CONDITION-BASED ASSET MANAGEMENT

AN INTEGRATED APPROACH TO ON-LINE PD MONITORING AND DIAGNOSIS OF MV PLANT CONDITION FOR APPLICATION AS A PRE-MAINTENANCE TOOL

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Through the application of a combination of new PD spot-test equipment, PD location equipment (cable-mapping and time-of-flight analysis) and PD Diagnostics, it is now possible for the MV Plant owner to systematically identify the condition of their 'critical' plant and then to constantly monitor this condition through the use of permanent, remotely-accessible on-line monitoring equipment.

Practical experience of carrying out this approach has shown the importance of reviewing historical plant history through discussions with the owner's operational engineers. This process can be supported through data-mining and intelligent software analysis of current and past data files enabling a complete 'picture' of the position of the condition of the plant and where it lies within it's 'life-cycle' to be carried out.

The UK Electricity Supply Industry faces a new set of challenges over the next decade as they strive towards improving (or at least maintaining) quality of supply standards whilst minimising operational and maintenance costs. It could be argued that, over the past 12-years, since privatisation of the UK Electricity Distribution Industry in 1990, the Distribution Network Operators (DNO's) in the UK have achieved a reduction in their operational and maintenance costs through downsizing and rationalisation of internal staff and outsourcing of some core functions. It can be noted that whilst such processes have gone on throughout the 1990's, the quality of supply in the UK has, by and large, been maintained at adequate levels. This has been due to a combination of generally high-quality, well designed in-service plant and installations and well-trained, experienced maintenance staff. A possible downside to the rationalisation and cost-cutting processes observed in UK electricity distribution companies is that they may not now have adequate financial or labour resources to maintain the quality of supply into the future through conventional asset management and maintenance approaches.

RELIABLE LIFE-EXTENSION

The reasons why this may be so are twofold with an ever increasing 'age profile' of installed equipment combined with a general trend towards reducing the in-house engineering and technical knowledge. The increasing age profile of installed UK MV Plant (see Figure 1 below) is one of the main drivers behind the application of On-Line Condition Assessment of plant as an Asset Management Tool with a view towards Reliable Life-Extension of MV Plant beyond it's 'design life' or 'life expectancy'.

Figure 1: Typical UK MV Plant Install Rate (1940 to 2000)

This point can be illustrated by considering Table 1 below which shows the typical 'Actuarial Asset Life' (the period of time over which the asset's capital cost is 'written off') ascribed by UK Utilities for various types of distribution transformers, switchgear and cables. If the Asset Life values in Table 1 are compared to the times of heaviest installation of this equipment in the 1950's and 1960's (as shown in Figure 1) it can be seen that a lot of equipment is now approaching the end of its original life expectancy. Whilst this fact does not mean that all equipment that is reaching the end of its Actuarial Asset Life is about to fail, it does force the consideration of a condition-based approach to the management of these ageing assets. To achieve an effective Condition-Based Asset Management Policy plant condition should be checked both regularly and in a systematic manner. The following section describes a new approach to achieve this.

ASSET TYPE	TYPICAL ASSET 'DESIGN LIFE' (YEARS)
Transformers	
Transformers (> 11kV)	50
11kV ground mounted	45
11kV pole mounted	45
Switchgear	
Indoor Switchgear	45
Outdoor Switchgear	40
Cables	
132kV cables	60
33kV cables	60
11kV cables	70

Table 1: UK Utility Ascribed Asset Life of MV Plant

CONDITION-BASED ASSET MANAGEMENT APPROACH

The application of on-line condition monitoring equipment (partial discharge monitoring, insulation loss-angle, gas-in-oil, etc.) is becoming more widespread in the worldwide electricity industry. Accurate condition assessment and the subsequent management of in-service high voltage plant is becoming increasingly economically viable with continuous advances and cost reductions being made in sensor technology, data acquisition/processing and intelligent diagnostics. Whilst technology improvements continue apace it is of essential importance that the plant condition data obtained with it is combined with a complementary Risk-Based Asset Management approach.

