ASSET MANAGEMENT OF HV CABLES ON AN ELECTRICITY DISTRIBUTION NETWORK USING ON LINE CONDITION MONITORING

Graham EARP
EA Technology – United Kingdom
Graham.earp@eatechnology.com

John BURNS
NIE Networks – United Kingdom
John.burns@nienetworks.co.uk

ABSTRACT

This paper describes how an on-line partial discharge monitoring system has been used to determine and monitor the condition of underground 33kV cables on the electricity distribution network belonging to Northern Ireland Electricity Networks. It explains the reasons for moving to a continuous monitoring regime, describes how the system works, and shows how the information it produces has been used to protect against sudden failures and associated unplanned outages. Its use for future network planning is illustrated, including prioritisation and justification of investment strategies to best meet the needs of NIE Networks' business.

INTRODUCTION

Northern Ireland Electricity (NIE) Networks owns and operates the electricity distribution network which transports electricity to over 870,000 customers in Northern Ireland. Part of this distribution network comprises over 3,700km of HV underground cable, which ranges in age from present day to 75 years old. Naturally, some of these cables are now experiencing age related failures and require replacement. However, variation in the condition of the network cables means that many can still continue to provide further service despite their age. The problem facing NIE Networks is how to determine the relative condition of the individual cables so that it can select and prioritise those that need to be replaced, and how to perform the requisite strategic and commercial planning to justify their replacement.

Partial Discharge (PD) within cables is a destructive process resulting from the partial breakdown of the insulation inside the cable that will eventually lead to its failure if left unchecked [1]. Its detection and measurement can also provide a good indicator as to the health of an individual cable, as well as allowing the cable to be repaired or replaced before it fails catastrophically. EA Technology has developed a novel technique for performing on-line 24/7 PD monitoring of underground HV cables and, together with NIE Networks, has installed three separate systems to monitor the condition of the cables in three of NIE Networks' primary substations located in and around Belfast in Northern Ireland.

This paper explains how the system works and describes the three installations in Northern Ireland. It shows how the information produced by the system is used by NIE Networks in both the day-to-day management of the network, as well as for longer-term investment management decision making and planning.

BUSINESS JUSTIFICATION

In recent years, NIE Networks has concluded that partial discharge monitoring techniques can provide the best means for determining the condition of its cable network. Like for like, cables exhibiting a high level of PD have a greater risk of failure than cables with little or no PD activity. Historically, NIE Networks has employed off-line PD measurement techniques in a reactive capacity to assess the condition of its 33kV cables. While this has proven valuable for condition assessment, off-line techniques are time consuming and require outages, which present a heightened network risk.

Over the last few years both off-line and on-line periodic testing of cables in substations within Belfast has been carried out. The tests focused on mass impregnated Paper Insulated Lead Cables (PILC) which are known to have inherent problems with oil migration in the insulation. These cables have also been 'scored' during failure repairs and evidence of the paper insulation being in poor condition at or near the point of failure has been observed.

Without routine testing it is impossible to establish condition trending of these cables. On-line PD mapping techniques provide a continuous monitoring capability and can be a powerful tool for the risk management of these critical cables. In view of the increasing age profile of this asset base, NIE Networks decided to introduce on-line PD detection equipment across its critical 33kV circuits within Belfast. The data gathered is being used to provide a sound basis for prioritising future investment decisions and anticipating possible failures as well as permitting the deferral of investment of other cables of interest in order to extend their asset life. This will inevitably lead to improvements in cable reliability and operating life expectancy in a cost effective manner.

CABLE PD DETECTION

When a partial discharge occurs within a cable under normal in-service conditions it results in a small high-frequency current pulse between the two conductors i.e. phase-to-phase or phase-to-earth. At high frequencies the cable behaves as a transmission line and the current pulse will travel along the cable in both directions away from the discharge site. In the case of a phase-to-earth discharge (by far the most common due to cable screen construction), High Frequency Current Transformers (HFCTs) can be fitted around the earth strap where the cable terminates within the substation and used to detect the travelling current pulse (and hence the presence of PD) when it reaches the end of the cable. There is normally a mis-match of impedance at the cable termination which results in a proportion of each of the travelling pulses being reflected back and forth along the cable until they decay away due to attenuation. By comparing the relative timing of the reflected pulses, it is possible to estimate the location of the PD source, expressed as a percentage of the cable length [2].

