ON-LINE PARTIAL DISCHARGE TESTING OF OUTDOOR HV PLANT – APPLYING EXPERIENCES FROM 10 YEARS OF PD TESTING INDOORS

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ABSTRACT

The authors present a paper on the application of new technologies and techniques for the On-Line Partial Discharge (PD) testing of in-service, outdoor medium voltage plant. The techniques employed have evolved from over 10 years of experience of the authors and others in the area of On-Line PD testing of MV cables and switchgear in indoor substations. Due to the nature of outdoor equipment and the harsh environments in which it has to operate, the work described has focussed primarily on the key issues of PD pulse discrimination and noise reduction. The paper presents some real-life examples of the application of new techniques to test MV cables, switchgear, sealing ends, VTs and CTs, both indoor and outdoor. The paper concludes with some conclusions from the work carried out and provides some pointers towards how these techniques could be employed in permanent, low-cost PD monitoring solutions for outdoor MV plant in the switchyard.

INTRODUCTION

IPEC Engineering and High Voltage Solutions have been developing *wideband*, *On-line partial discharge test systems* for monitoring and screening of medium voltage distribution plant for the past 10 years. This work began initially in the UK and, over the past 6 years, has been expanded into an increasing number of countries around the world. These developments have been achieved through both direct industrial application and collaborative projects with academia and industry.

The initial developments were focussed on the PD testing and PD mapping (location) of medium voltage (MV) and high voltage (HV) cables, much of this work having been done in collaboration with London Electricity/EDF Energy. The technology development was driven by a realisation that the fault rate on the ageing, mainly PILC/Paper insulated, MV cable networks in the UK was gradually increasing and, in the longer term, likely to accelerate. EDF Energy's objectives include: -

- Improving system reliability;
- The ability to objectively prioritise of cable replacement/refurbishment by identifying the high-risk network sections of the network.

Alongside the core HV cable application, the technology has also been used successfully to test switchgear, transformers and rotating plant. All of this plant has had one thing in common, it has been housed indoors and has thus been relatively free of external interference. This paper presents the more difficult application of the technology to the PD testing of *outdoor* MV and HV insulation The main issues here being how to discriminate between the *highly dangerous, internal PD activity* and the *relatively* benign surface discharges and corona which are present on outdoor plant. Figure 1 shows a low-light photograph (taken at night) of a ring of surface discharges at the top of a 400kV post insulator.

Figure 1: Low-light Photo of Surface Discharge

TEST EQUIPMENT

The measurement system applied is based around the wideband *(0-400MHz)* OSM-Longshot test unit which utilises a high-speed Digital Storage Oscilloscope (DSO) front-end to make high-resolution measurements of PD signals. After collection of the PD signals a range of analysis software (PDGold©, PDMap© and ScopeControl©) is then used to categorise and analyse the data collected. The latest DSO hardware allows for entire 50/60Hz power cycles to be sampled at up to 500MS/s (Mega Samples per second) or one sample every 2ns.

For testing MV/HV cables a sampling rate of 100MS/s is normally adequate, whilst for switchgear, cable sealing ends, VTs and other solid-insulated equipment it is often necessary to apply the faster sampling rates. This allows a highly resolved 'picture' to be built up of the individual PD pulses as they occur over the power cycle and enhances the ability to accurately detect and analyse PD signals with frequency components of up to 200MHz.

OUTDOOR ON-LINE PD TESTING

The convenience and non-invasiveness of On-line PD testing has led to increased demand for this type of testing from a wide range of MV and HV plant asset owners, those in both the electricity supply industry and beyond. Over the past 12 months the authors have responded to requests from customers to test a range of HV plant located in 'harsh' outdoor environments. In particular, testing has been carried out on cast-resin insulated plant such as current transformers (CTs), voltage transformers (VTs) and porcelain cable sealing ends further to the explosions of in-service plant. This requirement has put many new demands on the PD test system and PD detection methods as described herein.