This section describes a new 4-Phase, Risk-Based Asset Management approach which supports the new PD Detection technology for the management of MV electricity distribution plant. The underlying principles behind the approach are described through a 4-Phase Plan as shown in Figure 2 which provides for systematic 'closed loop' condition assessment and management of MV plant. The importance of considering an integrated Asset Management philosophy to complement new condition assessment technology solutions is illustrated when a distribution network is viewed 'holistically'. For example, it is not cost-effective to continuously monitor 100% of installed MV plant due to the high cost of doing so (certainly when compared to existing Utility Budgets for condition assessment). Additionally and statistically it is likely that typically over 95% of installations will be working satisfactorily and are 'fit-for-purpose'. It is the remaining 5%, the 'critical' plant within a network (based on condition and/or location), which should be focussed on, assessed in more detail and possibly monitored continuously.

The focussing of monitoring, assessment and maintenance resources to the plant in most need is an obvious advantage but in order for this to be achieved the utility requires a systematic approach. The requirements for carrying out a systematic Condition-Based Asset Management Approach can be summarised as follows:

- Need to Identify 'Critical Plant' (typically less than 5% of network)
- We Need to Direct Monitoring/Maintenance Resources to 'Critical Plant' (condition and/or location criticality)
- Require EARLY WARNING SYSTEM to detect 'Trend to Failure'
- Need to monitor all plant condition parameters and correlate with operational data (load, voltage etc)
- Need to generate a 'Condition-Based League Table' of assets based on age, type, condition/location criticality
- Need to have dynamic, iterative processes which continually review the 'criticality' of plant and respond to any changes or trends in condition
- Need to be able to apply the condition knowledge into a Decision Support System for asset management and maintenance purposes.

The above requirements have been adopted into the 4-Phase Asset Management approach described in Figure 2 below.

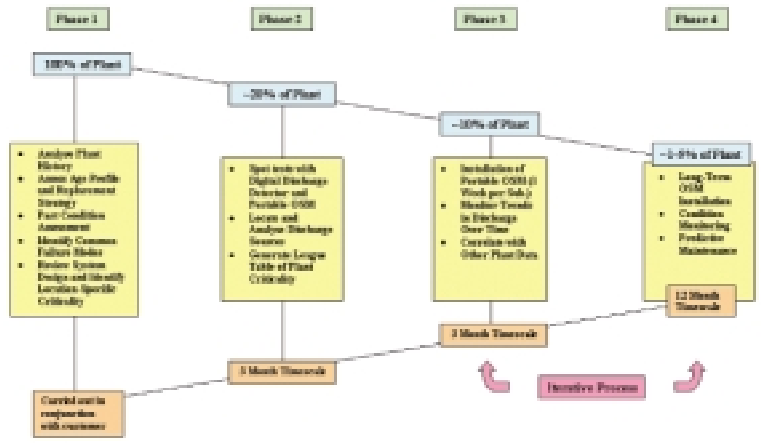

Figure 2: 4-Phase approach for Condition Assessment of MV plant.

BREAKDOWN OF THE 4-PHASE NETWORK ASSET MANAGEMENT APPROACH

Phase 1 - Review of Network & Plant History

This should be carried out on 100% of Network and involves a study of the following factors:

- Analysis Plant Failure History (statistical analysis)
- Data-mining, Past inspections
- Assess Age Profile and Replacement Strategy
- Identify Common Failure Modes of Plant
- Identify 'Location Specific Criticality' (LSC) - critical loads (hospital, data-parks etc)
- Review of Quality of Supply (Incidents, Interruptions and Customer Minutes Lost)
- Costs of Faults (Opex and Capex)

Results in: Identification of 'Suspect Plant', Critical Sites (LSC) and 'Suspect Plant Families' (typically 10 to 20% of network).

Phase 2 - Spot Testing Program

This is a 'PD Screening' exercise and is carried out on the 10 to 20% of network identified in Phase 1 and involves:

- One-day inspection of substations to evaluate 'snap-shot' condition (5 minute test per plant item)
- Locate and Measure PD Activity (level, phase and waveform shape)
- Utilising Portable PD Spot Tester (OSM-ST1) with PD Gold™ 7Software and Calibrated PD Sensors

Results In: Identification of substations for extended (1 week plus) monitoring in Phase 3.