The above principle of operation is used by the CableData Monitor™ (CDM) system described here. A major advantage of this technique is that it can be deployed non-intrusively while the cable remains in normal service i.e. it is an on-line system that it monitors for PD under normal cable operating conditions with the system volts applied and, unlike some traditional methods, it does not require an outage for detecting PD.

CABLE MONITORING INSTALLATIONS

Three separate CDM systems were installed at three separate NIE Networks substations in Northern Ireland. Each system is configured as per the block diagram shown in Figure 1.

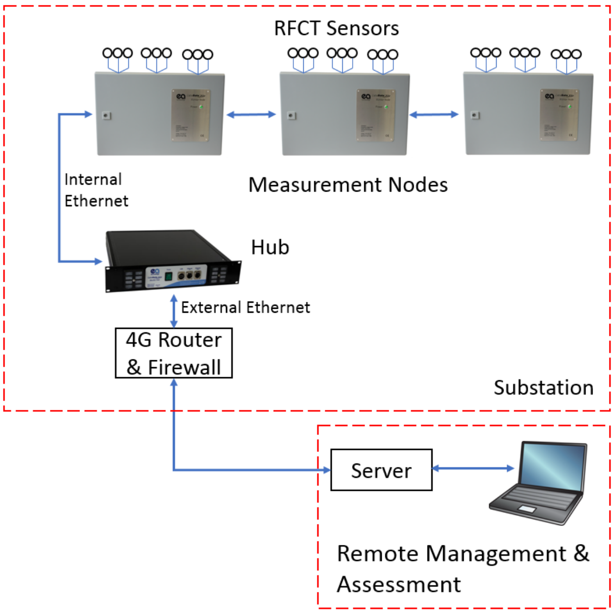

Figure 1 CDM System Block Diagram

The Hub is installed in an IP54 enclosure inside the substation (Figure 2) and the three Nodes connect to it using standard copper wire Ethernet cable (Figure 3). Each measurement Node has 9 inputs, each of which can monitor a single power cable by connecting it via a coax cable to an RFCT sensor clipped around the cable earth termination (Figure 4). Thus, each of the installed CDM systems in this configuration can monitor up to 27 individual power cables. The Node boxes are mounted physically close to the cables that they are monitoring within the substation, but the Hub can be some distance away. Data collected by each of the nodes is passed to the Hub where it is processed and stored. Each Hub is equipped with a 4G modem to provide a 24/7 continuous monitoring service and allow remote interrogation/investigation using a suite of built-in analysis tools.

Figure 2 Hub Unit Installed Within IP54 Enclosure at Carnmoney Substation

Figure 3 Node Units Installed at Belfast Central Main Substation

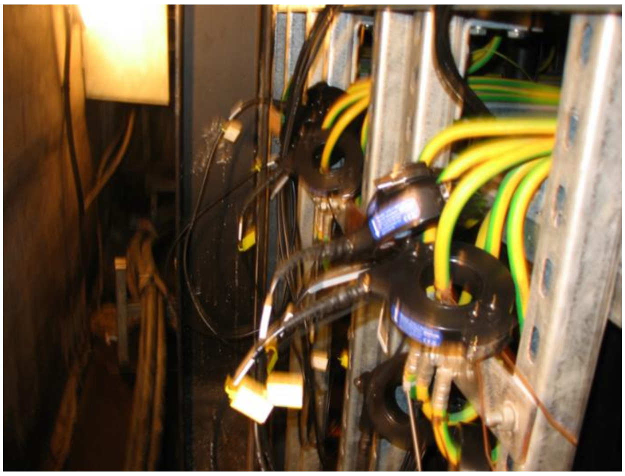

Figure 4 RFCTs Installed Around Cable Earth Straps at Skegoneill Substation

The remote communication link is totally separate from any of NIE Networks' corporate IT networks so there is no cyber security risk to NIE Networks. Custom thresholds can be set on a range of parameters that can be used to trigger warning alerts when they are exceeded. The Hub can issue email and SMS text notification messages to inform EA Technology when an alert has been triggered and further investigation is required.

