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**Non-intrusive techniques for detecting partial discharge in HV and EHV switchgear**

Dennis, Graham

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**NON – INTRUSIVE TECHNIQUES FOR  
DETECTING PARTIAL DISCHARGE IN HV  
AND EHV SWITCHGEAR**

**Volume 1 of 1**

**Graham Dennis**

**A thesis submitted for the Degree of Master of  
Philosophy**

**University of Bath**

**Department of Electronic and Electrical Engineering**

**October 2008**

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*Dedicated to Marlene, Carl, Julia and the memory of Norma*

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Last but not least, I would like to pay special tribute to my wife Marlene for her unfailing support and patience during the long process of producing this thesis. Her typing and secretarial skills were invaluable, her very presence and understanding were the motivation for me to complete the task. Thank you very much.

---

# ABSTRACT

This research work is concerned with the study of Partial Discharge activity in High Voltage and Extra High Voltage metal clad switchgear that forms part of an electricity distribution or transmission system.

PD activity is likely to occur wherever there is a void in solid electrical insulation, usually formed during the extrusion or moulding process or as a result of needle like protrusions, floating particles, contamination or loose contacts within the switchgear. Dry cable terminations on MV switchgear may also exhibit surface discharges due to the use of faulty materials and, or, poor jointing techniques.

Partial discharge activity results when the voltage gradient across a void or due to the other irregularities mentioned above cause a partial breakdown of insulation strength, but not a complete failure. If the PD activity is not detected and remedial action taken, the particular component will gradually deteriorate resulting in complete failure of the insulation allowing a power arc to flow to earth and usually resulting in catastrophic failure of the plant.

The work presents a significant contribution to the understanding of the PD phenomena and provides the reader with a staged approach to understanding the relevance of the effects from first principles to a detailed insight into the causes and methods of detection.

The thrust of the research has centred on gaining an in depth appreciation of the ways in which PD activity causes deterioration of various switchgear components and developing ideas for a commercially viable scheme suitable for retro-fitting to a wide variety of plant already in commission on electricity systems. Finite Difference Time Domain modelling has been used extensively, together with a comprehensive literature search in order to determine the most suitable sensor and connection arrangements for an electromagnetic PD detection scheme.

A conceptual scheme suitable for GIS EHV installations is outlined. The FDTD studies were verified using an EHV GIS test rig.

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## Chapter 1

# INTRODUCTION

### 1.1 Background

Partial discharge is the most prominent indicator of electrical insulation degradation [1]. With gas insulated switchgear (GIS) partial discharge measurements offer the opportunity to identify imperfect components within the overall insulation system and assist in the prevention of early failure.

Partial discharges occur in solid insulation due to the presence of minute voids which may be formed during the manufacturing process. The resulting voltage gradient across the void is affected, mainly by temperature and humidity and will eventually break down. At this point a partial discharge takes place across the void and energy in the form of light, heat, smell, sound and electromagnetic waves may be released. The discharge does not completely bridge the electrode to earth (Fig.1) however, if a number of voids in a particular component cause deterioration of the insulation and link together to form a conducting path between the high voltage system and earth a catastrophic failure of the plant will occur (Fig.2)

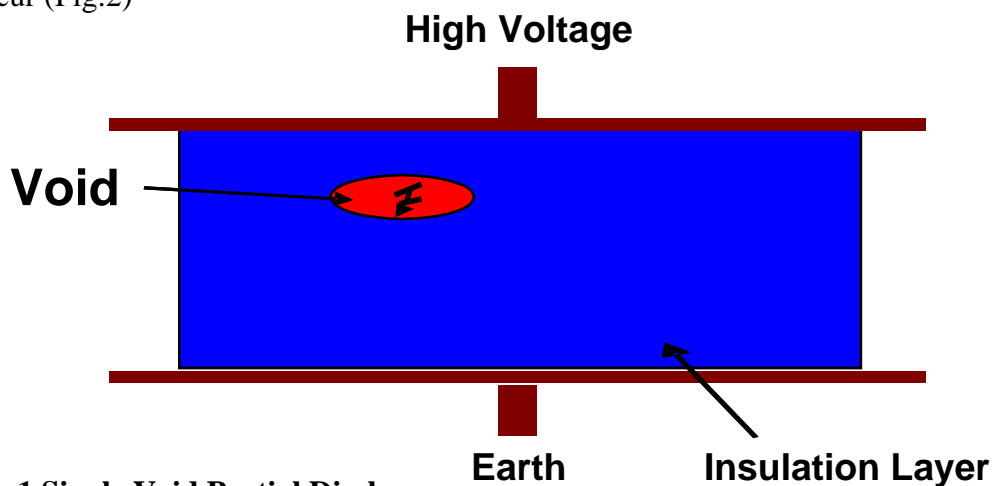
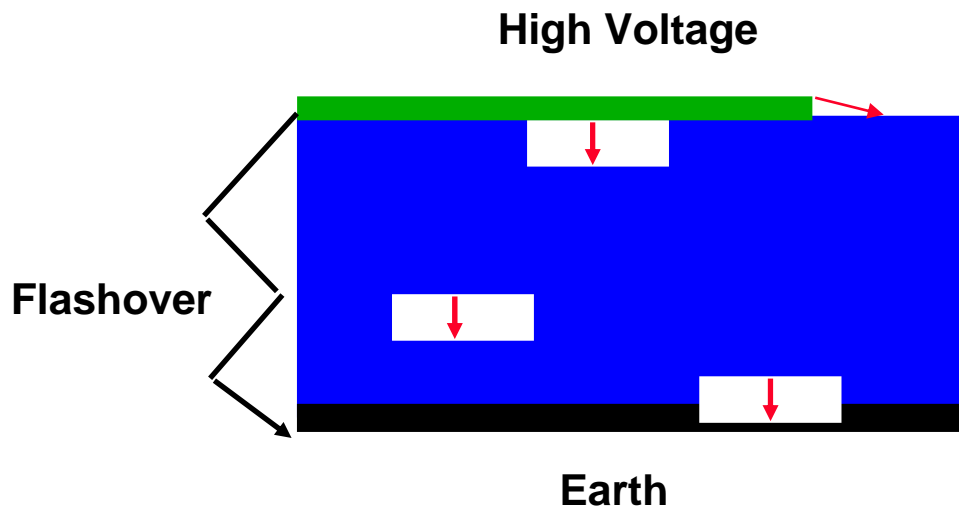


Fig.1 Single Void Partial Discharge



**Fig.2 Multiple Void Flashover**

## ***1.2 HISTORY***

Partial discharge detection to monitor GIS in service has been used in the UK since the late eighties by both Scottish Power and The National Grid Company [2]

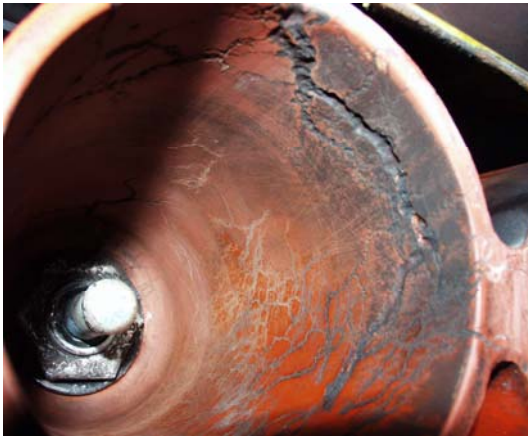
The author was involved in the mid seventies with early trials on PD detection on 66kV switchgear in one of the UK's Regional Electricity companies. A number of switchboards were taken out of service and capacitor bushings installed at various positions along the gear. An oscilloscope recorded the number and amplitude of the pulses from each bushing. The early trials proved that PD detection was possible and in the main operators were looking at trends rather than absolute values in an attempt to determine when remedial action should be taken. There were also problems in filtering out external noise interference.

Considering new installations partial discharge techniques are invariably used to detect problems when new GIS switchboards are being built and commissioned. Problems arise when particles are brought into the gas room and subsequently may lead to internal breakdown. Traces of (conductive) dirt on the surfaces of internal insulators and spacers can also occur which can cause surface discharge (tracking) and lead to breakdown.

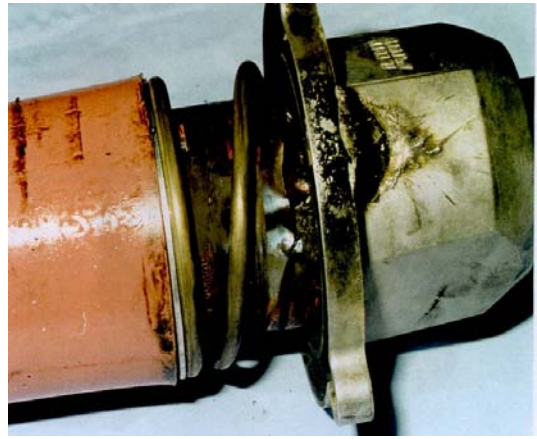
### ***1.3 EXISTING INSTALLATIONS***

There is a large population of ageing transmission/distribution plant and equipment installed on electricity companies' networks and in many industrial and commercial locations. In order to achieve effective utilisation of these assets and make sound decisions on maintenance strategies, asset refurbishment or replacement, it is necessary to have reliable information on the condition of existing plant. The trend to extend maintenance periods and optimising the availability of switchgear brings with it a need for interim non-intrusive diagnostic techniques to give confidence in the continuing safety and reliability of the equipment

During the past decade there have been a number of extensive supply interruptions in countries around the world. The most severe blackouts were experienced in the USA, New Zealand and the UK, London suffered two massive blackouts. These events have motivated utilities to consider appropriate solutions. Asset management which requires diagnostic testing, preferably online, in order to determine the condition of all plant on systems is now widely applied to electricity networks and partial discharge detection is pivotal to this role. The very high investment costs of switchgear, particularly EHV, render the need for monitoring to determine the precise state of the gear essential if catastrophic failures are to be avoided. Network operators not only in the UK but around the world also have pressures from the Regulators and the Health and Safety Executive. They are required to take all the prudent measures they can to avoid loss of supply and eliminate potentially hazardous situations for staff and the public. Figs. 3,4 and 5 show components on which PD activity was detected and remedial action taken. Figs. 6 and 7 show the results of ignoring PD activity.



**Fig. 3 11kV Cast Resin Circuit breaker Spouts**



**Fig. 4 33kV Cable Termination**



**Fig. 5 11kV Cast Resin Busbar Moulding**



**Fig. 6 Failed 11kV Voltage Transformer**



**Fig. 7 Failed 25 kV Substation**

PD surveys on MV gear are normally carried out using hand held instruments which detect electromagnetic or ultra sonic disturbances and give an instantaneous reading of their amplitudes and number of pulses over, typically, a two second period. Simpler instruments provide only a visual indication of the state of the equipment – essentially a “go/no go” test.

When PD activity is suspected or detected instruments are available to carry out short term monitoring on the effected switchboards. The results are stored, usually, on a compact flash memory card and they may be analysed using bespoke software. Hand held instruments which are specifically designed to detect lower frequencies in the ultrasonic range (20-40 kHz) are also used to compliment the EM tests.

This thesis will look at developments in equipment available for partial discharge testing of switchgear operating in the 3.3kV – 400kV range and outline a proposal for a UHF scheme suitable for retro-fitting to GIS.

## ***1.4 SYSTEMS CURRENTLY AVAILABLE AND RECENT DEVELOPMENTS***

During the period when the UK Electricity Supply Industry was nationalised all R and D work on distribution plant, overhead lines and cables was carried out at a centre, owned by The Electricity Council, close to Chester. In the early 80’s, original research into the possibility and practicability of using a non-intrusive method of detecting PD activity in MV switchgear was carried out by a small team. A unique method, the Transient Earth Voltage (TEV) was invented and an instrument, the PDL1 designed and manufactured.

In 1996 a paper written by a member of the research team, explaining the TEV technique was published by the IEE [3] As a result of the original work, a whole suit of instruments operating on the TEV principle have been developed [4] for use on switchgear working at voltages up to 66Kv

In the main the thrust, over the past five years, has been to refine the transient earth voltage detection techniques (TEV) and to complement this with reliable ultrasonic devices[5] For important MV switchboards permanent monitoring schemes are available which are fully web enabled allowing the operator to receive alarms remotely via SMS or email, to interrogate data and remotely configure settings.



**Fig. 8 Double probe instrument**



**Fig. 9 Single probe instrument**

Figures 8 and 9 show double and single pole hand held PD instruments suitable for surveys on switchgear operating at up to 66kV [6] Development work [7] on UHF detection of PD activity for application as permanent schemes on EHV equipment has concentrated on improving signal to noise ratios, improving external sensors and reliably characterising the nature of the discharge and pin pointing its location

## ***1.5 AREAS BEING RESEARCHED***

Hand held devices for use mainly on MV switchgear embody capacitor probes which detect electromagnetic waves or ultrasonic detectors which are particularly useful for locating surface type discharges at, for example, dry cable terminators on switchgear. Research and development work recently carried out by a leading organisation in this field [6] has resulted in a hand held device which is capable of detecting PD activity in both the EM and ultrasonic frequency ranges.

A hand held device capable of responding to both EM and ultrasonic frequency ranges with a display to enable the nature of the PD disturbance to be characterised would be a major step forward. This additional information would enable the likely source of the PD activity to be more accurately located.

