3100 words with case studies (US)

Partial Discharge (PD) techniques for measuring the condition of ageing HV/MV switchgear

By Neil Davies, Director, EA Technology International

Throughout the world, the electricity transmission and distribution industry is experiencing major issues: ***pressure*** from governments and customers to keep their systems operating reliably, ***pressure*** from shareholders to reduce overhead costs and ***pressure*** to replace ageing equipment.

Owners and operators of high voltage (HV) and medium voltage (MV) networks are facing ever increasing challenges to maximize utilization of existing equipment and reduce operational costs, whilst maintaining and improving system performance. Yet they all have the same problem: an ageing infrastructure of equipment that has been installed and in operation for 20, 30 and in most cases 40 years.

Switchgear in general has a proven record of reliability and failures are rare. However, when switchgear fails, the consequences are often catastrophic. Damage to switchgear itself can be extremely expensive. The consequences can involve damage to plant and buildings: and on rare occasions death or serious injury to people.

Undetected degradation of switchgear may lead to sudden, explosive failures – sometimes with catastrophic results

Switchgear maintenance is usually considered low priority by most companies, but a solid maintenance program is much less costly than the impact of switchgear failure. Giving maintenance the thought and effort it deserves improves safety, reliability and profitability: and the latest non-invasive maintenance procedures are proven to prevent switchgear failure.

One of the most valuable new methods for monitoring the condition of HV and MV switchgear involves the use of instruments to measure Partial Discharge (PD) activity non-intrusively.

Causes of Switchgear Failure

PD activity is a major cause of the long term degradation of insulation in HV and MV switchgear. EA Technology's experience of working with switchgear operators for more than 30 years indicates that PD activity is a factor in around 85% of disruptive substation failures.

Issues of the mechanical operation of switching equipment are relatively easy to address, using tests and maintenance procedures prescribed by the manufacturer. But standard maintenance procedures are unlikely to detect the degradation of insulating components, which are associated with the ageing process and are the most common cause of unexpected failures, especially if triggered by environmental or electrical stresses.

The majority of the degradation processes affecting insulating components, such as bushings, cable termination, current and voltage transformers, are associated with PD activity. This can be defined as a localised electrical discharge in an insulation system that does not completely bridge the electrodes. PD activity associated with the ageing and degradation of insulation typically increases with the evolution of the defect. Therefore, the measurement of PD activity can be used as a diagnostic tool, to assess equipment condition and to locate the defect source, enabling selective intervention to rectify or remove the ageing component prior to complete failure.

What is Partial Discharge (PD) Measurement?

The basis of PD detection and monitoring is that the most common failure mode for electrical assets is insulation breakdown, leading to flashover. These types of breakdowns produce the most dramatic failures of switchgear and transformers, often leading to explosions and fires in the event that protection systems fail to operate.

Insulation and insulation systems do not usually break down quickly. They are more likely to suffer progressive deterioration over time, manifested in the form of increasing PD activity. Fortunately for the owners and operators of electrical assets, it is now possible to measure and quantify PD activity in live switchgear with unprecedented accuracy. This non-intrusive approach to assessing the condition of switchgear insulation has been adopted by many countries throughout the world.

Taking PD measurements using portable, lightweight and simple-to-use instruments is an ideal method for evaluating HV electrical assets with a range of insulation types, including oil, compound (bitumen) and cast resin. During a temporary over-voltage, during a high voltage test, or under transient voltage conditions during operation, partial discharges may occur on insulation of this type, which includes gas, liquid, and solid materials. If these partial discharges are sustained due to poor materials, design, and/or foreign inclusions in the insulation, degradation and possible failure of the insulation structure may occur.

In practice, PD activity in HV and MV insulation takes two forms: surface partial discharge and internal partial discharge.

