# ADVANCES IN CONTINUOUS PARTIAL DISCHARGE MONITORING

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## *ABSTRACT*

*The Advanced Substation Monitor is a significant step on the path towards a fully automated monitor for MV circuits in substations and switchrooms. This paper details the steps in that development as well as describing key results that have been achieved on the way.*


## INTRODUCTON

The development of an advanced partial discharge (PD) monitor for electricity substations has not come about by one single invention. The history is one of continuous sustained development of all aspects of the fault detection, identification and classification process. This development has been driven by a perceived need for automation of the process in order to reduce costs and to minimise the need for human domain expertise. The traditional method of detecting PD in substations has been to employ trained operators to take portable equipment on site to perform spot testing of the installed equipment. This method is both expensive and time consuming and it would not be cost effective to train and deploy experts to monitor every critical circuit in a network.

By automating the collection and analysis of data, many hundreds or thousands of circuits can be monitored and reported with minimal human intervention. The data are analysed and information presented to the operators and managers of the monitored equipment in a way that is easily and immediately assimilated.

## PROGRESSION FROM SPOT TESTING TO CONTINUOUS INTELLIGENT MONITORING

Each stage of the development process has stood on the shoulders of the previous one. The mass of data collected has been used as the raw material to provide the information needed to refine the process.

### Substation Monitor OSM v1

The initial step from spot testing to the first continuous monitor was achieved by multiplexing the input of the tester to many sensors and by automatically logging the results. The multiplexed sensors were connected to a computer-based data logger (Figure 1).


Figure 1.

Each sensor was polled on a timed basis. The resulting logged data were analysed by a Domain Expert in the same way as Spot Test data had been. This work was reported by Zhao et al [1]. The significant advantage of this monitor was the availability of time series data that could be used to measure trends in partial discharge over a period of time. An additional benefit was the facility to detect intermittent data, where it is extremely unlikely that a spot test would pick this up. The disadvantage of this equipment was the simplicity of the algorithm used to detect and identify PD and the quantity of PD data that it generated. These had to be inspected visually by the Expert in order to identified and classify them.

### Substation Monitor OSM v2

The version 2 monitor contained additional analogue filtering in an attempt to reduce the noise in the stored data. This version of the monitor has the greatest appeal to the Domain Expert because the logged data is unprocessed in the general sense and little or no information has been lost by the application of the filtering. It still has the problem that the mass of data stored must be processed by human intervention and this was proving to be a bottleneck in the wider application of continuous monitoring.

### Substation Monitor OSM v3

The first major step in automating the monitoring process was taken in the development of the v3 monitor (Figure 2).

Figure 2.

This monitor used software tools that were originally developed for spot testing to identify signals that appeared to be PD. This implementation of the algorithm was chosen to be "leaky" as it was considered better to have false positives that could be eliminated at a later stage by inspection, rather than rejecting signals that were from partial discharge in the monitored equipment. This process was still inherently dependent on human intervention and the challenge faced by the development group was how to not only accurately identify, but also to classify the type of partial discharge being detected by the instrument.

**Advanced Substation Monitor ASM**

The complete automation of the identification and classification of sensed partial discharge signals is a major undertaking. It requires improvement to the hardware of the monitor and to the software in both the monitor and the database. Figure 3 shows an installation of the ASM which incorporates these improvements.

Figure 3

Sampling must be faster and with greater resolution than in previous monitors in order to provide good data for the identification and classification software. The software must be more sophisticated in order to implement the various algorithms that are developed through the project and it must be amenable to change so that systems can be updated as knowledge of the domain increases. Most importantly we have restructured the process by which the data is analysed within IPEC so that there is a continuous learning process that facilitates the development of the identification and classification of algorithms as data is collected.

**Knowledge process**

The diagram (Figure 4) below is an illustration of the knowledge acquisition and dissemination process. This process has been a critical part of the development of the Advanced Substation Monitor. At each stage of the development, data from the previously installed monitors have provided the information to set the requirements and generate test cases for the next stage.

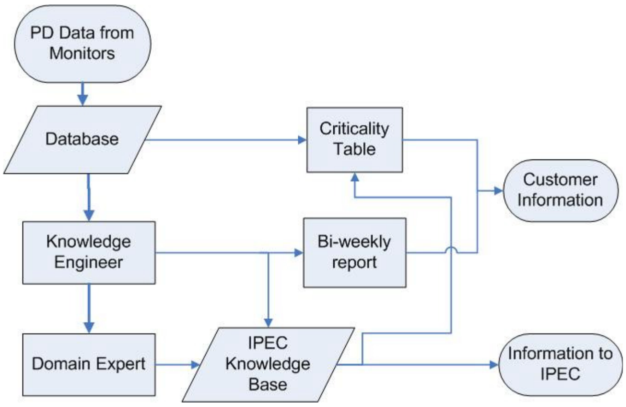


Figure 4

Data are routinely collected from IPEC OSM v2.5, v3 and ASM monitors. The majority of these monitors are deployed in the distribution substations of our key customer and project partner EDF Energy plc. A significant minority are installed in the switch-rooms of critical manufacturers both in the UK and abroad. The data are stored in the main database, where they are processed by software to provide Criticality Tables and inspected by a Knowledge Engineer to check the performance of the algorithm and to identify improvements to the process. Where there are contentious or ambiguous results, these are checked with the Domain Expert within IPEC and from time to time by reference to other experts in the field of PD measurement. All this information is stored in the IPEC Knowledgebase where it contributes to the immediate decisions on criticality and provides material for future algorithm development.