Work is also ongoing [6] to refine the technique of using a parabolic reflector with a remote ultrasonic detector in order to detect PD activity at cable terminations at pole top positions.

PD alarm schemes which locate the source to a particular panel for use on MV equipment using both EM and ultrasonic detectors are now becoming available. Bearing in mind the very large numbers of MV switchboards on electricity companies systems they are an attractive low price option when compared to a full monitoring scheme. If such schemes were web enabled to facilitate remote interrogation this would add considerable merit to their performance.

Much progress in diagnostic techniques for GIS installations has been made in the last few years. They are used increasingly in factory testing, site commissioning and during the service life of the equipment [7].

Typically schemes use either UHF couplers fitted internally or at non metallic barrier positions or ultrasonic devices positioned along the bus chambers to detect the presence of PD activity within the gear. The principal advantages of the UHF method are its high sensitivity, the ability to locate discharges accurately by time of flight measurements and that it can be used readily in a continuous and remotely operated monitoring system [8].

The results from on site GIS installations have been promising though they show the need for further developments as outlined below.

1. Complex and often intermittent discharges can be found in GIS and a better understanding of the physical processes leading to breakdown is needed to allow the diagnostic data to be interpreted.



2. Continuously monitoring one or more GIS can produce very large quantities of data and it is important not to over burden the operator with its interpretations. The data needs to be analysed by an expert system and the operator informed only when a condition arises which needs his attention.
3. A monitor installed in a GIS to detect defects in the insulation can in addition be used to record the condition of circuit breakers, transformers and other equipment, so providing a complete diagnostic system on which predictive maintenance of the GIS can be based [7].

It is these aspects which are becoming increasingly important and where the main advances can be expected.

## ***1.6 NECESSITY FOR PARTIAL DISCHARGE ASSESSMENT***

The number of catastrophic failures of electrical switchgear is small in relation to the installed population. However, when a failure does occur, the consequences are often serious with respect to injury to personnel, damage to equipment and loss of availability of electrical supply.

Analysis of failure statistics has shown that a high percentage of failures can be attributed to breakdown of solid insulation [12] This insulation breakdown is often preceded by partial discharge activity and therefore non-intrusive detection of this activity is an effective tool for the detection of deterioration in the insulation.

The use of condition monitoring for the detection of partial discharge activity becomes increasingly important with the trend within electricity companies towards the adoption of condition based, rather than time or age based maintenance. Bodies such as the UK Health and Safety Executive are now including the use of condition monitoring tools within their guidance documents

as an illustration of good practice in the use, care and maintenance of switchgear [11]. Therefore, the use of condition monitoring is also becoming more widespread by owners and operators of switchgear within industrial and commercial organisations.

For these reasons, the development of equipment suitable for widespread use by personnel that are not necessarily highly trained in the use of condition monitoring tools, but nonetheless which provides beneficial and meaningful results, is essential. Improvements [7] in both portable and fixed ultrasonic schemes have been made, but accurate characterisation and location of the PD sources, particularly in large SF<sub>6</sub> switchboards requires considerable expertise.

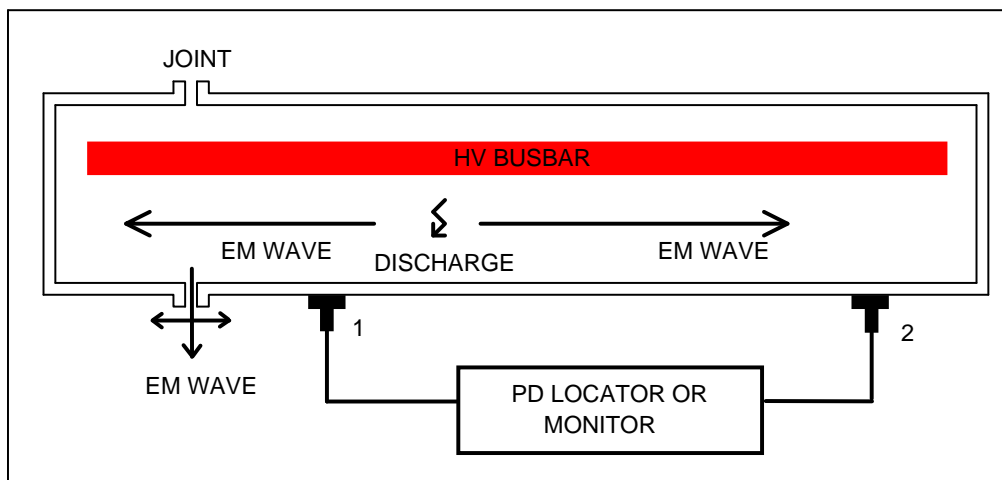
## Chapter 2

# CHALLENGES AND PROBLEMS

### 2.1 *PD detection techniques for MV switchgear*

#### 2.1.1 The Transient Earth Voltage (TEV) Technique

If a partial discharge occurs in the phase to earth insulation of an item of high voltage plant such as a metal-clad switchboard or a cable termination, a small quantity of electrical charge is transferred capacitively from the high voltage conductor system to the earthed metal-cladding. The quantity of charge transferred is small and is normally measured in pico-coulombs. The transfer occurs typically, in a few nanoseconds. For pulses of such short duration, test specimens cease to act as lumped components and behave instead as transmission lines. Their electrical behaviour is determined primarily, by the distributed capacitance and inductance of the specimen. As charge is given by the product of current and time, a discharge of 1,000pC and 10ns duration would result in a current of 100mA[5] Fig.10 is a simplified cross section showing just one phase of a high voltage busbar with a gasketed joint on the left hand side.



**Fig. 10 Transient Earth Voltage Detection of Partial Discharge Activity**

When the partial discharge occurs, electromagnetic waves propagate away from the discharge site in both directions. The currents associated with these waves produce voltages given by the product of the current and the impedance into which the current flows. In this case the impedance is the characteristic or surge impedance which, for a loss-free transmission line is given by:-

$$Z_o = \sqrt{\frac{L}{C}} \quad \text{where } L \text{ and } C \text{ are the inductance and capacitance per unit length of the transmission line.}$$

$Z_o$  varies from approximately 10 ohms for a single core 11kV cable to approximately 70 ohms for a large 33kV metal-clad busbar chamber [20] A discharge of 1000pC can, therefore, locally elevate the earth potential by between one and seven volts for 10ns. Due to the skin effect the transient voltages on the inside of the metalwork cannot be directly detected outside the switchgear. However, at an opening in the metal cladding, such as the gasketed joint in Fig. 10 the electromagnetic wave can propagate out into space. The wave front impinges on the outside of the metal cladding generating a transient earth voltage on the metal surface. The transient voltage has a nanosecond rise time and an amplitude which can vary widely from millivolts to volts [3]

The TEV magnitude is a function of the magnitude of the discharge and the attenuation of the propagation path. The attenuation of the propagation path is itself a function of the internal structure of the switchgear and the size of the opening. In the example above this would be the thickness of the gasket.

The TEV is measured with a capacitive probe placed on the earthed metalwork of the switchgear. If two probes are used it is possible to locate the item of plant containing the discharge by comparing the arrival times of the pulses at the probes. In fig.10 the signal will arrive at probe 1 before it arrives at probe 2.

### 2.1.2 Capacitive Probes

Using the TEV principle the input to the probe is obtained from a single conductor, namely the metal cladding of the plant under test. The signal input to the instrument must be provided on two conductors, the centre conductor and the screen of the coaxial cable and, for the instrument to operate, there must be a difference between the voltages on these conductors.

The transformation from a one conductor system to two is achieved in the probe, Fig 11 a, by connecting the central conductor of the coaxial cable directly to the capacitive coupling plate and terminating the cable screen approximately 20mm back from the plate. As a consequence, the central conductor is more closely coupled to the source than the screen. Fig.11 b shows the detail.

The coaxial cable has distributed capacitance and inductance, internally, of 96pF/m and 240nH/m respectively. These values give a characteristic impedance ( $Z_{0i}$ ) of 50 ohms, resistive, and it is this impedance value that determines the ratio of the voltage to the current for waves travelling inside the cable.

Because the cable screen has an open end in the probe, electro-magnetic waves also propagate along the outside of the cable. The cable screen and its plastic sheath act as a cylindrical, surface wave-guide which can support both Transverse Magnetic (TM) and Transverse Electric (TE) mode waves. The ratio of the voltage to the current for the waves on the exterior of the cable represents a characteristic impedance ( $Z_{0e}$ ) whose value is a complex function of the electrical properties and physical dimensions of the cable and the mode of propagation.



Fig. 11a. PD Probe

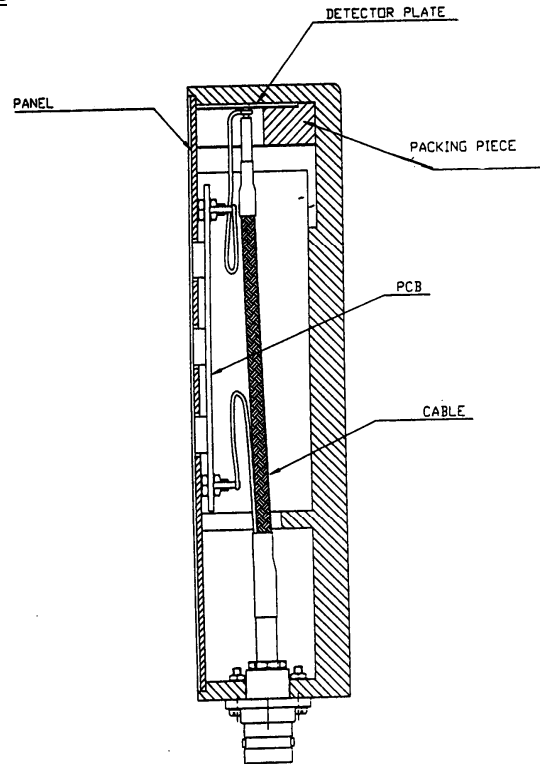


Fig.11b. PD Probe - connections

### 2.1.3 Effect of Reflected Pulses

At high frequencies an item of plant such as a switchboard behaves as a series of transmission lines with different characteristic impedance. Numerous branches connect to the mainline, each with a mismatched terminating impedance. In addition, shunt impedances are connected to the lines at intervals. The result is a complicated transmission network that exhibits multiple reflections when excited with an impulse.

The network is generally fairly lossy and so the initial pulse detected by the PD instrument is often the largest. When this occurs, the measured signal magnitude will be unaffected by reflections. However, if the losses are relatively small, the reflected pulses can add, constructively, to give a total amplitude greater than the magnitude of the initial transient. In these circumstances the signal amplitude measured by the PD instrument will be slightly enhanced but the increase in amplitude will generally be too small to significantly affect the signal amplitude measurement. Reflections can, however, frustrate attempts to locate discharge sources by the measurement of signal amplitude alone.

To overcome this limitation, instruments featuring two probes are available and discharge sites may be located by comparing the times of arrival of the transients at the two probes. ( See fig. 8 ) This method is largely independent of any reflections because it is the arrival of the initial pulse that triggers the instrument and determines which channel is given as 'First'. This measurement establishes the direction of travel of the discharge transient and, hence, which probe is electrically nearer to the discharge source.

It is apparent from the above that reflections resulting from connected circuits or plant and earthing arrangements may have a small effect on the measured signal amplitude. They are unlikely to affect location measurements because 'precedence' is determined by the arrival of the initial pulses at the two probes. No reflections will be received by the probes until sufficient time has elapsed for the incident waves to reach these mismatches in impedance and the resultant reflections to return to the measurement position. By this time, 'precedence' will have already been established by the instrument.

#### 2.1.4 High Frequency Skin Effect

When a partial discharge occurs in an item of high voltage plant, the charge is deposited on the earthed metalwork adjacent to the discharge site. A pulse of current then travels away from the discharge site in as many directions as the geometry of the metalwork will permit. The pulse travels at a speed given by  $c/\sqrt{\epsilon_r}$  where  $c$  is the velocity of light in vacuum and  $\epsilon_r$  is the relative permittivity of the dielectric.

From electromagnetic theory it can be shown that the current density within a conductor decreases exponentially with increase in the distance from the surface. At a depth  $\delta$  the current density falls to  $1/e$  of its value at the surface

where  $\delta$ , the skin depth, is given by  $\frac{1}{\sqrt{\pi\sigma\mu f}}$

Where  $\sigma$  is the conductivity,  $\mu$  is the permeability of the material,  $\mu_0$  is the free space permeability and  $f$  is the frequency [26]

From this expression it can be seen that the skin depth is inversely proportional to the square root of the frequency. At 30MHz, for example, the skin depth for mild steel and copper are approximately 4 microns and 12 microns respectively [25] The bandwidth of a typical PD instrument extends to 60MHz. From the above calculations clearly the high frequency partial discharge currents are constrained to flow in a thin layer on the surfaces of the conductors. For an internal discharge, the charge is deposited on the inner surface of the earthed metal screen and so no signal would be detectable externally if the screen were continuous. In general this is not the case. Continuity is either lost, or impaired, at isolation points, gasketed joints, the base of cable sealing ends, etc. sufficiently for the high frequency transients to be detectable externally. It is these signals that are measured by PD instruments.

