD have a wide range of customers in many different industries, ranging from electricity utilities with wide-area distribution networks to industrial and commercial customers with small networks (such as offshore oil rigs and internet data centres).

Customers have the option to purchase, rent or lease PD test and monitoring equipment from us. An alternative to equipment hire or purchase, for our clients who do not have sufficient test labour resource in-house, is for the client to purchase specific on-line PD test services from HVPD's highly trained PD Test Engineers.

The majority of HVPD's customers fall into the four categories below:

1. **Asset Owners who own and operate PD Test and Monitoring Devices**

These customers can be any owner of MV or HV plant, for example electricity utilities, power generation facilities, heavy industries, factories and petrochemical plants. These customers purchase the PD test & monitoring technology and training from HVPD and carry out PD testing on them, using their own personal and asset management program. In such cases HVPD provide remote and/or site support only when required. Examples of such customers include EDF Energy, British Gas Group and the Saudi Electricity Company (SEC).

2. **Asset Owners who employ HVPD to provide PD Test Services**

These are owners of high voltage plant who employ HVPD Ltd to carry out PD testing on their plant on a one-off (typically after failures have occurred) or on a regular (typically on an annual or bi-annual basis). These customers also hire PD monitoring technology and remote-monitoring asset management services from HVPD Ltd, with HVPD's Engineer in Manchester, UK managing the recorded data. Examples of such customers include E.ON, BP, Saudi Aramco and Scottish Power.

3. **Test Service Providers who provide PD Test Services to asset owners using HVPD Portable PD Test Technology**

These are companies who provide test services themselves to medium voltage high voltage asset owners. These Test Service Providers purchase HVPD's portable test devices and training to offer PD test services to their clients. HVPD provides remote and/or site support when required to these test company clients but does not deal directly with their clients. Examples of such test companies include Kinectrics, ERIKS and Emerson Process.

4. **Medium Voltage and High Voltage Plant Manufacturers.**

These customers purchase HVPD PD test devices and PD sensors to carry out PD testing as part of the commissioning tests on their HV plant, to ensure the system is PD-free prior to handing over to the end user. HVPD also supply permanent PD monitoring systems and sensors. Examples of such MV and HV plant manufacturer customers are AREVA, Siemens and Al-Ahleia Switchgear.

Diagnostic Testing of MV and HV Cables - Technical Discussion

Cable Diagnostic Test Options

There are only a limited number of diagnostic tests which are possible for MV and HV cables. These can be listed and separated into two main categories which are *On-line Test Methods* (for testing plant 'live') and *Off-line Test Methods* (for testing out-of-service with portable power supplies (VLF, Resonant Test, OWTS test systems) :-

Off-Line Testing (requires an outage)

- DC Insulation Resistance (IR) Test
- Loss Angle (Tan Delta) Test
- ***Off-line PD tests***, energised with external supply: VLF(0.1Hz), OWTS, Resonant
- Low frequency loss methods, including step tests and relaxation tests
- Propagation methods, capacitance, resistance and impedance tests

On-Line Testing (does not require an outage)

- Thermography (thermal imaging of cable terminations & switchgear)
- ***On-line Partial Discharge methods*** (with HFCT sensors on earth of cable) for Cable PD Measurements including cable mapping (location) and monitoring

The On-line and Off-line cable test technologies both have their advantages and disadvantages, as shown below in Figure 5. For example, whilst On-line testing is more economical than Off-line testing (due to the capability of testing up to 5x more feeders per day), it is not always possible to make suitable connections to the cable under test due to the earthing pre-requisites not being met.

