INCIPIENT FAILURE DETECTION & LOCATION FOR UNDERGROUND CABLES

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Summary

The dream of detecting and locating incipient failure in underground cables before electrical failure actually occurs, and the avoidance of repetitive failures, has enormous potential benefits in terms of customer satisfaction, capital and operational cost savings and quality of supply statistics.

During 1998 London Electricity achieved a 15% reduction in the number of MV incidents that caused loss of supply to customers. This paper describes a compendium of techniques that have been developed and implemented in London, and give examples of how a combination of these have been used to identity, prioritise and locate incipient failure in cables, joints and terminations ranging from LV to 132kV. Some features of incipient failures recovered for forensic examination are described.. The development and application of these techniques is progressing rapidly, an update of progress will be given at the conference.

LONDON ELECTRICITY

London Electricity can trace its history back at least as far as 1883. It is geographically by far the smallest of the twelve Regional Electricity Companies (REC) that supply England and Wales but one of the largest by most other measures.

London Electricity supplies some 2 million customers and a simultaneous maximum demand in excess of 4,300MW in an area of just 650 km^2 of central London.

The majority of the load in London is commercial in nature comprising banks and international finance houses, corporate offices, government, shopping and entertainment. The remaining load is mostly domestic with just a small element of light industry. The domestic and industrial loads are generally winter peaking whereas the commercial areas tend to have both winter and summer (air conditioning) peaks

THE CHALLENGE

The challenge for electricity utilities as we move into the 21st century is to deliver ever more reliable service at reduced cost and with fewer technical and support staff. 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.

London Electricity is proud to have been able to meet or exceed each of the standards set by the Regulator and have consistently been one of the best performing Regional Electricity Companies$_1$ in the UK . As part of its process of continuing improvement, London Electricity has adopted a twin strategy of seeking wherever possible to eliminate failure before it occurs and using remote control system$_2$ to manage the risks associated with the unforeseen cable failures and damage that do occur.

Some 98% of the supply interruptions that occur in London, arise from cable systems and terminations (rather than plant and equipment failures). Network performance statistics also indicate that incidents on the 11kV (& 6.6kV) MV systems affect the most customers. Customer dissatisfaction, however, tends be localised and driven by repetitive LV system related incidents. By contrast HV (22-132kV) system incidents that result in losses of supply are comparatively rare and only account for a few percent of customer minutes lost (SAIDI$_3$).

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 to both reduce operational costs and improve operational performance.

MANAGEMENT OF COMPLEX CABLE SYSTEMS

In major cities the power infrastructure comprises many different systems and standards built up over a century but must meet a changing customer load base that is developing on a daily basis.

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 this 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 much sooner.

Each year a proportion of the system is replaced as the city is changed and developed, 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 Manager'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.

LE 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.

FAULT CAUSATION

In looking for incipient faults the analysis of cable failure statistics provides the crucial key to understanding the types of faults that occur as well as when and where they are most likely to occur. Pareto analysis would indicate that we should expect 80% of failures to occur on 20% of the network. In practice as networks are managed this proportion should move towards 60/40.

Analysis of MV cable failure indicates two primary modes of failure:

- **External:** Failure of the cable sheath or cable joint water barrier leading to the ingress of moisture and electrical failure. Failures typically arise from damage during installation or during streetworks, cracking of lead plumbs on cable joints due to thermal cycling, corrosion of armour wires or lead sheaths which leads to arcing under fault conditions and secondary failure. Analysis indicates that some combinations of cable types and environments have significantly higher distributed risk than normal and in these cases selective replacement programme may be appropriate. Elsewhere the application of targetted condition monitoring techniques can identify individual circuits with high risk of failure. Some of the condition monitoring techniques include :
    - Tan δ and delta tan δ
    - Zero sequence impedance
    - Partial discharge mapping
    - Time domain reflectrometry

- **Internal:** Cable failure from overloading itself is rare but most failures can be attributed to thermal runaway in the insulation due to poor jointing practice or the presence of voids in the insulation. Manufacturing defects, whilst not unknown are also thankfully comparatively rare in the UK. Condition monitoring techniques include:
    - Pressure tests (AC & DC)
    - Fall of potential
    - VLF partial discharge mapping
    - Tan δ and delta tan δ
    - Thermal imaging of terminations
    - Ultrasonics

CABLE CONDITION MONITORING TECHNIQUES

A wide variety of off-line techniques to monitor the condition of cable have been developed over recent years.

