PD Monitoring—A Critical Tool For Condition-Based Assessments

As medium-voltage facilities age, utilities leverage diagnostics to aid in asset management decisions.

By Cliff Walton, EDF Energy Networks, and Ross Mackinlay, High Voltage Solutions Ltd.

The United Kingdom's electricity supply industry will face a new set of challenges over the next decade as it strives to improve and maintain supply standards while minimizing operations and maintenance (O&M) costs.

Since the privatization of the UK's electricity distribution industry in 1990, the distribution network operators (DNOs) have reduced their O&M costs by downsizing internal staff and outsourcing some core functions.

A possible downside to this cost cutting approach is that the distribution companies now may not have adequate financial or labor resources to maintain the quality of supply in the future with traditional asset management methods. The reasons for this are twofold. There is an ever-increasing "age profile" of installed equipment combined with a trend toward reducing in-house engineering and technical knowledge. The increasing age profile of installed UK medium-voltage (MV) plants (Fig.1) is driving the application of on-line condition assessment as an asset management tool to extend plant life. This is illustrated in the table on page 40, 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.

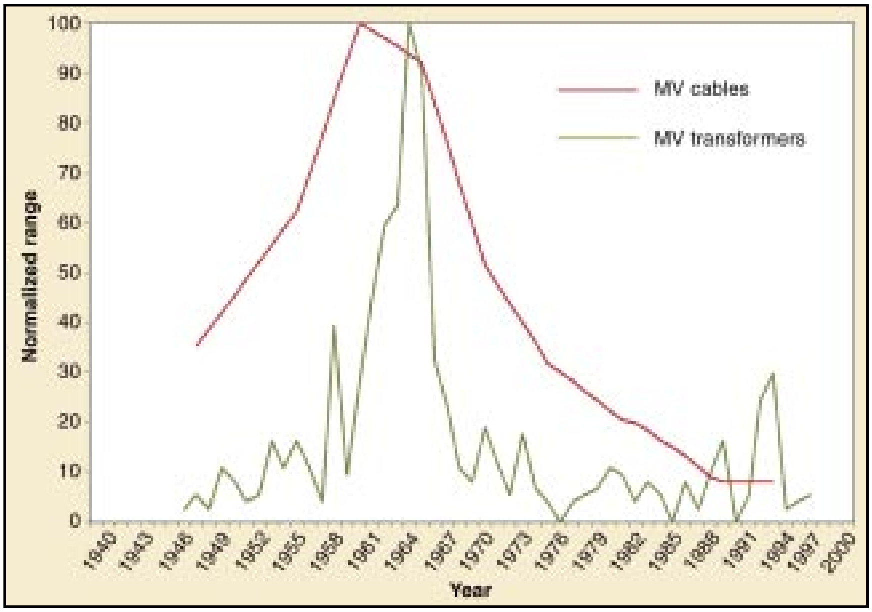

Fig.1. Typical UK medium-voltage plant install rate (1940 to 2000).

If the asset life values in the table are compared to the period when the volume of equipment installed in the UK was at its maximum (during the 1950s and 1960s), then a large quantity of equipment is now approaching the end of its original life expectancy. While this does not mean that all equipment nearing the end of its actuarial asset life is about

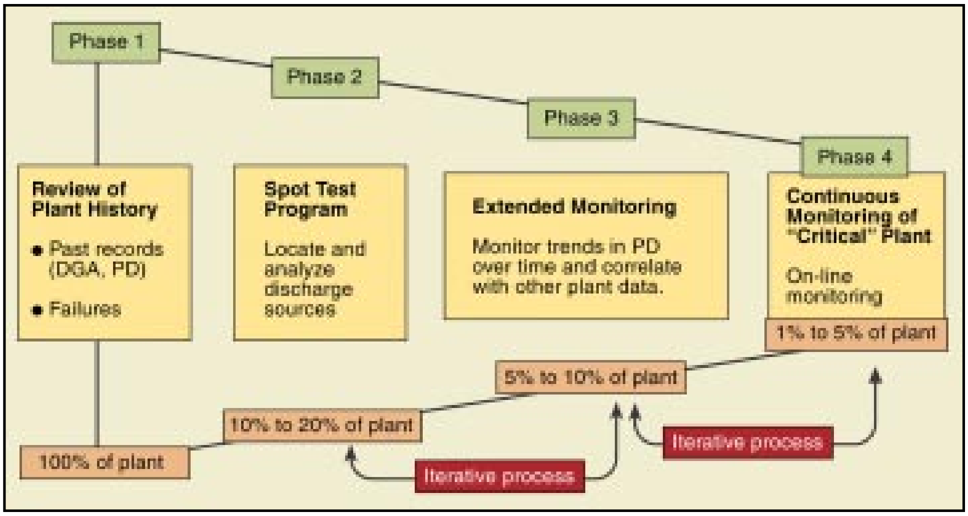

Fig. 2. The four-phase approach for condition assessment of medium-voltage plants.