ON-LINE CABLE TESTING	OFF-LINE CABLE TESTING
Advantages	**Advantages**
No need to isolate the circuit	Proven technology
Circuit loaded when tested	Better sensitivity than On-line
Economical & Non-invasive	**Drawbacks**
Teed circuits can be tested	Circuit not loaded during testing
Drawbacks	An Outage is required
Data interpretation can be difficult	Expensive & Time-consuming
Earthing pre-requisites necessary	Teed circuits cannot be tested easily

Figure 5: Advantages & Disadvantages for On-line vs Off-line Cable PD Testing

On-line vs Off-Line PD Testing - Discussion

Whilst the most attractive diagnostic tests to the plant owner in terms of interruption and cost are the *On-line Tests* (where no outage is required), these cannot always be carried out due to the earthing pre-requisites for on-line PD testing not being met. In these cases the cable feeder to be tested must be switched out an off-line test is required. A comparison between the two techniques is given below in Figure 6.

	Online – HVPD Longshot™ Spot Tester with Portable Transponder	**Offline – OWTS, VLF, Resonant or Power Frequency**
Number of Cables Testable per day	10 - 20 cables per day can be tested	2 - 4 cables per day, dependant on external factors i.e. outages, switching
	Quick and easy to deploy, turn up connect up and test!	Can be time consuming due to switching and safety requirements
Calibrations	No calibration required - uses calibrated HFCT sensors	A Calibration is required before every test to ensure accurate results
Test Conditions	Testing performed under normal working conditions, load and at power frequency	Artificially-created, 'pseudo' working conditions applied by offline voltage source i.e. no load

Figure 6: Comparison of Techniques - On-line vs Off-line Cable PD Testing.

Based on the partial discharge projects carried out over the past 10+ years, HVPD would recommend a combination of *both* On-line and Off-line PD testing to provide the most robust and cost-effective asset management toolkit. An example of the complementary application of the technologies is given overleaf.

When to use *Off-line* Cable PD Testing

Off-line testing should be used as part of the commissioning tests for testing newly-installed cables. This technique should also be used to accurately locate the site(s) of PD on the cable detected by the On-line tests (see below). The data from this can be then be used to accurately locate defects and to plan repairs & maintenance

For ***new installations*** of power cables **On-site, *Off-line* PD Testing & Diagnosis** is recommended, for the following reasons:

- to detect poor workmanship in cable accessories, during the after-laying tests with the Off-line PD test in combination with the voltage withstand test)
- to check that the cable and cable accessories are PD-free up to the test voltage used (typically $1.7U_0/2.0U_0$ for new cables)
- in the case of PD presence along the cable, to evaluate the PD level in pC's, to locate the site(s) of the PD and repair of the particular accessory

When to use *On-line* Cable PD Testing

On-line testing is recommended for quick, 'look-see' tests on large populations of in-service cable feeders to both identify PD activity and to locate where the PD is. For *service-aged* power cables On-site, *On-line* PD Testing & Diagnosis as part of the routine condition testing is recommended, for the following reasons:

- testing during service life to detect whether PD activity has initiated and to support maintenance and operation decisions, by detecting and localising PD's in cable insulation and cable accessories

- in the case of PD presence an evaluation of the PD occurrence (PD-levels, Cumulative PD activity & PD trends) and comparison to the acceptance norms for particular types of cable insulation and accessories.

On-line vs Off-Line Testing - Conclusions

On-line Partial Discharge methods, including location, and monitoring is the most cost-effective diagnostic test for detecting an *early warning* against failure of MV cable insulation. For this reason it is recommended that this technique is applied when there are large populations of in-service cable feeders to be tested for PD activity.

Due to the higher measurement sensitivity possible, Off-line testing is recommended to be used as part of the commissioning tests for testing newly-installed cables. For in-service, aged cables, both the On-line and Off-line techniques can be used in tandem to accurately locate the site(s) of PD on the cable detected by the On-line tests. The data from these tests can be then be used to accurately locate defects to accessories or localised cable sections to provide reliable engineering data from which to plan repairs & maintenance.