On-line PD Sensor Connections

In order to carry out On-line PD measurements it is necessary to achieve suitable and safe access to the HV plant to be tested for the connection of the PD sensors. A variety of sensors are suitable for on-line PD testing of outdoor equipment including Transient Earth Voltage (TEV), High Frequency Current Transformer (HFCT), RF Antenna and Ultrasonic Sensors/Probes. The TEV and HFCT are seen as most advantageous as they allow direct coupling onto the equipment under test for detection of internal discharges The RF Antennae and ultrasonic probes are used in conjunction with the TEV/HFCT sensors for detecting and eliminating external signals that can confuse measurements. An illustration of the PD sensor connections for on-line testing of outdoor HV cables and cable sealing ends is shown in Figure 2.

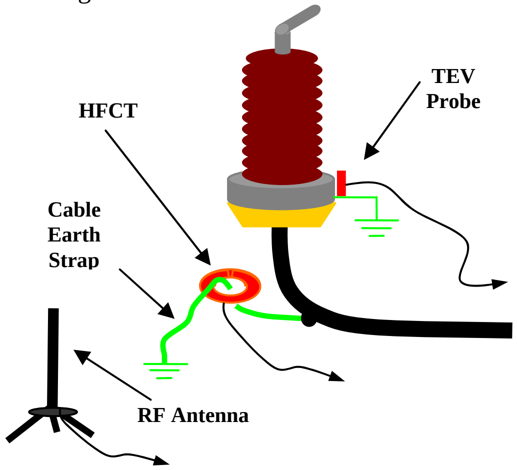

Figure 2: Sensor Connection for HV Cable Testing

Whilst the HFCT connection around the earth strap of the cable is inherently safe and can be employed in almost all installations of HV cables, the TEV connection at the base of the sealing end will be depend on the asset owner's safety rules. If attaching sensors to the sealing end base is not permitted a second option is to connect the TEV on the cable directly below the sealing end.

Sensor Calibrations

In order to provide calibrations for the on-line PD test sensors, it is necessary to carry out calibration tests to compare the response of the sensors with the output from conventional laboratory resonant circuit tests (IEC270). As the new wideband On-line PD test system operates across the frequency range of DC to 200MHz it is necessary to carry out calibration tests at a number of signal frequencies in the active range in order to get the best 'fit' for the calibration constant. The Calibration constants evolved through this process are then used to convert the outputs from the HFCT and TEV sensors' (measured in mV) into pico Coulombs (pC).

RF Noise and Interference in Outdoor Situations

One of the main challenges to carrying out PD testing in outdoor environments is the identification and location of any *internal* PD pulses (these being potentially fatal), whilst simultaneously rejecting RF noise and corona.

Corona & Surface Discharge Interference

When PD-like discharge signals are measured in an outdoor, open environment the source of the discharge is not always from within the HV plant item under test. The sources of such external signals can be corona on the equipment under test or other HV equipment in vicinity; and discharges on insulator surfaces when they are wet.

RF Interference

RF interference is a particular problem when the PD measurements are made in outdoor switching yards where the pylons and overhead connections act as antennae for radio signals in the air. In these instances any PD activity tends to be mixed together with a lot of noise pulses and thus the traditional 'peak and count' measurements are not sufficient.

Analysis of Interfering Discharge Signals

When discharge signals are detected it is crucial to establish whether the source is local or from afar. One useful criteria is to use multiple sensors and use time-of-flight analysis. It has been found with the TEV sensors that signals that have travelled a significant distance have a greater 'preamble' before the peak than those close by to the sensor. The effect is similar to the sound of thunder in a lighting strike. The further away the thunder, the more the waveshape is spread out, and the less like an impulse it then becomes. Also noteworthy is that the waveshapes can be different for different origins.

This can be for several reasons:-

- Pulses are close to the sensor, and produce the largest amplitude signal at the start of the pulse.
- PD signals which have travelled some distance, often have a peak amplitude in their middle
- PD sites which originate in cables often have a monopolar pulse shapes.
- Signals which have travelled down cables lose some of their HF components and have longer risetimes and lower frequency content.
- PDs which originate on the surfaces of insulators often exhibit slower pulses than internal PDs.
- Pulse shapes can often be fixed by the geometry of the HV plant which cause them. Hence large outdoor sealing ends represent different circuits than small components in confined enclosures, and thus produce different pulse types.

