An Update on Cable and Switchgear Incipient Fault Monitoring

By

Cliff Walton
Cre8 Innovation Solutions Ltd

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Cre8 Innovation Solutions Ltd, UK

Abstract

There has been a rapid escalation in interest in on-line techniques for the detection and location of incipient faults in both cables and switchgear since the last review [1] presented at Euro TechCon in November 2003. This update summarizes some of the reasons for these developments, identifies some key developments, promising techniques and trends that have been presented at recent conferences and then points a possible direction for future research and development.

Introduction

The United Kingdom's electricity supply industry, like those in many other developed countries, will face a new set of challenges over the next decade as it strives to improve and maintain supply standards while minimizing operations and maintenance (O&M) costs and embarking on major asset renewal programmes.

Since the privatization of the U.K.'s electricity distribution industry in 1990, the distribution network operators (DNOs) have reduced their O&M costs by downsizing the number of internal staff and outsourcing some functions. A consequence of this approach is that the distribution companies are continually striving to improve their asset management methods. The reasons for this are twofold: there is an ever-increasing profile of "aged" installed equipment, combined with a trend toward reduced in-house engineering and technical knowledge.

The increasing age profile of installed U.K. medium-voltage (MV) plant is driving the application of on-line condition assessment both as an asset management tool to extend plant life and now as an effective tool to prioritize where capital renewal should take place first.

Much of the volume of the U.K. distribution system was installed during the 1950s and 1960s and consequently a large quantity of equipment is now approaching the end of its original life expectancy.

In recognition of the ageing asset base the UK regulator Ofgem as part of the 2005 Regulatory Distribution Control Review has recognized that for some companies the time has began to begin increasing the rate of capital renewal. In total these proposals allow for UK investment of £5.7 billion over the years 2005 – 2010 to deliver improved performance, an increase of 48 per cent over expenditure in the previous price control period [2].

While this does not mean that equipment nearing the end of its planned asset life is necessarily about to fail, it does imply the renewal or refurbishment of these assets should be effectively prioritized and managed with a condition and risk-based approach.

In addition recent regulatory incentive changes [2] mean that DNO now have balanced financial incentives. Ofgems's new interruptions incentive scheme will have symmetrical annual rewards and penalties depending on each DNO's performance against their targets for the number of customers interrupted per 100 customers (CI) and the number of customer minutes lost per customer (CML). The proportion of revenue exposed under the scheme will be 1.2 per cent for CI and 1.8 per cent for CML respectively.
To achieve an effective condition-based asset management policy, the plant condition needs to be checked regularly and in a systematic, economic and effective manner.

The costs and difficulty in obtaining outages to facilitate offline tests, and the operational risks incurred in arranging such outages are increasingly seen as a major deterrent to regular condition sampling. Additionally the variability of operating conditions and evidence of the rapid rate of fault evolution means that even recently tested circuits may fail shortly after apparently healthy off-line testing.

Increasingly assurance is being achieved by a combination of the selective installation of permanent remotely monitored online condition monitoring and location systems at sites of perceived higher risk in conjunction with offline confirmatory and pinpointing techniques.

Why focus on Cables and switchgear?

All components of power systems are from time to time subject to faults. However the impact of such faults is far from uniform with some types of faults having much more serious consequences in terms of customer service, operational impact, cost and regulatory impact than others [3]:

> ***Protection and Control*** system failures have the largest potential impact but currently most reported asset management appears concentrated on ensuring the equipment has been specified, installed, set and tested correctly. On-line condition monitoring of protection systems have yet to be widely reported. Switchboard failures are fortunately comparatively rare but their impacts are amongst the most serious on distribution systems with such failures potentially impacting tens or even hundreds of thousands of customers for many hours or in some cases days whilst temporary repairs and large scale load transfers are arranged. Their impact on continuous process industries can be particularly devastating with the value of lost production running into many millions of pounds.
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> ***Transformers:*** Generator transformer failure is fortunately rare but extremely serious as the inability to generate can place severe financial burdens on owners who may in consequence need to purchase power at spot market prices to meet contractual obligations. Distribution transformer failures in contrast, whilst they are also fortunately comparatively rare and also can be very expensive to repair or replace, do not usually result in immediate loss of supply. In consequence transformer condition monitoring is the subject of much activity internationally with many conference papers and is not further considered here.

Cables: MV and to a lesser extent HV underground cable failures are however comparatively common and for many operators beginning to show small but significant year on year increases. They regularly affect several thousand customers or more for an hour or more, and are thereby responsible for the vast majority of both interruptions and customer minutes lost in the UK and therefore directly impact the financial results of DNOs. The increasing constraints on undertaking streetworks for repairs also mean that outage times and emergency repair costs are rising rapidly.

