Diagnostics for MV cables and switchgear as a tool for effective asset management

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Summary

The introduction of diagnostics into the maintenance and operation of high voltage plant should show clear benefits if it is to be a useful tool in running a competitive electricity distribution company. This paper shows that the potential is certainly there, but some investment is required if the potential is to be realized. In a regulated business, this may be one of the essential tools in cost reduction and hence in competitive advantage. The examples of diagnostic methods applied to a network, come from London's 11kV cable network.

INTRODUCTION

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".

Timely location and targeted replacement of specific sections of unsatisfactory circuits enables the effective service life of the whole circuit to be economically extended.

As some 98% of the supply interruptions in London arise from cable systems, LPN is seeking to develop techniques to eliminate cable faults before they occur. LPN have 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.

REGULATORY AND BUSINESS DRIVERS

LPN is the owner and Asset Governor of the Distribution Network in London, LPN's predominant network assets comprise approximately:
2,000km EHV cables (above 11kV)
19,000km LV cables
8,000km MV cables
100 EHV/MV substations
13,000 distribution substations
2.1Million customer connections

The distribution business has arms length contractual relationship with about thirty competitive supply businesses that operate within London. LPN's charges and performance are regulated by the Office of Gas & Electricity Markets (OFGEM). London's Network is characterised by high load & customer density with high customer numbers per circuit, per km and per transformer.
Not only are the cost of cable laying for repairs, replacement and reinforcements very high but the disruption and traffic congestion caused by cable laying are most unpopular with Londoners.

Regulatory Requirements

As part of the third Distribution Price Control Review (DPCR) in April 2000, the electricity industry regulator set network performance targets for each of the distribution companies in terms of:

> **Frequency:** System Average Interruption Frequency Index (SAIFI) or customer interruptions per 100 connected customers.
>
> **Availability**: System Average Interruption Duration Index (SAIDI) or customer minutes lost (CML)
>
> Targets for reducing multiple interruptions have also been proposed, details of which have yet to be finalised but which are expected to be onerous.

Revenue was also reduced by a one off cut of typically 27% followed by a 3% reduction year on year.
In addition to this, a system of financial incentives based around performance against some of these measures is to be implemented in 2002 with initially 2% of revenue at stake.
The suggestion from the regulator is that companies will be placed within an incentive framework intended to mimic a competitive market. Companies that do well in meeting their agreed targets whilst maintaining Medium Term Performance, being financially rewarded whilst those who do less well being penalised.

THE CHALLENGE

Distribution companies need to consider how the required scale economies can be effected 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 customer satisfaction.

LPN and LE Group are proud to have consistently been one of the best performing Regional Electricity Companies in the UK. As part of its process of continuing improvement, London Power Networks has adopted a twin strategy of seeking, wherever possible, to eliminate failure before it occurs and using remote control systems to manage the risks associated with the unforeseen cable failures and damage that do occur.

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. By contrast HV (22-132kV) systems are generally designed such that single incidents do not result in loss of supply. Failures on HV switchgear are even rarer, perhaps one or two a year but the consequences are very much higher with the possibility of many tens of thousands of customers being interrupted.

Figure 1 shows the split in quality of supply incidents as a function of plant related cause. With some 70% of the costs of running and maintaining the distribution network being related to cable systems, the strategic focus of network and asset management must be upon the efficient and effective management of MV and LV distribution systems. However the consequences of a major HV event must never be ignored.

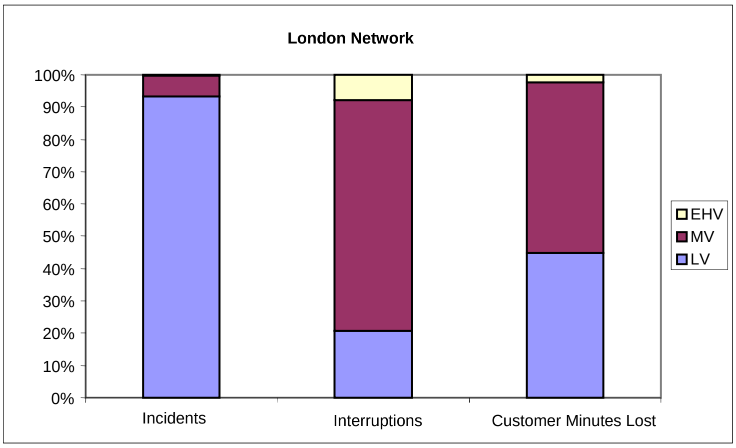

Fig 1 Quality of supply related to plant

The Regulatory and business drivers for reducing faults and particularly repetitive faults on underground circuits are clear; as well as savings in operational, and capital expenditure there are the positive benefits to be obtained from excelling in a competitive business frame and from regulatory competitive incentive regimes that will doubtless become ever more significant over time.

