On-line Partial Discharge Assessment and Monitoring of MV to EHV Cables

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Abstract

To effectively manage their electricity networks, owners and operators around the world have a very real need to understand the condition of their often ageing Transmission and Distribution assets. Of all the major asset classes, underground cables often have the least available condition data but at the same time have a significant impact on network performance. One of the predominant causes of cable failure is partial discharge (PD) and collection of PD data can help fill this information gap. This paper discusses the practicalities and application of on-line partial discharge testing and monitoring of cables from MV to EHV.

Keywords: partial discharge, PD, cables, condition assessment, monitoring, transmission and distribution

1. Introduction

When maintained in good condition, underground cable distribution systems provide high security of supply. The impact of cable failure on network performance can be high and failure rates around the world have been found to be variable. Typical acceptable failure rates for underground XLPE distribution cables are less than 1 fault per 100km per year but much higher failure rates have also been reported. The cause of failures can relate to issues introduced at the manufacture, installation and operation stages of cable lifecycle. Cable failure rates can be reduced by eliminating root causes from cable installation for new cables and detecting hidden faults on aged cables by applying partial discharge testing in the maintenance stage [1].

2. PD Failures of Cable Terminations

Partial discharge has long been accepted as a major cause of failure of HV/MV switchgear and non-intrusive instruments for the detection of PD are widely used by many utilities with excellent outcomes. Reference [2] provides details of results from a large national distribution company where the number of outages due to MV switchgear failure were reduced by 71% over a 5 year period resulting in over 470 fewer failures per year. A high proportion of these faults were identified on cable terminations, one example is shown in Fig. 1. Whether the cable termination problems are classed as cable issues or plant (switchgear / transformer) issues is an ongoing debate. However, what is apparent is that the non-intrusive detection of these defects using Transient Earth Voltage (TEV) and ultrasonic techniques is well established and effective in detecting termination faults. The rest of this paper will therefore concentrate on the detection of faults down the cable.

Fig. 1. Partial discharge caused by incorrect installation found on a cable termination using non-intrusive PD instrument.

3. Partial Discharge on Cables

Considering PD on the cable installations themselves, the traditional method of measuring for PD has been to take the cables off line and energize using a power supply, often operating at Very Low Frequency (VLF). The technique is a very effective method of understanding the condition of the cable and location of defects. However, it is time consuming and complex to perform the testing. This tends to limit off-line techniques to more of a reactive test e.g. after failure and repair or targeted at specific circuits under consideration for replacement or overlay. To gain more widespread application across the cable network, there has been a trend to explore the application of on-line partial discharge testing techniques.

3.1 Non-intrusive Detection of PD on Cables

3.1.1 Practicalities of Sensor Placement

Once a PD event has occurred through the electrical insulation of a cable, a set of radio frequency current pulses both equal in magnitude but opposite in polarity are seen on the line conductors and the earth conductor. In addition, if a PD event occurs between two phases, the effect of equal magnitude and opposite polarity is seen on the phase conductors that the PD event occurred. On-line PD detection utilizes this effect by measuring these pulses using Radio Frequency Current Transformers (RFCTs) placed on the earth sheath of the cable. One example of this is shown in Fig.2. There is a very important and practical consideration that needs to be taken into consideration when looking at the applicability of taking these on-line measurements. If the RFCT is placed over both the line conductor and the earth cable at the same time, the discharge currents are cancelled. The connection must therefore always be made by monitoring the earth cable only (or the line conductor after the earth has been taken off, provided the line current is low).

Fig. 2. RFCTs installed on the earth conductor of single-core cables.

If these earthing arrangements are not available, for example the earth sheath is taken off inside the cable boxes, then high voltage safety practices must be followed. The tests remain non-intrusive in that they require no disruption to the power delivery. High voltage areas can be accommodated through the use of dielectric and arc flash PPE, hot sticks, and other energized conductor work methods. Alternatively, the RFCT sensors can be permanently installed during a shutdown. In practice our experience has shown that in North America free access to ground straps occurs only at cable risers. Outside North America about 75% of cables are safely accessible. However, access is dictated by local policies and procedures in place at the time cables were commissioned; so for some companies it may be that almost 100% of cables can be tested while others almost none.