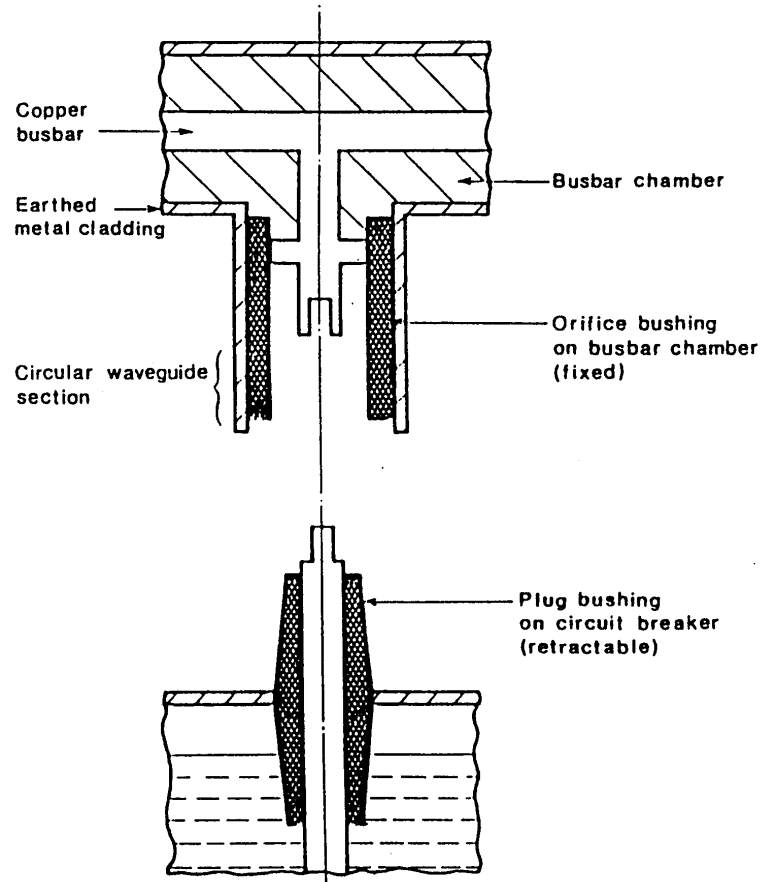
### 2.1.5 Anomalous Effects due to Wave-guide Cut-Off

These effects arise primarily when a discharge site is located in an orifice bushing. Figure 12 shows, diagrammatically, the isolating contacts of a circuit breaker (or a voltage transformer). If there is a discharge site in the fixed orifice bushing of the busbar chamber, shown in the diagram (or current transformer chamber) then, with the contacts mated, strong TEV signals will be detectable externally on the earthed metal-cladding of the busbar chamber in this area. This is to be expected as a large discontinuity exists in the earthed screen at this point.

The signals on the metal-cladding of the circuit breaker can be almost as large as those on the busbar chamber due to capacitive coupling between the two. In addition, the time difference between the signals will be small because the two parts are physically adjacent. It is unlikely, therefore, that a discharge site in the



orifice bushing can be distinguished from one in the plug bushing without separating the contacts.



**Fig.12 Wave-guide Cut-Off [25]**

Typical PD instruments using the TEV detection method have an upper cut-off frequency of 60/80 MHz, this is invariably too low to detect PD activity in an orifice bushing.

The cut-off frequency of a PD source from the orifice of a bushing depends on the mode of propagation of the electromagnetic wave and the size and shape of the cross section of the wave-guide. For a wave-guide of circular cross section, the  $TE_{11}$  mode has the largest critical wavelength. It is given by:

$$\lambda_c = D\pi / 1.841 = 1.71D \text{ where } D \text{ is the internal diameter of the wave-guide.}$$

If  $D = 0.2\text{m}$ ,  $\lambda_c = 0.341\text{m}$  and the cut-off frequency is 878MHz. This is the minimum frequency that can be transmitted by a wave-guide of this size (ignoring rapidly attenuated evanescent waves) and yet it is more than ten times the upper cut-off frequency (60/80MHz) of a typical instrument.

As a consequence, the components of the discharge transient that occur within the pass band of the instrument are reflected back into the busbar chamber. Consequently, no signal would be detectable externally unless there were alternative routes to the outside elsewhere on the item of plant under test. Note: If the orifice bushing contains stress-grading foils, some of the signal will be able to travel between the foils to reach the external surface of the metal-cladding.

If it is suspected that an orifice bushing, or its mating plug bushing, contains a discharge site it will normally be necessary to separate the two before the defective component can be uniquely identified. This will necessitate isolating the moveable component. If this causes the signals to disappear completely, it is likely that the discharge site is in the plug (male) bushing. If signals continue to be detectable on the fixed component, though possibly with considerably reduced amplitude or distributed differently, it is likely that the discharge site is in the orifice (female) bushing.

## ***2.2 PD DETECTION TECHNIQUES FOR EHV SWITCHGEAR***

### **2.2.1 Present position**

There are basically two technologies used in assessing the condition of GIS in service. Primarily schemes offered by switchgear manufacturers use the technologies for detecting either the high frequency electromagnetic waves emitted by PD sources or the lower frequency ultrasonic pulses. Both approaches are considered in detail in later sections.

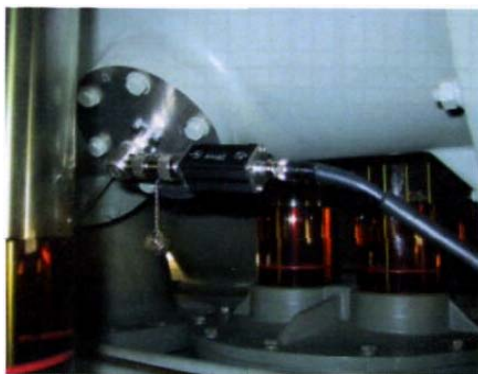
Other approaches for the detection of PD sources in GIS have included detecting light output from a discharge and analyzing the chemical by products [7] Detecting the light output from a discharge is probably the most sensitive of all diagnostic techniques because a photo multiplier can detect the emission of even a single photon [7] The radiation is primarily in the UV band and since this is absorbed strongly both by glass and SF<sub>6</sub> it is necessary to use quartz lenses and

a reasonably short path length. Used in the laboratory this is a powerful tool, but it's practical application in the field is limited due to the physical size of a typical GIS installation.

The chemical analysis approach has also proved to be impractical due to the dilution effects of the diagnostic gases, thionyl fluoride ( $\text{SOF}_2$ ) and sulfuryl fluoride ( $\text{SO}_2\text{F}_2$ ), into the large amounts of  $\text{SF}_6$ . [7]

An increasing population of service aged GIS equipment has reached its originally projected lifetime. Continuous on-line partial discharge monitoring helps considerably in the decision making process to refurbish or replace switchgear.

New GIS switchboards are invariably supplied with a UHF pd monitoring scheme or at least equipped with suitable internal sensors. Retrofitted schemes normally rely on external window antennas or ring sensors as shown in Figs. 13a and b. [7]



**Fig. 13a External window sensor and Pre-amplifier**



**Fig. 13b External ring sensor and Pre-amplifier**

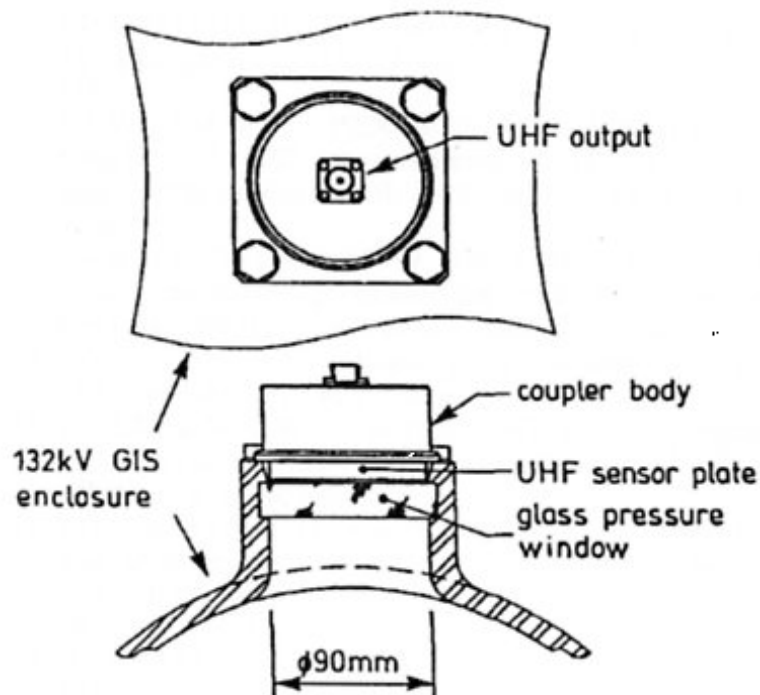
### **2.2.2 Electrical methods for detecting PD activity**

Several have been developed which include the use of narrowband and broadband PD detectors placed at suitable positions along the switchboard. The

electrical methods outlined for detecting PD sources in MV switchgear generally operate in a range between 2-80MHz. In order to achieve greater sensitivity UHF detection methods have been developed. PD current pulses in SF6 can be extremely short with rise times  $<50\text{ps}$  and the signals contain measurable energy at frequencies  $<3\text{GHz}$  [8]

For new or refurbished GIS, internal couplers mounted on inspection plates are used. The couplers can play a valuable role during commissioning tests [9]. To avoid the operational problems of taking GIS out of service to fit internal couplers, external couplers have been developed as shown in figure 14.

Typical locations include glass inspection windows and barrier couplers. With careful design, in certain circumstances, the sensitivity of external couplers can outperform internal couplers [13]. They can also be totally screened to eliminate external interference. It is normal practice to fit a wide band amplifier as part of the detector circuit [15]



**Fig.14 External PD Sensor [12]**

Well designed couplers are capable of detecting the PD activity from typical discharge sources within the GIS such as free metallic particles, electrode protrusions and floating electrodes all of which may lead to breakdown. The discharge pulses excite the GIS chambers into many modes of resonance at ultra-high frequency. The location of a particular PD source can be accurately located, for the whole installation, using time of flight of the PD wave between sensors.

Coupler sensitivity affects the signal output resulting from the transmission of electromagnetic energy from a PD source. Electrical methods of PD detection are now accepted technology for GIS and most manufacturers offer on line systems. The UK specification [15] for UHF couplers requires that the average sensitivity of a coupler over the frequency range 500-1500 MHz should produce an output voltage of no less than the 6mV rms for an incident UHF electric field of 1 volt per m, rms.

### **2.2.3 Acoustic methods for detecting PD activity**

#### **2.2.3.1 Introduction**

Besides emitting electrical signals, partial discharge activity produces also ultrasonic signals. Generally, such ultrasonic signals undergo a much stronger attenuation than the UHF signals. Especially, ultrasonic detection of partial discharge activity of embedded voids (spherical gas cavities) in epoxy resin material is hampered by this attenuation [1] Additionally, the sensitivity strongly depends on the position of the sensor. However, detecting ultrasonic signals on gas-insulated equipment can be performed on-line, does not involve any modification of the GIS, and is comparatively easy to apply, though the results often require analysis by an expert.

In 1990 Norway entered a new regime for the operation of it's electricity power system and there was concern about the condition of GIS installations. For the

previous two years the SETEF Energy Research Laboratory in Trondheim had been working with a local instrument manufacturer, to develop a portable non-invasive ultrasonic device for detecting PD activity in GIS.

The instrument was required to embody the following features:

- Good sensitivity to the detection of the most common defects found in GIS
- Immunity to external noise
- Localisation of defects
- Pattern recognition of defects

TransiNor developed a portable instrument, shown in Fig 15, with the above features. An article [27] describing the instrument “Acoustic Insulation Analyser for Periodic Condition Monitoring of Insulation Systems such as GIS, Cable Terminations and Joints” was published for V1 Sepope held May 24 to 29, 1998. Other manufacturers now offer ultrasonic detection equipment with similar features.



**Fig. 15 Portable instrument for acoustic diagnosis of PD activity in GIS**

### **2..2.3.2 Detecting PD activity**

The detection and analysis of acoustic waves generated by PD sources can be extremely complex. The acoustic wave may be distorted by a variety of factors including division due to multiple pathways, transmission losses in different media and at their interfaces and frequency dependent velocity effects. To add

to the complications of detection of and analysis there are different wave types (longitudinal, transverse etc) that travel at different velocities and suffer reflections at impedance discontinuities. Even with all the above problems and with a skilled operator using the various equipment available acoustic detection in GIS is widely practiced with reasonable success [12] With some instruments it is possible from the analysed waveform to determine the characterisation of the defect. In practice acoustic detection is considered as complimentary to the electrical techniques of primary PD detection in GIS.

### **2.2.3.3 Acoustic properties of signal propagation in GIS**

The shape of the detected signal will depend on the type of source, the propagation path of the signal and the sensor. The GIS itself may be compared with a plate. In a plate several acoustic wave modes may exist, of which the first order anti-symmetric Lambwave [16] is the most significant. The propagation velocity of this wave depends on frequency, plate thickness and material. In the lower frequency regime the propagating velocity increases with the square root of frequency, and in the higher range ( $>100$  kHz) it approaches  $0.9 \cdot V$  ( $V$  being the velocity for the transverse wave) [16]. When a signal propagating on the enclosure hits a discontinuity (i.e. flange) it will partly be reflected and partly transmitted. Because the materials used in most enclosures have a very low absorption, a signal will ring for long time due the multiple reflections. Some defects (e.g. particles, corona at enclosure surface) act as point sources directly on the enclosure (Figure 16).