OFF_LINE

- **Pressure and fall of Potential tests**
  Traditional MV DC pressure test equipment is light and portable and consequently still widely used, but DC tests may cause damage to polymeric insulation and in themselves say very little about the condition of paper cables. Some indication of the condition of paper insulation can however be gauged by recording the fall of potential from the fully charged state every 10 seconds once the supply is disconnected. Comparing results with a normal cable of similar type and length will often indicate incipient failure. The introduction of AC VLF testing has major advantages: the insulation is repeatedly stressed by polarity reversal, experiences a greater rate of change of voltage and has more opportunities to fail than a DC test at equivalent voltage. There is some evidence that faults that cannot be found using DC tests breakdown rapidly with VLF AC, and it is certainly worth trying where faults cannot be broken down.

- **VLF partial discharge mapping**
  The technique of partial discharge mapping has been used on high voltage cables for over ten years. The method uses a low frequency high voltage power supply to energise the cables, which are isolated from the network for the measurements. London Electricity have two VLF test vans equipped for Partial Discharge measurements.

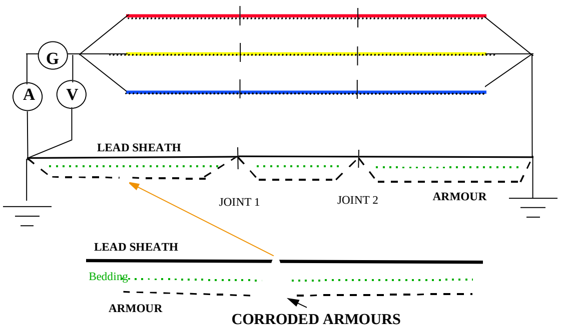
Developments in the past year include a dual ended testing method for greater location accuracy and a transponder method for locating discharges in multi-ended circuits that was originally developed for live line partial discharge mapping applications.

VLF mapping is especially valuable following a previous fault on the same circuit to ensure that all the unsatisfactory cable is removed and further repetitive failures do not occur shortly afterwards. It is also valuable for confirming live line locations, although experience shows that VLF may not reveal some of the infrequent discharge cycles that can be observed live.
Several failures have been observed at locations which have been VLF identified as high risk and within a few weeks. These failures tend to indicate a practical field accuracy of ± 20m on typical 0.5km sections. Other sections which have been deliberately left in service and tested at intervals have not shown significant development of discharge levels nor failed in service. Gaining a better understanding of how partial discharge failure develops over time is the subject of further trials.

- **Tan δ and delta tan δ**
  Modern digital instrumentation fitted to the VLF test vans enables the loss angle to be automatically displayed each time a cable is tested. By testing the cable at differing voltages the effects of insulation contaminants and discharge losses can be effectively separated. These are essentially bulk techniques in that they can identify a poor circuit but on their own are unable to pinpoint specific problem sections.

- **Zero sequence impedance**
  By measuring Xo/Ro with a suitable digital averaging test set a coefficient can be obtained that is independent of route length. By comparison with results from other circuits a variety of conditions may be detected concerning the earth return path, particularly corroded armour wires and earth bonds. The techniques can also be used to identify the presence of unrecorded sections of plain lead (unarmoured) cables which in London have been found to have a particularly high fault rate.
  Again this is essentially a bulk technique but there has been some success in identifying faulty joints with Zo and then locating them with time domain reflectrometry . The development of simple and effective techniques to pinpoint such defects in earth continuity will not be straightforward in view of the potential presence of multiple earth paths.