Information is presented to the Customer in three different forms. The Criticality Table (Figure 5) is the primary display, where all the circuits are ranked according to the level of activity and the changes to the activity detected in the circuits being monitored. Additionally a regular report summary is provided and SMS and email alarm messages are sent when critical changes in the level of activity are taking place.

For the future, we have included a facility to allow a worker to interrogate a sub-station monitor to check on equipment condition before entering a potentially hazardous area. This gives the worker the information to plan their entry and to minimise the Time Exposed to Danger.

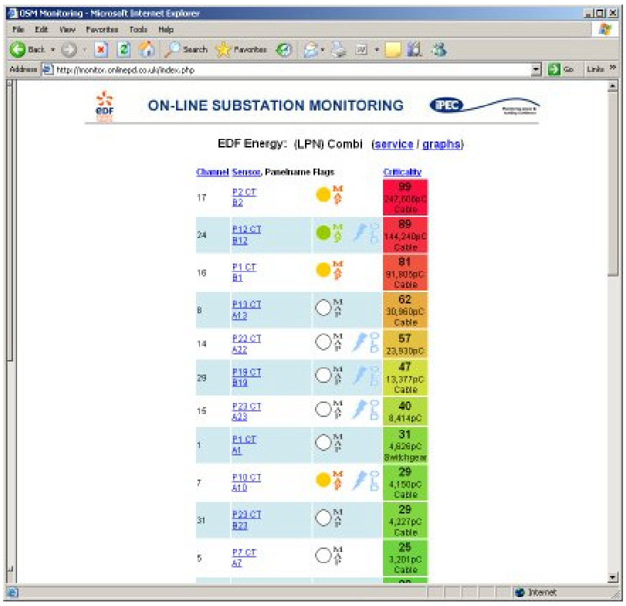


Figure 5

The knowledge derived from the data is held by IPEC and it is this that is used to form the basis of the algorithm developments to be incorporated into the ASM. Iteratively the monitors containing these algorithms then form the basis for the collection of new customer data and the next stage of development.

## EXAMPLE OF ASSET MANAGEMENT

An increasing trend in partial discharge activity was detected by the monitor on a circuit east of London. The increase in activity occurred over a period of about 7 weeks. (Figure 6) There was an increase in both the individual discharge magnitudes and the rate at which they occurred although the increase in the discharge rate was the more pronounced.

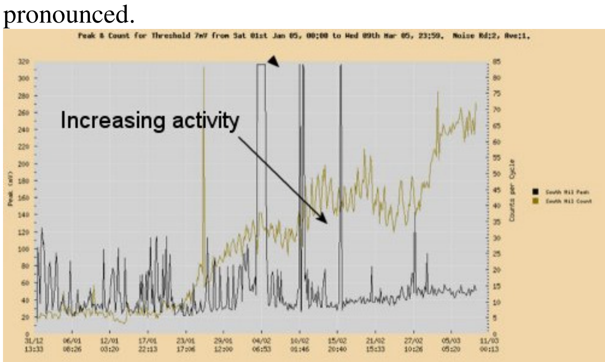


Figure 6

It was apparent from the waveshape of the discharge signal that the source of the activity was not near the monitor so further investigation was carried out using off-line VLF mapping. On-line mapping was also carried out and the two mapping results were compared [2]. Both methods indicated that there was a discharging area approximately 850m from the cable end.

Following consultation with Asset Management and Customer Relations, a decision was made to remove a 150m section of the cable to remove the faulty area and eliminate the possibility of any further problems with this cable section which dated back to 1963.

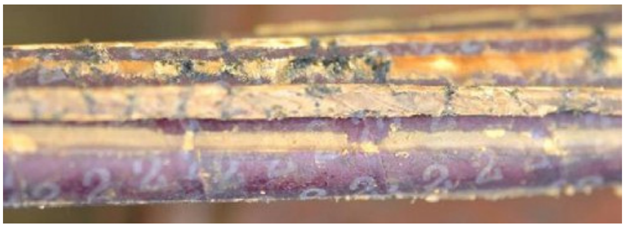

Figure 7

After removal, the cable section was analysed. The investigation showed traces of carbonisation on the outer layers of the belt paper as well as on paper around the cores as shown in figure 7. After re-energisation, the discharges had stopped.

## DETECTING PERIODIC AND INTERMITTENT EVENTS

Traditionally, partial discharge testing has involved scheduled, periodic testing of MV plant. This inspection is carried out by field engineers using portable equipment at intervals of between 6 and 24 months. However it is clear from field experience that this approach is flawed due to variations in PD activity over time and the rate at which a fault can initiate and develop to a failure.