Surface Partial Discharge

When surface PD Activity is present, tracking occurs across the surface of the insulation, which is exacerbated by airborne contamination and moisture. Often moisture combines with the NOx gasses to produce nitric acid which attacks the surrounding metalwork and leads to severe corrosion of the equipment. Insulation surfaces affected by such an acid attack produce an ideal surface for tracking to occur, leading to the creepage distance of the insulator being compromised. Tracking is the result of carbonization of the surface of insulation, brought on in the early stages by the breakdown of contaminates.

Surface PD leads to erosion of the insulation as illustrated in Figure 1 and tracking phenomena as illustrated on the CT (Current Transformer) in Figure 2.

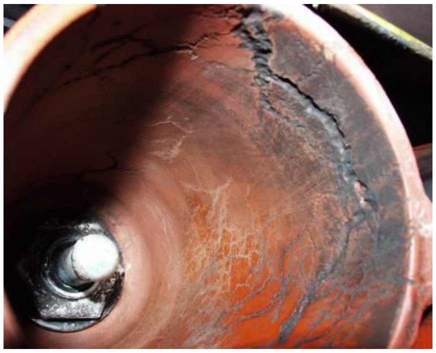


Figure 1 – Damage caused by surface PD activity

Figure 2 – Treeing surface erosion on a current transformer

Surface discharges tend to occur between the particles of a contaminant, producing heat, light, smoke, sound, electromagnetic radiation and ozone and nitrogen gasses. In the early stages of this type of degradation process, and if an air path from the discharge site to the outside of the equipment is present, the high frequency sound waves generated by the partial discharge activity are readily detected using sensitive ultrasonic detection equipment in the 40kHz range.

Surface discharges are best detected using an ultrasonic detection instrument. However, there must be an uninterrupted air path between the discharge site and the instrument to allow the sound pressure waves to be detected externally.

Internal Partial Discharge

Internal partial discharge occurs within the bulk of insulation materials and is most commonly caused by age, poor materials or poor quality manufacturing processes. The current transformer illustrated in figure 3 was known to be exhibiting internal partial discharge. When it was removed and sectioned, the damage was seen to be at the top and is illustrated in the figure on the right.

Figure 3 – Internal partial discharge

Within all insulation material, however manufactured, microscopic voids or cracks are present. When in use, the insulation has one end connected to high voltage and the other to ground, causing these voids and cracks to charge up and discharge with the 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. These arcs produce heat, light, smoke, sound and electromagnetic radiation: but 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 and increases 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. This occurs 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 (TEVs). They were given this description because they only last for a very short time and are travelling down to earth (ground). It was found after extensive trials that these TEV signals 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.

When new switchgear is tested for partial discharge under factory conditions, very expensive bench top test equipment is used and the reading is expressed in pico-coulombs (pC): a value obtained by direct measurement with the switchgear out of service. Once the switchgear or other equipment has been installed and in service for some time, pico-coulomb readings from direct measurements become relatively meaningless, as the individual service history (fault operations, maintenance history) of each item of HV/MV equipment will lead to variations in their individual insulation systems. Furthermore, whilst partial discharge measurements on new switchgear are a very reliable indication of the build quality as it leaves the factory, it is older switchgear that is at more risk from failure due to partial discharge.

If allowed to continue unchecked, either mechanism (surface or internal partial discharge) will lead to failure of the insulation system under normal working stress, resulting in catastrophic failure of the equipment.

Interpretation of TEV Measurements

The pulses that are being measured on the outside of the equipment are represented in the Lissojous Figures contained in Annex A of IEEE std 1291 – 1993, an example of which is shown in Figure 4:

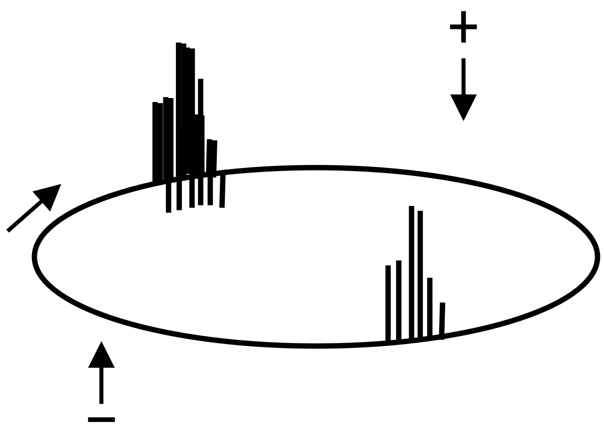


Figure 4 - Lissajous Figure of Internal Discharge in a Solid Dielectric Cavity
ref IEEE std 1291 – 1993