ZERO SEQUENCE TEST



- **Time Domain Reflectrometry**
  The routine use of a pulse echo test set can identify and locate a number of latent defects in earthing and bonding systems before they cause failure

- **Thermal imaging of terminations & ultrasonics**
  Established thermal & ultrasound techniques can be used either during routine inspection or as part of the localisation of live line results, to determine the presence of overheating connections and discharges. The possible use of ultrasonics to detect voids in compound filled chambers is under investigation in a UK research establishment.

- **Destructive tests**
  Destructive tests techniques such physical examination and "Step Voltage to Breakdown" can also be selectively employed to determine the suitability for circuits to be retained in service and to monitor the rate of aging.

The principal difficulty with off-line techniques is that, by definition, the circuit needs to be out of service for the tests. Taking circuits out is expensive in terms of resources and increases system operational risks.
With a large system (London has 17,000 MV circuits) any prescribed proactive or destructive testing regime is likely to prove impractical or be too infrequent to have the dramatic impact required. For example it would take two off-line teams 10 years to go once round the system with each team preparing and proactively testing four circuits a day ! Experience has shown that cable conditions can deteriorate rapidly, so that even if a cable tests healthy now it may still fail in a few weeks or months.

It is concluded that proactive and indeed destructive off-line techniques have an essential part to play but only as part of an overall prioritised cable management plan.

ON-LINE

Development of on-line techniques has come along way in the past year$_4$ and further progress can be anticipated but at least initially their most significant role will be in identifying high risk circuits for circuit risk management and to prioritise the application of on-line and off-line condition monitoring and location techniques. Three complimentary techniques have been developed and deployed on selected sites and circuits:

- Partial discharge detection & location
- Incipient current burst detection & location
- Time domain reflectrometry

Partial discharge detection & location

On-line partial discharge detection and location methods use HF current sensors and/or cable bushing capacitors, combined with a appropriate filters, signal detection and processing systems. The development of suitable low cost HF sensors which can be fitted to switchgear whilst it is live and in service has been a critical enabling technology which in time is expected will allow the widespread deployment of real time monitoring systems.

The signal levels of discharges in PC (Pico-Coulombs) can be calculated as follows:-

$$\textbf{Charge (Q)} = \int I \, dt$$

Where I is the current of the PD pulse at the cable sealing end, and the integral is carried out over the pulse width of the PD pulse. This assumes that the terminating impedance is smaller than the cable impedance, which in most on-line cases is true.

With the transfer Impedance of the CT as

$$Z_T = \frac{\text{(Output Volts from CT into 5O}\Omega\text{)}}{\text{(Input Current through CT)}}$$

The charge will be :=

$$\textbf{Charge (Q)} = (l/ Z_T) * \int V_{CT} \, dt$$

Where V_{CT} is the voltage measured at the output of the CT. For typical sensors having a transfer impedance Z_T =2..2, and a buffered signal reducing the signal by a factor of two, the charge will be:-

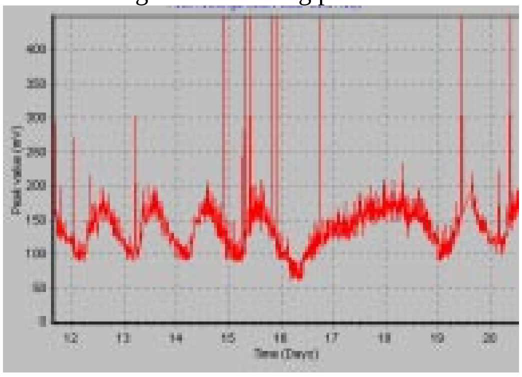
$$\textbf{Charge (Q)} = 2*(1/2.2) * \int V_{CT} \, dt$$