The circuits being monitored with the CDM were selected in relation to their criticality with respect to the consequence of failure - which includes both network risk and physical location. Most of the circuits have been historically subjected to both on-line and off-line PD spot measurements, including Very Low Frequency (VLF) testing, and have a history of repeated failures which are well documented. The chosen substations also have a high concentration of PILC cables which made them well suited to make full use of the measuring capability of the CDM system.

In addition, NIE Networks had already identified (through previous historical data) circuits that would need intervention. It was decided to monitor these circuits as this would provide the opportunity to use the CDM to help physically locate the positions of the partial discharge and to retrieve these sections of cable or joints to carry out further analysis of any evident failure modes.

MEASUREMENT AND ANALYSIS

The CDM can perform a range of PD related measurements. Some of those commonly used are described below.

Event Amplitude Mean

Every two-minute logging interval, the CDM computes the mean value of the magnitude of all the PD pulse events it has detected within that two-minute window for each cable being monitored. This provides a good measure of the overall PD level on an individual cable and can be used for trending and triggering alerts if certain threshold settings are exceeded. An example of PD developing over several months on one of the cables being monitored by the CDM can be seen in Figure 5.

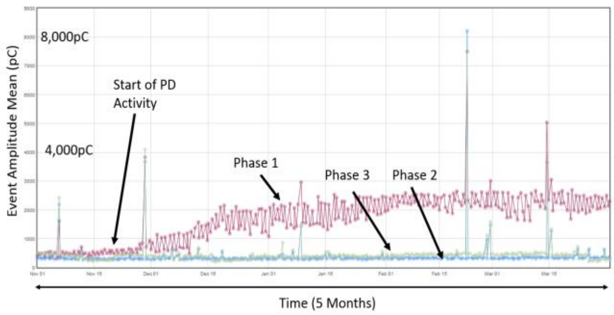

Figure 5 Cable PD Trend Analysis Showing PD Developing on One Phase of a Three Phase Circuit

Phase Plots

The phase plot shows the relative magnitude of each PD pulse event detected (in pC on the Y-axis) against the phase position at which it occurred on the 50Hz mains cycle (0-360° on the X-axis). This type of plot is useful to distinguish between electrical interference and genuine PD activity because:

- Genuine PD will normally occur around the same point on each half cycle when the supply voltage exceeds the inception voltage of the PD source.
- Electrical noise tends to be randomly distributed across the entire cycle and will not exhibit the clustering effects indicative of PD activity.

Hence, genuine cable PD will normally appear as a pair of event clusters separated by 180° as depicted in Figure 6. The plot intensity also gives a visual indication of the number, relative magnitude, and distribution of the individual PD pulse events, as well as allowing the typical maximum values to be used to evaluate the severity of the PD.

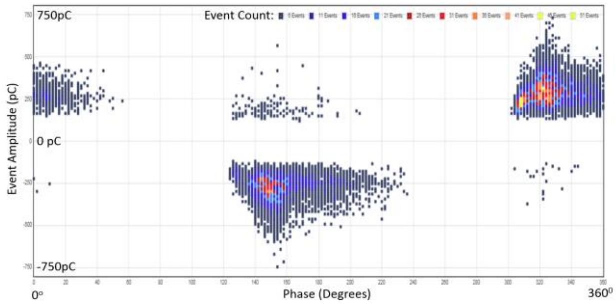

Figure 6 PD Event Phase Analysis

Waveform Capture

The CDM can be used to capture actual event pulse current waveforms. Examination of the waveforms is another method of determining whether or not the activity on a cable is genuine PD or is coming from some other potential source. Cable PD waveforms are typically characterised by narrow (less than 1us) unipolar pulses with a fast rise time. If PD pulse reflections are present, and the cable records are available, then using a knowledge of the cable make up/joint positions etc. it is also possible to estimate the location of the PD source along the length of the cable from the waveform trace. An example of a cable PD current pulse waveform with multiple reflections that would enable location of the PD source is shown in Figure 7. The fact that the indirect pulse is close to the double reflected direct pulse implies that the PD source is close to the near (monitored) end of the cable [2].

