ERA High Voltage Plant Life Extension Conference, November 2000, Laborelec, Belgium

Effective Asset Management for Life Extension of HV Plant

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Abstract: The market for the condition assessment of high voltage plant contains a myriad of technologies ranging from simple, low-cost 'spot-test' equipment to complex, high cost, on-line monitoring equipment. Whilst the application of condition monitoring equipment is becoming more widespread in the electricity industry it is important to consider an appropriate asset management philosophy to provide for reliable, extension of the 'original design life' of installed equipment. The authors present a new management approach to provide cost-effective management of High Voltage plant through the application of a combination of new spot-test equipment and permanently installed equipment. The HV Plant Asset Management approach is illustrated through a 4-phase plan which provides the plant owner with an opportunity to systematically identify their 'critical' plant through the use of spot-test equipment, semi-permanent (portable) installations and permanent on-line monitoring equipment. A case study of the application of the new technologies and methodologies for the condition assessment and management of 132/33kV Substations in the UK Electricity Distribution System is presented.

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Keywords: Acoustic Emission, Partial Discharge, Remote-Access, Critical Plant, Asset Management

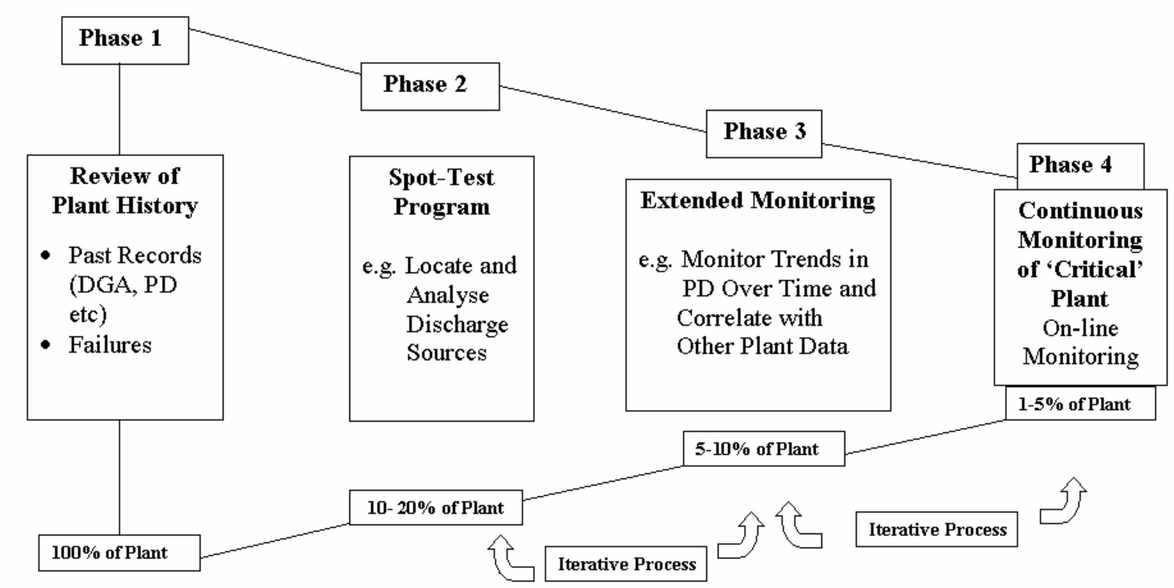
I. INTRODUCTION

Whilst there are many options available in the market for the condition assessment of high voltage plant it is the task of the HV Plant owner to identify which test equipment to use, which plant it should be used on, the frequency of the tests and what are the benefits to them of carrying out condition monitoring. This is no easy task and requires extensive knowledge of plant failure mechanisms, the causes of failure and the period of time from the onset of a trend-to-failure to the actual failure of the equipment (the lead-time-to-failure - 'LTTF'). For effective spot-test programmes to work the equipment must be inspected at intervals of a minimum of ½ the LTTF so that the trend to failure can be identified well in advance of catastrophic failure of the equipment. Whilst some knowledge exists on the average LTTF for various types of HV plant, it is known that failures have occurred in the past within days (or even hours) of the onset of the 'trend to failure'.

Furthermore, some external and internal events, such as nearby lightning strikes or circuit breaker failure, may result in a failure mode where there is no trend. Subsequent condition assessment tests produce results which need to be interpreted in a pass/fail manner. These external events do not mean that monitoring is of no advantage. Indeed the application of condition monitoring equipment (partial discharge, insulation loss-angle, gas-in-oil etc) is becoming more widespread in the worldwide electricity industry. It is however important to consider a complementary asset management philosophy to provide for reliable, extension of the 'original design life' of installed equipment. For example it is not cost-effective (at the present time) to continuously monitor 100% of installed plant due to the high cost of doing so and the fact that typically over 90% of installations will be working satisfactorily. It is the other 10%, the 'critical' plant within a network (based on condition and/or location), which should be focussed on and monitored continuously. Extending this argument further, for potentially expensive outages it is possible that the HV plant owner will err on the side of caution by replacing plant at an early stage, prior to installing long-term, continuous monitors, rather than risk an unplanned outage.