$$=0.909 * \int V_{CT} \, dt$$

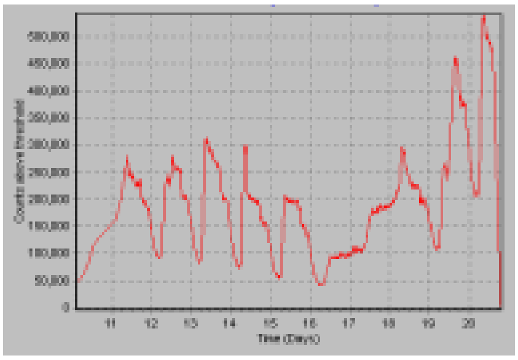
This expression can be used to calculate the pulse size and is not dependent on cable parameters. Ideally the area under the V_{CT} pulse should be accurately measured using some suitable software. However, experience has shown that discharge pulse shapes are broadly similar in shape, and that the range of pulse widths is quite small (300ηS - 2.5μS) and much smaller than the wide range of variability in pulse magnitude typically measured. In consequence the product of the pulse height and the base width provides a simple comparative approximation of the pulse charge although for most comparative purposes the magnitude alone provides a very effective first pass screening measure .

- **Real time partial discharge monitoring**

The development of a 32 channel multiplexed real time partial discharge monitoring system for use in HV/MV substations shows that levels of activity on individual circuits varies widely from hour to hour. The monitor captures and stores both the peak level of discharges that occurs during the monitoring period:



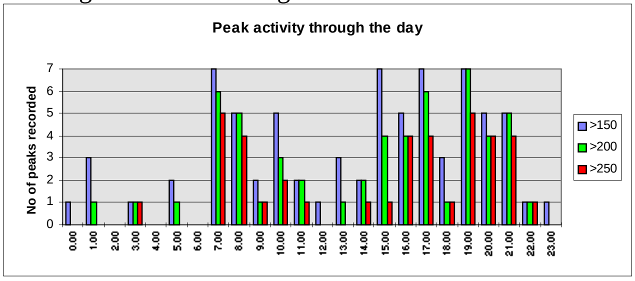
and the number of discharges that exceed selected threshold levels:



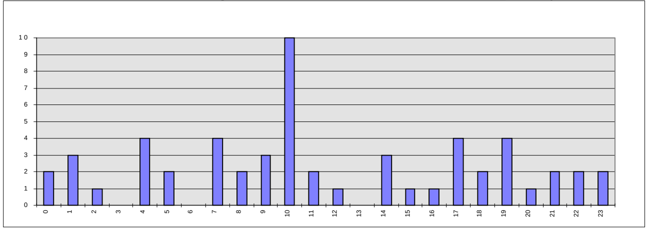
Whilst more extreme conditions can be detected and located now, a clear linkage between activity and remaining time to failure has yet to be established although a variety of damage functions are being tested for correlation with fault performance. Preliminary analysis indicates that discharge activity may be sensitive to rate of rise of load. The drivers for the less frequent but particularly large magnitude discharges, could similarly be related to cable temperature and core movement. Further research in these areas is a priority.

In making live line measurements consideration has to be given to the problem of HF noise generated by power electronics devices. Pulses from power electronics can generally be distinguished from partial discharge pulses because of their shape, repetition patterns, synchonisation with power frequency, consistency of magnitude and cyclical nature. Building smart filters that recognise and exclude such noise is a further challenge to automating incipient fault recognition.

When comparing the time of day that the largest discharges occurred during a winter week.



some similarities can be seen with the times of fault that have occurred during the winter months in the past year



- **Live line partial discharge surveying**

Portable on-line methods enable large numbers of main substation feeder circuits to be quickly scanned at appropriate times of the day to prioritise further investigations and investment.

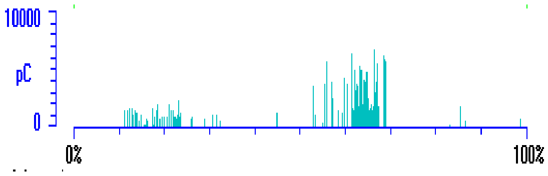
A prototype handheld device has been developed to enable the peak discharge level and the activity rate to be sampled quickly and easily. Results from the surveys are entered into a database which enables correlation with other factors and network performance to be investigated.