Diagnostics, system performance, and economics

The timely location and targeted replacement of specific sections of unsatisfactory circuits enables the effective service life of the whole circuit to be economically extended. The next generation of condition-based, asset management tools will be focused on enabling increasingly limited capital expenditure investment to be directed at those networks with the poorest performance, highest operational costs or the largest potential gains in terms of customer satisfaction and customer minutes lost (CML).

Diagnostics for MV cable networks is a valuable tool to help improve the network performance. However, as with all such tools, they will cost something to gain these improvements, and the question arises *"Is it worth it?"*

In other words, the technology when applied to any network should be assessed to make sure that the return on investment is a positive one. The point about cable networks is that the measures of performance are sometimes difficult to put economic figures to. They encompass things such as cost of a failure saved, improvement in customer minutes lost compared to a fixed level (where it might not matter what the improvements might be provided they do not trigger the economic criteria), or simply the economic cost of delaying a failure.

Listing the areas where savings can be made is relatively easy. Putting costs to these will depend on the type of network in which the cable is being used. The costs saving categories are:-

- Saving the cost of failures
- Saving the cost of multiple repairs
- Saving customer outages
- Savings in a capital replacement scheme by delaying replacement
- Savings on improving asset quality at commissioning
- Safety considerations due to failures in terminations and exposed joints
- Special cases of power supplies to sensitive or high value sites where unexpected outages might be a problem

There may be other economic savings dependant on the type of network being used. However, the main categories are probably listed above.

The cost of the diagnostics is also a non trivial calculation. If the diagnostics were perfect, the cost of implementation would still not be easy to calculate. Also the success of the project depends on how well the implementation is carried out. A perfect diagnostic that no one looks at is still useless.

Of the studies carried out on *large, public electricity utility networks*, the largest savings are to be made in *deferring the capital replacement programmes* of the cable population. This is simply because the capital cost of replacement is so large compared to the other costs, that by saving even a small amount of this cost tends to ‘swamp’ the other costs.

However, for industrial customers, this is not the case as normally, for them, the cost of interruption can swamp the capital cost of cable replacement. Oil platforms, industrial processes, nuclear reactors, hospitals and other high profile or sensitive power supplies can have a very large cost of interruption. Such customers have little difficulty in justifying the cost of diagnostic measurements, or continuous monitoring. If the cost of an outage is greater than say £200k/day, such asset owners tend to be very focussed on the condition of their plant. Whereas if the cost of an interruption is perceived as merely the cost of repair (such as the automatic re-configuration of a utility network) then such asset owners tend not to carry out diagnostics.

A large part of the asset management of cables comes from any cable replacement policy. This is normally failure rate dependant, as clearly the utility cable owner with severely failing assets has a different problem to the factory owner with a large cable network, but no failures to date. Failures are a good guide to determine whether policies actually exist or not. Prediction of failure rates obviously gives a reasonable estimate of the likely future costs. All asset owners should do this. For large networks, the failure rates are not too difficult to predict in the short and perhaps medium term.

All the costs can then be estimated, and a decision made about diagnostics, replacement and priorities.

Hence a Condition-based Asset Management plan for tackling the cable network economics should contain the elements given in Figure 7 below.

Element of the economic plan for the cable network	Ideas to be included
For the network, look at all the types of cables installed, their service life and their failure rates	• Include age and cable type in the survey of failure rates • Make a prediction of future failure rates • Calculate the future annual total failures
Estimate the costs for all the failures	• Include all the knock on costs for industrial users • Include costs of time and materials • For costs of interruptions, make a guess at the cost of a failure, and a customer minute lost • Include costs for risk to the whole business (i.e. too many failures, and the whole business might not get the licence renewed)
Predict the future failure rates for all the circuits on the network	• Try to predict future trends. As a default, use the current failure rates • If failure rates are very low, make sure random failure events are included
Draw up a policy for replacement where this might be necessary	• Make a decision about cable types and failures in an individual circuit. This is a difficult task. • Include the effect of diagnostics on the amount of cable to be replaced. (The policy could be diagnostically based!)
Ensure that a programme of diagnostics be included, so that economic decisions about usefulness of the diagnostics can be made on engineering grounds	• Put costs of training and time for all the engineering staff using and carrying out the diagnostics • Make two cases. Those with and those without diagnostics, to help choose the best approach

Figure 7: A Condition-based Asset Management Plan – the Main Components.