The majority of LE's 10,000km of underground 11kV cable is of 3-core belted paper insulated design with lead sheaths and steel wire armouring, some of which dates from the early part of the 20th Century. However, extensive failure analysis indicates that age by itself is no indicator of performance with some circuits installed in the early parts of the century performing perfectly whilst other sections have had to be replaced sooner.

Each year a proportion of the system is replaced as the city is redeveloped, but the relatively high level of system performance cannot justify wholesale replacement of established networks on the basis of age alone. This leaves the asset owner's dilemma of "where best to invest the next available £ to achieve maximum value" and in turn leads to the thought:

If it were possible to identify high risk sections of circuits in advance, and to replace just the few defective metres, just before failure occurs, the performance and costs of running the systems could be improved dramatically.

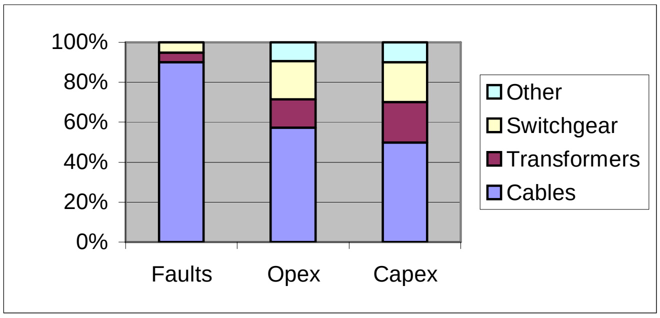

Fig 2 Contributions to faults, operational, & capital expenditure from different plant types

LPN have been using a variety of techniques to understand fault causation and the characteristics of incipient failure in order to achieve some of these benefits. Figure 2 shows the typical relative expenditure arising from different plant types. The figure shows why the diagnostic techniques have initially been targeted at MV (6.6kV and 11kV) rather than HV systems, because for London that is where the biggest gains are to be made. The techniques are also applicable to networks ranging from 22kV to 132kV.

PARTIAL DISCHARGE DETECTION AND MONITORING METHODS

Techniques generally fall conveniently into on-line and off-line methods. Recent results from the on-line monitoring for cables, has shown how much variability there is in the long term PD (partial discharge) behavior of plant. Cables and switchgear do not show a PD "level", but rather a time dependant activity itself dependant on load, current, voltage, temperature and insulation condition. Hence the on-line methods can actually give a better understanding of the behaviour of the plant under investigation than the off-line counterparts.

For switchgear, PD sensors are capacitive probes (held magnetically to the switchgear) or ultrasonic peizo pickups. The capacitive probes require higher frequencies for detection (say in the range 1MHz to 100MHz) and are suitable for short range detection. This generally means within 10m or so. The ultrasonic detectors are most useful with air insulated switchgear, or with discharges which are close to the metalclad surface of the switchgear. Noise is a perennial problem, and should be eliminated using gating methods or timing methods. Both are common in PD detection systems, but it should not be underestimated how difficult it can be to eliminate noise from PD detectors. Figure 3 shows some 33kV switchgear with three sensors (cable CT, capacitor, ultrasonic) being interfered with noise from an adjacent 132kV substation.

