DETECTING AND LOCATING MV FAILURE BEFORE IT OCCURS.
EXPERIENCE WITH LIVE LINE PARTIAL DISCHARGE ON UNDERGROUND PAPER
INSULATED 11KV CABLES IN LONDON

C M Walton

London Power Networks (LPN) UK

Keywords: Incipient Fault, Live line Partial Discharge, Directional discharge, Condition Monitoring, Asset Management, Worst Served Customers

First year results of live line Partial Discharge monitoring of 11kV have shown very encouraging results in being able to detect and locate failure BEFORE it occurs. LPN have recently installed live line multi-functional monitoring equipment on 300 higher fault rate 11kV feeder circuits. Preliminary results from this large scale trial will be presented which is expected to monitor the inception and progress to failure, or the effects of proactive intervention, of approximately 100 MV faults over the next 12 months.

The paper considers the regulatory and business drivers for improving the quality of supply and the costs of running an urban underground distribution system in a capital city.

Detecting and locating incipient failure in underground cables before electrical faults occur has significant benefits in terms of customer satisfaction and quality of supply statistics particularly for “worst served customers” and investment targeting.

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

The paper shows the results of live line condition monitoring for some 24 months on one high fault risk substation that have shown encouraging results in being able to detect and locate failure BEFORE it occurs.

The paper describes web enabled 64 channel PD multiplexers with improved methods of installation and data transfer current being installed in large substations together with a small 8 channel system for smaller distribution substations.

Timely location and targeted replacement of specific sections of unsatisfactory circuits enables the effective service life of the whole circuit to be economically extended.
DETETION ET LOCALISATION DES DEFAILLANCES MOYENNE TENSION AVANT QU’ELLES NE SE PRODUISENT
EXPERIENCE AVEC DES DECHARGES PARTIELLES SUR DES LIGNES SOUS TENSION DE 11KV A LONDRES (CABLES SOUTERRAINS AVEC ISOLANT PAPIER)

C M Walton

London Power Networks (LPN) Royaume-Uni

Mots-clefs : Défaillance naissante, Décharge partielle sur des lignes sous-tension, décharges directionnelles, surveillance de l’état, Gestion des équipements, Client le plus mal servi.

La première année de surveillance de Décharge Partielle sur des câbles sous tension de 11KV a montré des résultats très encourageants en ce qui concerne la détection et la localisation de défaillances avant qu’elles ne se produisent. LPN a récemment installé des équipements multifonctions de surveillance sur ses 300 circuits d’alimentation 11KV les plus défectueux. Des résultats préliminaires de cet essai à grande échelle seront présentés, ceux-ci devraient montrer la naissance de la défaillance et ses progrès jusqu’à la défaillance elle-même, les effets d’interventions anticipées d’approximativement 100 défaillances Moyenne tension.

La présentation parle des réglementations et affaires clés permettant d’améliorer la qualité d’alimentation et le coût associé au bon fonctionnement d’un réseau de distribution urbain dans une capitale.

Détecter et localiser la naissance de défaillance sur un câble souterrain avant qu’une défaillance électrique ne se produise à des avantages non négligeables, en termes de statistiques comme la satisfaction du client et la qualité d’alimentation, en particulier « Le client le plus mal servi » et les objectifs d’investissements.

La localisation et le remplacement de section spécifique (non satisfaisante) d’un circuit permettent une augmentation de la durée de vie du circuit tout entier.

Comme 98% des coupures d’alimentation à Londres proviennent des câbles, LPN Powerquest cherche à développer des techniques afin d’éliminer les défaillances des câbles avant qu’elles ne se produisent.

Le document montre les résultats de surveillance sur un système sous-tension dans une sous-station ayant un fort risque de défaillance ; ces résultats sont encourageants en ce qui concerne la détection et la localisation de défaillances avant qu’elles ne se produisent.

Le document montre des multiplexeurs 64 voies (compatibles avec Internet) avec méthode d’installation et un transfert de données améliorés, actuellement installés dans de larges sous-stations. De petits systèmes 8 voies pour des sous-stations plus petites sont aussi utilisés.
DETECTING AND LOCATING MV FAILURE BEFORE IT OCCURS. 
EXPERIENCE WITH LIVE LINE PARTIAL DISCHARGE DETECTION ON UNDERGROUND PAPER INSULATED 11kV CABLES IN LONDON

C M Walton

London Power Networks (LPN) UK

INTRODUCTION

Detecting and locating incipient failure in underground cables before electrical faults occur has significant benefits in terms of customer satisfaction and quality of supply statistics particularly for “worst served customers” and investment targeting.