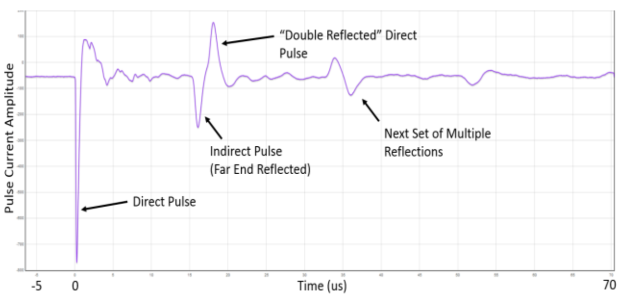

Figure 7 Captured PD Waveform Analysis

PD CLASSIFICATION

Once the Event Amplitude Mean, phase and waveform information has been used to confirm the presence of PD on a cable, the event magnitudes from the phase plot can be used to classify the PD level. Whilst there are different approaches that can be used to do this, the values given in Table 1 are typical of those widely recognised within the literature and by PD practitioners. Using this method also allows the results of the on-line CDM measurements to be compared to alternative traditional off-line measurements such as Very Low Frequency (VLF) testing. Whilst in general EA Technology has found good correlation between the two methods, some caution has to be exercised as the cable energising conditions used by the two techniques are quite different and this can affect how the PD source behaves.

PD Level	XLPE		PILC	
	Cable	Accessories	Cable	Accessories
Acceptable – no action required	PD Free	0-500pC	0-2,500pC	0-4000pC
Some concern - monitor	<500pC Ideally PD free	500-2,500pC	2,500-7,000pC	4,000-10,000pC
Major concern - investigate	>500pC	>2,500pC	>7,000pC	>10,000pC

Table 1 Classification of Cable PD Levels

RESULTS

Since they were installed in October 2017, the three CDM systems have been monitoring a total of 72 cables for over 12 months. After the first few months monitoring a detailed assessment was made of each of the cables allowing them to be classified based on their condition in terms of green/amber/red, as shown in Table 1. The assessment included a description of the nature of the PD including any trends, an estimated location (where cable records were available), and recommendations for further investigation/monitoring where there was any reason for concern. A summary table was produced for each substation; an example of which is shown in Figure 8.

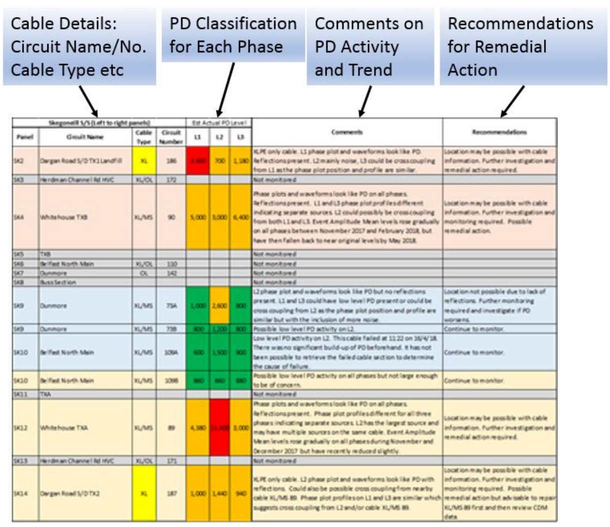

Figure 8 Example of Cable Categorisation and Prioritisation Summary Table

As well as providing a useful benchmark against which to judge future changes in cable condition, this provided a readily visible means for prioritising remedial work. The historic trend data captured over the previous months was used to establish appropriate alert threshold levels to enable notifications to be set up to communicate any significant deterioration in the existing PD levels, or the initiation of any new sources going forward. This monitoring method has proven to be particularly effective in both managing existing PD as well as detecting the sudden development of new PD sources – an example of which is now described.

DETECTION OF FAILING 33KV VOLTAGE TRANSFORMER

Figure 9 shows an example where the CDM has detected a new PD source starting to discharge fairly abruptly and continuing to increase at a rapid rate over a short period of time to relatively high levels. Alert notifications were triggered immediately the PD started. The PD behaviour was investigated remotely using the CDM. The Event Amplitude Mean trend data showed that the PD was affecting many of the cables in the substation to differing degrees. The phase plot and waveforms were not characteristic of cable PD and, for this reason, it was thought likely that the PD source originated in the HV switchgear rather than on one of the actual cables.