It can be seen from that for each type of activity, the pulses shown have two distinct features: the size (or magnitude) of the individual pulse and the number of pulses per cycle. In all instances, the underlying feature is that as the partial discharge activity increases over time, the magnitude and number of pulses per cycle increases. The method of interpreting the TEV readings relies on being able to combine two aspects in the manner shown in Figure 5.

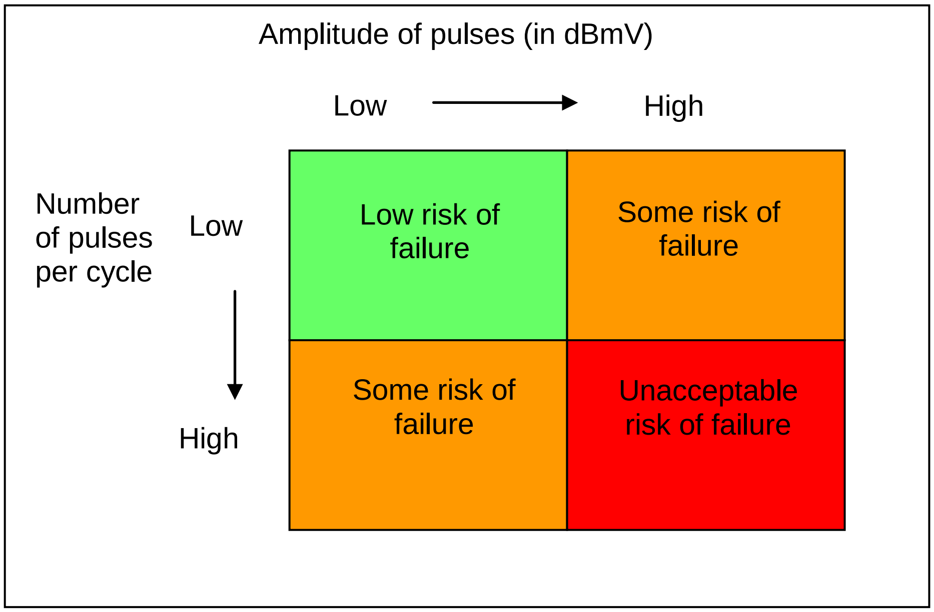


Figure 5 – Analysis of Transient Earth Voltages (TEV's)

As shown, a low number and low magnitude of pulses means that there is little risk of insulation failure. Either a low number of high magnitude pulses or a high number of low magnitude pulses means that the risk of insulation failure is increasing and more regular testing should be undertaken. Finally, a high number of high magnitude pulses means that the risk of failure may be unacceptable and intervention is required at the earliest opportunity.

EA Technology began making partial discharge measurements of switchgear using TEV detection instruments in 1983. Since that time, EA Technology has assembled, with the co-operation of all the UK power utilities, a database of partial discharge survey results, with over 100,000 entries, covering many different manufacturers and types of high-voltage switchgear and associated equipment.

When a survey is undertaken, the TEV readings (in dBmV) are compared with the database results. If the level of partial discharge is within the top 5% of the database values for comparative equipment (of the same voltage level, insulation type and design), then it is deemed to be in the 'red' quadrant of Figure 5. If the readings are in the top 25% of the database values, then the equipment is deemed to be in the 'amber' quadrant. Below this level, the equipment is deemed to be in the 'green' quadrant.