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
2.1m 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.

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. In particular to reduce operational costs and improve operational performance although the consequences of a major HV event must never be ignored.

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.

TECHNIQUES FOR REDUCING THE NUMBER OF INTERRUPTIONS AND MULTIPLE INTERRUPTIONS

The majority of LE’s 10,000km of underground 11kV cable is of 3core belted paper insulated design with lead sheaths and steel wire armouring, some of which dates from the early part of the last 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.*

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. Initially these techniques have largely 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.

**Off-line condition monitoring techniques**

Analysis of MV cable failures indicate two main causes ie cable sheath/joint water barrier failure leading to the ingress of moisture, and failure attributable to poor jointing practice or the presence of voids in the insulation.

Techniques for incipient fault detection and location of incipient MV faults have previously been reported to the CIRED 1999 conference in Nice[2]. Several off-line techniques are routinely used to monitor the condition of underground cables including:

- Pressure Testing AC/DC
- Fall of Potential Testing
- Tan δ Testing
- Zero Sequence Impedance Testing

For the off-line detection of partial discharges (PD), London have been using VLF, Oscillating Wave and resonant Partial Discharge Mapping (PDM) equipment at voltages from 6.6kV to 132kV.

Off line Partial Discharge Mapping has been in use for a number of years. LPN’s main contractor, 24seven utility services, has two VLF test vans equipped for PDM and a portable Oscillating Wave Set. Failures have been observed with PDM at high discharge level locations, but other cables deliberately left in service, have not always shown significant development of discharge levels nor failed in service.

It has been estimated that with existing resources, it would take 10 years to PDM all of the MV circuits once which is clearly impractical for system management. However as on-line monitoring has shown that cable conditions can deteriorate rapidly in weeks[3], it can be concluded that off-line techniques have an essential part to play but only as part of an overall cable management plan.

**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 multiplexors to monitor for partial discharges on live MV cable systems in order to prioritise circuit refurbishment and/or renewal.
Partial Discharge Detection & Location
On-line partial discharge (PD) detection and location methods use HF current sensors (fig 1) and/or cable bushing capacitors, with appropriate filters, signal detection and processing systems. Experience has shown that discharge pulse shapes are similar in shape, and the range of pulse widths is quite small (300\(\eta\)S - 2.5\(\mu\)S). The product of the pulse height and the base width provides a simple approximation of the pulse charge. Although for most comparative purposes the magnitude alone suffices as the trend in activity rate above a threshold has proved to be far more significant in predicting failure.

**Real Time Partial Discharge Monitoring Results**
Spot live line PD readings taken at different times of the day can vary significantly, so an on-line continuous monitoring system was developed. 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.

The time that an incipient fault can be “seen” before electrical failure actually occurs, varies widely from the 150 days shown in figure 2 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 3**
However, in many cases the characteristic "lift" that seems to be the immediate precursor as shown in figure 3, 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.

**Periodic activity**
The activity rate and often to a lesser extent the pulse magnitude appears, by inspection, to fluctuate periodically through the day as seen in figures 2 and 3. Preliminary comparison of some half hour feeder load profiles with PD activity has been made using a neural net. This analysis points to some degree of complex correlation between the rate of rise of load and activity and also between pulse magnitude and the point of load inflection. Some periodic correlation with load may be explained by thermal movement of the conductors, the changing viscosity of insulating oil/resins with temperature and the resultant changes in internal pressures within the cable or joint.

Long term studies of many circuits will be needed to validate and justify such hypothesis, particularly as there is not necessarily a direct correlation between the feeder load profile as measured at the source substation with that of the load or temperature at the point of discharge.

Once the relationships with load are understood, real time correlation of PD activity with control and telemetry data may be necessary in order to account for changes in activity trends that are related to feeder loading and operational switching activity.
Noise
Experience has indicated that operational switching and the operation of transformer tapchangers create large magnitude short duration pulses that permeate widely throughout the power system. Such switching noise can reliably be removed by a suitable noise rejecting algorithm.
Noise caused by electronic power supply switching is at present more problematic. For single core cables the pulses in separate phases can be measured and then pulse phase resolved with respect to a voltage reference which enables discharge and electronic noise to be separated.
Most of London’s MV cable are 3 phase belted paper cables where there are opportunities for discharge between phase and earth, phase to phase and even in the rotating 3phase field at the interstices of the cable.
The ability to evaluate PD activity against a range of magnitude thresholds has proved to be key in both noise rejection and in revealing failure mode trends.
In most cases comparison of threshold activity rates enables the identification and elimination of electronic noise sources but there is more work to do in this area to identify a simple, reliable and low cost solution.