Concentrating upon, and then being able to selectively replace sections of circuit most at risk, enables capital and labour resources to be directed to maximum impact. Results from real time monitoring show the importance of measuring activity at appropriate times in order to avoid taking readings during particularly quiet periods.

Once a feeder with a high level of discharge has been identified the next level of prioritsation is to locate individual sections of cable with high levels of discharge activity.

- **Live line partial discharge mapping**

In its simplest form live line data is processed to measure the location of the discharge event using the time differences of the first pulse arrival and that from a reflection at a system open point. Its magnitude is calculated using the area under the current/time curve to calculate the charge. This processed data may then be used to produce the partial discharge map which shows the discharge activity as a function of the cable length in a similar manner to off-line VLF mapping. In real systems open points may too remote to obtain clear reflections and moving them is often operationally undesirable and may be resource intensive.



Three systems have therefore been developed and tested for achieving on-line partial discharge locations:

- **Synchronised Pulse arrival** : the timing signal from the global positioning system has been used to time the arrival of discharge pulses at remote points in the system from which the location of the discharge can be calculated. The system has been proved to work but the accuracy of the prototype system which used commercial GPS timing was no better than 100m at best. Anti dithering software or access to military signals could enhance the performance significantly but there is still remains the requirement for the GPS aerial system to see the sky, which in a city centre is not as easy as it sounds!.

- **Injected Pulse Synchronisation** : injecting a HF synchronising pulse into the MV system overcomes the accuracy and "sky" problems of the GPS approach. By using the injected pulse to trigger a PC oscilloscope, discharges can later be synchronised, their time difference compared and a discharge location calculated.

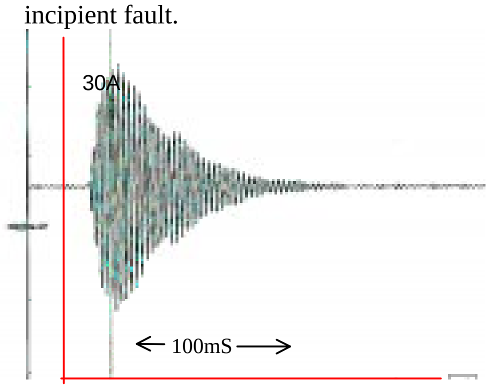
The approach has disadvantages in requiring test equipment at both ends of the circuit and the bringing of the data to a common location for analysis. Specialised comparison software would be needed to be written to make the system commercially viable but the approach works well and is particularly suited to infrequent discharges with variable magnitudes.

- **Transponder:** A transponder which receives incoming discharge pulses, processes them and after a selectable time delay injects a known HF pulse back into the MV system. The transponder can be used to measure circuit lengths by "time of flight" and can be used to produce PD maps in a similar form to that previously used with VLF mapping. The advantages are that all the data manipulation can be done at one end of the circuit and results are available immediately. The prototype transponder is the current method of choice for locating partial discharges and sources of electronic noise.

- **Directional partial discharge indication**
  The time of flight of a discharge pulse crossing a ring main unit or small multipanel switchboard is typically of the order of 6-10ηS. With suitable HF sensors fitted on cable glands or bushing of distribution switchgear then the direction of travel can be determined with digital oscilloscope. Low cost statistical discharge comparators are being developed to de-skill the process of direction determination. In the medium term it can be expected that distribution remote terminal unit modules will provide remote indication and alarms for magnitude, activity, damage and pulse direction as a standard option using this technique.

- **Incipient current burst monitoring**

Analysis of telemetry alarms indicates that quite often several instances of fleeting earth fault and overcurrent alarms occur before an MV feeder trips. Extremely sensitive, high speed fault recorders indicate that for each such alarm detected by telemetry system there may be many other much smaller events that herald the incipient fault.



Such bursts of current may range from just a few to several hundred Amperes but typically only last a few tens of milliseconds and are far too small and short to cause operation of conventional main overcurrent protection.