Phase 3- Short Term Monitoring

- Installation of Portable Monitor (OSM-P32), typically 1 week per substation to obtain PD data from weekly load cycle.
- Monitor Trends in Discharge Over Weekly Loading Cycle
- Correlate with other Condition and Operational Data (e.g. Load, temp etc)

Results in: Selection of Critical Substations chosen for Continuous, Long Term Monitoring in Phase 4.

Phase 4 - On-line, Continuous PD Monitoring

- Long-Term Permanent OSM Installation (OSM-V1.102) focussing on 'suspect plant'
- Continuous Partial Discharge Monitoring of 'Critical Plant' to provide an 'Early Warning System' to detect Trend to Failure and thus enable predictive maintenance.

ITERATIVE TESTING PROGRAMS

It can be noted from the 4-Phase Plan (Figure 2) that intermittent, iterative partial discharge testing is recommended between Phase 2, 3 and 4. This testing can be split into three main categories:

1. PD Location, Mapping and Diagnosis due to an Increase in the PD Activity above a pre-set threshold on a 'critical' plant item being monitored by permanent monitors in Phase 4.
2. Condition-based PD assessment and remaining life prediction of equipment which has reached the repair/refurbish/replace stage of their life-cycle - testing carried out as per 1.
3. A Periodic review (every 2 to 5 years) of the Condition-Based League Table' of HV Plant through a repeat of the 4-phase plan.

In the case of 1 and 2 above, specialist On-Line PD Location Test Equipment is utilised. An example of the application of this type of equipment to the mapping, location, diagnosis and repair of a 3km long mixed cable circuit is given in the Case study (see next page).

SUMMARY

In order that the Utility's Asset and Maintenance Managers can best control their CAPEX and OPEX spend they must have an accurate, up-to-date 'snapshot' of the condition of their installations in order that they can prioritise their capital/maintenance/management spend towards those installations which are most in need.

With the quantified data on the criticality and condition of plant formed through the 4-phase approach, the Asset Manager has the opportunity to systematically predict preventative maintenance action in advance of the time when it is required. By carrying out such an approach, the Utility Asset Manager will be able to attain the following level of control:

1. Optioneering - they will hold reliable, quantitative condition data on which to exercise Replace, Refurbish or Retain options.
2. Comfort - they have significant 'comfort' that the asset will last another X years (up to the next review).
3. Management - they will be able to prioritise maintenance/ replacement programs in advance, focussing on the installations most in need.
4. Regulatory - they will satisfy all safety, security and risk assessments as laid down.
5. Cost Reduction - they can extend the life of their assets with minimal CAPEX and OPEX outlay by only replacing those installations which are in poor condition with high 'criticality' and low reliability.

CASE STUDY

The following Case Study describes On-line Cable Monitoring and Pre-fault Location using an On-Line PD Monitor (OSM from IPEC) and an On-Line Cable Mapping System incorporating the PD Map Software from High Voltage Solutions Ltd, UK.

The On-Line Mapper enables the identification, measurement and location of partial discharge activity in MV Cables. In this example PD activity in a 33kV 'mixed' (PILC, XLPE & EPR) cable feeder was initially detected by a Permanent PD Monitoring System (OSM) which was installed at the customer's substation. An increasing trend of discharge activity activated a threshold alarm on the installed OSM unit and the customer was alerted to a potential problem. Following the alarm signal detailed data files containing highly resolved data from the circuit were automatically downloaded from the OSM monitor to the IPEC webserver over the system's Internet connection. Further analysis of this highly resolved data confirmed the presence of significant partial discharge activity on the cable feeder with activity measured in the range of several thousand PicoCoulombs (pC).