In the SF<sub>6</sub>-gas the signals propagate by about 140 m/s. The gas acts as a low-pass filter [17]. When the signal hits a surface/enclosure only a fraction of the energy is transmitted into the enclosure, exciting the first order anti-symmetric Lamb wave [14,16]. The coupling between gas and enclosure improves with increased gas pressure. Only certain combinations of frequency and angle of incidence allow excitation of the plate, because there has to be coincidence between the pressure wave in the gas and the plate wave in the enclosure. This results in high frequencies being injected at almost perpendicular angles, while

low frequencies are being injected at a skew angle. Defects close to the high voltage conductor (e.g. corona from sharp points) first excites a pressure wave in the gas, which then excites the enclosure before it finally is picked up by the sensor (Fig 17)

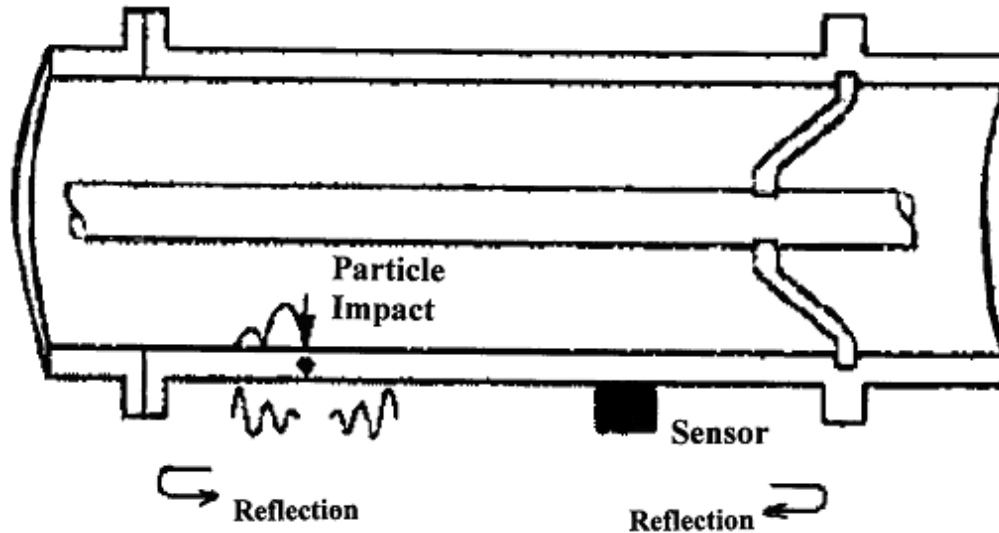


Fig. 16. Sound propagation in a GIS from a particle [27]

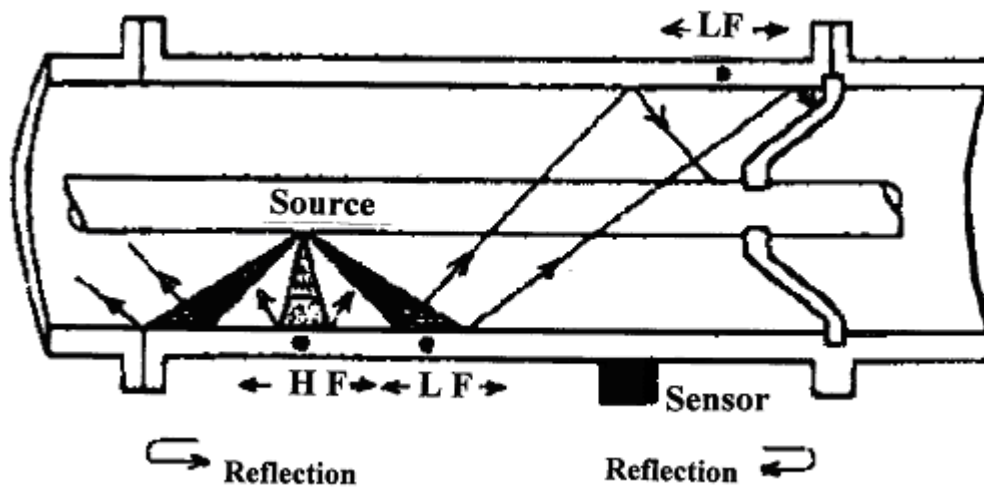


Fig. 17. Sound propagation in GIS from corona at center conductor [27]

Usually acoustic emission sensors are used. These sensors operate in resonance and therefore have a high sensitivity. However, their frequency response normally is highly non-linear over the frequency range. The choice of sensor will influence the sensitivity for the various defects. The best sensors found have a resonance in the 30-40 kHz regime.



#### 2.2.3.4 Defects in the insulation system of GIS.

Defects in the insulation system of GIS may be left after the production and erection, and may also be produced during operation (e.g. particles produced by fast earthing switches). The most likely defects [18] are shown in Figure 18

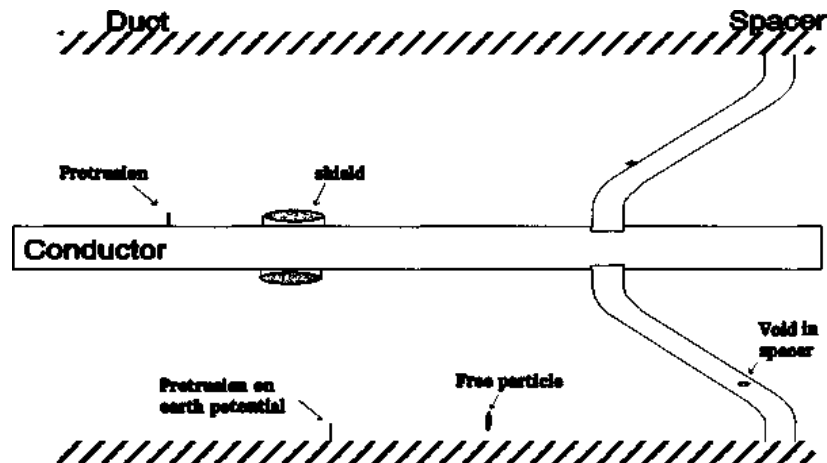


Fig.18 Defects in the insulation system of GIS [27]

#### 2.2.3.5 Protrusions on earth and live parts.

A protrusion from live or earth parts will create a local field enhancement. Such defects will have little influence on the AC withstand level, because the voltage varies slowly and corona at the tip will have time to build up a space charge that shields the tip. For impulses like lightning surges or very fast transients produced by disconnector operation, there is not enough time to build up such space charges. Consequently, the lightning impulse withstand level ( LIWL ) will be heavily reduced. Usually protrusions exceeding 1-2 mm are considered harmful [18,19].

#### 2.2.3.6 Particles: free moving and fixed to spacers.

Free moving particles have little impact on the LIWL, while the ac withstand level can be significantly reduced from their presence. The reduction will depend on their shape and position; the longer they are and the closer they get to the HV-conductor the more dangerous they become. If they move on to a spacer they become even more

dangerous. A particle on a spacer may with time lead to deterioration of the spacer surface.

#### **2.2.3.7 Voids and defects in spacers.**

A defect within a spacer will give rise to discharges, electrical trees and eventually lead to breakdown.

#### **2.2.3.8 Electrically and mechanically loose shields.**

If a stress shield becomes mechanically loose it may in the end become electrically floating. A floating shield adjacent to an electrode is likely give rise to large discharges between shield and electrode. If these defects are activated (e.g. discharging) they will emit acoustic signals. Location is usually done by searching for the location with the strongest acoustic signal level.

### **2.2.4 The defects in GIS and their acoustic signatures**

#### **2.2.4.1 Free moving particles**

Particles will jump around when the electric field is strong enough so that coulomb forces exceed gravity. Each time the particle hits the enclosure it emits a wide band transient acoustic pulse-which travels back and forth on the part it is contained within. The sensitivity of some instruments is sufficient to detect sub-millimetre particles with a good signal to noise ratio.

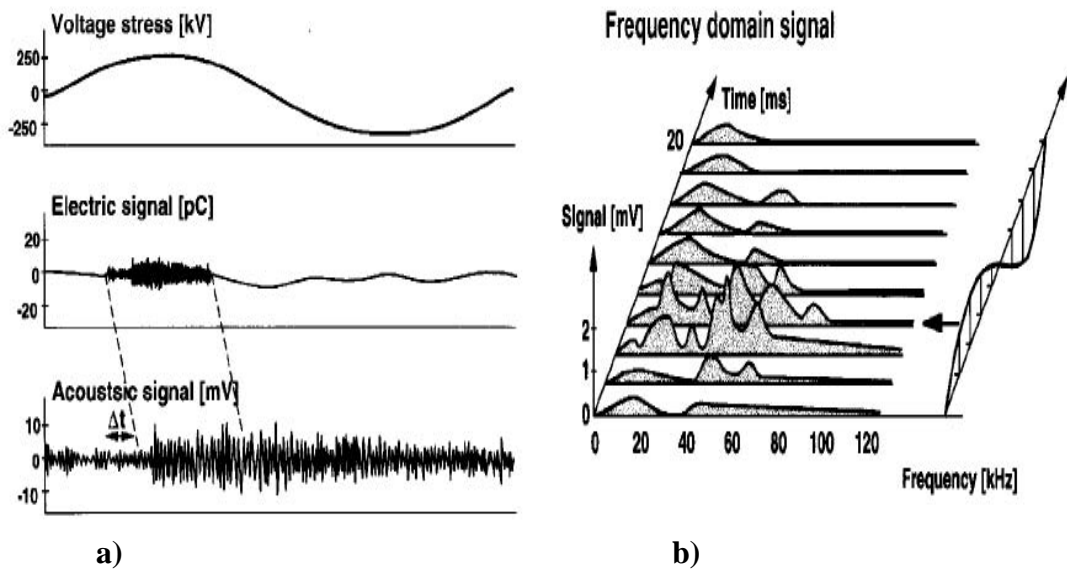
When measuring acoustic signals on a GIS, the raw signal contains both the direct incident wave at the sensor and the multiple reflections. Only the directly incident signal should if possible be measured as this signal will not be "polluted" by the geometry of the enclosure. This can be done by gating choosing appropriate live- and dead-times. Sometimes external sound sources (e.g. heavy outdoor corona) may result in unwanted noise. Because the signal from the particles are wide band, a high-pass filter (e.g. 100

kHz) can be applied to remove the noise which usually is predominant in the lower frequency regime. The particle signal will still be detectable, even if the amplitudes are somewhat reduced. As these are linear systems a correction factor can be used to compensate for the filtering. Particle movement may be initiated either by a high voltage or a mechanical shock (e.g. circuit breaker operation). During measurement, a hammer tap [23] is often applied to activate the particle in order to detect it.

#### **2.2.4.2 Protrusions**

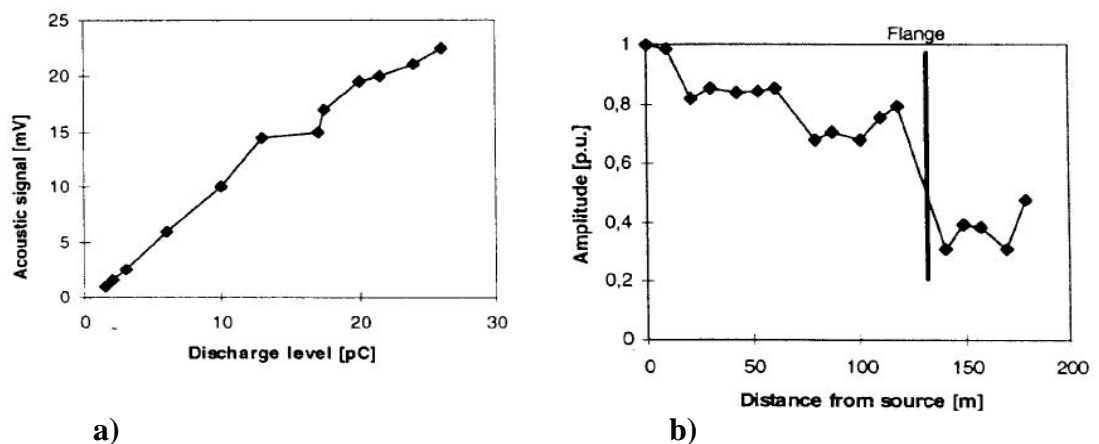
A protrusion will create a field enhancement. If the ac field exceeds a certain level a discharge will first occur at the negative peak. When the voltage is raised further, the number of discharges will increase and large discharges will occur also at the positive peak. These discharges heat the gas and create pressure waves in the gas. The discharge rates are usually higher than what can be resolved by the acoustic sensors. The pressure wave is fed into the enclosure resulting in a typical signal like shown in Figure 19a. From Figure 19b it can be seen that the acoustic signal is continuous with a 50 Hz modulated envelope. This signal is created by interference of multiple reflections in the gas/enclosure interface and at the flanges. It is the high frequencies that create the peak in the envelope. These high frequency signals are absorbed more quickly in the gas and therefore they die out faster than the low frequency signals which "ring" for a long time.