With reference Figure 7 above, the plant owner should take into account the different costs which might be associated with the different elements of the economic plan. At the end of this process, there should be a business case for the costs of running the cable network and for inclusion of the diagnostics where these prove to be a gain. All the costs can then be estimated, and a decision made about diagnostics, replacement and priorities.

Economics for Large, Utility Medium Voltage Networks

HVPD studies on large utility MV networks show that the largest savings are to be made in *deferring and/or targeting capital replacement programs* of the cable population. This is simply due to the capital cost of replacement being so large compared to the other costs, that saving even a small amount of this cost tends to dominate the other costs. For example, in many utilities, the cost of an interruption is perceived as merely the cost of the repair, particularly when automatic re-configuration of the network is available.

Economics for Small, Industrial Medium Voltage Networks

HVPD studies on *industrial customer networks* show that this is not the case and a different cost driver normally dominates. In these cases, depending on the process which depends on the power supply, the cost of an interruption can dominate the capital cost of cable replacement. Oil platforms, industrial processes, nuclear reactors, data centres and other high profile or sensitive power supplies can have a very large cost of interruption (running into many millions of £'s per day!). Such customers have less difficulty in justifying the cost of diagnostic measurements, or complete system monitoring. As a 'rule-of-thumb', if the cost of an outage is greater than say £200k/day, such asset owners tend to be very focussed on the condition of their MV and HV plant!

Permanent vs Portable Monitoring Solutions

The costs of installing permanent PD monitoring technology to monitor 100% of large utility networks are presently prohibitive (although this may change in the future). For example, for a typical UK utility with 1,000 primary MV substations, and a typical cost per monitor of £25,000, the projected capital costs for 100% coverage are £25 Million!

The alternative of using portable PD monitors, moved between different substations for a week at a time requires significantly less capital investment. For example, assuming 80% monitoring utilisation (of 40 weeks per annum per unit), 25x portable monitor units would be required to monitor the 1000 primary substations at a capital price of £750k, or £750 per substation. These portable monitors would require test technician resources, to install and de-commission the portable monitors on a weekly basis. With 25 units, 3x test technicians would be required at an estimated cost of £300k per annum. With analysis, databasing and reporting labour costs estimated at a further £150k a total cost operating cost of £450k per annum is estimated, or £450 per substation.

It is clear from the simple analysis above that an alternative to the large-scale installation of permanent PD monitors for large-scale MV networks possible. The new portable PD technologies described in this paper, when incorporated into a structured, condition-based asset management plan such as the 4-phase plan described herein can offer an alternative.

Why Carry Out On-line PD Testing?

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

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 11 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).

Examples of HVPD On-line PD Testing Pilot Projects

The project scope for HVPD Ltd 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 On-line Partial Discharge (PD) surveying and monitoring on the customer's small and large distribution networks.

Past HVPD Ltd 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 MV (3.3kV to 45kV) plant and HV (66kV to 500kV) plant.

Pilot Project to Test for 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 terminations and cable sealing ends further to explosive failures of customer cable sealing end and terminations up to 275kV. This 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.

If any PD activity is detected the source of the PD is located using On-line Cable Mapping (cables and accessories) and Time Of Arrival measurements with distributed 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 HVPD-Longshot^{TM}, the Portable Transponder Type PTT 2000-CT and PDMap© Software.