Overhead lines typically have significantly higher fault rates than underground cables but MV circuits frequently supply much fewer customers and repair times for single events are much faster. Failure of single EHV lines does not usually result in major outages, but in conjunction with inappropriate protection and control arrangements have frequently been cited when reviewing the causes of major incidents. Online condition techniques for overhead lines are generally at the concept/embryonic stage and progress will perhaps be worthy of review at a future conference.

The primary focus of this paper therefore concentrates on the development of online detection and location of incipient faults in MV switchgear and cables where the drivers and technologies have developed significantly since the last TechCon conference.

MV Switchgear

Encouraging results from the use of continuous ultrasonic monitoring of on-line partial discharge events in critical MV switchboards by IPEC Ltd have been reported in case studies[4]. In one instance a significant change of activity was captured well ahead of the eventual catastrophic failure of a large multi-panel switchboard at a major international airport. In another case study a major interruption to a large continuous process semiconductor factory was avoided by the remote online recognition of incipient failure in a circuit breaker and prompt action by the operator to isolate and repair a set of discharging contacts in an advanced stage of failure.

Moore [5] reports good progress toward the development of automated Radiometric Substation Discharge Monitoring for the detection and location of partial discharges in high voltage open switchyards. Using impulsive wideband antennas and advanced signal processing to exclude background noise, this provides locational accuracy of:

- Bearing ±1°
- Range ±0.5 m (source at 10 m)
- Range ±5 m (source at 100 m)

This provides sufficient accuracy to resolve between phases of plant items even in 33 kV substation switchyards. Case studies involving the successful identification of faulty bushings in both 33kV and 400kV grid sites have been presented.

At this stage a comparatively small number of critical sites and circuits are continually monitored. Given the general reliability of the main plant, it is to be expected that it will be some time before sufficient data is available to draw firm conclusions. However for critical sites and equipment with a track record of discharge and failure, such systems do have clear potential for risk management application.

MV Cable systems

Offline systems

The level of interest in condition monitoring of MV cable systems [6] has grown rapidly in recent years and a wide variety of papers have been presented. The majority of which concentrate on the detection and location of partial discharges and/or the measurement of tan delta and the change of loss angle with voltage. Offline systems and associated guidance as to the criticality of results are now routinely employed by many utilities using both VLF 0.1Hz as presented by Mohaupt [7] and Oscillating Wave Systems (OWS) as presented by Pezold [8], the comparative merits of which continue to be debated but both of which are held to be of far greater diagnostic value and potentially less damaging to insulation than conventional DC HiPot testing.

An alternative Dielectric spectroscopy approach proposed by Papazyan [9] for the Detection and Location of Water Treeing in polymeric cables using multi-frequency injection techniques is a new entrant in the offline stable.

Recent developments have however been mostly concentrated in the area of online partial discharge location and detection systems.

Online Systems

On-line condition monitoring of equipment - partial-discharge (PD) monitoring is becoming more widespread in the worldwide electricity industry. Accurate condition assessment and the subsequent management of in-service, high-voltage plant is becoming more economically viable, with continuous advances and cost reductions being made in sensor technology, data acquisition/processing and intelligent diagnostic software [10].

Cotton et al [11] have established the limitations for an effective “zone of sight” for online systems as a function of the attenuation of PD signals due to cable type, length and intermediate switchgear and the need to correct for the effects of attenuation.

However advanced intelligent noise reduction systems as reported by Mackinlay [12] allow detection system to begin to sample below and into the background noise levels in order to be able to detect much smaller signals. Such developments, essential for online polymeric cable monitoring and in order to “see” further along PILC circuits, are already being reported.

However, it is clear that at the current stage of development the underlying requirement for online systems for PILC and Polymeric cable systems are, at this time, are still very different:

Polymeric Cables– Partial discharges in cables (as opposed to accessories) are typically found to be very small – often in the order of a few tens of pC and even though the signal propagation is much better than in PILC cables, the remote detection of small discharges above the background noise levels of energised circuits remains problematic.

Whilst there has been much debate, there is still no evidence that water trees are routinely associated with partial discharge but is does appear that over-voltage can result in water trees being converted to electrical trees as reported by Boggs [13]. In such cases when breakdown eventually occurs it can be very rapid indeed.

In practice most online systems for polymeric cables have to date concentrated upon detecting problems with joints and terminations which typically have much higher discharge levels than those occurring in main cable insulation.