3.1.2 Dealing with Noise

When carrying out on-line testing with the cable in service a difficulty that will be encountered is dealing with noise on the cable earth system. Noise will often occur in the same frequency band as PD signals and will be detected by the RFCT sensor. Simply measuring amplitude can therefore provide false alarms of PD and will only have limited application. Simple devices will typically utilize in-built filters to try and overcome the effect of noise e.g. a high pass filter in the 1.4 – 1.8MHz range. This has the effect of blocking much of the noise on the earth system but at the same time reduces the ability of the instrument to detect PD signals far down the cable. As the current pulses transmit down the conductor and earth cable from the discharge source, the signals attenuate and ‘flatten’ effectively cutting off the higher frequencies to the point that they are filtered out. Despite the use of high pass filters, simple measurements can still be prone to false alarms and have not been found to be particularly effective for initial widespread screening of cables for PD.

Table I demonstrates this from the results of recent testing of a representative sample of circuits on a utility network. The circuits chosen were from a number of different substations in different geographic locations on primary and distribution networks using XLPE cables operating at 11kV and 33kV. The samples included a mixture of 3-core cable measurements and single phase cable measurements.

TABLE I
PD Testing of 14 XLPE Cables on Distribution Network and Use of Simple RFCT Amplitude Device with Different Filters

Signal	Green	Amber	Red
Cable group A – all 12 cables are good (Green)			
No Filter	0	0	12
500kHz Filter	0	3	9
1.8MHz Filter	8	3	1
Cable group B – 2 cables are moderate (Amber)			
No Filter	0	0	2
500kHz Filter	0	0	2
1.8MHz Filter	0	2	0

Table II provides detail of a classification of discharge amplitudes typically applied to XLPE cables.

TABLE II
XLPE Cable PD Classification for pC Reading

PD Value	Action	Color
0-1000pC	Normal	
1000 – 2000pC	Investigate Possible source, plan repair	
> 2000pC	Serious PD Activity	

Table I shows that of the 14 cable XLPE cable circuits tested, 12 (cable group A) had no PD and 2 (cable group B) had moderate levels of PD. Without the application of any filtering all 14 indicated Red, with a 500kHz filter 9 indicated Red and the remainder amber. Even with the application of a 1.8MHz filter 1 sample was classified erroneously as serious red-level discharge and 3 erroneously as amber-level discharge. False readings are highlighted in red. Therefore 4 out of 12 or 33% of this small sample incorrectly suggested further investigation was warranted when no PD was present.

To improve the diagnostic capability from this simple amplitude-only measurement we need to capture information on the pulse shape and reference captured signals to the 50/60Hz supply frequency. To capture this information, additional processing capability is required, as per the equipment shown in Fig. 3.

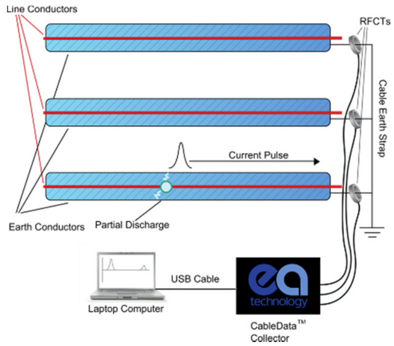

Fig. 3. Equipment for 3-phase On-line measurement of cable PD.

To help with the analysis, the equipment makes use of a supply reference or if one is not locally available the instrument will detect the reference from the connected RFCTs. In the case of this particular CableData Collector instrument a series of filters are automatically applied during the capture process as well as it capturing raw unfiltered data. This enables better subsequent interpretation of the data but with automatic application of filters the data capture process is simple, quick, accurate and a non-specialized function. The improved analysis is demonstrated in Fig.4 and Fig. 5. Both of these show similar amplitudes recorded by the instrument of 3000 – 4000pC, clearly in the red zone for XLPE cable. Looking at the waveform and the phase-resolved plot of Fig. 3 it is a relatively simple matter to conclude that there is no phase locked signal and the waveform is not consistent with partial discharge. Fig. 5 on the other hand shows as clear phase resolved nature to the activity with a pulse shape indicative of PD.