The dawning of the new millennium signals new challenges for the worldwide electricity supply industry as suppliers strive towards improving quality of supply standards and the safety and security of the system whilst minimising operational and maintenance costs. Accurate condition assessment and the subsequent management of in-service high voltage plant is becoming increasingly viable with continuous advances being made in sensor technology, data acquisition and processing. Whilst technology improvements continue apace it is also important to combine plant condition data with a complementary risk management approach. This paper describes a novel approach for the condition assessment and management of HV plant through the use of a combination of plant sensors, data acquisition modules and remote-access Internet platforms. The underlying principles behind the approach are described through a 4-phase plan which provides for systematic 'closed loop' condition assessment and management of HV plant. This is followed by a case study on 132/33kV substations.

II. AN OVERVIEW OF MANAGEMENT APPROACH FOR HV PLANT LIFE EXTENSION



1: 4-Phase Approach for Condition Assessment of HV Plant

A 4-phase management approach is suggested for the condition assessment and management of HV plant, as summarised below:

Phase 1: Review of Plant History

This is carried out through discussions with the owner's operational and maintenance engineers to ascertain how the plant has performed in the past. Important information includes routine spot-test inspection, detail of past outages and results from specific condition assessments which are typically carried out on an 'as required' basis. This information provides the basis from which 'suspect' plant; particular plant families and critical locations within equipment can be identified for further condition assessment.

Phase 2: Spot-Test Program

This involves detailed analysis of the plant identified as worthy of further investigation in Phase 1. The purpose of the short duration spot tests is to identify the location and magnitude of particular problems e.g. partial discharge activity within the plant. Equipment which can be utilised for PD detection include acoustic emission sensors, electromagnetic PD sensors and ultrasonic airborne acoustic sensing with antennae. It is through a combination of these sensors that the location and magnitude of the PD can be most accurately ascertained. The best combination of sensors depends on the plant type, type of fault and location. All sensors used should be connected through a single data acquisition module for analysis such as a multi-channel; portable digital oscilloscope and computer based data acquisition system.

Phase 3: Extended Monitoring

It is well known that most condition parameters are random and can vary significantly, increasing and decreasing over short periods of time due to changes in load, temperature and other parameters. For example it is important that to properly assess PD activity monitoring should be carried out over a period of time which covers such operational variances. For the purposes of this project this period was chosen to be 1 week. A portable data capture, processing and data storage platform was used for this with analogue and digital sensor inputs from a range of condition sensors connected through a single data acquisition module. The inter-relationship between condition parameters can then be assessed to provide a further data-set for the diagnostic inference process.

Phase 4: Continuous On-line Monitoring

The results obtained from Phases 1, 2 and 3 are then combined through an inference algorithm to identify the 'condition specific criticality' (CSC) of the plant within the system. It is important at this point to also consider the 'location specific criticality' (LSC) of the plant which relates to the relative importance of the equipment within the macro system. This is carried out through discussions with the owner's asset managers. By multiplying the two factors a 'Combined Absolute Criticality' (CAC) rating for each substation is produced. The appropriate level of monitoring and assessment of plant within each substation can be set from the CAC rating. It is the plant with high CAC ratings (higher risk) to which continuous monitoring systems should be applied.

III. MONITORING PARTIAL DISCHARGE (PD) IN SUBSTATION PLANT

One of the major causes of faults in high voltage equipment is partial discharge. Partial discharge can be produced in oil, paper or solid polymeric insulation through localised breakdown. In addition to this, discharges between copper windings can cause degradation of insulation systems.

There are several methods of detecting partial discharge. Directly it can be detected by electromagnetic or acoustic methods (typically in the ultrasonic frequency range). This paper describes direct methods for PD location and monitoring. In the case of 132/33kV substation plant, the use of a combination of electromagnetic sensors, acoustic detection sensors and radio frequency antennae is most appropriate as this allows for the detection of both the location and magnitude of the discharge activity to be determined.