Where polymeric cables are provided with wound copper screen wires (as opposed to foil wrap or lead sheaths) this presents the opportunity to use a variety of sheath based sensors in cable pits. These are capable of resolving discharge location to a high degree of accuracy. Experimentation and fieldwork shows that PD’s occurring in premoulded accessories can last from months to years before final breakdown
The same paper by Fournier [14] interestingly and perhaps surprisingly highlights the potential of thermographic cameras to identify discharging in-situ joints in pits.

PILC cables

In the UK, paper insulated lead covered (PILC) cables form the vast majority of the installed asset base even though such cables have not been routinely installed for some time. PILC with its continuous lead sheath, traps PD signals within the sheath preventing signals from being detected outside.

The majority of PILC online sensing is therefore undertaken through the use of high frequency current sensors fitted to earth bonding leads at cable terminations [15]. Recent developments have included the development of a variety of sizes of split core HF sensors for a wide variety of installation conditions including fully screened versions for locations subject to higher levels of external HF noise. Alternatively small capacitors used for voltage sensing have been used where they are already provided in switchgear, or can be economically retrofitted to cable terminations.

Significant developments

Renforth [16] previously reported a risk-based asset management approach and PD web based detection technology that provides systematic closed-loop condition assessment and management of MV plant.

The following criteria necessary for an effective condition-based asset management programme were derived by developing a integrated asset management philosophy focusing on the critical plant within the network:

*Identify critical plant and circuits (typically less than 5% of network).
*Direct monitoring/maintenance resources to critical plant (condition and/or location criticality).
*Establish an early warning system to detect trend to failure.
*Monitor key plant condition parameters and correlate with operational data (load, voltage).
*Generate a condition-based table of assets based on age, type, condition/location criticality.
*Establish dynamic iterative processes that continually review the criticality of plants and respond to any changes or trends in condition.
*Apply the condition knowledge into a decision support system for asset management and maintenance purposes.

Michel [17] reports building on these concepts with an extensive web based condition online assessment system monitoring many hundred of MV circuits. A comprehensive case study details the successful complete cycle of prioritisation, detection, trend recognition, location, off line confirmation, replacement of an identified defective section, followed by post event confirmation of clearance.

The same paper [17] presents mapping of discharge activity from the same circuit obtained first by on-line and later by offline location systems using the transponder approach previously reported by Walton & Mackinlay[10] and by Mackinlay[12].

Mackinlay [12] also reports advanced automated event recognition using “longshot” waveform analysis with characterisation of online events into a range of classes representing local, cable and noise events for further statistical analysis.

Van der Wielen [18] presents a dual ended automated online location system with integrated pulse synchronisation and calibration tools. He also compares on-line results over time for a test circuit with known offline defects and finds good agreement with the known defects. The 3d mapping of event over time as well as with circuit length, confirms the variability of discharge activity over time even without changes in circuit loading.

PD Criticality Factors

A wide variety of factors can now be reliably and routinely measured online for local processing and remote evaluation including:

Pulse size mV (ability to detect at a distance)
Pulse size pC
Pulse activity
Cumulative energy
Rate of change of activity
Thermal loading hysteresis
Time of day activity
Phase pattern
Phase pattern evolution
Pulse asymmetry

The degree to which such factors can be used individually or in combination over time to provide reliable assessments of the “criticality” or level of risk presented by an individual circuit and the approximate location or “localisation” is a matter of ongoing research for which there is no substitute for large scale field trial experience. The experience reported by Michel [17] and others confirms that discharge activity over time does not necessarily follow a smooth exponential curve to failure, rather is often characterised by cycles of intense activity followed by quieter periods, sometimes with several such cycles, before the ultimate failure and circuit trip.

Business case for deployment

The degree to which savings can be made using PD detection and mapping of circuits depends ultimately on both the accuracy of the testing the interpretation of the results and the effectiveness of the intervention business processes. However, the perceived benefits depend on the value placed on the avoidance of supply interruptions and repair costs, especially if these have added or unseen costs because of difficult city locations. Therefore, the benefits from applying this technology are attributable to:

Deferring cable replacement.
Avoiding unnecessary repair costs.
Improving network reliability
Deferring interruptions on sensitive circuits.

An estimated 90% of the potential savings are attributable to deferring cable replacement and improving network reliability.

Recent on-line PD testing surveys have shown that a small percentage of the U.K. cable population is at immediate risk. However, depending on the cost of an interruption, there is still some merit in replacing sections of cable that are discharging above acceptable threshold levels.

It is apparent that if cable circuits can be "targeted" through a systematic approach, the cost benefit of PD monitoring and mapping can be greatly improved. Failure history, current service history, local knowledge of the cables and joints, replacement planning, and other relevant data are all valuable aids in determining which circuits to test to maximize the utility's benefit.