PD Measuring Instruments

PD testing has been used to check the condition of insulation systems in MV/HV assets for many years, so it is a well proven technology in its own right. However, it is only quite since the early 2000s that more lightweight, portable and effective monitoring tools have been developed and its full potential as a strategic technique for asset maintenance and management has been realised fully.

The latest developments in PD measuring instruments are based on building dual sensors into single instruments: ultrasonic sensors principally to measure surface PD activity, plus TEV sensors to measure internal activity. This has led to the launch of a whole family of new instruments, each of which has a specific role in the detection, location, measurement and monitoring over time of PD activity.

Perhaps the most historically significant of the new PD tools is EA Technology's UltraTEV Detector™: the world's first dual sensor handheld PD detection tool, which in 2007 won the Queen's Award for Industry: Innovation – one of Britain's top industrial awards. It is now standard issue for substation use with every electricity network operator in the UK and has been widely adopted by operators worldwide.

The UltraTEV Detector™ has been compared to a Apple iPod because of its ease of use, minimum training required and the user friendly interface, beneath which lies a great deal of technological development. A single button turns it on and a simple traffic light system shows the operator instantly if PD activity is at one of three levels: green indicates OK, amber indicates that the asset require further investigation, and red shows that it requires immediate intervention and/or that PD activity is at a dangerous level.

The latest handheld instruments measure PD activity as both ultrasonic and TEV emissions

Whilst the basic Detector is invaluable for taking 'first pass' PD readings quickly, it has spawned a range of even more sophisticated dual sensor instruments of increasing versatility. The UltraTEV Plus+™ (pictured above) for example, presents ultrasonic emissions as numerical decibel values and audible signals, which engineers can listen to via headphones, with the option of a directional dish microphone for measuring PD activity in overhead assets. Measurement of internal PD activity in the form of TEV signals is presented as numerical values: and a continuous PD measurement mode incorporates maximum level, pulse count per cycle and severity level.

Dual sensor alarm systems continuously monitor assets for critical PD activity

Dual sensors are also built into the UltraTEV Alarm™ system (pictured), which provides permanent or semi-permanent monitoring for PD activity in multiple assets or whole substations. When PD activity reaches critical levels, the system automatically generates alerts via SMS or email.

The UltraTEV Locator™ features twin probes to locate the source of PD activity accurately, using time of flight measurement of pulses, as well as quantifying the level of PD activity in single probe mode. The UltraTEV Monitor™ uses multiple probes, networked to a central server, to monitor PD activity over time in hundreds of assets simultaneously, and includes software which automatically analyses and interprets activity in the form of condition reports. This has also been joined by the PD Monitor GIS™, a system specifically designed to monitor the condition of extreme high voltage gas insulated switchgear by measuring internal partial discharges in the UHF range.

CONCLUSION

At its most basic level, the ability to detect and measure PD activity in live assets is an extremely valuable technique for spotting faults in the early stages of their development, before they become failures and outages. It is also a uniquely effective way of ensuring the safety of personnel, to the extent that it is now standard practice for many engineers to check for PD activity every time before they will enter a substation.

However, it is rapidly becoming apparent that the greatest commercial value of PD measurement is the ability to use accurate data on the condition of assets to change fundamentally the way they are managed. Instead of basing asset maintenance and replacement on time schedules, assets can be managed more efficiently on the basis of their actual condition. The results of this change include less needless invasive maintenance, less downtime, potentially longer asset life, greater safety and lower operating costs. The availability of data on the condition of each asset also leads to more intelligence-based (and cost effective) decisions on asset replacement and refurbishment.