By providing suitably sensitive (but resilient to full short circuit current) real time detectors on outgoing feeders, circuits with advanced incipient failure can be identified. Suitable risk management switching can then be invoked to minimise the number customers at risk of interruption whilst other real time condition management techniques are employed.

- **Incipient fault passage indicators and alarms**
  To enable the next level of localisation of incipient current bursts, provision has been made for suitable sensors in new and refurbished MV switchgear and a facility has been left to incorporate a soft (ware) incipient fault passage detector within the RTU of LE's remote control and telemetry programme.

- **Ultrasonics**
  The real time monitoring of ultrasonic discharge activity in cable end boxes, switchgear and transformers is now commercial available for particularly high risk or criticality circuits

London Electricity have found :

- A significant level of correlation between high discharge levels and circuit failure over a 3-6month period. However some circuits with apparently high levels of discharge amplitude have continued to remain in service much longer than others.

- Initial measurement activity concentrated upon the magnitude of the discharge pulse as in general the variation of magnitude far outweighs the variation of the main pulse width. It is clear from the more than a thousand measurements that have now been take that some circuits discharge much more frequently than others even if the pulse amplitude or charges (pC) are otherwise similar.

- Recent surveys have therefore also included measurement of the rate of discharge of various sized pulses. Provisionally an inferred discharge energy is being calculated from the amplitudes and frequency observations. It is too soon to be sure if this will have an improved correlation with prediction of circuit failure and comes with a health warning!

- Variations in both amplitude and activity rates do occur from day to day and indeed from hour to hour but that nevertheless, a single sample set of measurements at an appropriate time can provide a reasonable guide as to which sites to initially apply repeat surveys and trend monitoring.
- But such one off surveys cannot find discharge sites that are not discharging at the time of measurement!

- That discharges can develop from minimal to large levels of discharge and failure in less than three months.

- Some previously very active and regularly discharging circuits can become inactive for considerable periods before resuming.

- As a rule of thumb London Electricity have adopted a "concern" level of 70mV above which we would seek to monitor discharge development by repeat surveys and an "action" threshold of 200mV above which we aim our target trend monitoring and PD location resources.

Conclusion

By seeking to understand the causes of failure, monitoring the condition of circuits and taking appropriate action, London Electricity achieved a 15% reduction in the number of MV incidents that caused loss of supply to customers during 1998. During the next Regulatory Review period (2000-2005) it is London Electricity's intention to continue to develop the techniques described in order to invest smarter to achieve better results for all it's stakeholders.

The paper has outlined a compendium of methods for incipient fault detection and location including three methods of live line PD mapping. The work has shown encouraging correlation between the PD activity and service performance. This is particularly true for the failures occurring following testing. However remaining life of cables is not always accurately predicted. A summary of the findings are:-

- Live line detection and location PD method works well for HV paper insulated cables, and shows some correlation with service conditions. Large PD activities detected before failure (~600mV) reduce to negligible levels (~20mV) after repair.

- The PD method does not give a time to failure of a cable system yet. This may be improved in the future, when PD levels throughout the cable life may be measured.

  The positions of PD activity in MV cables correlates well with failures, mechanical damage, and joint problems with an accuracy of around ± 20m.

- Some failures have occurred in cables which have shown no PD at the sites of failures. However for operational reasons no examinations of these failures has been possible to correlate with the PD data.

- Measurements on polymeric 132kV cables have shown no PD activity within the cables. However, accessories can show PD activity. No correlation with failures have yet been made, although an "at risk" joint has been removed from service following live line test results.

- There seems to be no 'safe' limit for paper insulated cables. It is difficult to measure PD levels correctly, but failures in paper insulated cables have been associated with PD levels as low as 1000 pC. A 'safe' limit for paper insulated cables will probably be less than this.

- On-line PD methods can provide excellent diagnostics for use on networks, with very large cost/benefit ratio compared to wholesale cable replacement. Some aspects of off line techniques are complementary to the on-line methods.

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