UK Utility Ascribed Asset Life of MV Plant	
Type of Asset	**Typical Asset Design Life (years)**
Transformers	
Transformers (> 11kV)	50
11-kV ground mounted	45
11-kV pole mounted	45
Switchgear	
Indoor Switchgear	45
Outdoor Switchgear	40
Cables	
132kV cables	60
33-kV cables	60
11-kV cables	70

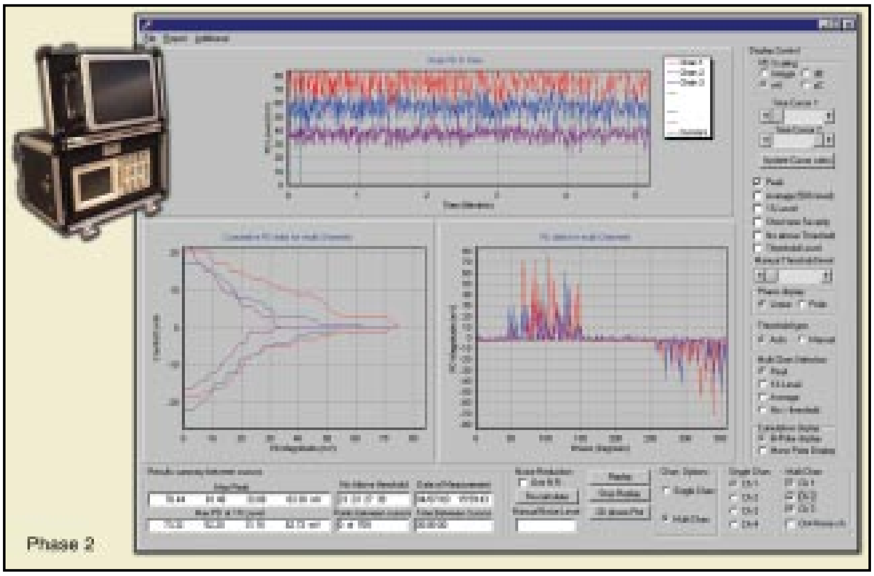

Fig. 3. Phase 2: Short-term monitoring images.

to fail, it does imply these assets should be managed with a condition-based approach. To achieve an effective condition-based asset management policy, the plant condition should be checked regularly and in a systematic manner.

A Condition-Based Asset Management Approach

On-line condition monitoring of equipment—partial-discharge (PD) monitoring, insulation loss-angle and gas-in-oil—is becoming more widespread in the worldwide electricity industry. Accurate condition assessment and the subsequent management of in-service, high-voltage plants are becoming more economically viable, with continuous advances and cost reductions being made in sensor technology, data acquisition/processing and intelligent diagnostic software. Although technology improvements continue apace, it is essential that the resultant data be risk managed.

After evaluating its needs, EDF decided to implement a new risk-based asset management approach and PD detection technology that provides systematic closed-loop condition assessment and management of MV plants. By developing an integrated asset management philosophy, EDF was able to focus on the critical plants within the network, which yielded the following key criteria necessary for an effective condition-based asset management program.

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

The above requirements have been adopted into the four-phase asset management approach (Fig. 2).

The Four-Phase Network Asset Management Approach

Phase 1: Review of Network & Plant History. This should be applied to 100% of the network and the study of the following factors:

- Analysis plant failure history (statistical analysis).
- Data-mining and past inspections.
- Assess age profile and replacement strategy.
- Identify common failure modes of plant.
- Identify location-specific criticality (LSC)—critical loads (such as hospitals and data-parks).
- Review of quality of supply (incidents, interruptions and customer minutes lost).
- Costs of faults, operational expenditure (opex) and capital expenditure (capex).

This exercise results in the identification of the 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 applied to some 10% to 20% of the network identified in Phase 1, an exercise that involves:

- Conducting a one-day inspection of substations to evaluate snapshot condition (five minute test per plant item).
- Locating and measuring PD activ-

ity (level, phase and waveform shape).