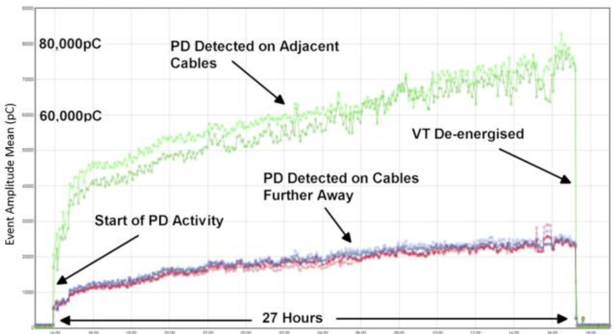

Figure 9 Detection of PD on Voltage Transformer (VT)

An engineer arranged to visit the substation in order to perform PD measurements on the HV electrical panels using a hand-held UltraTEV Plus instrument. High levels of Transient Earth Voltage (TEV) were discovered around the panel housing the 33kV Voltage Transformer (VT) which was located physically adjacent to the highest reading CDM monitored cables. On closer inspection it was observed that the VT could be heard audibly discharging. Arrangements were made to promptly remove the VT from service and replace it with another one. The plot in Figure 9 shows that the PD stopped as soon as the VT was de-energised and did not return after the replacement was fitted. This intervention prevented the VT failing completely, together with any collateral damage that may have occurred had it failed catastrophically. The example also shows that, in certain circumstances and with the appropriate analysis, the CDM can detect other PD sources in addition to those directly on the cables it is monitoring. The opportunity to energise the defective VT under controlled laboratory conditions, run it to failure, and then perform a forensic examination is currently being explored. This would provide useful information that could be used to relate time to failure to the measured trend data as well as establishing the exact cause of breakdown.

USE OF INFORMATION

NIE Networks has combined the PD condition information with data from its historic fault and post fault analysis records to identify the worst performing circuits. As a result, approximately 5.34km of 0.15 square inch 33kV HSL construction PILC cable installed in various sections distributed across five primary circuits has been prioritised for replacement. It was also discovered that a particular vintage of cable (circa 1954), and hence a particular type of cable, was more prone to condition-related deterioration than others.

This information has enabled NIE Networks to formulate and manage its replacement investment programme based on the true condition of the cables, allowing it to target the expenditure where it is most needed and where it will deliver maximum benefit in terms of reduced outages and reduced customer interruptions. Removal of the defective cable sections/joints from service is planned to take place during 2019.

Identifying the defective sections with the CDM also means they can be removed intact before a catastrophic failure occurs. This enables the defective sections to be examined forensically to determine the nature of failure mechanism before the forensic information is lost as a result of a disruptive failure [3]. As well as providing valuable feedback to validate the cable monitoring system itself, understanding the nature of the cause of failure means that measures can be taken to prevent the same thing happening again in the future.

CONCLUSIONS

This paper has shown how the PD levels in different cables can be continuously monitored to provide valuable condition information that can be used for both day to day management of the cable network, and also for making better informed future investment strategy and planning decisions. Within NIE Networks, alert thresholds have been set to trigger remote notifications if PD levels on monitored cables exceed certain pre-set levels. This means that appropriate remedial action can be taken in a timely fashion if the level of the PD is deemed to have become critical. It has been shown that the system is also capable of detecting non-cable faults in some instances. A recent example of where the potential catastrophic failure of a 33kV VT within one of the monitored substations has been avoided has been described.

Various PD related parameters have been analysed to assess the current condition of the individual cables and to classify them into low, medium, and high-risk categories. NIE Networks has used this information to prioritise its replacement programme and to justify the expenditure and plan for the work this involves. By reducing the likelihood of in-service failures this increases the performance of the network as well as enhancing personal safety of those working in close proximity to it.

FUTURE PLANS

A programme to replace some of the discharging joints and cable sections identified by the CDM is set to commence during 2019. Where possible, the ex-service cable components will be forensically examined to identify the failure mechanism and correlate this with the measurements made by the CDM system. This will allow the behaviour pattern of the observed PD to be better understood in relation to the severity of the developing defect. This will enable the performance of the CDM to be enhanced, and also offer the potential to improve the techniques for estimating time to failure when PD is discovered on an in-service cable. This will provide real benefits as an aid to improve decision making when managing aging underground cable networks as well as for future network investment planning. It is expected to be able to provide an update on this work programme by the time of the CIRED 2019 conference.

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