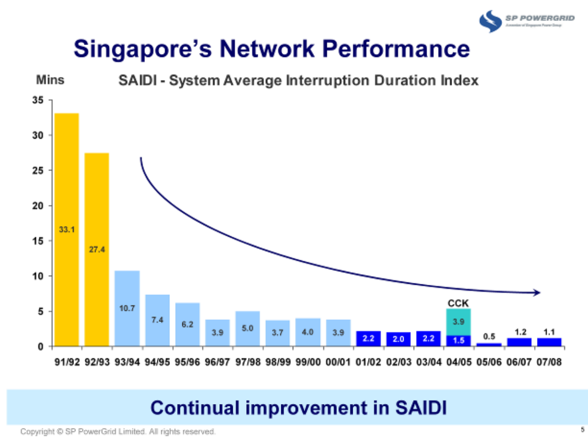
As the experience of SP Powergrid in Singapore shows, the bottom line is that condition measurement pays rich dividends.

More information from Neil Davies:

t. +44 151 347 2308
e. neil.davies@eatechnology.com
w. www.eatechnology.com

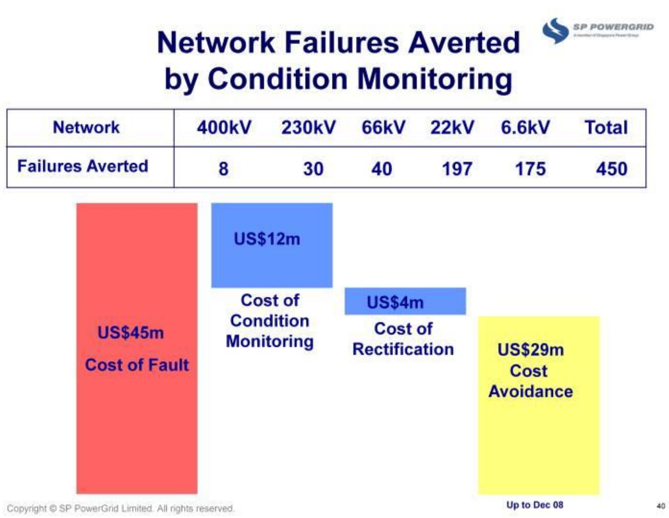
CASE STUDY 1: SP Powergrid, Singapore

SP Powergrid's network includes nearly 10,000 substations, 40,000 switchgear sets, 14,000 transformers and 30,000km of cable. Since incorporating condition monitoring into its systems, it has dramatically improved an already excellent performance. The System Average Interruption Duration Index (SAIDI) has averaged less than 1 minute pa over a recent three year period.



NB: The blip in 2004/5 was caused by a third party supply issue outside SP Powergrid's control.

SP Powergrid estimates that over the last eight financial years, condition monitoring has enabled it to avert 450 network failure incidents, with a net financial saving of US$29 million. In addition to improving customer service, it has been able to pass cost savings on to them.



CASE STUDY 2: ESB Networks (Dublin Ireland)

In 2002, a post-fault forensic investigation revealed that insulation failure was the root cause of a catastrophic failure of switchgear that occurred shortly after a switching operation. The failure was on a cast-resin ring main unit (RMU) that had been installed on ESB Networks' (Dublin, Ireland) 10kV distribution network for more than 20 years. This failure resulted in the need for the utility to revisit the process and procedures it had developed to manage the ageing switchgear population.

As a result of the failure, ESB placed an immediate operational restriction on all 250 substations equipped with the same type of switchgear. The restriction required that this type of switch only be operated after it had been de-energized by switching further up the line. The restriction resulted in severe disruption to customers' supplies and led ESB to experience major difficulties in managing network operations.

Following field trails, ESB has solved this problem by issuing all operational switching and inspection staff with handheld partial discharge measuring instruments, to check that PD activity is at a non-critical level prior to switching.

CSE STUDY 3: ABB (Italy)

ABB (Italy) conducted similar trials to assess the capability of commercial non-intrusive PD measuring equipment to detect and locate different PD sources induced in a 17.5 kV metalclad/internal arc switchgear assembly, comparing the performance with a conventional electrical detection system.

ABB concluded that commercial equipment, based on TEV and ultrasonic methods, clearly demonstrated the capability to identify the presence of PD sources. The UltraTEV Detector™ device by EA Technology was identified as the most versatile in terms of ease to use and clear indications of PD levels.