The signals produced from corona at the HV-side will be small, usually less than 20 times the noise level, and they will be continuous and stable. As the acoustic signals from the discharge pulses interfere, each single discharge cannot be resolved. Therefore the peak-value will depend both on the magnitude and the number of the discharges. Because this is a continuous signal the crest factor (ratio between peak and rms-level) will be small.



**Fig.19. Typical signal from a protrusion at live side in a GIS detected with 150kHz resonant sensor: a) electric and acoustic signal b) phase-resolved frequency analysis of the signal. [27]**

Figure 20a shows how the acoustic signal level varies with the peak level of discharges, and how it varies with distance between source and sensor. As the final signal is created by interference between forward and back-travelling waves in the enclosure, it is understandable that the dependence on sensor location is small within the part containing the source. The fact that much of the energy in the waves stays within the part with the defect, results in a drop in the signal level once a flange is crossed as shown in Figure 20b.

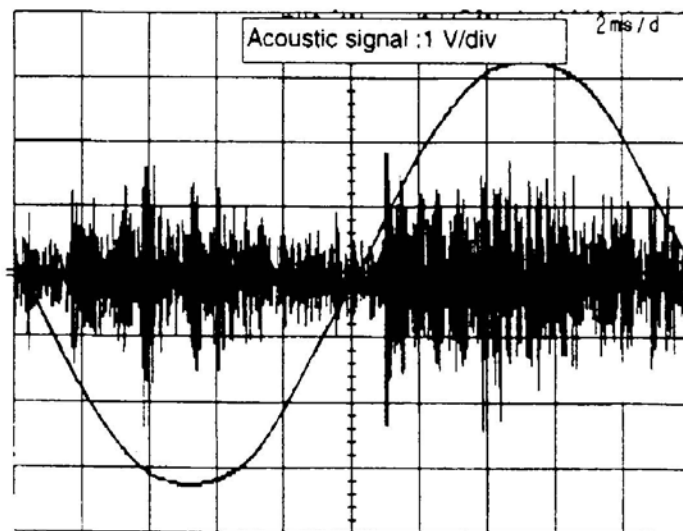


**Fig. 20 a) Acoustic peak signal vs.max. electric discharge signals in a 300kV GIS [17]**  
**b) Dependence on signal level vs. sensor location [17]**

There is no accurate method presently available for calibrating the acoustic method for corona type signals, several independent investigations using different types of enclosures demonstrates sensitivities in the 2-5 pC range [20,21,22]. The standards (IEC 517) set a limit for acceptance of 10 pC, while Cigre SC 33 advises a level of 5. The acoustic method will in most cases have a sensitivity better than this.

### 2.2.4.3 Floating Shields

Loose stress shields may start to vibrate, and eventually become electrically floating. A large floating metallic object will be capacitatively charged and when the withstand voltage between the object and its base is exceeded a large discharge/arc will occur. Such discharges occur at the rising flanks of the voltage, and will produce a large continuous signal with mainly a 100 Hz envelope as shown in Figure 21. The signal level will usually be constant and have a low crest-factor.



**Fig. 21. Signals from a floating shield (Ref. 40 dB gain) [27]**

#### **2.2.4.4 Voids and defects in spacers**

Voids and defects inside spacers will create discharges once the initiation voltage is exceeded. Usually such voids are found during the quality control in the factory. Because the sound absorption in filled epoxy is very high the chance to detect them with acoustic measurement is small.

#### **2.2.4.5 Particles on spacers**

A particle which moves on to a spacer may behave in many ways. It may move around on the spacer and where it may discharge and deplete charges. This is particularly relevant for horizontal spacers (e.g. located at the bottom of a riser). It may also become fixed to the spacer and create discharges towards the spacer surface. The spacer surface is not a self-healing insulation material and may during time be deteriorated (e.g. carbonised) and eventually break down.

Presently, knowledge of generation of acoustic signals from particles on spacers surfaces is relatively limited [24] In principle, signals from mechanical impacts may occur, which because they are very energetic, may be detected at the outside of the enclosure even if the absorption in the spacer is high. The particles can also generate sound waves in the gas that propagate like those from a protrusion. If the particle is located at the inside of a conical spacer, the spacer will act as a barrier for the pressure wave and reduce sensitivity.

Some eight years ago investigations were made at CESI [28] They reported that discharges produced by metallic particles and carbonised tracks located at the outside of conical spacers for a 420 kV GIS could be easily detected. However more work needs to be done on such defects to give final statements about possibilities and limitations for detection and rules for signal recognition.

## Chapter 3

# BACKGROUND APPROACH

### ***3.1 Study of PD detection and schemes available***

A thorough and in depth study was made into PD detection in GIS in order to understand the various possible approaches and in order to be able to assess the merit of various schemes. The study enabled a design for a UHF PD scheme suitable for retro fitting to EHV GIS to be outlined [see 4.1] Schemes offered by most switchgear or PD equipment manufacturers fall into two broad categories: (a) UHF schemes (b) Acoustic schemes. The electrical schemes use various detectors fitted internally for new installations or externally at inspection windows or band joints for a retro fit installations. The majority of acoustic schemes use external acoustic emission sensors operating in resonance in the 30-40khz to improve their sensitivity.

### ***3.2 Literature search***

Some 130 papers published over the past 15 years from a wide range of sources, together with many textbooks and manufacturers' technical literature have been studied. The present "state of the art" for PD detection in GIS is set out below.

#### **3.2.1 Summary of diagnostic methods for PD detection in GIS**

In the main the papers describe systems that continuously monitor any partial discharge activity by measuring the UHF electromagnetic fields or the acoustic effects from the discharges occurring in busbar chambers of EHV switchboards insulated using SF<sub>6</sub> gas. Acoustic methods for PD detection have been detailed

in section 2.2.3. This section deals with measuring PD effects by detecting electromagnetic fields.

### **3.2.1.1 Causes of breakdown**

Breakdown in gas insulated chambers can occur for a number of reasons including:

1. The presence of free particles such as metallic swarf or other particles within the gas-filled chamber that move around under the influence of the electric field
2. Sharp protrusions on the metallic structures that cause corona discharges and streamers. The protrusions may be due to poor finishing during manufacture, mechanical damage or adhesion of free particles to otherwise smooth surfaces. These problems can occur with metallic structures at either high voltage or earth potential.
3. Sparking metallic structures such as stress shields that should be bonded to either the high voltage busbar or to earth but are, in fact, left electrically floating.
4. Defects either within, or on the surface of, insulation structures such as support barriers and bushings.

In each case, if such a defect is present, partial discharges are likely to occur. Whether, or not, these lead to total breakdown depends on many factors including: the type of discharge, its position, magnitude, frequency of occurrence, the ability of the surrounding structures to withstand the damaging effects of the discharges, etc.

When a PD occurs, a sudden collapse in voltage occurs in the vicinity of the PD. The rate of collapse is determined by the physical dimensions of the PD and the drift velocities of the electrons and ions involved. For discharges in air, the rate of voltage collapse is approximately 22ns per mm gap length [25]



### 3.2.1.2 Displaying UHF Data

Experience in interpreting UHF data shows that although the point on wave of the discharge pulses remains the basis of interpretation, displaying only the peak discharge magnitudes (as, for example, with the peak-hold on a spectrum analyzer) gives only a limited amount of information. This is also the case when studying the breakdown caused by a free particle, where an increase in the time interval between bounces indicates that the particle may be moving closer to the HV conductor and approaching the condition where breakdown can occur [7]. Again, when attempting to separate some of the defects associated with barriers it is found that the differences between them are quite small, and additional information is needed to separate them. With experience the operator of a spectrum analyzer becomes able to gain some idea of the repetition rate of the discharge pulses by assessing how rapidly the spectrum builds up, but it is clear that both the amplitude and repetition rate of discharge pulses taken over a number of cycles are fundamental to the interpretation of the data [7]. This conclusion is reinforced by observations taken from GIS in service, where it has been found that some of the discharge patterns are much more complex than those studied in the laboratory. It appears that a defect may have been emitting more than one signature, or that more than one defect was present, but in either case the importance of more detailed interpretation, and the ability to separate multiple sources, is evident.

The requirements of a data display are to give the engineer, in a convenient form, sufficient information for him to identify any defect which might be present in the GIS, but not to overload him with surplus data. Many defects repeat the same pattern of discharge pulses on the voltage waveform, and can be recognized within a few cycles. Free particles are an exception, because they bounce asynchronously with the power frequency and as the particle moves closer to the HV conductor, a pulse may be seen only every ~10 cycles [7].

### 3.2.1.3 Interpreting UHF Data

The defects most likely to be found in a GIS were studied in the late 1990s at the University of Strathclyde using a 420kV GIS test rig. The tests included corona, free metallic particles, floating components, particles attached to barriers and voids in barriers. All have characteristics which enable them to be identified.

Typical examples are given in figs 22, 23, 24 and 25 the data being displayed as a 3D (amplitude point on wave cycle number) “snapshot” of all the discharge pulses occurring in 1s [7]

#### a) Corona

A fixed needle point results in a corona type discharge initially appearing as low level intermittent pulses on the negative peak of the wave. In a deteriorating situation the discharges would become positive streamers. A slight increase in voltage stabilizes the discharge, and gives occasional pulses on the positive half cycle (Figure 22} Finally leaders are formed which are hot channels of high conductivity and act as extensions to the point, they are seen as occasionally high level discharge signals on the positive peak [7]

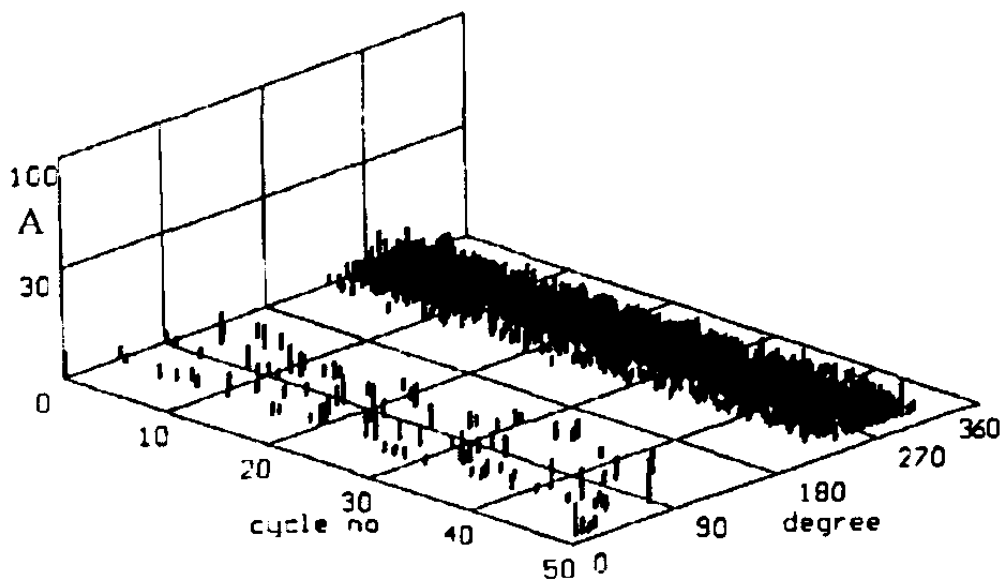
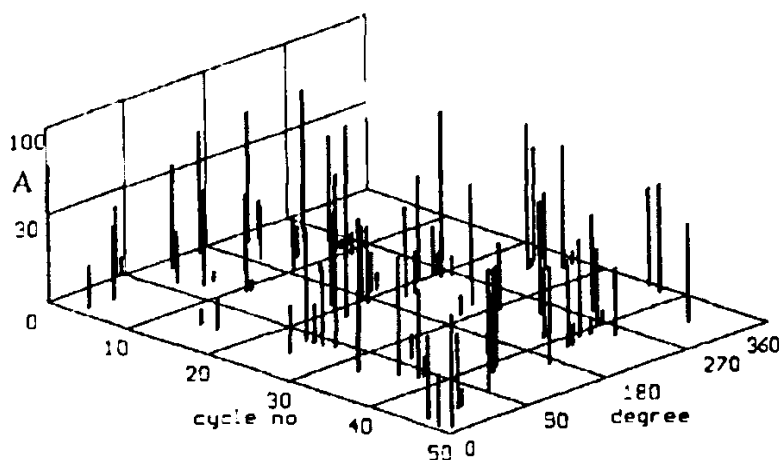


Fig. 22 PD from a needle on the busbar

### b) Free moving metallic particles

Free moving metallic particles are the most common defects being critical at power frequency voltage for gas insulated substations. A free conducting particle resting in contact with an electrode of an energized system is a localized perturbation of the conductor, which acquires charge and distorts the electric field. The shape, location and orientation determine the induced charge distribution. Depending on the accumulated charge of the particle and the applied electric field, an electrical force acts on the particle. The charged particle will lift and dance along the floor as soon as this force exceeds the gravitational force. This generates a discharge pulse each time contact is made with the floor, since the particle then assumes a new value of charge. The pulses occur randomly over the complete power frequency cycle as shown in Fig.23. At higher voltages the particle will start to jump towards the busbar, and after several cycles may reach it. Two factors combine to make this an especially serious condition which often leads to breakdown: (i) as the particle approaches the busbar it discharges and generates a voltage transient which increases still further the stress at its tip, and (ii) breakdown can occur by leader propagation well before any space charge has had time to develop and shield the tip [28].