By using this unique combination of hardware and software modules, the HVPD-Longshot ^{TM} can be used as a tool for commissioning new cable sealing ends and also assessing the insulation condition of aged ones. For further information on this application refer to HVPD Technical Document: *"HVPD Ltd – Technical Document for HV & EHV Cable Sealing On-line PD Testing May 2009".*

Pilot Projects to Test a Wide-Area Distribution Network

These involve the test and analysis of the customer's power networks in detail in order to establish optimized, 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^{TM} Unit) and diagnostic PD spot-testing (with the HVPD-Longshot^{TM} Unit) of *all* of the MV and HV cables and plant on the customer's 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 is 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 at strategic positions and how to use on-line PD test data in condition-based asset management programs.

The Pilot Project involves analysing the different 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.

The Pilot Project also involves assessment of optimising the deployment of portable HVPD PD Monitors (HVPD-Mini and HVPD-Multi) with multiplexers and data concentrator units to allow multiple items of MV and HV plant to be tested with cost benefits through reduced hardware requirements.

For further information on how HVPD can provide our customer's network-wide PD monitoring and asset management solutions please contact HVPD Ltd via:

Tel: + 44 (0) 161 877 6142 e-mail: info@hvpd.co.uk

Wide Area Distribution Network PD Monitoring with Portable Monitors

HVPD recommend the use of a combination of both portable and permanent PD monitoring technology for a large utility or industrial medium voltage distribution networks (6.6kV-45kV). For wide-area distribution network PD monitoring, a combination of the 16-Channel HVPD-Multi Monitor and the 4-Channel HVPD-Mini Monitor can provide a 'holistic' solution for continuous, On-line PD monitoring of MV cables and switchgear in wide-area networks.

The HVPD-Multi Monitor technology is designed for use in primary substations and can be supplied in a portable, 16-Channel form for temporary installations (to monitor up to 16x cable feeders using 16x HFCT sensors) or as a permanent monitor (with up to 64 channels for large substations. 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.

The HVPD-Mini Monitor 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.

These two technologies allow PD Monitoring of Primary Substations, PD Monitoring of RMU's and Secondary Substations and the combination of the two to provide *Wide-Area Network PD Monitoring*, as described below.

The reason why it is necessary to combine these two technologies to provide a *Wide-Area Network PD Monitoring Solution* is illustrated in Figure 6 overleaf and is due to *the effective range of the mini monitors* being *either* up to 2.5km *or* up to 3x Ring Main Units/Switches out from the primary substation. This range limitation is due to attenuation of PD signals as they pass along the cables in the network with typically around 20-30% of attenuation of the PD signals being observed as they pass through a RMU or switch (hence the limitation of up 3x Ring Main Units/Switches)

It is possible to extend the effective monitoring range of the monitors out from the primary substation (beyond the 2.5km *or* 3x Ring Main Units/Switches limitation by placing distributed HVPD-Mini ™ Monitors at suitable RMU's or secondary switches out in the distribution network. This application of the HVPD-Mini ™ is illustrated in Figure 1.

Finally, through the combination of the two technologies, it is possible to provide *Wide-Area Distribution Network PD Monitoring using the* HVPD-Multi Monitor at the Primary substation with distributed HVPD-Mini ™ Monitors at suitable RMU's or Secondary switches out in the distribution network. This is illustrated in Figure 2.

Application 1: **PD Monitoring at *Primary MV Substations* -** to monitor PD in both the cables and primary switchgear.

Application 1, the PD Monitoring of cables and switchgear at primary substations is illustrated below in Figure 6. In this case a HVPD-Multi Monitor unit (with 16x HFCT split-core sensors attached to the earth connections of the cables) has been deployed to monitor 16x feeder cables.

