ABSTRACT

Over the past 30 years handheld instrumentation has been developed that enables the detection of Partial Discharge (PD) activity with the plant in normal service. The continuing challenge in making meaningful field based partial discharge measurements is to reliably relate the severity of any detected partial discharge activity to the risk of failure of the item under test. The risk will be a function of such factors as the location within the test item, ambient conditions, materials, the severity of the activity and the history of failure (if any). This paper describes some of the field experience gained whilst using this equipment and how this has influenced the latest developments in handheld PD instruments. The paper also introduces results from recent laboratory based accelerated ageing tests on 11kV vacuum switchgear that employed cast resin insulation material where surface partial discharge activity was observed from inception to failure.

Index Terms—Partial discharge, switchgear, condition assessment, reliability, distribution networks

1.0 INTRODUCTION

There is a general trend within electricity distribution utilities and operators of large private electricity networks to extend intervals between intrusive maintenance of HV/MV switchgear. This brings with it a need for interim condition assessment and the application of diagnostic techniques to give confidence in the continuing safety and reliability of the equipment. There are a number of techniques available for assessing the condition of insulation and appropriate use of these tools provides valuable data that can effectively target maintenance and ensure resources are more efficiently deployed during outage periods.

Partial discharge activity has long been accepted as a major cause of failure of HV/MV switchgear, [1 & 2]. Traditional techniques for the detection of partial discharge involved taking plant out of service and energising via a discharge free power supply and measuring signals using coupling capacitors and conventional PD detectors e.g. according to IEC 60270. Whilst practical and beneficial for factory acceptance testing or further investigation work, this type of testing by its nature is not suited to wide ranging in-field application and owners and operators of electricity distribution networks have looked to employ handheld non-intrusive partial discharge detection instruments for the purposes of both condition assessment and enhancing operator safety [3].

2.0 PARTIAL DISCHARGE IN SWITCHGEAR

In practice, partial discharge in HV/MV insulation can be considered to take two forms, surface partial discharge and internal partial discharge. When surface partial discharge is present, tracking occurs across the surface of the insulation which is exacerbated by airborne contamination and moisture leading to erosion of the insulation. Internal partial discharge occurs within the bulk of insulation materials and is caused by age, poor materials or poor quality manufacturing processes. If allowed to continue unchecked, either mechanism will lead to failure of the insulation system under normal working stress potentially resulting in catastrophic failure of the equipment.

2.1 SURFACE PARTIAL DISCHARGE

The first materials used for solid insulation in electrical applications were primarily porcelain. Ceramic materials were chosen as they are very effective insulators and are largely immune to electrical degradation, however, since the 1970’s and 1980’s manufacturers have employed increasing amounts of polymeric materials to the point where ceramic materials are only now used in specialist applications. Polymeric materials, although generally offering good electrical insulation properties, are subject to surface ageing and degradation processes and any electrical activity on the surface of such materials causes tracking damage. Tracking is the formation of permanent carbonaceous paths or lines on the surface of a material. The stages in the formation of electrical tracking are:

- The initial presence of contaminants and or moisture on the surface forming a conducting film
- The leakage current though the film is interrupted at a narrow point which results in a small discharge arc
- The discharge will cause high localised heating of the surface and a small spot of carbonised material will result

With further contamination of the surface, the process repeats until the spots become extended lines in the direction of the field. High localised heating caused by the discharge can result in surface erosion and finally a complete conducting path can form resulting in a phase to earth or phase to phase short circuit. Also, surface partial discharge activity creates nitrous oxides and these gases can react with any moisture in the air to create nitric acid. This highly acidic environment can severely corrode...
metallic components and form droplets of nitric acid on surfaces.

From extensive testing of switchgear with partial discharge tracking across the surface of insulation it has been observed that surface discharge activity often has low amplitude but very high discharge rate. An example of this can be seen in Fig.1 where surface discharge was occurring across the polymeric insulation of an 11kV circuit breaker.