Experiments and tests by various investigators have been carried out. The simulated defects should produce apparent charge lower than 5pC when measured with the



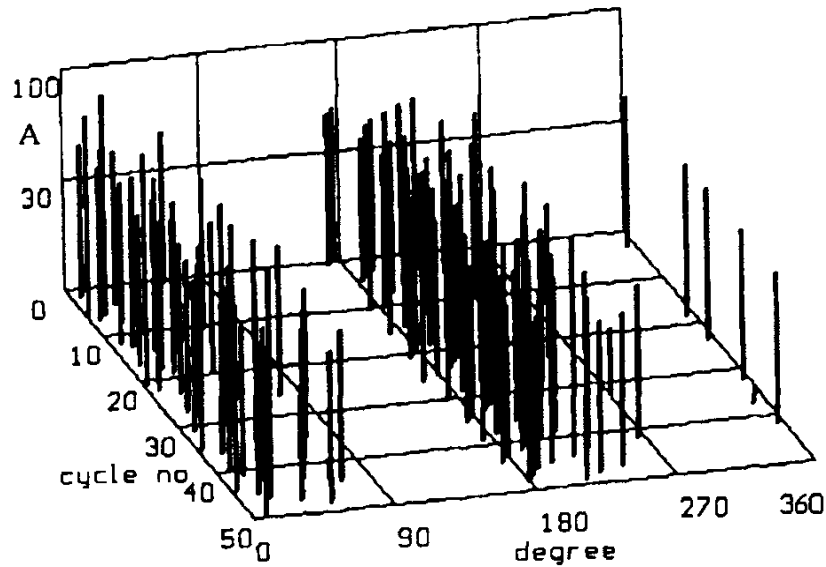
**Fig. 23 PD from moving particle**

standard method [29]. Maria et al [30] placed copper and aluminum wires of 3mm length, with diameters of 0.25 and 0.38mm respectively, on the bottom of the enclosure under the HV conductor. Five wires of each material were tested and the voltage was increased up to particle ‘lift-off’ PD inception value. Gupta et al [31] observed that, for a single loose particle in the enclosure, PD pulses appear almost throughout the AC cycle. However, there is cluster of discharges during the rising part of the positive and negative half cycles.

Meijer et al [32] has further investigated the moving particles in three different movement stages: shuffling, moving and jumping. Considering the possibility and consequence of a moving particle to attach itself to an electrode (resulting in corona), or to attach itself to a spacer (resulting in potential breakdown along the gas-solid interface), the particle is placed in a conducting dish to ensure that it will not be attracted to the spacer while having the same freedom to move. Through experimental investigation, the following conclusions have been drawn: The shuffling stage can be determined by phased-resolved PD pattern or spectral analysis; Phase-resolved pattern analysis is not sufficient to discriminate between moving and jumping particles; Due to gaps occurring in the spectra of jumping particles, differences in the averaged spectrum and the spectrum consisting of the maximum amplitude of each frequency, can be seen; The ratio of both post-processed spectra are differently distributed for moving and jumping stages; The distributions are shown to be independent of particle type, GIS setup and type of gas.

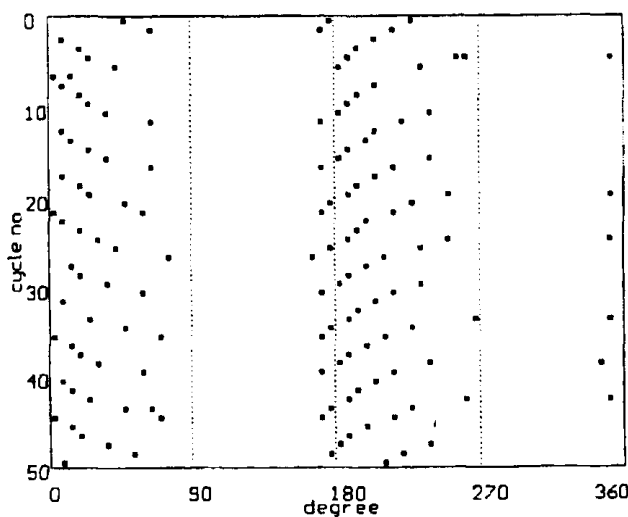
### c) **Floating Electrode**

This arises if the contact to, for example, a stress shield deteriorates and sparks repetitively during the voltage cycle. The sparking is energetic because the floating component usually has a high capacitance, and this degrades the contact further. Metallic particles are usually produced, and may lead to complete breakdown. The discharges are concentrated on the leading quadrants of the positive and negative half cycles, and their amplitude does not vary with the applied voltage [28]. Typical results are shown in Fig. 24



**Fig. 24 PD from floating particle**

When the gap is symmetrical, breakdown occurs at the same points on each cycle. However should the breakdown occur at a higher voltage on one polarity than the other, the effect is to progressively advance or retard the point of breakdown on the cycle. This gives rise to a characteristically curved pattern, most evident in the plan view of the discharge pulses shown in Fig. 25. Since most gaps are slightly asymmetrical, the curved pattern is likely to be seen and gives a positive identification of the defect [7]



**Fig. 25 Asymmetry of PD from a floating electrode (plan view)**

The 3-D displays are very convenient when interpreting data, but less so when identifying long-term trends in the discharge. For these the data is best displayed as a 2 D record of amplitude or count rate against point on wave.

### ***3.3 Areas of interest and problems***

#### **3.3.1 Introduction**

Increasingly network operators are appreciating the importance of total asset management. There is constant pressure to improve customer supply standards and minimise system disturbances within a framework of qualifying and justifying capital expenditure.

Within the electricity industry there are many switchboards operating across all the voltage ranges which are some 30/40 years old. Non-intrusive partial discharge detection on switchgear operating at distribution voltages is well established and used.

Within the UK and abroad there are large numbers of switchgear operating at voltages in excess of 90kV which do not have partial discharge detection schemes fitted. It is well established and accepted that undetected partial discharge activity within switchboards is one major cause of catastrophic failure.

Typically switchboards operating at voltages in excess of 200kV may be fitted with high frequency partial discharge schemes. These schemes require the switchboard to be fitted, either during manufacture or subsequently, with partial discharge detection couplers within the gear which include an external connector. The schemes tend to be expensive and incur costs in excess of 10% of the total switchboard project.

The main areas of interest are to explore all the options available to develop a cost effective, continuous monitoring PD detection scheme, suitable for retrofitting to switchboards operating at voltages in excess of 90kV. The main issues to be addressed include:

- The development of a three stage UHF amplifier to provide the front end signal processing of PD signals detected in SF6 switchgear. The signals contain most of the energy in the band 500 – 1300 MHz.
- Investigation and development of suitable external PD sensors for application to switchgear inspection windows and flange joints.
- Investigate cross-coupling between adjacent open –garter flange sensors.
- Investigate interference induced in open garter flange sensors by external RF sources in the vicinity of the GIS switchboard.
- Derivation of a 50Hz reference from single and three phase busbar configurations.
- Determining a suitable method within a PD monitoring scheme to identify types of PD activity

### **3.3.2 Scope for the application of PD schemes**

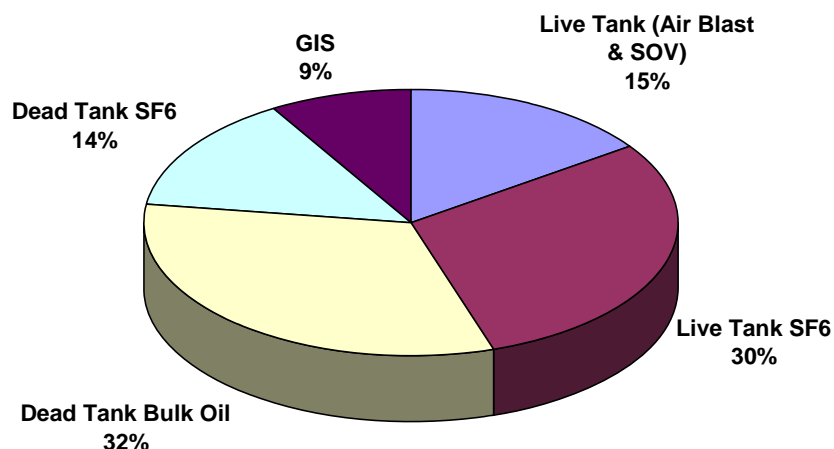
In August 2005 EA Technology Ltd. Produced a confidential report [33] listing the number, age and types of EHV switchgear in commission and being installed on the UK networks and identifying the types likely to benefit from having a PD scheme fitted. Extracts from the report are included below with their approval.

### **3.3.3 Switchgear operating at voltages above 90kV – current population**

- Live Tank - Air Blast & Small Oil Volume (SOV)
- Dead Tank – Bulk Oil
- Live Tank – SF6
- Dead Tank – SF6
- GIS

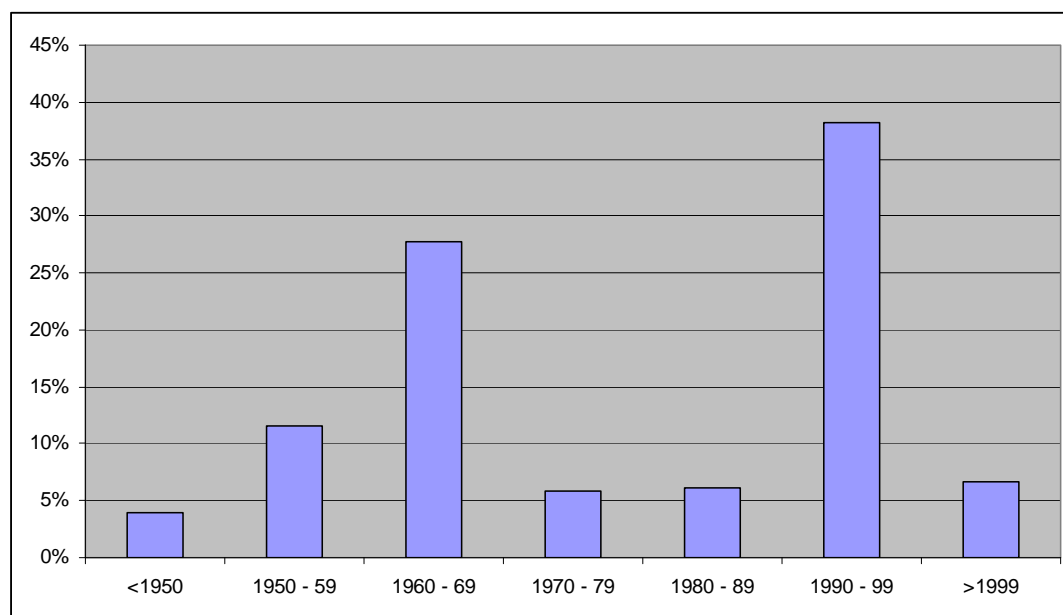
Figure 26 shows the breakdown of the population and reveals that there is still a significant proportion of the older technology circuit breaker i.e. bulk oil and air blast installed on the network. Just over 50% of the circuit breakers are SF6 with the smallest proportion of these being extensible GIS installations. However, at 9% of the population this is still a significant proportion. Of the 15% categorised

as Live Tank (Air Blast & SOV) the majority were air blast breakers and small oil volume circuit breakers only accounted for 1% of the total population.