Partial discharge is a very complex phenomenon and its development over time is affected by many factors. Discharges generally occur in damaged or poorly manufactured insulation at points of high electrical stress. The size and repetition rate of discharges are functions of the fault size, surface conditions and the internal gas composition, pressure and temperature. All of these parameters are likely to change over time as environmental and load conditions change as well as a result of the discharge activity itself.

As a result, partial discharge activity can be sporadic with periods of very low or no activity following periods of high activity. The load on a high voltage system does not directly effect PD, however the resulting change in temperature causes physical changes within the insulation that can affect it. This could manifest itself as either an increase or a decrease in PD activity during periods of high load. Approximately 15% of the discharging circuits that are currently being monitored show a relationship between the level of discharge activity and the load on the circuit as shown in figure 8.

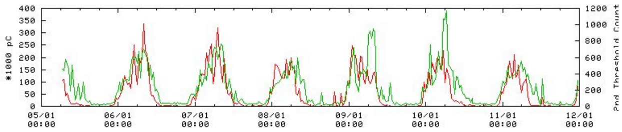

Figure 8

Such variations in activity over time make periodic spot testing of plant unreliable as a test may be completed in only a few hours during which time discharge activity may be temporarily dormant.

## RAPIDLY DEVELOPING FAULTS

Current practice is to inspect equipment on a routine basis a few times over its design life. This means that the return time between inspections of a given piece of equipment can be measured in years, or at best months. For Distribution Network Operators (DNOs) that have pressure to reduce the number of Customer Minutes Lost (CML) and for manufacturers with critical processes such as semiconductor manufacture where continuity of supply is paramount, prediction of impending failure is very valuable.

An example of a rapidly developing fault is shown in figure 9. This was activity detected over a period of less than a month on air insulated MV switchgear. As the frequency and intensity of activity increased, an alarm was raised, the equipment was taken out of service and maintenance planned for the following week. The result was uninterrupted supply with no consequential loss.

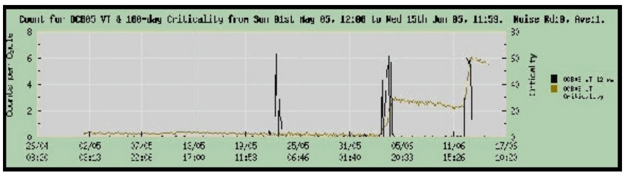

Figure 9

As we increase the Knowledgebase, a picture is being built up showing how long a circuit exhibits measurable discharge prior to failure. It is clear from these results that a significant number of failures could not be detected by periodic testing as the lead time to failure is shorter than the time interval between tests.

## HARDWARE DEVELOPMENT FOR THE ASM

The Monitor Hub is a data acquisition unit developed specifically for the capture and analysis of partial discharges. In order that the system can be used to completely cover all plant in the largest substations, a capacity of up to 128 PD sensors was built-in. To allow elimination of partial discharge cross talk between MV circuits, acquisition is carried out simultaneously on any two selected channels.

As well as the input PD signal, the signal lines carry a DC voltage which is used to power active sensors, for instance acoustic sensors that require very high gain amplifiers. The input stages were developed with a very wide bandwidth, so that the system could support PD sensors with output frequencies from 40kHz to 800MHz.

Signals from the PD sensors are sampled at 100MS/sec and 12 bits dynamic range for up to 10 power cycles. The acquired data is then transferred to an embedded PC for analysis. The sensitive electronics are fully protected against the very large voltage spikes and current surges that occur when a circuit fails. The very high resolution of the sampled data allows the use of sophisticated signal analysis. Wavelet-based noise reduction was adopted as it is generally accepted as the most effective technique for VHF and UHF PD signals [3][4].

An expert system uses knowledge rules to identify pulses in the captured data that originate from partial discharge as distinct from those generated by external noise sources. Key characteristics of PD waveshape are extracted and quantified. These parameters are then used to estimate the location of the PD source. Similarly, the distribution of the discharge activity across the 10 captured cycles is used to classify the PD source.

Once every 24 hours all these elements are combined to generate a ‘Criticality’ for each circuit. Stored on the central database, the Criticality is a simple indicator of the circuit condition allowing easy comparison across a large population of circuits. When analysed as a league table of critical circuits the user has a valuable resource for targeting asset maintenance and replacement.

## CONCLUSIONS

We have illustrated the development of the ASM and the process that has been used to get close to a fully automated monitor of PD on circuits in switchrooms and distribution substations. This type of monitoring has predicted the failure of components and has been used for reactive maintenance of circuits just prior to total failure, as well as providing information for the planning and scheduling of maintenance for circuits that are showing early signs of failure. To date we have concentrated on a few key customers and from our experiences and from the results obtained on these hundreds of circuits, we are confident that this method can be more generally applied.

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[2] Matthieu Michel, Comparison of Off-Line and On-Line Partial Discharge MV Cable Mapping Techniques
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[4] X. Zhou, C. Zhou, D. Guo, D.M. Hepburn, B.G. Stewart, A. Nesbit, Rejection of Composite Noise in PD Measurement for Power Plant Condition Monitoring.
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