2.2 INTERNAL PARTIAL DISCHARGE

Within all insulation material, however manufactured, microscopic voids or cracks are present. When under electrical stress these voids and cracks charge up and discharge with the 50/60Hz cycle like small capacitors. Eventually, because the breakdown strength of air is less than that of the surrounding insulation, the air breaks down with a (very small) arc and a partial discharge occurs. As the void is buried within the insulation material, only the electromagnetic radiation is detectable externally. This discharge action also erodes the voids making them bigger and as they get bigger the discharge energy dissipated with each discharge increases in magnitude. During this process carbonisation of the inner surface of the void occurs which progressively builds up to make the void conductive increasing the electrical stress on the next void. This causes the process to be repeated throughout the insulation system leading to enough conductive voids in the insulation to cause it to fail even under normal working voltages and particularly following transient over-voltages caused, for example, by switching operations.

The electromagnetic pulses produced by internal partial discharges are conducted away in every direction by the surrounding metalwork. This charge in motion gives rise to an electric current which, when it impinges on the impedance of the metal casing, leads to a very high frequency voltage pulse. These high frequency voltage pulses (between 0.1mV and a few volts) escape through joints in the metalwork and pass from the inner to the outer surface of the equipment and then down to ground. The voltage pulse will stay on the surface of the steelwork as their high frequency leads to a skin effect. These pulses were first observed at EA Technology in 1974 by Dr John Reeves and were termed Transient Earth Voltages (TEV’s). They were given this description because they literally only last for a very short time and are travelling down to earth (ground). It was found after extensive trials that these TEV signals, measured in dBmV, are directly proportional to the magnitude of any active partial discharge activity and the condition of the insulation for switchgear of the same type and model, measured at the same point. This produced a very powerful comparative field based technique for non-invasively checking the condition of switches of the same type and manufacture whilst the equipment is live and in service.

In contrast to surface discharges, internal void discharges as they develop will have consistently high amplitude levels but have much lower discharge rates. Fig.2 shows one example of PD measurement on a cast resin CT on switchgear operating at 10kV.

2.3 DETECTION TECHNIQUES

The most appropriate detection technique for partial discharge activity in substation environments depends largely on the type, nature and location of the activity. The most appropriate technique for the detection of internal partial discharge activity where there is no external observable physical manifestation is the detection of high frequency Transient Earth Voltages and the most appropriate method for the detection of surface partial discharge activity is by the use of airborne ultrasonic detectors. Whilst internal discharge activity will never be detected using airborne ultrasonic instruments, there are occasions when surface partial discharge activity can be detected by both TEV and ultrasonic techniques. The fact that both techniques detect the same problem can help with determining the probable cause of the detected partial discharge. Instruments with the capability of detecting ultrasonic activity together with the TEV magnitude and discharge rate (pulses per cycle) such as the UltraTEV Plus (Fig.3) are ideal tools for the non-intrusive detection of partial discharge defects. Equipment with the ability to
measure all of these parameters also go a long way towards classifying the type of discharge detected. In Fig. 3, it can be seen that the ultrasonic measurement is being carried out with the aid of headphones. The ultrasonic signal is heterodyned down to the audible range and the noise characteristic is another important parameter for helping to determine the nature of the defect being detected. Indeed, in many ways it is a more important parameter than the level of ultrasound being detected.

![Image](image_url)

**Fig. 3**: UltraTEV Plus ultrasonic measurement (LHS) and TEV measurement (RHS)

A common type of discharge problem that can often be detected using both TEV and ultrasonic techniques involves discharge to earthed components from floating metalwork. One such example of this type of discharge involved a particular design of withdrawable voltage transformer. The original design of end cap, Fig. 4, in the fuse holder left a small gap between the fuse contact and the earthed holding plate. This gap encouraged surface partial discharge due to a difference in potential across the two surfaces but because the holding plate was earthed, Transient Earth Voltages were generated by the partial discharge activity and could be detected externally. After consultation, the manufacturer of the voltage transformers provided a simple retrofit solution as shown in the right hand side of Fig. 4, a simple spring to eliminate the potential difference.