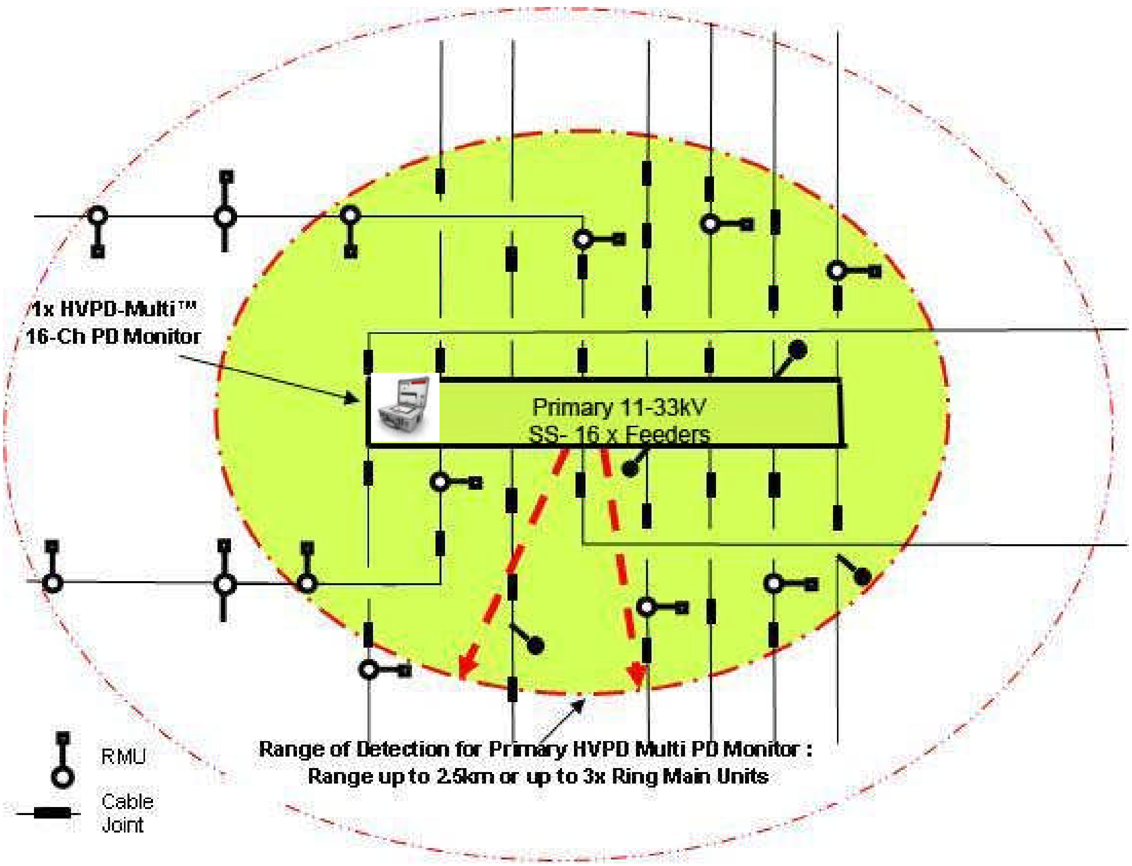


Figure 1: Application 1: Primary S/S Monitoring with a HVPD-Multi Monitor

It can be noted from Figure 6 above that *the effective range of the* HVPD-Multi monitor is *either* up to 2.5km *or* up to 3x Ring Main Units/Switches out from the primary substation. This is due to attenuation of PD signals through the network with typically around 20-30% of attenuation of the PD signals as they pass through a RMU or switch.

Application 2: **PD Monitoring at *Ring Main Units* (RMU's), Padmounts and other Secondary Switchgear** - to monitor PD activity in both the cables and the RMU or other secondary switchgear

It is possible to extend the effective monitoring range of the PD monitoring out from the primary substation beyond the range limitation shown in Figure 1 by placing distributed HVPD-Mini ™ Monitors at suitable RMU's or secondary switches out in the distribution network. This Application 2 is illustrated below in Figure 2.