- Using portable PD spot tester (OSM-ST1) with PD Gold™ Software and calibrated PD sensors.

This results in the identification of substations for extended monitoring (longer than one week) in Phase 3.

Phase 3: Short-Term Monitoring. To assess the current conditions on the crucial spot locations:

- Install portable monitors (OSM-P32), typically one week per substation to obtain PD data for a weekly load cycle.
- Monitor trends in discharge over weekly loading cycle.
- Correlate with other condition and operational data (load, temp)

This results in the selection of critical substations chosen for continuous, long-term monitoring in Phase 4

Phase 4: Online, Continuous PD Monitoring. Long-term permanent OSM installation (OSM-V1.102) focusing on the suspect plant.

Continuous PD monitoring of critical plant to provide an early warning system to detect trend to failure and thus enable predictive maintenance.

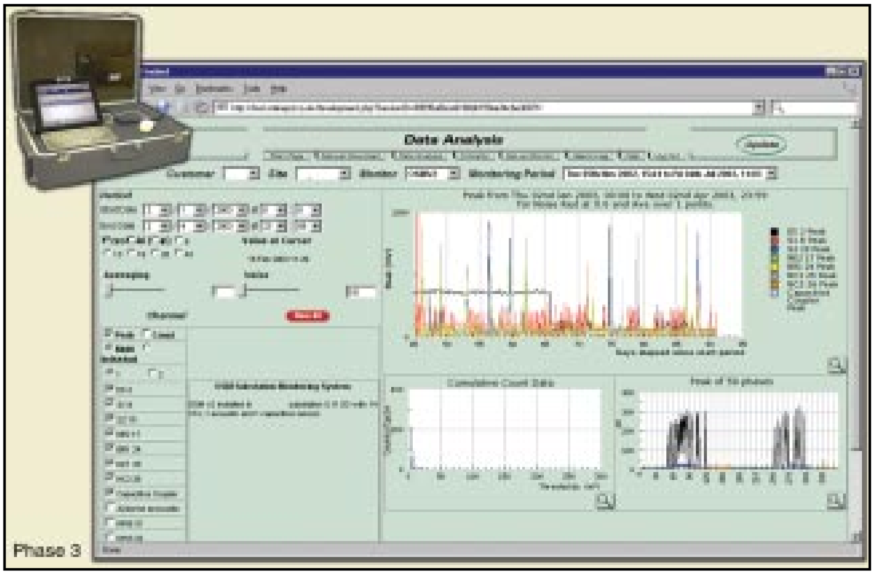

Fig. 4. Phase 3: On-line continuous monitoring images.

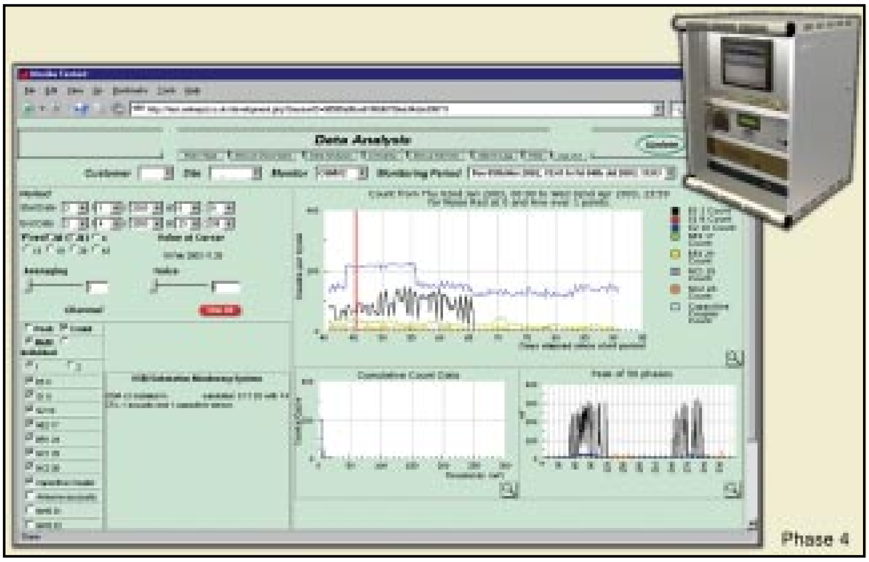

Fig. 5. Phase 4: Long-term permanent monitoring images.