A series of spot tests to identify the severity and source(s) of the partial discharge activity were instigated as a result of the above. This testing utilised a portable Digital Discharge Detector (OSM-ST1) with integrated On-Line Cable Mapping Software (Cable Map) and Manual Transponders. In this example two discharging sites on the 33kV cable were detected with very high levels of discharge of up to 9,000pC.

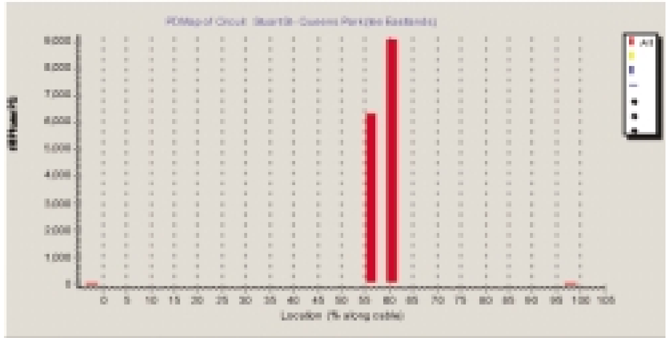

Figure 3: On-Line PD Map of 33kV 'Mixed' Cable

After consultation with the customer's circuit route maps the discharges were shown to correspond to two cable joints which were subsequently excavated at the location sites. After excavation of the joints they were then tested for partial discharge using a combination of Transient Earth Voltage (TEV) transducers, hardware filters to eliminate interference from other sources and a fast digital storage oscilloscope. The TEV transducers pick-up, through capacitive coupling, very fast transients which are induced in the cable or cable joint earth every time a partial discharge occurs. As the earth acts as a screen around cables and joints, TEV voltages only emanate from points where there is a break in this screen. From these points they travel along the outside surface of the earth. The TEV signals are very high frequency and therefore attenuate rapidly with distance from the source and the TEV sensors can only be used when in close proximity to the discharge source as in this case.

The TEV signal measurements confirmed high levels of PD in the two excavated joints which confirmed that the On-Line Cable Mapper had successfully identified the discharging joints. As the PD activity was sufficiently large to put the security of the circuit at risk the joints were replaced. The accuracy of the On-Line PD location in this case was 0.4% and 0.7% of the cable length for the respective joints (this represents an accuracy of between 10 and 20m over a 3km cable). It should be noted that the technology enabled all testing to be carried out on-line with no outage required. Final PD Monitoring tests show that the discharge activity on the cable had been successfully removed through replacement of the discharging joints. This effectiveness of the testing is illustrated in Figures 4a and 4b.

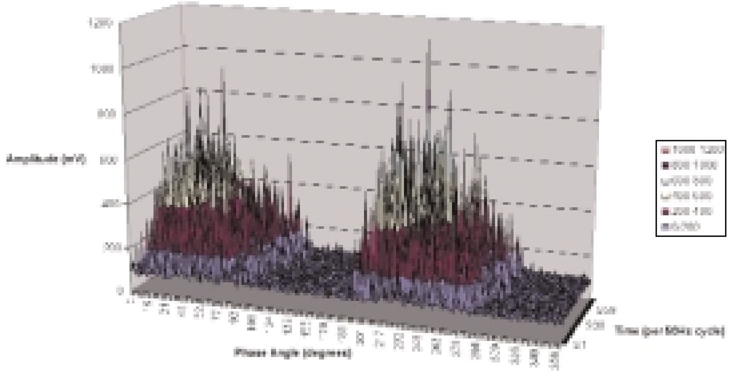

Figure 4a : PD Activity before joint replacement

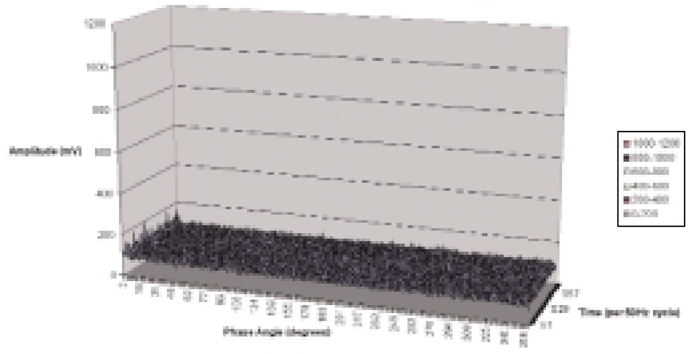

Figure 4b: PD Activity after joint replacement

DECISION SUPPORT SYSTEM (DSS)