**Figure 26. Types of Circuit Breaker Currently Installed on the UK System**

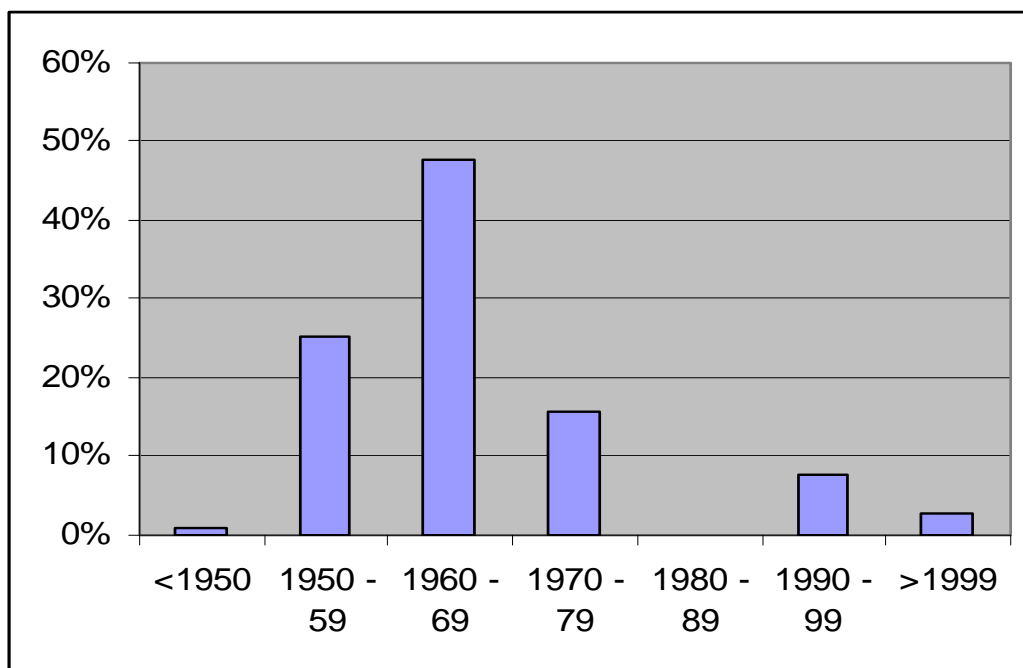
The age profile of the population is shown in Fig 27



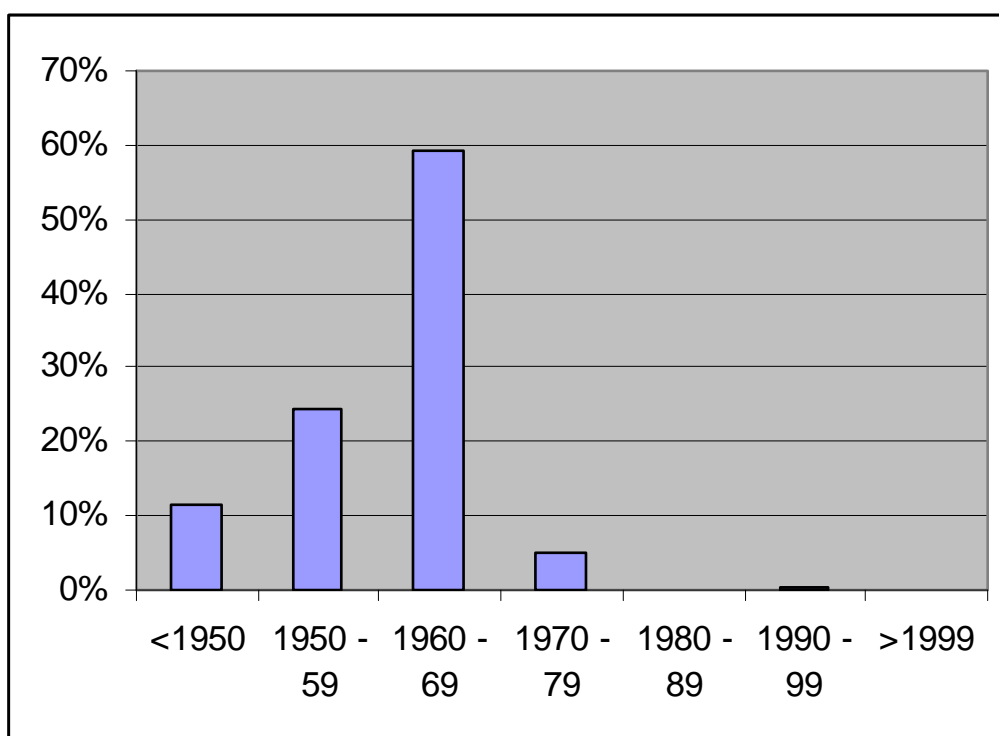
**Figure 27. Age Profile of Circuit Breakers (All Types)**

The profile shows that 50% of the population was installed pre 1980 and the majority of these were installed in the 1960s. The other noticeable peak is in the 1990s when 38% of the population was installed. Further analysis of the data in the report reveals the obvious trends in the types of switchgear being installed onto the networks (Figures 28 – 32).

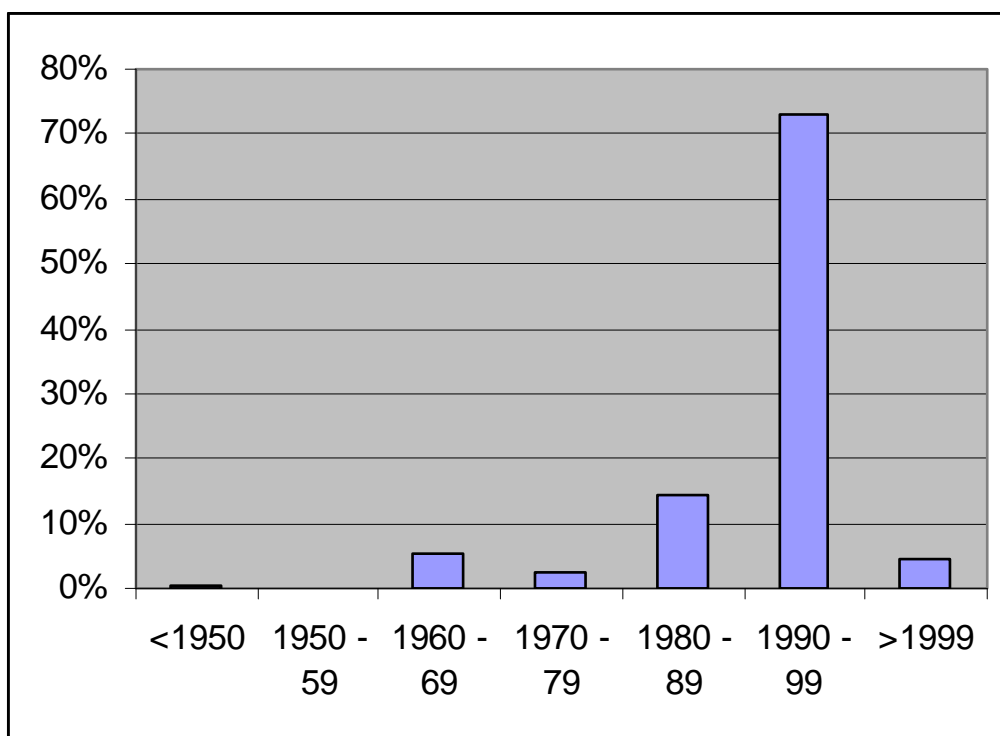
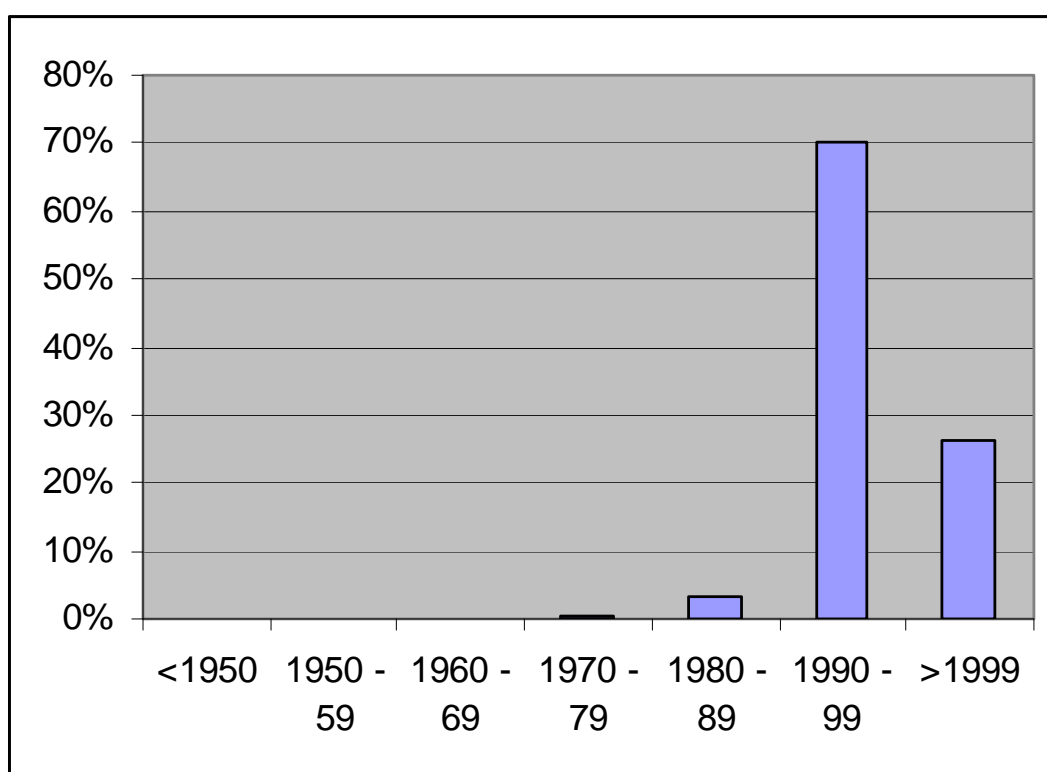


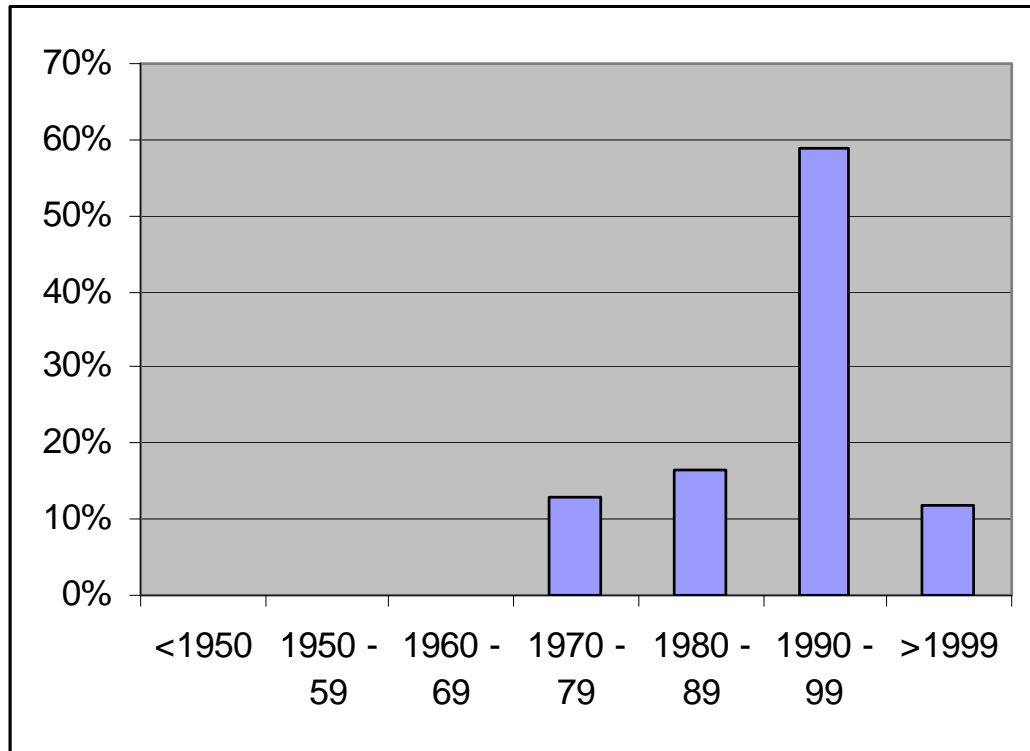


**Fig. 28. Live Tank (Air Blast & SOV) Age Profile**



**Fig. 29. Dead Tank Bulk Oil Age Profile**

**Fig. 30. Live Tank SF6 Age Profile****Fig. 31. Dead Tank SF6 Age Profile**



**Fig. 32. GIS Extensible Age Profile**

### 3.3.4 Switchgear replacement and new schemes policy

Analysis of figures 27 – 32 shows switchgear installation trends. SF6 technology has replaced the older oil and air blast technology since its introduction in the 1970s with the Live Tank SF6 designs being introduced before Dead Tank SF6 designs (due to availability). One noteworthy statistic is that there are GIS installations that have been on the system now for just over 25 years. For new installations the preference is again to install outdoor SF6 circuit breakers primarily due to cost considerations. Where sufficient land is already owned that enables the construction of new bays without disturbing existing circuits then outdoor switchgear is usually installed.

Indoor GIS installations are considered to be very expensive, however, they will be considered if a financial case can be made in place of outdoor installations. The biggest factor that results in GIS installations is the reluctance from planning authorities to approve outdoor installations in built up areas. GIS is also considered where space or land is at a premium.

### **3.3.5 Failure statistics for EHV switchgear**

There is limited data from the national data base [34] but from information available it is clear that for air blast and bulk oil designs the largest potential problem and cause of failure is moisture ingress through defective seals and gaskets causing damage to the internal insulation. Moisture often results in long term tracking which would normally be picked up by a PD scheme. This condition appears to be most prevalent on dead tank oil circuit breakers which account for some 32% of the total population.

There is much less long term experience of open busbar SF6 circuit breakers and in particular dead tank SF6 circuit breakers and therefore there is some uncertainty as to the potential asset life of these designs. The reported incidents for both live tank and dead tank SF6 circuit breakers in service in the UK is related mainly to mechanical and loss of gas issues. However, through work carried out by EA Technology Ltd. in other areas of the world with higher populations of installed GIS operating at voltages of 110kV and above, it is apparent that flashovers do occur on GIS installations. This can be very damaging and expensive at these operating voltages. For example, some of the reported failures on GIS installations in the Far East were due to flashovers within busbar chambers of 3-phase encapsulated switchgear and the effect was very disruptive to the network.

### **3.3.6 The applicability of PD measurements on EHV circuit breakers**

In general EHV circuit breakers have a very good track record and a very low failure rate. This is particularly true for the older bulk oil and air blast designs that have been installed on the network for a long period of time. Experience has shown that with adequate maintenance regimes a life expectancy of 50 years or more is not unreasonable. However, with the large number of units installed during the 1960s, some 30 percent of the population will be approaching the 50 year mark at around the same time. Some sort of assessment will be important in providing confidence in the continuing safety and reliability of equipment and

also in helping with the replacement prioritisation decisions. Partial discharge testing can and should play a part in this assessment for the air blast, small oil volume and bulk oil circuit breakers in addition to the later GIS installations.