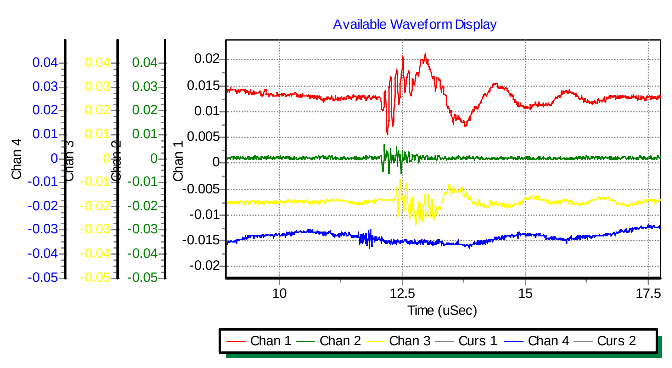

Fig 3 Noise on various sensors on switchgear
(Chan 1=CT, Chan 2=Capacitive, Chan 3=CT, Chan 4=Ultrasonic)

The cable CT's are high frequency devices attached around the earth strap of the cable. Figure 4 shows a recording of PD using noise reduction by a gating method. In this case, the capacitive sensor was used to gate noise on the cable CT.

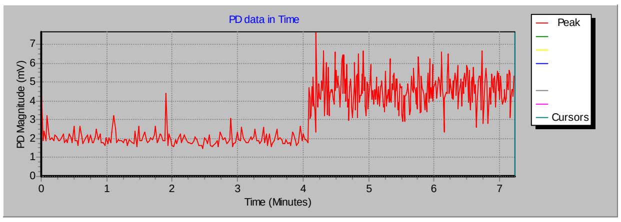

Fig 4 PD recording with and without noise reduction

The gating method of noise reduction is very powerful, but can still not be enough. An example of this is switching noise on a cable. This can only really be removed by a software method looking for pulses fixed in the power cycle.

For PD mapping, traditionally an off-line method, (where the power supplies to energize the cable are VLF or oscillating wave), the prospect of mapping on line gives the added advantage of recording the site of activity in addition to the other PD parameters. Using high frequency current transformers (CT's) the method is useable now, but further development is being undertaken to solve the main problems of noise and long circuits.

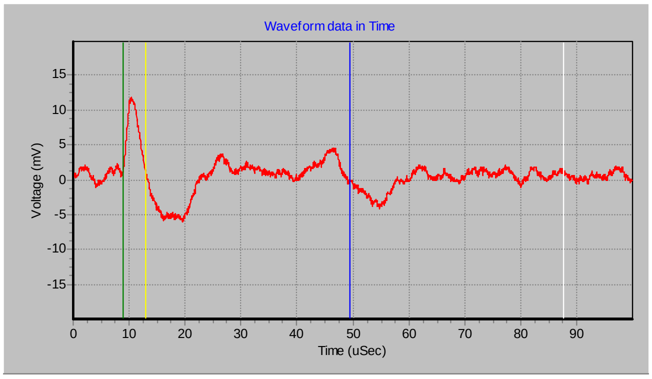

Fig 5 On-line PD mapping waveform

Figure 5 shows a waveform recorded on a 33kV cable. Using conventional Time Of Flight (TOF) methods, the waveforms of the type in figure 5 can be characterized using computer generated cursors, and a map generated from the results. The PD magnitudes are measured by integrating the area under the curve. The charge in the PD event is the integral of the current, measured at the output impedance of the cable. Figure 6 shows the resulting on-line map of the cable.

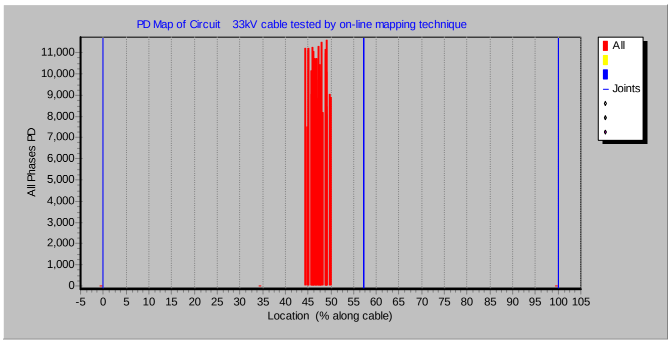

Fig 6 On-line PD map of 33kV cable

Notice the one site (or many sites very close together) in this case. The cable had experienced several failures in a few hundred metres in the area of the PD events. A later spot measurement showed a reduction in these PD levels. This merely emphasizes the benefit of on-line monitoring, over say several weeks to capture the activity of the circuit in a representative way. The next section gives some results from monitoring cables, but not using PD mapping methods.