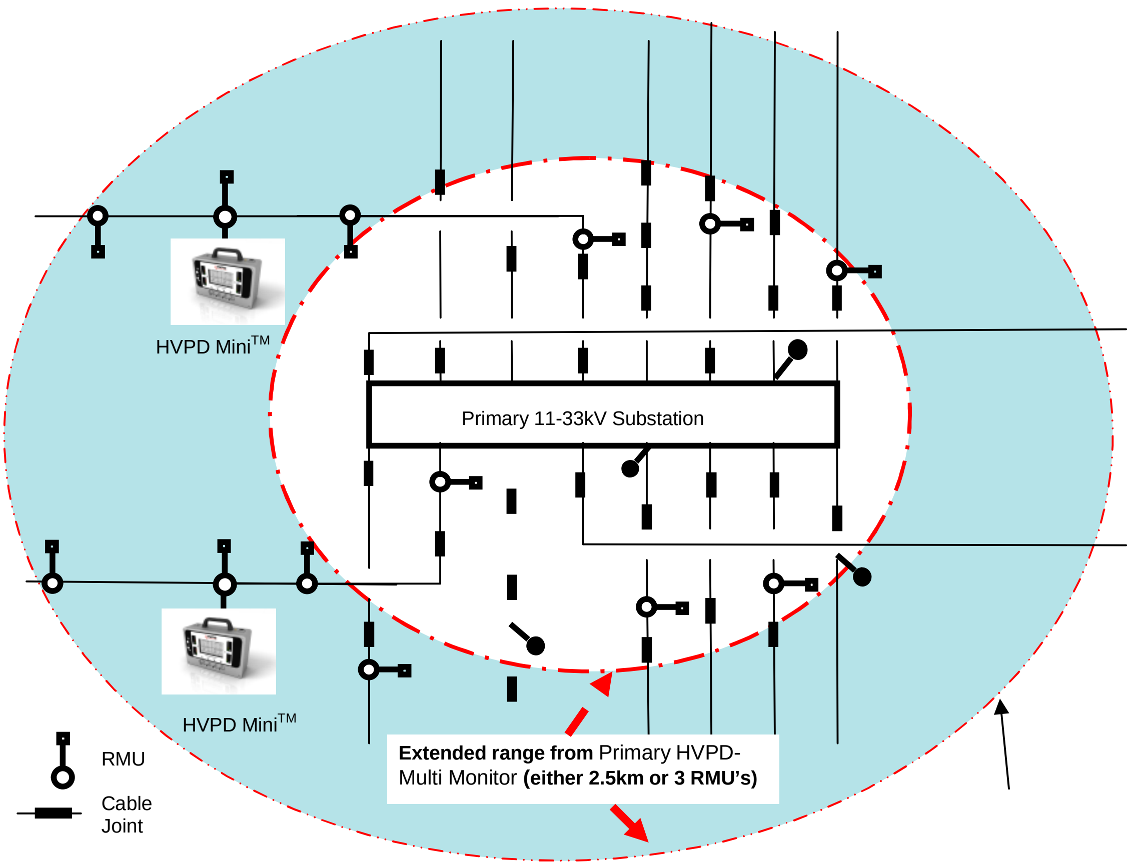


Figure 2: **Application 2: RMU/Secondary Switchgear PD Monitoring with Distributed HVPD Mini ™ Monitors**

This application, with 2x HFCT sensors placed either side of a RMU or padmount switch to provide *'Precedence Detection'* measurements, was the first application envisaged for the unit from discussions with our UK DNO partners. In this case, the timing between the pulse arrival times on the 2x HFCT sensors is measured by the Mini Monitor and, if the pulses arrive together (i.e. they arrive together within 10ns of each other), then they are considered as being synchronous ('SYNC') and the origin of these 'SYNC' pulses is within the RMU itself (10ns is the equivalent of 2m across the bus or earth bar). If the signal one channel precedes the other channel by between 10-50ns (equivalent to 2m to 10m in 'copper work') then this is outputted as a 'precedence' measurement, providing a pointer towards the source of the PD.