Figure 3 shows a corona discharge pulse on Ch 4 measured by a TEV sensor on the B phase circuit breaker of a 132kV feeder in an outdoor switchyard. Channels 1 – 3 show the same discharge pulse received by TEV sensors on the circuit's incoming feeder cable sealing ends (located around 10m from the circuit breaker). It is clear that the pulse arrives first on Ch4 and that its frequency slows significantly by the time it reaches Channels 1 – 3. There is also a change in the pulse shape with Channel 4 showing a fast risetime pulse with a sharp decay, whilst have much slower risetimes and decays.

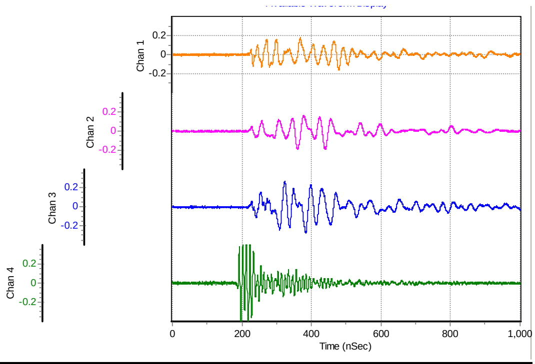

Figure 3: Corona discharge pulse waveforms
Ch 1: R, f=30MHz, Ch 2: Y, f=29MHz
Ch 3: B, f=30MHz, Ch 4: Circuit Breaker, f=100MHz

'Knowledge Rules' for PD Detection

In order to determine if a detected pulse is a PD or not the following characteristics are analysed: risetime, and falltime, width, frequency content, phase position on power cycle and arrival time (comparison between multiple sensors).

By combining recent experiences of the On-line PD testing of outdoor HV plant with experiences from testing indoor plant a number of 'knowledge rules' have been developed by the authors for the classification of pulses. These new rules have been implemented in a new PD 'Event Recogniser' software module for testing outdoor HV plant to complement those rules that already exist for MV cables, switchgear and rotating machines.

NEW TEST TECHNIQUES EVOLVED

In order to improve the efficiency of the measurements a shielded measurement set up was introduced by placing 3x RF Antennae around the equipment under test in addition to the directly coupled TEV sensor. Time-of-flight analysis is then used to discount interfering signals that are coming from outside the shielded area. The optimal sensor positioning for a four sensor set-up used for testing cable sealing ends is shown in Figure 4. The TEV is coupled onto the sealing end base plate and the 3x RF antennae are placed on the ground around the equipment under test (Y phase sealing end).

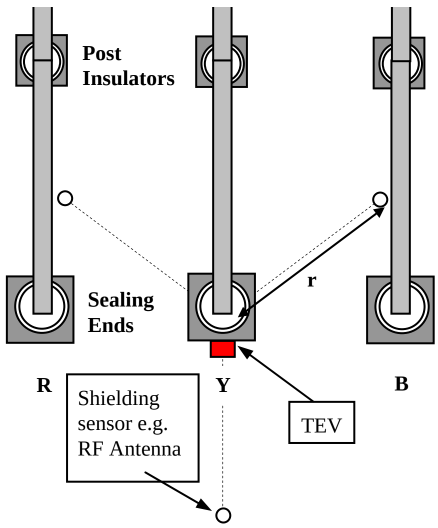

Figure 4: Sensor Positions for Shielded Measurement

The exact sensor set-up is very much dependent on the equipment spacing at site. The distance, r and reference point for sensor position should be chosen so that the distance between the adjacent pieces of equipment and shielding antennas is smaller than that to the equipment under test. This is done to ensure any external signals will reach one of shielding antennas first.