III (i) - PD Detection in HV Plant

Highly stressed electrical insulation in high voltage plant is subject to degrading ageing processes. This degradation is characterised by partial discharge activity. Voids or discontinuities in the insulation create areas of stress enhancement which lead to this discharge activity. This causes further damage to the insulation, leading to failure of the plant. Plant failure results in costly downtime or in the case of catastrophic failure, injury or even loss of life. Preventing plant failure by predictive maintenance is therefore essential to operators in terms of both economics and safety. Utilising a system of Reliability-Centred Management/Maintenance can prevent unscheduled outages and equipment damage whilst also extending the period in between scheduled outages and ultimately extending plant life.

Discharges within insulating systems generate acoustic waves and electromagnetic pulses which radiate in all directions from the discharging source. In the case of acoustic waves their initial frequency and magnitude are dependent on the nature of the discharging source. The attenuation of acoustic energy as it is transmitted through most common insulating materials increases exponentially with frequency. This causes insulating materials to behave like a low pass filter for the acoustic energy. The frequency distribution of the acoustic energy created by a partial discharge is therefore a function of the frequency content of the discharge and the length and nature of the transmitting medium. Consequently, both the centre frequency and the magnitude of the acoustic energy reduce with distance from the source.

Historically the most common method of detecting partial discharge activity has been by picking up electromagnetic signals. RFI (Radio Frequency Interference) detection is typically used to monitor the ambient electrical discharge activity in a substation or transformer house. Monitoring trends in activity using RFI can indicate the presence of PD activity, but little information on the nature and extent of the activity.

Depending on the type of plant and location of the discharge within the plant, other non-invasive EM detection (current transformers and capacitive couplers) can reveal more information on the nature of the discharge. It is also beneficial to monitor operational parameters of the equipment such as load as well as environmental conditions and correlate trends in these with the discharge activity.

III (ii) - Details of Equipment for Spot Testing of 132/33kV Substations

Detailed analysis of five 132/33kV substations was carried using a specialised, opto-isolated ultrasonic detection device in conjunction with highly sensitive acoustic transducers and two types of electromagnetic transducer (current-transformer and capacitive coupler).

The acoustic data was analysed using IPEC's Portable Acoustic Discharge Detector in conjunction with a portable digital oscilloscope and computer based data acquisition system. The unit incorporates a fibre optic link to maintain isolation when connected to the transformer.

IPEC's US-k100 transducer was used for the spot-test inspections. The US-k100 has an integrated pre-amplifier giving a sensitivity of 65 dB and has a bandwidth from 80 to 130 kHz. The sensors were used in conjunction with the UltraSense detector for the monitoring of acoustic energy emitted by discharges in plant.

Figure 2: Ultrasonic Partial Discharge Transducer US-k100

Both the centre frequency and magnitude of the acoustic energy reduce with distance from the source due to the frequency dependent attenuation of insulating materials. The frequency components of discharge energy at the points where it can be measured on electrical plant tend to be below 250kHz. However, when monitoring partial discharges measurements tend to be taken above 40kHz in order to avoid interference from external acoustic sources. The transmitter and receiver units were connected via a fibre optic connection. The signal amplifier in the receiver unit has two gain settings, 40dB and 60dB. The signals detected were output via the BNC connection on the receiver unit and were monitored on the oscilloscope. Signals were also acquired via an analogue/digital data acquisition card in a PC for post analysis.

IV. TEMPORARY OSM INSTALLATION

A portable 32-channel portable PD detection system (see Figure 3 below) was installed at the site to monitor the transformer over a period of 7 days.

Figure 3: The OSM-P32 Portable Monitor

The system contained a universal data acquisition unit, which provided the opportunity to monitor a number of operational parameters in addition to partial discharge. These other parameters included transformer load, transformer temperature, humidity and fan operation. The premise behind this testing was to provide further information to correlate with the results from PD monitoring through the collection of real-time data. An example of the results from a 1-week installation of the OSM-P32 are shown in Figure 4.

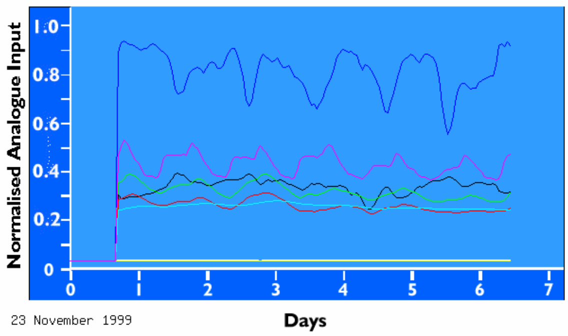


Figure 4: Data from 1-week Installation of OSM-P32

The data generated from the 1-week installation confirmed the results from the spot-tests. It was noted that the PD activity was load-dependent as when the site was active, the magnitude of the discharges in the areas of interest was high and regular. When the site was quiet (low load), there was little or no PD activity. The periods of PD activity were confirmed to range from a few minutes to a few hours, depending on the sensor location, transformer temperature and loading.