London Electricity's Use of an On-line PD Monitor and PD

EDF Energy (London) offered a 33-kV cable circuit on which to test the application and benefits of on-line cable monitoring and pre-fault location using the On-Line PD Monitor (OSM from IPEC) and an On-Line Cable Mapping System incorporating the PD Map™ Software (Cable Map™) from High Voltage Solutions Ltd. UK.

The On-Line Mapper enables the identification, measurement and location of PD activity in MV cables. In this trial, the PD activity on the 33-kV "mixed" (PILC, XLPE and EPR) cable feeder was initially detected by a permanent OSM PD Monitor that was installed in London Electricity's substation. An increasing trend of discharge activity activated a threshold alarm on the installed OSM unit and London Electricity 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 Web server over the system's Internet connection. Further analysis of this data confirmed the presence of significant PD activity on the cable feeder with activity measured in the range of several thousand pico-Coulombs (pC).

A series of spot tests to identify the severity and source(s) of the PD activity were instigated. This testing used a portable digital discharge detector (OSM-ST1) with integrated Cable Map™ software and a manual transponders (pulse booster). Two discharge sites were identified on the

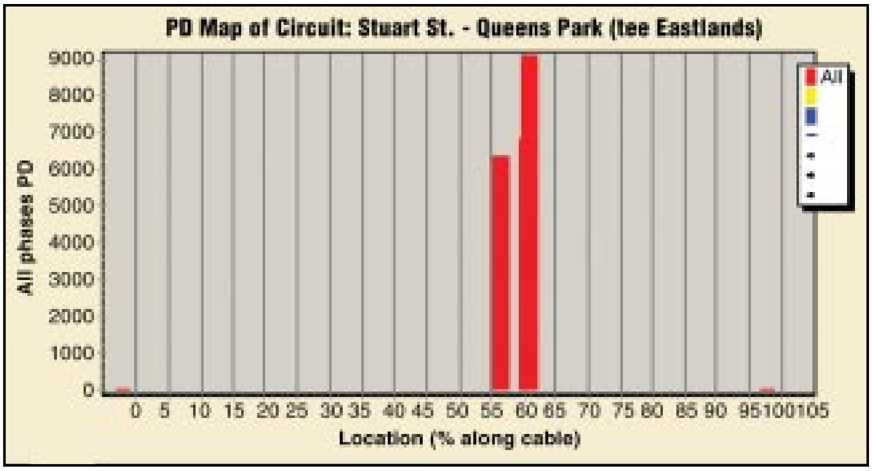

Fig. 6. On-line PD map of 33-kV "mixed" cable.

The failure risk cost is the prime driver for the optimum replacement times for equipment, so a detailed failure mode analysis that includes statistical failure rate predictions is required to determine the future failure risk cost.

33-kV cable with the detection of high levels of discharge (up to 9,000 pC). A PD map of the cable circuit is shown in Fig. 6.

Consultation with EDF Energy's circuit route maps indicated the discharges corresponded to two cable joint positions. Following excavation, the suspect joints were tested for PD 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 signal measurements confirmed high levels of PD in the two excavated joints that confirmed the On-Line Cable Mapper had successfully identified the discharging joints. As the PD activity was large enough to put the security of the circuit at risk, the two joints were replaced. The accuracy of the on-line PD location on this circuit was within 0.4% and 0.7% of the cable length for the respective joints (an accuracy of between 10 m and 20 m [33 and 66 ft] over a 3-km [1.8-mile cable).

The technology enabled all testing to be carried out on-line without the need to de-energize the circuit. Final PD monitoring tests show that the discharge activity on the cable had been successfully removed through replacement of the discharging joints (Figs. 7a and 7b).

The Economics of Condition-Based MV Plant Management

With the basic four-phase plan in place and the network's "critical plant" identified, the next challenge to the asset manager was how to best manage and maintain this critical plant at a minimum cost. It can be noted that four main cost drivers for MV plant management are capital costs, maintenance costs, replacement costs and failure risk costs.

While it is relatively easy to extrapolate the future capital, replacement and maintenance costs using inflation and cash discount rates, it is more difficult to predict the failure risk costs. The failure risk cost, as the largest unknown for future planning, is the prime driver for the optimum replacement times for equipment, so a detailed failure mode analysis that includes statistical failure rate predictions is required to determine the future failure risk cost.