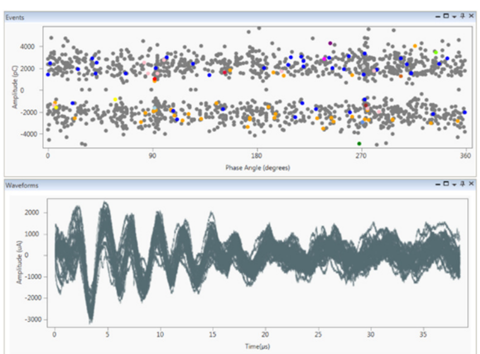

Fig. 4. On-line measurement of cable with noise on the earth system.

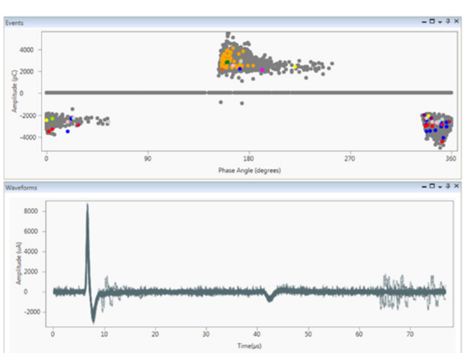

Fig. 5. On-line measurement of cable with partial discharge.

Without the ability to look at the waveform or reference signals to the 50/60Hz supply, both of these measurements would be classified as serious PD. Therefore, for equipment to be used for screening of networks, it is important to have this ability. Without this, as demonstrated in Table I and Fig. 4, there can be a high, potentially unacceptable number of false positives. Along with taking up valuable engineering resource and time to investigate these false positives, it can quickly lead to loss of confidence in the use of on-line technology to detect PD and be a barrier to adoption of a useful tool for the asset manager.

Another point to note about noise on the earth is that these measurements were taken on an electricity distribution network. On industrial networks with higher numbers of potential interference sources such as Variable Speed Drives etc., the instances of high noise interference has typically been found to be worse.

3.1.3 Practicalities for Measurement

The benefits from on-line cable PD testing are maximized when it is used extensively across a network. Testing large numbers of circuits will help assess the overall condition of the network, show how the assets are ageing, predict future failure rates and help assess the level of on-going expenditure (Capex and Opex) needed to meet requirements for future network reliability. As shown, high levels of noise present on the system can lead to a requirement for filtering and waveform pattern analysis to detect PD signals within this noise. This can make accurate interpretation of at least a proportion of the data a specialized task.

As soon as we introduce specialists into the equation, we invariably start limiting the application due to complexity of measurement equipment and the availability of the specialists to take and interpret results within the substation. The way to overcome this constraint is to make the collection of the data a simple and automatic process. The device shown in Fig. 3 and used to capture the samples in this paper has been purposely designed to simplify the collection process; automatically applying filters and allowing expert interpretation to be carried out away from site on a standard computer. This allows site measurements for a set of 3 single core cables to be carried out in approximately 5 – 7 minutes. Data analysis of a simple situation takes only a few minutes and can be done by any operator with basic training. When analysis is complex it may take around an hour by a trained specialist. Therefore, with the correct application of equipment and appropriate personnel, large volumes of the network can be assessed in a relatively short period of time.

4. Field Failure Experience

A major UK utility recently completed an evaluation of the technology with positive results. As this was a technology assessment, no attempt to address suspected cables was made during the trial. Over an 18 month period

188 33KV cables were tested with an online cable test device as described above. The cable results were classified into green, amber, and red as shown in table II above.

Within the 18 month test period and six months afterward, 13 cables failed. The results below showed that the red and amber categories had significantly higher failure rates. This proved to the utility that this type of online testing was effective at identifying at risk cables.