Application 3: ***Wide Area Medium Voltage Network PD Monitoring*** **using 1x HVPD-Multi Monitor and multiple HVPD-Mini Monitors**

The final application for the technology is for when the customer requires *Wide Area Medium Voltage Network PD Monitoring.* This requires the use of both the HVPD Multi Monitor at the primary substation and multiple HVPD Mini Monitor units distributed around the network and is illustrated below in Fig. 3.

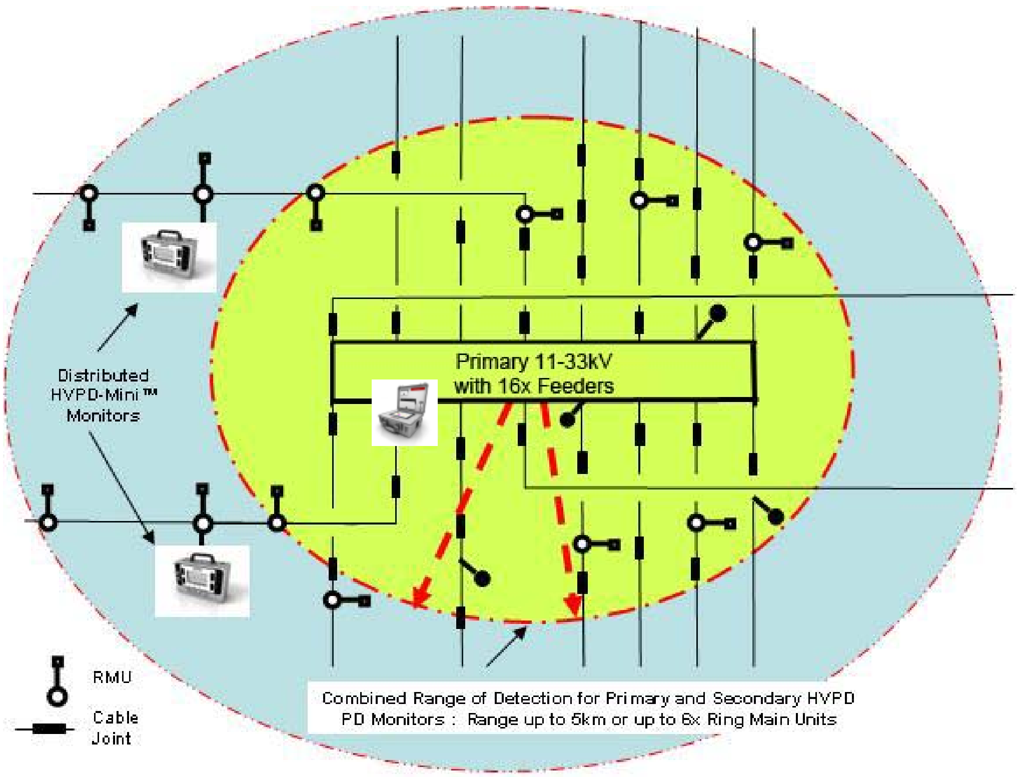


Figure 3: Application 3: Wide Area PD Monitoring Solution with the HVPD-Multi Monitor at the Primary Substation and at Distributed Mini Monitors at RMUs

Discussion and Further Information

In a modern electricity distribution business, condition-based asset management is one of the essential tools to enable the *reliable, cost-effective life extension* of existing plant and cables to be achieved. This document introduces some of the ways by which large electricity network operators can improve their Asset Management practices by applying the new generation partial discharge test and monitoring tools. By careful application of the new technology, it is possible direct limited investment to those networks with the poorest performance, highest operational costs and the largest potential gains in terms of customer satisfaction. For further information on how HVPD Ltd can help you achieve these benefits please contact us via, Tel: + 44 (0) 161 877 6142 or info@hvpd.co.uk

*******End of Main Body of Document********