Three main options are available in forecasting future failure risks:

- Applying average failure data from past studies of the failure rates of various types of plant against time in service.
- Using historical failure data

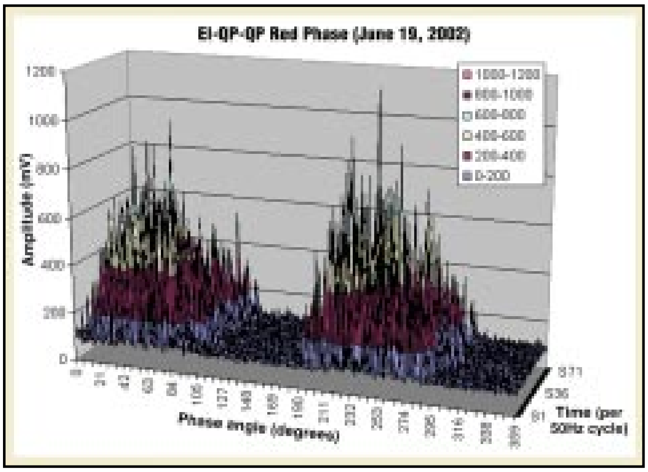

Fig. 7a. PD activity before replacement of discharging joints.

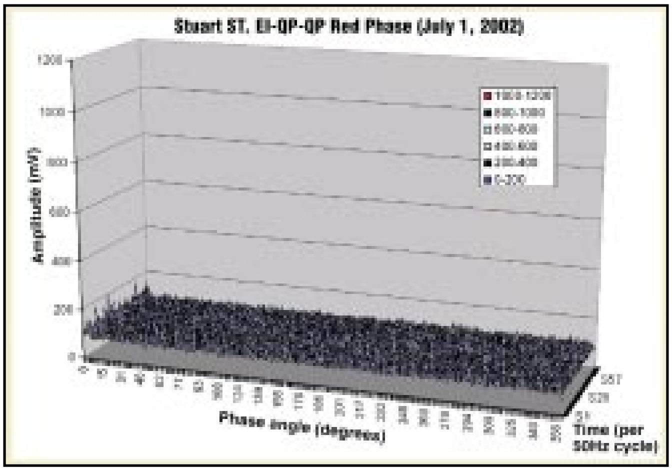

Fig. 7b. PD activity after replacement of discharging joints.

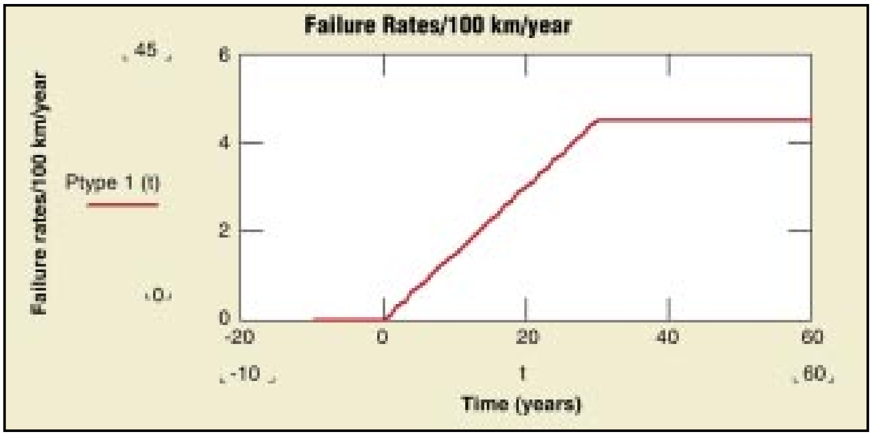

Fig. 8. MIPC failure rates with age in service.

from the customer's own network (if available).

● Using condition data and future life predictions evolved from the four-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 plants into the future to show the trend in time. A prerequisite of carrying out any of the above options is to have the asset plant age profiles for various types of equipment (Fig.1). 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 as a function of time can be predicted into the future.

Future Failure Rate Predictions—Mass Impregnated Paper Cables

This example describes how the future failure rates of mass impregnated paper cables (MIPC) can be predicted using option 1. Failure data from studies in the UK and Europe (Fig. 8) have shown a slow and linearly rising failure rate for MIPC over the first 30 years of life, reaching around four failures/100 km/year (6.4 failures/100 mile/year) at 30 years, a failure rate that then remains constant with age.

The total failure rate can be calculated from the product of the functions described in Figs. 8 and 1. The product of the average failure rate of the cable type and the installed capacity for the year, at some future date, gives the total number of failures in any given year of the Future Life Cycle (Fig. 9).