TABLE III
PD related failures of 33KV cables

Cable category	Quantity Identified	Failed Within 2 Years
Green	157	< 2%
Amber	14	21%
Red	17	41%

5. The Case for Permanent Monitoring

The use of periodic measurement to understand the condition of assets immediately brings business benefits; enabling more effective management, and informing replacement or expenditure decisions. Progressing onto permanent monitoring systems enables the same assets to be monitored under a variety of different operating and environmental conditions and of course can be a less labor intensive way of collecting condition data. Online monitoring also provides benefits by warning of developing failure modes. Early warning can provide an opportunity to minimize the negative effects of failure and therefore reduce the potential for negative consequences such as loss of supply or costs such as damage to equipment and secondary consequences.

So permanent monitoring has the ability to bring additional benefits to an organization. However, there will always be a calculation to be made weighing up the balance of additional benefit and the cost of implementation. One way of quantifying the economic benefits of on-line condition monitoring is to consider the decision in terms of risk reduction. Reference [3] demonstrates how using a means to quantitatively evaluate risk and understanding how on-line condition monitoring can be used to mitigate the risk associated with electricity assets, a significant proportion of the population of assets can often warrant the installation of permanent monitoring solutions.

An asset group where this approach often concludes in favor of permanent monitoring of assets is EHV cables. For these assets the consequence of failure is high elevating the calculation of risk (probability × consequence). Another factor adding to the justification of permanent monitoring is the difficulty in accessing such installations regularly.

5.1 Full Time EHV Cable monitoring

Fig. 6 shows a 220kV cable tunnel where a power authority chose to install a permanent PD monitoring solution for its cables. There were three circuits to be monitored, installed in two adjacent parallel tunnels. Each circuit was 3.4km in length with a total of 8 sets of grounding boxes for each circuit. Each grounding box required RFCT sensors to be installed on each side of the grounding point for each phase as PD signals will not pass along the total length of the cable circuit due to the change in impedance at these points. It is worth noting that due to these complex earthing arrangements on higher voltage installations the distributed monitoring system enables easier analysis of data when compared with individual spot check measurements.

Fig. 6. 220kV Cables in Tunnel requiring On-line PD measurement.

Fig. 7 shows the RFCTs installed onto the earthing cables linking the cable joints to the grounding boxes. Each sensor connects to a local node unit near each grounding box. The nodes daisy-chain and communicate back to a hub server installed at the substation. The hub controls and monitors the system, collects data for analysis and provides some automatic configurable alarms to provide early warning of degradation. Due to the distances involved between nodes, links are made using fiber-optic cable. Each local node obtains a phase reference source.

Fig. 7. RFCT sensor on earthing of 220kV Cables in Tunnel.

Despite these significant changes in hardware, the principle of the analysis remains effectively the same with detection of amplitude, phase patterns and waveform analysis. The obvious benefit of early warning of unexpected degradation was realized soon after the monitoring system was commissioned on these circuits with phase resolved PD detected on one of the cable joints as shown in Fig. 8.

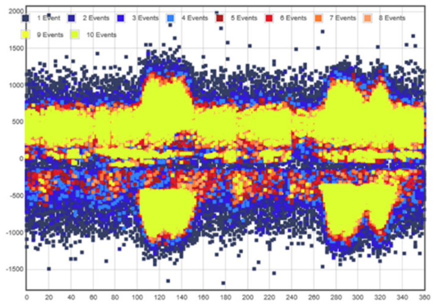

Fig. 8. Phase resolved chart from monitor installation on 220kV cables.

6. Conclusion

The paper has demonstrated that the ability to monitor and effectively screen cable networks for PD activity on-line is available and shown to be effective. The work presented shows that effective screening of cables cannot simply rely on measurement of PD amplitude, as noise on the earthing system can cause a significant level of false positives. To determine if PD is present and to assess its severity, requires measurement of amplitude, analysis of the waveform and phase resolved analysis of the signals.

Automatic application of filtering and simple capture of data to allow remote analysis can reduce the need for specialist resource at site and make best use of this valuable time. Using the most appropriate resource to carry out the different elements of the task will enable up to date condition data for cable networks to be quickly and cost effectively gathered. Use of this information allows better informed asset management decisions to be made, can reduce or lessen the impact of failures and improve network performance.

Finally the paper gave an example where the criticality and assessment of risk on three parallel 220kV cable circuits led to the decision to install a permanent partial discharge monitoring system and showed how immediate benefit had been delivered through the early detection of a defective joint.

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