With the basic 4-Phase Plan in place and the network's 'critical plant' identified the next challenge to the Asset Manager is how to best manage and maintain this critical plant on an individual basis into the future. In order to facilitate this decision-making a Decision Support System (DSS) can be applied. The DSS is a computerised tool for aiding management decisions and they are becoming more common in industry due to their ease of use and also the financial benefits they can accrue for users. The DSS' models and figures can be recalculated for different economic cases, types of equipment, failure rates, age profiles and replacement plans, as required, to carry out statistical and 'what if' analyses. This can maximise the potential savings available to the Utility and assist in budgeting for capital investment requirements.

The output of a development DSS to aid in the decisions of repair, replacement and other maintenance of in-service, MV Plant is shown in Figure 5. The vertical line shows the optimum replacement point predicted by the developmental DSS for a hypothetical MV cable feeder (in this case 9.75 years is the estimate of the optimum balance between risk and cost).

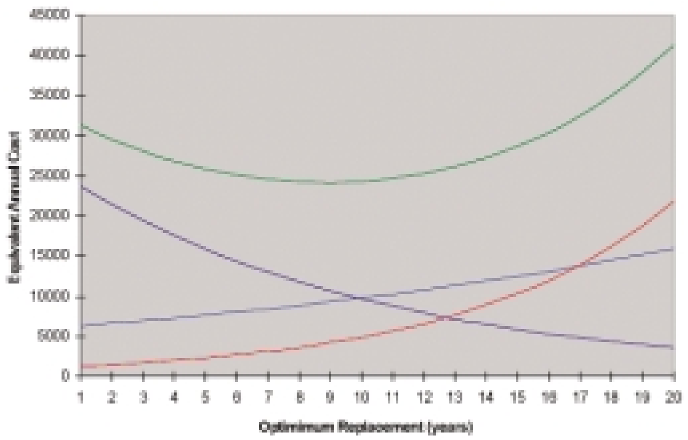

Figure 5: An Asset Management DSS for MV Plant

A DSS such as that described can interface directly with a Utility's existing Work Management Databases and Software Packages to provide an interactive, 'seamless' IT solution. Furthermore the DSS can be designed to display the information the customer wishes to see, in the format of their choice. The Figure 5 graph is a demonstration of how the information is displayed in a summarised format. In this instance it can be noted that there are three main Cost Drivers which have been taken into account include Capital Costs, Operational/ Maintenance Costs and Failure Risk Costs.

Whilst it is relatively easy to extrapolate the Capital Costs and Operational/ Maintenance Costs into the future through the use of Inflation and Cash Discount rates it is a lot more difficult to predict the Failure Risk Costs. As the Failure Risk Costs are the biggest unknown for future planning and as they are the prime driver for the optimum replacement times it is necessary to carry out a detailed failure mode analysis including statistical failure rate predictions from which the future Failure Risk Costs can be calculated.

There are three main options available in forecasting future failure risks as follows:

1. Apply average failure data from past studies of the failure rates of various types of plant against time in service.

2. Use failure data from the customer's own network (if this is available).

3. Utilise the condition data and future life predictions evolved from the 4-phase Asset Management Plan on the Network.

The ultimate aim of these processes is to forecast the likely failure rates of the various types of MV plant into the future to show the trend in time. A pre-requisite of carrying out any of the above options is to have the Asset Plant Age profiles for various types of equipment (refer to Figure 1 for examples). By combining the Asset Plant Age Profile with the Fault Profile (as a function of time in service) the future fault rates and total number of faults per annum as a function of time which can be predicted into the future.