V. PERMANENT ON-LINE MONITORING

The results from the spot-testing and 1-week installation were discussed in conjunction with NGC and it was agreed that there was a sufficient degree of PD activity within the Transformer to warrant the installation of a permanent monitoring system on-site.

A permanent 64-channel PD detection system (OSM-F64) was installed on site to provide continuous condition monitoring of the transformer. The system incorporated the same ultrasonic transducers (US-k100) as used in the spot-test program with additional inputs for load, temperature and humidity sensors (as used in the 1-week installation).

The OSM-F64 incorporated a custom designed multiplexer which allows the system to monitor up to 64 channels simultaneously. The system's signal capture electronics records pulses down to a nanosecond level to detect individual 'incidents'. All plant condition data is then stored on a local hard-drive. Information held in the hard drive can accessed at any time using direct dial-up networking. Alternatively the data can be downloaded to a web-server every 24 hours and made available on the Internet. Using either method data can be analysed using a standard web-browser.

The OSM-F64 was installed on-site with the ultrasonic sensors placed around the transformer at the main positions of interest (as identified through the spot-test inspection). Focus was made on the positions where high levels of discharge were detected earlier by placing two or three sensors at these points. The data acquisition unit on the OSM-F64 was 'tuned' to filter out false readings from sources other than partial discharge such as lower frequency effects from mechanical vibration. Whilst focus was made at the points of high PD detection, sensors were also attached at positions around the transformer were little or no activity had been detected previously. The rationale here was that it was also important to provide a number of reference inputs to the system which would be used to compare any changes to activity at the 'hot spots'. Further to this it was also agreed that mechanical vibration should also be monitored using the US-k100 transducers at the points of maximum acoustic emission from this source. By monitoring vibration as well as the other condition parameters a further input is provided for the on-line plant diagnostic process. The results so far are very promising and further testing of suspect transformers are planned for the near future.

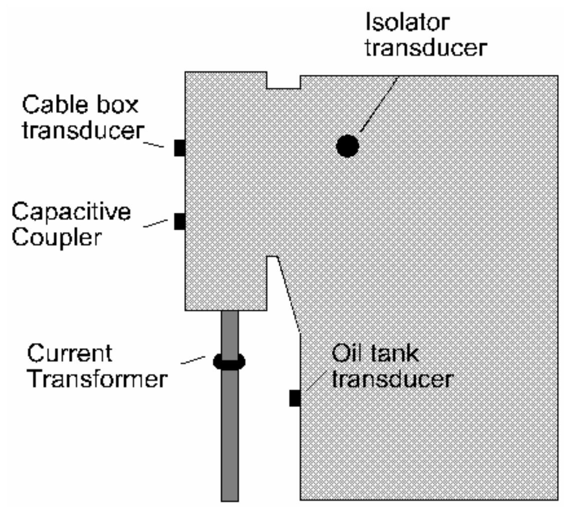


Figure 5: Sensor Positions on 33kV Switchgear Panel

VI. CONCLUSIONS

The authors have presented a novel approach to the condition assessment of HV plant through the application of new sensor technology, data acquisition modules and spot-testing. It is suggested that for effective condition monitoring and management of HV equipment that a combination of spot-testing, temporary installations and permanent on-line monitoring is applied. Through the 4-phase process described herein a systematic management scheme can be developed. In simple terms the benefits of carrying out each phase of the process can be summarised as follows:

Phase 1 incorporates all historical data and operational experience held by the owner to provide a focus for which equipment should be spot-tested.

Phase 2 enables the identification of the source and magnitude of PD activity to be determined whilst 'filtering out' other phenomena such as background noise and mechanical vibration effects.

Phase 3 provides the opportunity to correlate the PD activity with other condition and operational parameters to begin to determine trends in activity.

Phase 4 takes the information collected from Phases 1, 2 and 3 to provide focus for the long-term monitoring of the plant. This includes where the condition sensors should be placed, what they should be 'tuned' to sense and what other condition information should be collected.

VII. FUTURE WORK

The next stage of the development work will be to use the sensors and communications platform described herein to gather plant monitoring data from a large number of 132/33kV substations. This data will be used to compile a database on plant condition which will be made available on the Internet via the IPEC web-site. The data will be analysed by experts whose input will be used to train artificial neural network software. Data-mining techniques will be applied to the data to look for trends and patterns which are indicative of different types of faults. The objectives to be achieved by the end of this work are a database of varied plant monitoring information, an intelligent analysis software package and an **'expert system'** for condition diagnosis and assessment of high voltage plant portable on-line monitoring system.