Next steps

In reviewing the reported progress it is evident that whilst significant progress has undoubtedly been made, that a considerable number of fresh challenges have been identified. Amongst these are the development of:

- Advanced intelligent noise reduction systems to be able to detect and characterise much smaller signals, essential for online polymeric cable monitoring and in order to "see" further along PILC circuits.
- Advanced automated analysis to account for the impact upon circuit risk of variation in discharge activity due to circuit thermal loading, switching and network reconfiguration events.
- Automated recognition of the type of failure modes and their evolution over time towards failure and leading to quantification of the risks of failure at a particular time and place.
- Single end localisation, multi-tee location and pinpointing for PILC circuits
- Real time risk management
- Equivalent detection and location system for circuits including overhead lines.

Challenges from the CIRED 2005 RT1b

After debating the reported development in the field of online monitoring, delegates at the CIRED 2005 RT1b round table were invited to consider the following questions before the next meeting in 2007:

What evidence is there that diagnosis:

Has enabled utilities to significantly improve performance?
Can be a cost effective programme?
Provided a credible and useable indication of comparative risk?
Can be used to predict future performance and life?

Technical Challenges

What is the future for off-line monitoring?
How does circuit loading affect the life of cables?
How can we see through the noise of on-line monitoring?
What are the critical signs of an asset nearing the end of life - how long to we have to react?
Can we determine the type of defect and its criticality?
How can discharges be pinpointed for excavation to within a metre or two?

Asset Management

What cable management regimes are in place ?
What evidence is that they work?
Why has it taken so long for techniques to become established as the norm?

Summary

The ongoing trend in the electricity supply industry is to optimize asset management strategies and investment. A clear trend towards applying risk and condition-based approaches as alternatives to traditional asset replacement policies is becoming evident. This is being achieved through the application of advanced on-line condition monitoring technology and prediction techniques allied with a systematic, phased asset management approach and the appropriate use of off-line techniques. By this systematic approach, the cost-benefit of reliability/risk based MV plant assessment can be greatly improved. However, by taking into account failure history, current service history, local knowledge of the network, replacement planning and risk of failure vs. capital/operational expenditure, asset management decisions can also be made quicker and more efficiently with the use of dedicated decision support systems.

The number of researchers, developers and operators activity engaged in on-line condition assessment and location system has grown rapidly in recent years as the benefits of such approaches have become more widely appreciated.

Such systems have clear application now for private high value networks, critical infrastructure, high risk customers and networks with a relatively poor performance records. Extensive commercial deployment of such systems has now begun and successful case studies are beginning to emerge. More can be expected to follow rapidly.

However is also clear that further development work is required so that these approaches can be widely deployed on most distribution networks. This work will include the development of low-cost high performance monitoring systems, sensors with real-time "intelligent" diagnostic software systems for on-line PD cable mapping and remote automated monitoring of HV and MV plant.

Acknowledgments

I wish to acknowledge the contributions of the many published authors whose words and ideas I have extensively used, mangled and compressed in the preparation of this short overview. With my apologies to those many published authors on the subject whose works have regretfully had to be omitted but whose ideas and concepts have nevertheless been indirectly referred to in preparing this short overview for what is proving to be a rapidly expanding field of interest.

This contribution is therefore largely based on an overview of just a few of a large number of papers and presentations by recognized experts presented at CIRED 2003 CIRED 2005, RTDN 2005 as well as a condition monitoring tutorial given at CIRED 2005.

For further information on appropriate on-line technologies and an integrated asset management approach, contact Cliff Walton on +44 (0)208 328 6560 or via e-mail at cliff@cre8is.co.uk

www.cre8is.co.uk

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About the author

Cliff Walton

Cliff is Technical Director for Cre8 Innovations Solutions Ltd. His career in electricity distribution spans over 30 years and covers a wide range of senior roles and responsibilities. He has been responsible for the development and implementation of strategy and innovation in major utilities. He has worked with a number of overseas utilities and has written and presented many papers on a wide variety of technical and asset governance and management issues.

He studied electrical power engineering at South Bank, London and engineering business management at Warwick University.

He is a Chartered Electrical Engineer, a Fellow of the IEE, Senior member of the IEEE and member of the Institute of Directors. He is a visiting Professor at Imperial College London.

A founding member of the Patrons Group of the Institute of Asset Management, and is currently Deputy Chair of the IEEE UK&RI Power Engineering Society.

As a member of the organising committee for Cired 2005 in Turin, he chaired the round table RT1b on MV cable condition monitoring systems and well as leading a tutorial on distribution condition monitoring.

cliff@cre8is.co.uk
www.cre8is.co.uk

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