Cost Benefits of PD Monitoring and Mapping on Paper Cables

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

● Deferring cable replacement.

● Avoiding unnecessary repair costs.

● Improving network reliability.

● Deferring interruptions on sensitive circuits and savings from reducing legal claims for negligence. An estimated 90% of the potential savings are attributable to deferring cable replacement and improving network reliability.

Recent on-line PD testing surveys have shown that a small percentage of the UK cable population is at risk. However, depending on the cost of an interruption, there is still some merit in replacing sections of cable that are discharging above acceptable threshold levels. It is apparent that if cable circuits can be 'targeted' through a systematic approach, the cost benefit of PD monitoring and mapping can be greatly improved. Failure history, current service history, local knowledge of the cables and joints, replacement planning, and other relevant data are all valuable aids in determining which circuits to test to maximize the utility's benefit.

Summary

The ongoing trend in the electricity supply industry is to optimize asset management strategies. One option is to apply a condition-based approach to replace traditional asset replacement policies. That is best achieved through the application of advanced condition monitoring technology and prediction techniques allied with a systematic, phased asset management approach.

By this systematic approach, the cost-benefit of reliability/risk based MV plant assessment can be greatly improved. However, by taking into account failure history, current service history, local knowledge of the net-

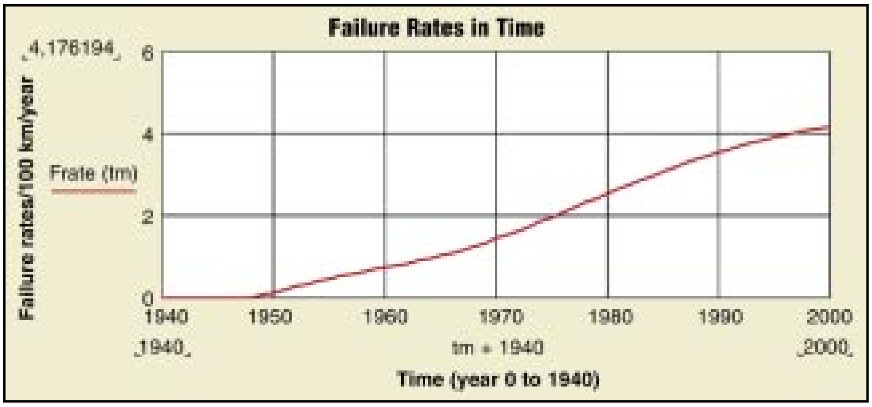

Fig. 9. MIPC failure rates in time.

work, replacement planning and risk of failure vs. capital/operational expenditure, asset management decisions can be made quicker and more efficiently with the use of dedicated decision support systems.

Further development work will continue by IPEC, High Voltage Solutions with the utility partner, EDF energy, on "intelligent" diagnostic software systems for on-line PD mapping and remote monitoring of MV plants to allow predictive maintenance and failure prevention.

Acknowledgments

This article is based on a paper the authors presented at the CIRED 2003 17th International Conference & Exhibition on Electricity Distribution, which was held in Barcelona, Spain, May 12-15, 2003 and published in the AIM conference proceedings. Lee Renforth (lee@ipec.co.uk) and Colin Smith of IPEC Ltd. contributed to the paper.

Cliff Walton studied electrical power engineering at South Bank, London, and engineering business management at Warwick University. His career in electricity distribution spans more than 30 years and covers a wide range of roles and responsibilities. Currently head of strategic development for EDF Energy Networks, he is responsible for the development and implementation of strategy and innovation. In his recent roles, he has championed the development of fault causation analysis, incipient fault detection and location techniques and well as creating the strategies behind the implementation of one of the world's largest distribution remote control, telemetry and automation projects. He is a chartered electrical engineer and member of both the IEE and IEEE.

e-mail

Ross Mackinlay studied physics at Lancaster University (BA) and Oxford University (PhD) and then joined the Electricity Council Research Centre (ECRC) at Capenhurst researching in electricity distribution equipment. In 1989, he became head of Cables & Dielectrics at EA Technology (formerly ECRC), and in 1993, he was appointed group manager of Cables and Power Technology at EA Technology. Since 1998, he had managed his own company, High Voltage Solutions Ltd., an engineering and scientific consultancy. Mackinlay as measurement expert, has developed a several new PD monitoring products and software for on-line PD detection, and is recognized as one of the UK's foremost experts in the field of PD diagnostic methods for cables, switchgear and other high-voltage plant.

e-mail

www.tdworld.com