Step change in activity before failure
Occasionally, as the example in Fig 4 shows, the activity rate having increased then drops off some time prior to the failure. This may or may not be accompanied by an increase in PD magnitude. The explanation for this effect has yet to be determined but may result from the structure of the discharging materials changing either by becoming conductive or the void growing too large to discharge frequently.

Restoration
When a feeder trips, and is de-energised, the discharge activity falls to background induced noise levels only. With the discharging section isolated, the remainder of the feeder can be restored to service and a pronounced step change down in discharge activity can be observed.

After repairs, and the circuit is returned to service there will often be a brief rise in discharge activity lasting a few days as the cable components and internal pressures recover from the repair "surgery". This can be clearly seen in the trace (Fig 4). These results indicate that off line and off load PD testing that is done when the circuit has been de-energised for some time may not be directly comparable with live operational conditions.

Fault Not Found
In the sequence shown in fig 5, 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 and understanding their evolution will be critical in reducing the number of customers affected by multiple interruptions.

Effective reach
The most remote fault seen was at 3095metres from the source substation, which is probably towards the end of the practical reach of the current generation of monitoring on paper cables. There remains a considerable difference between “seeing “ an incipient failure materialising when analysing PD data after a known fault and being able to confidently predict failure before it occurs. With very remote faults this becomes ever more difficult owing to the level of pulse attenuation and dispersion that occurs along the circuit.

PD Monitor developments
PD multiplexers transmitters (Fig 6), with simplified methods of installation and data transfer, have since been installed in a further ten high risk substations covering some 300 higher risk MV circuits and more will be installed in 2001.

Fig 5
Fig 6 8 channel PD Multiplexing Transmitter
A single coaxial cable carries both the 24V supply and data, which is collected by a central hub unit (Fig 7).

There is a flexible system of up to 8 transmitters, each capable of accepting inputs from 8 PD sensors, providing a total of 64 channels each multiplexing a range of up to eight activity thresholds as well as peak and average magnitude.

Instances of fleeting earth fault and overcurrent alarms often occur in the period immediately before a MV feeder trips. By providing real time detectors on outgoing feeders, those with advanced incipient failure can be identified, and up to 4 Incipient Current Burst Monitors (ICBM) can also be fitted to each transmitter unit. This equipment is still being evaluated.

It is expected to collect data from 100 MV faults over the next twelve months, and this should enable the reliability of these methods to be confirmed, and for reliable predictive techniques to be developed.

Remote Data Access
With the continuing internet revolution, fixed communication links are being replaced by website technology with webservers being set up at each of the multiplexor sites. Novel methods of analysing the collected data are being developed to process the large volume of data which is generated by the multiplexed data hubs.

Discharge Site Location
Having identified a feeder with a high level of partial discharge activity, the next stage is to identify the individual section of cable involved. The simplest method is by switching, whilst monitoring the PD readings at the primary substation. This method has been tried with some success, but it is time and resource consuming. Routine switching involving those feeders previously identified as at risk, may also reveal useful information. Off line PDM tests can then be used to pinpoint the source of the partial discharges.

The distributed multiplexor is ideal for major substations but is perhaps less suitable for small switchboards where a small and portable device is more suited. A small 8 channel uPD monitor (Fig 8) is currently being evaluated, the unit has an onboard processor and data storage and can be downloaded either by direct connect to a PC or remotely via a dial-up or GSM radio modem.

This type of live line PD monitor can be deployed at distribution substations part way along feeders that have already been identified from Main Substation PD monitoring as having high discharge levels. Because pulses travelling across switchgear suffer significant attenuation, the levels of PD activity measured on either side of MV switchgear can be used determine PD direction. The directional information can then be used to localise the discharge source to a particular section of circuit.

The development of on-line discharge mapping techniques previously reported is progressing well and results will be reported separately at a later conference.

SUMMARY

There are strong Regulatory and Business drivers to take competitive distribution businesses to the frontier of efficiency. LPN and it’s business partners are developing a range of on-line techniques aimed at reducing the number of MV and HV incidents that cause loss of supply to customers, by monitoring the condition of feeders and taking appropriate action before failure occurs.

Where inspection indicates that the problem is due to poor jointing, installation damage or local environmental deterioration then localised repair, refurbishment or replacement is appropriate. Where extensive or type failure is detected then complete replacement may be prioritised. This targeted approach is substantially lower cost, faster and environmentally more beneficial than large scale cable replacement based on age, type or whole circuit performance.

REFERENCES