![Image](image_url)

**Fig. 4**: Discharge damaged fuse contact (LHS) and solution to problem (RHS)

Non-intrusive partial discharge equipment such as the Partial Discharge Locator and Partial Discharge Monitor [4] was used extensively to survey a number of these voltage transformers whilst they remained in service to identify those that were exhibiting the signs of partial discharge activity and required the retrofit spring solution. The sound characteristic of the discharge was distinctive crackling and popping; the TEV magnitude was high - typically in the region of 15 pulses per cycle. All of these parameters are now easily measurable using a single handheld instrument such as the UltraTEV Plus.

### 3.0 LABORATORY TESTING OF SWITCHGEAR

A test environment was constructed in a laboratory that consisted of an 11kV circuit breaker and cubicle inside a locked steel cage. The circuit breaker was supplied by a power utility from a de-commissioned substation and was of a design that is widely installed on the distribution network in the UK and is known to be prone to partial discharge activity.

The circuit breaker utilises a vacuum interruption medium and essentially has three vacuum bottles mounted on a cast resin monobloc that forms a withdrawable ‘truck’. The truck can be withdrawn and the circuit breaker locked into the earth position for maintenance or any other purpose.

An on-line partial discharge detector with a data logger was installed to observe the level of partial discharge activity. In addition, an ultrasonic monitor was employed using five airborne ultrasonic microphones placed around the circuit breaker to observe and record the level of ultrasonic activity resulting from surface partial discharge. Further data loggers with integral sensors to measure temperature and relative humidity were placed inside the cubicle, inside the open cable box and at some distance away from the circuit breaker to provide ambient background readings for comparison. Finally, transparent perspex covers were placed around the front of the circuit breaker cubicle and a humidification unit was installed inside the covers to increase and control the relative humidity. In addition, a small fan was installed to ensure an even air flow.

Before the initiation of the long term test each of the phases was tested in turn in the open and closed positions. The voltage was controlled from a variable source and increased incrementally up to a maximum of 10kV ac phase to earth. The yellow and blue phases were found to be discharge free up to 10kV whilst the red phase was found to have 100pC of discharge in the closed position at an inception voltage of 7.5kV. There was no visual evidence of partial discharge activity on the circuit breaker.

The circuit breaker was energised under controlled conditions in July 2004 using a three phase discharge-free test transformer at the nominal working voltage of 11kV (6.35kV phase to earth) with the monitoring equipment installed onto the red phase of the test equipment. Apart from occasionally being de-energised for observation and testing purposes the equipment was in continuous operation until eventual failure in October 2006.
3.1 TEST RESULTS

When the circuit breaker was first energised no partial discharge was measured using the direct measurement equipment or non-intrusive instruments. To initiate discharge activity at working voltage, the humidity level was increased and within 5 minutes partial discharge activity was measured at 30pC, increasing to 200pC after a further 30 minutes. TEV readings were 14dB with a pulse rate of 7 pulses per cycle. The ultrasonic activity was immediately detected showing red on the UltraTEV Detector [3]. This ultrasonic indication was apparent at the 30pC discharge level.

Testing continued for the next 12 months and the discharge activity varied between zero and 800pC largely depending upon the ambient conditions. However, although there was correlation, there was no direct link between the magnitude of discharge activity in pC, the magnitude of 40kHz ultrasonic noise and the percentage Relative Humidity (%RH) in the atmosphere. By September 2005, the partial discharge activity had become audible so the circuit breaker was de-energised and the truck was racked out and inspected for signs of partial discharge activity, Fig. 5. White powder, verdigris and significant amounts of tracking can be easily seen at the top of the red phase vacuum bottle and from the closest earthed metalwork. The discharge area was left untouched and the circuit breaker was put back into service and re-energised.

Somewhat surprisingly, Fig. 6 shows that after the examination (where the circuit breaker had been allowed to dry out) and the humidity within the test environment was allowed to follow the natural profile, the level of discharge activity measured in pC dropped to very low levels and sometimes zero. The level of ultrasonic activity correspondingly dropped with the reduction in partial discharge as the humidity naturally fell and remained below 50%RH; this despite the obviously degraded state of the primary insulation as shown in Fig. 5. Note, in Fig. 6 the base line for no detectable ultrasonic activity is a level of 0.5 on the secondary y-axis.