CASE STUDY 1: SURVEY OF 25KV LOCOMOTIVE VOLTAGE TRANSFORMERS

Following catastrophic insulation failure of two in-service, cast-resin 25kV VTs mounted on the top of their electric locomotive trains, the decision was made by the customer's engineers to carry out a fleet-wide survey of 106 in-service VTs for partial discharge activity. It was agreed that PD testing would provide a good indication of the insulation condition of the VTs and thus identify any VTs that were likely to fail in the near future.

In this test the HFCT sensor was placed around the primary winding earth cable at the bottom of the VT and the TEV sensor was placed on the surface below the VT to detect PD pulses flowing out of the VT along any close by earthed metal surfaces such as the carriage housing.

The internal PDs measured (Figure 5) in this equipment have similar characteristics to those observed in other solid-insulated equipment such as switchgear and cable sealing ends and so can be detected in similar ways.

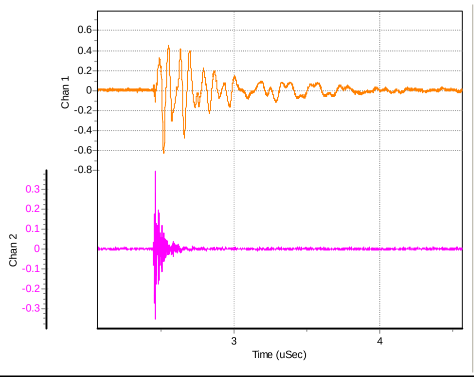

Figure 5: 25kV VT Internal PD pulse Shape
Ch1: HFCT, f=12.5MHz, risetime=54ns
Ch2: TEV f=230MHz, risetime=11ns

By using the On-line PD test method the customer was able to quickly screen and test all 106 of their in-service VTs. Further to the detection of high PD levels (of up to 20,000pC) in a number VTs tested, the suspect VTs were taken out of service and tested off-line in the laboratory. These off-line PD tests verified and confirmed the results from the On-line testing and, due to concerns about the service reliability, the decision was made to replace the VTs on the entire fleet of trains.

CASE STUDY 2: 132KV HV SEALING ENDS

The consequences of the breakdown of the internal insulation system in a HV cable sealing end are normally catastrophic. Forensic assessments of such failures have shown that internal insulation failure normally causes an explosion of the ceramic or polymeric pothead with debris flying up to 100m from the sealing end. Further to failure and explosion of a 132kV cable sealing end (this occurred within a few weeks of installation) the plant owner was forced to place restriction orders commissioned an on-line PD survey of over 30 of their in-service 132kV cable sealing ends. Using a combination of the methods described herein all of these sealing ends were tested and were found to be discharge-free.

CONCLUSIONS & DISCUSSION

IPEC/HVSL are often asked the same question time and again by our HV cable owner customers:

"What is safe level for PD activity in my HV cables?"

The answer to this can only be, *"there is* ***no safe level*** *for internal discharges in cable systems"*. All internal discharges 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 rule is for outdoor HV insulation, where porcelain sealing ends do not degrade in general under surface PD activity (they can however flash over due to tracking over accumulated dirt, which is why they tend to be replaced by silicone materials in high pollution areas).

In the case of HV XLPE cables, terminations, joints and connectors it would be expected that they should be discharge-free in service. The levels of PD activity in the case where the terminations/sealing ends are not correctly constructed, are difficult to assess, as such occasions are uncommon. However, in general, at transmission voltages, internal PD activity, even at very low levels of a few tens of picoCoulombs, will probably be fatal in service with the only question being the time to failure. Hence it is essential to ensure that these installations are tested to be PD free on commissioning.

Historically, PD tests have been found to be difficult to achieve on site, mainly due to the low levels of PD which are significant and also due to extraneous interference. As XLPE cables are all PD tested in the factory before dispatch they themselves are very unlikely to be the source of any PD activity. With XLPE systems, the difficult components to ensure PD free operation the joints and terminations/sealing ends which are made up on site. These accessories are thus the focus for the On-line PD Testing of HV cable systems as described herein.

Acknowledgments

The authors would like to thank Carlos Carqueja from Portugen Energia, Portugal and John Evans from Alstom Transport, UK.