EXPERIENCE WITH LARGE SCALE TRIAL OF ON-LINE CABLE CONDITION MONITORING

Much of the recent work in London has centred on the development and proving of simple and therefore low cost on-line multiplexers to monitor for partial discharges on live MV cable systems in order to prioritise circuit refurbishment and/or renewal.

On-line PD detection methods use HF current sensors and/or cable bushing capacitors, with appropriate filters. Although for most comparative purposes the magnitude alone suffices, the trend in activity rate above a threshold has proved to be far more significant in predicting failure.

Real Time Partial Discharge Monitoring Results

A 32 channel multiplexing discharge monitor has been in operation in one of LPN’s larger (3*60MVA 132/11kv) higher fault rate substations since January 1999.

During the first twenty months of monitoring, there were twenty seven 11kV feeder trips on this substation. To better understand the characteristics of failure, no attempt was made to intervene to prevent failure, although in some cases some pre fault location and analysis was carried out. Six of these faults were due to external causes (five damages and a flood) and as would be expected, no abnormal PD activity was recorded before these events. Four of the incidents were unfortunately not recorded during periods when the equipment or the software was being upgraded. Twelve of the 17 remaining faults showed clear and rising levels of activity for periods of 5-150 days before failure.

Estimating time to failure

How long do we have before failure is a key question.

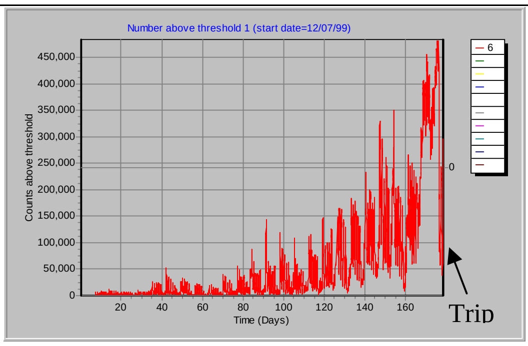

Fig 7 PD activity before circuit trip

The time that an incipient fault can be “seen” before electrical failure actually occurs, varies widely from the 150 days shown in figure 7 down to just a day or two. At this juncture, it is not possible to be certain how long a circuit will remain in service.

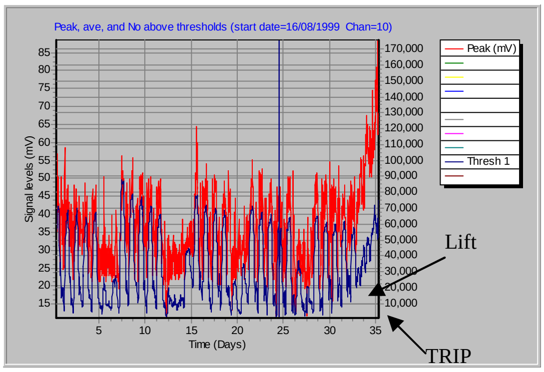

Fig 8 PD behaviour prior to failure

However, in many cases the characteristic "lift" that seems to be the immediate precursor as shown in figure 8, occurs 2-17 days ahead of failure. In this case both the PD magnitude and activity rate increased significantly over the final two days having followed a complex function of the load curve characteristic over the previous twenty days.

Fault Not Found

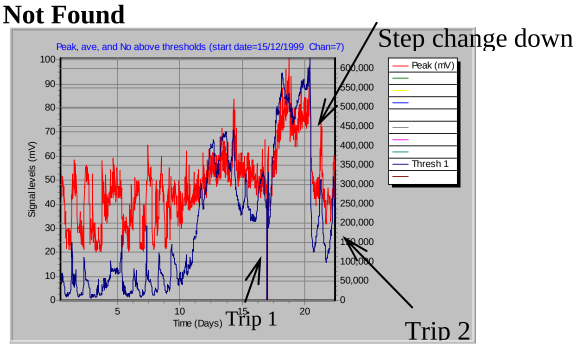

Fig 9 Trip but no fault found

In the sequence shown in fig 9, no fault was found by conventional AC pressure testing after the circuit tripped and the feeder was reconfigured and restored. Initially the activity rate started to rise again before a step change down and eventually tripping out again. In the initial failure there were some 130 days of pre-warning period followed by 8 days of "lift" before trip. Each year 30-40 "Fault not found" events occur in London

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