EXAMPLE OF FUTURE FAILURE RATE PREDICTIONS - MASS IMPREGNATED PAPER CABLES

This example describes how the future failure rates of mass impregnated paper cables can be predicted using Option 1 - Failure Data from Past Studies. Failure Data from studies in the the UK and Europe have shown a slow and linearly rising failure rate for MIPC over the first 30 years of life, reaching around 4 failures/100km/year at 30 years, and then becoming flat from this point onwards.

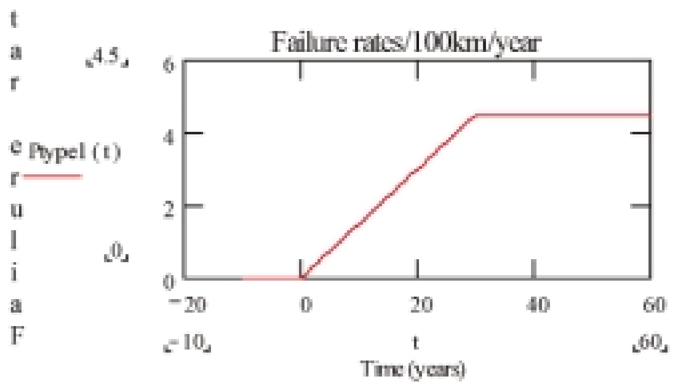

Figure 6: MIPC Failure rates with Age in Service

The total failure rate can be calculated from the product of the functions described in Figure 6 and Figure 1: Age Profile, i.e. it is the product of the average failure rate of the cable type and the installed capacity for the year (age profile), at some future date. This gives the total number of failures in any given year of the Future Life Cycle (Fig. 7).

Figure 7 : MIPC Failure Rates in Time

COST BENEFITS

The degree to which savings can be made using partial discharge detection and mapping of mass impregnated paper cables depends ultimately on the accuracy of the testing. However, savings are also dependent on the value placed on avoidance of interruptions, and on the costs of repairs, especially if these have added or unseen costs, say in difficult city locations. The savings from applying the technology to come into the following categories:-

1) Savings due to not replacing cable until necessary
2) Savings in costs of avoiding unnecessary repairs
3) Savings from improvement in Network Reliability
4) Savings by avoiding interruptions on sensitive circuits
5) Savings in legalities in claims of negligence
6) Other Savings (e.g. failures during testing yielding a more reliable system).

An explanation and breakdown of all of these savings is not possible within the scope of this paper. However it can be stated from the cost-benefit analysis study carried out that the main savings are to be gained through 1 and 3 i.e. the Avoidance of Early Replacement of Cables and Improvement in Reliability. These two savings represent over 90% of the potential savings from the list.

Recent On-Line PD testing surveys carried out by the authors have shown that the cable sections which are at risk are relatively small as a percentage of the population. Depending on the cost of an interruption, there is still some merit in replacing sections of cable which are discharging above acceptable threshold levels. There are also large savings to be achieved in the use of PD monitoring and mapping to guide the customer's replacement program. It is clear that if cable circuits can be 'targeted' through a systematic approach such as that described in the 4-phase plan presented in this paper, 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, can be used to pre-filter the set of circuits which should be tested to bring the most benefit to the utility.

CONCLUSION

With the ongoing trend in the electricity supply industry towards minimising equipment replacement rates and reducing operational expenditure, modern Utilities must look towards applying new Asset Management approaches. It is proposed that one option is to consider a condition-based approach to asset management to replace conventional asset replacement policies. This can be best achieved through the application of advanced condition monitoring technology and prediction techniques allied with a systematic, phased asset management approach.

If a distribution network is targeted in a systematic way, the cost benefit of Reliability/Risk Based MV Plant assessment can be greatly improved. By taking into account failure history, current service history, local knowledge of the Network, replacement planning and risk of failure versus capital/operational expenditure, asset management decisions can be made quicker and more efficiently with the use of dedicated Decision Support Systems (DSS's).

Further work is being carried out by IPEC and our partners (London Electricity and High Voltage Solutions Ltd) in the development of 'intelligent' diagnostic software systems for on-line PD mapping and remote monitoring of MV Plant to allow predictive maintenance and failure prevention.