The test continued for another twelve months to September 2006 and again the circuit breaker truck was racked out and visually examined. During this examination, the cast resin monobloc appeared damp with moisture that was subsequently found to be nitric acid with a pH level of 3. The continuing very advanced path of partial discharge development between the top of the ‘live’ vacuum bottle retention clamp and the nearest earthed component can again be seen in Fig. 7. Comparison of Fig. 5 and Fig. 7 reveals how the treeing and tracking effectively advanced from the ‘live’ towards earth and the earth towards ‘live’.

In October 2006 the circuit breaker was de-energised for calibration. When it was re-energised a short time later, it failed producing a substantial quantity of smoke and a large deposit of carbon and other material within the enclosure, Fig. 8. Upon inspection, it was clear that the tracking had caused a low resistance conductive path and short circuit allowing the release of fault energy.
3.2 DISCUSSION OF RESULTS
The objective of this project was to attempt to quantify the long held belief from many years of field testing switchgear and other substation plant that environmental conditions play a significant role in the inception and development of partial discharge activity. The levels of relative humidity, particularly when condensed on the surfaces of the circuit breaker, lead to an almost instantaneous increase in the levels of recorded surface partial discharge and it was remarkable to observe how the partial discharge activity could cease during dry periods, even during the advanced stages of damage to the cast resin insulation. It was also clearly observable that the absolute level of recorded ultrasonic activity showed no apparent upward trend as the degradation increased although a correlation was observed between the levels of relative humidity and the presence and magnitude of partial discharge activity.

Short term correlations (approximately one week) were observed between the magnitude of pC discharge activity and the level of recorded ultrasonic noise but they were not directly repeatable over a longer term i.e. over short term intervals higher pC meant higher ultrasonic noise but over longer terms the same level of recorded pC’s did not necessarily produce same level of noise. It was clear during this test that no direct link could be found between the level of discharge in pC with expected insulation life with surface partial discharge.

4.0 CONCLUSIONS
Non-intrusive detection of internal void type discharge activity can be achieved by detection of Transient Earth Voltages (TEV’s). Valuable information on the severity, the type and classification of the discharge activity can be obtained if the number of pulses per cycle is measured in addition to the amplitude.

For surface discharge activity ultrasonic techniques are often the most sensitive due to the low amplitude of discharge activity tracking across the surface of insulation. Surface discharges to earth or from floating potential metalwork can be detected using both ultrasonic and TEV techniques and this again helps with classification and diagnosis of problems.

Over thirty years of field experience has helped build up a significant knowledge base and enabled the development of simple to use hand held devices that are capable of measuring all of these fundamental parameters in a single instrument such as the UltraTEV Plus.

The laboratory work on switchgear taken from a distribution network has illustrated two serious points for consideration:

(i). For surface discharge activity there is no correlation between the amplitude of discharge activity measured in pC, the extent of insulation damage and the proximity to failure.

(ii). It is not possible to infer any reliable relationship between the amplitude of ultrasonic activity, the extent of insulation damage and the proximity to failure.

Attempting to trend levels of ultrasonic activity and trying to relate them to the potential seriousness of surface partial discharge or end of life is not valid and could potentially lead to misleading conclusions. It can be stated with confidence that following the detection of ultrasonic activity an investigation is always necessary to quantify the seriousness of the discharge problem. Even though this involves an intrusive inspection, any activity should be clearly observable under good lighting conditions.

A clear link was observed between environmental conditions in substations and the likely presence of partial discharge activity and hence condition of switchgear. The relative speed of degradation of modern insulation materials such as cast resin under optimum environmental conditions is remarkably rapid. In a substation environment, the degradation rate should be sufficient to allow annual inspections with partial discharge detectors that will detect any surface (or internal) partial discharge activity. This should leave enough time to visually inspect any detected activity and carry out necessary remedial work.

Finally, the laboratory testing has again highlighted that the highest risk to circuit breakers that are exhibiting partial discharge is during switching, a partial discharge spot-check using both TEV and ultrasonic techniques should always be carried out prior to any switching exercise to ensure the safety of the operator.

5.0 REFERENCES