The successful marketing of retrofitted PD schemes to EHV switchboards both in the UK and abroad would be reliant on the following factors:

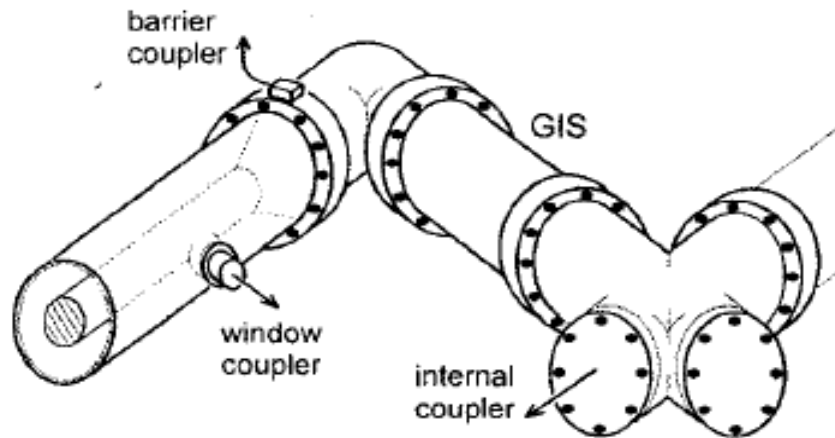
- Partial Discharge testing must be completely non-intrusive and must not involve retrofitting internal couplers or sensors
- The installation of monitoring equipment on GIS installations must in no way impair or add risk to the insulation performance.
- The scheme must provide concise information on the location, severity and nature of the PD activity detected
- The surveying or monitoring equipment must be integrated into the overall asset management strategy and its cost be commensurate with the perceived risk of switchgear failure.

### ***3.4 Proposed Solutions***

#### **3.4.1 External UHF couplers**

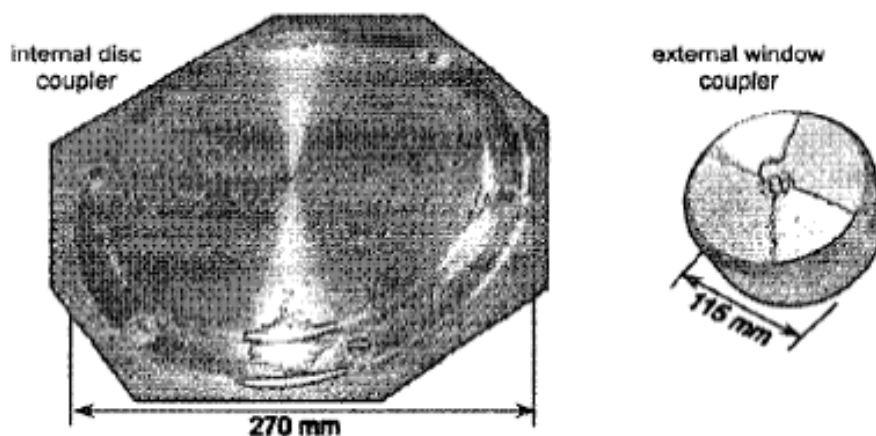
For operational GIS arranging an outage to fit internal couplers can rarely be justified due to the adverse effects on system security, the potential to adversely affect the overall insulation integrity of the switchboard and cost.

Older switchboards can particularly benefit from continuous UHF monitoring, this can often be achieved by fitting external couplers to detect UHF signals at apertures in the metal cladding. Work carried out in the year 2000 by the University of Strathclyde examined in detail the characteristics of external couplers fitted to inspection windows [13]



**Fig. 33 Examples of mounting locations for UHF couplers on GIS**

Fig. 33 shows how couplers can be fitted to exposed edges of cast resin barriers or at glass inspection windows. Fig. 34 shows an internal disc coupler and an external window coupler, whose frequency responses are compared in Fig.35. Although the internal coupler covers a wider band and has a higher peak sensitivity at  $\sim 900\text{MHz}$ , the external coupler covers a wider band and has a higher average sensitivity. The PD detection sensitivity of external UHF couplers can therefore compare favourably with that of internal couplers



**Fig. 34 Internal and external couplers**

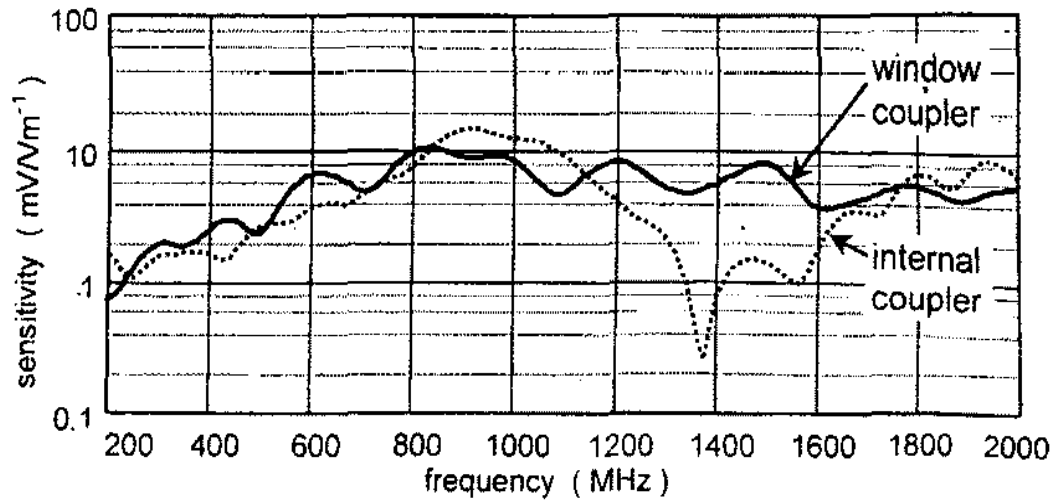
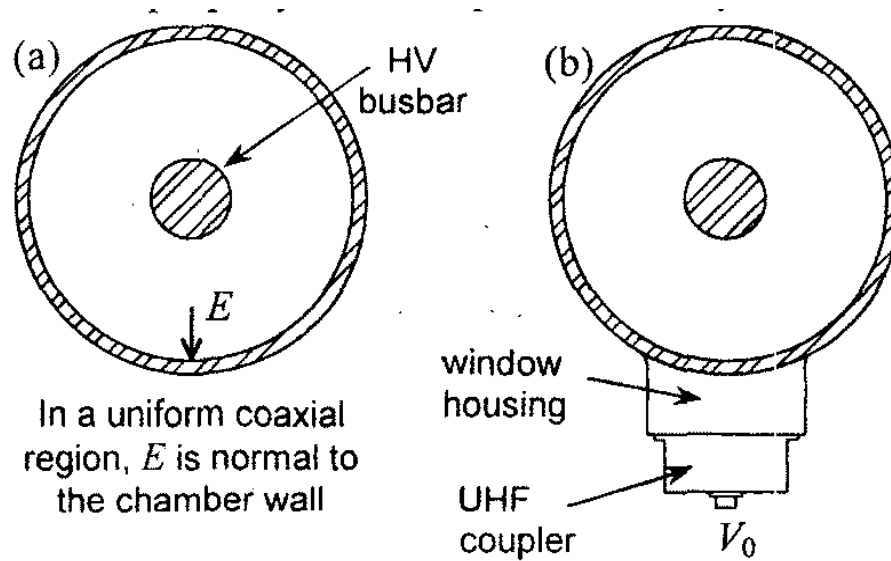


Fig. 35 Frequency response of couplers shown in Fig. 34

### 3.4.2 Sensitivity of UHF Window Sensors

Of all the factors affecting the transmission of electromagnetic energy from a PD source to the output of a coupler, the only one that can be influenced directly is the coupler sensitivity [13]. A calibration procedure [35] can be used to measure the sensitivity of new UHF couplers against the benchmark of a proven internal disc coupler. There is also a UK specification for coupler sensitivity [15].

The quantities used to characterize coupler sensitivity are illustrated in Figure 36. The presence of a coupler alters the incident field. Therefore, sensitivity of the coupler is defined relative to the electric field that would exist on its axis if the coupler were not present. By this means, the effects of field distortion are included in the calibration measurement as an inherent property of the coupler.

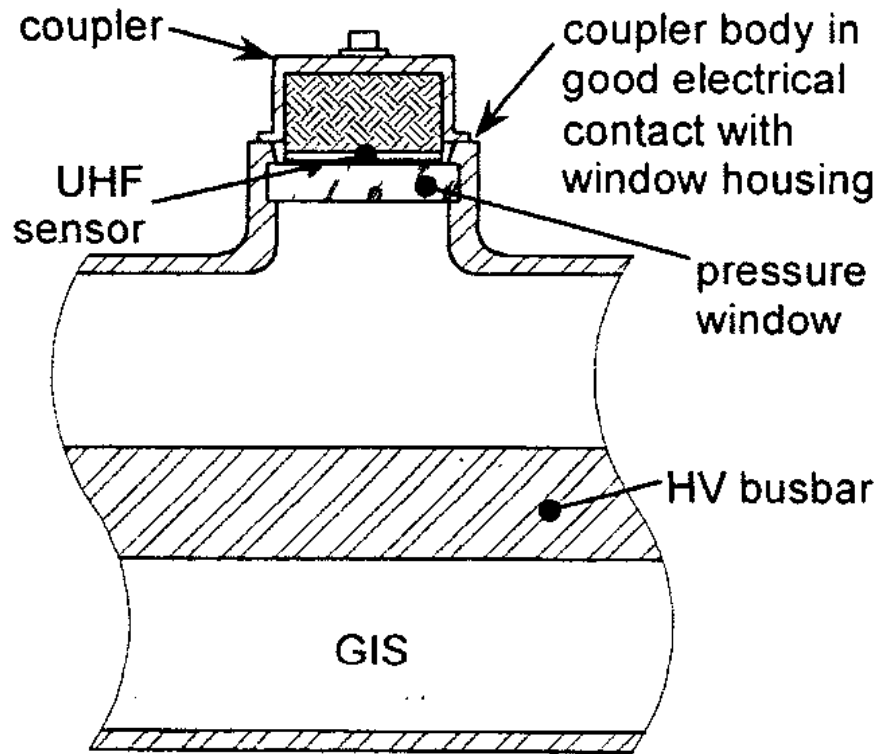


**Fig. 36. Section through a GIS showing quantities used to define sensitivity**

Sensitivity is defined as the ratio of the coupler output voltage  $V_0$  in Figure 36(b) to the incident electric field  $E$  normal to the chamber wall in Figure 36(a). This approach to calibration helps to ensure a fair comparison between couplers with regard to their overall performance in PD detection. For example, a certain coupler may function very well as a receiving antenna when tested in isolation, but if the structure on which it is mounted attenuates the PD signal, the overall sensitivity may be inadequate. The calibration procedure [36] has been designed to incorporate these effects in the sensitivity measurement by requiring the coupler to be tested on a plate that reproduces the dielectric aperture on the GIS.

When external couplers are used, the coupler itself is unlikely to affect the insulation rating. In terms of UHF sensitivity the resulting freedom to use antenna structures that are better suited to broadband reception can more than compensate for the less favourable coupler mounting position. Furthermore, an externally mounted coupler can still be completely screened, making the sensing element electrically internal, as illustrated in Figure 37





**Fig. 37 Section through a GIS chamber showing fully screened sensor**

The use of software packages to simulate various equivalent circuit approaches for both window and flange (garter) PD sensors together with studies on cross coupling and external interference between sensors, are discussed in section 4.

### **3.4.3 Expert Systems and PD Pattern Recognition Using Artificial Neural Networks**

#### **3.4.3.1 Introduction**

Continuous monitoring PD detection schemes can generate large amounts of data. A robust, reliable method of identifying the various PD signatures is essential to assist the engineer with the location of the defect(s). Computer-aided interpretation and classification of defects has been pioneered by Kreuger and his coworkers [37-39] At present the interpretation is based on analyzing the shape and phase of the data, a common application of artificial neural networks (ANN)

is in the solution of such pattern recognition problems [40-42] Gulski in particular has extracted a number of statistical operators to describe the shape of the point on wave characteristic, thus forming a second statistical signature which is applied to an ANN.

An artificial neural network is a non-linear and interconnected assembly of simple processing elements. The processing ability of the network is stored in the inter-unit connection strengths or weights, obtained usually by a process of adaptation to or learning from a set of training patterns.

Artificial neural networks can generally be divided into three categories: ANN based on physical models such as the Hopfield neural network and Boltzman neural network; ANN based on the adaptive signal processing principles such as the multi-layer feed forward neural network using back-propagation (BP) algorithm; ANN based on the self-organised theorem such as the adaptive resonance theory (ART) and the self-organising map (SOM). [43]

The network should enable the extraction of features that can represent the information contained in the input signal. In addition to the general time domain pulse properties, PD signal time series can be transformed into other domains. It should be noted that the transformation carried out to generate new features for source characterisation does not produce new information, they represent the existing waveform information in ways that facilitate source characterisation. Moreover, statistical methods can be used to extract data from a group of signals originating from the same source. It would be virtually impossible to obtain the same information from one signal alone.

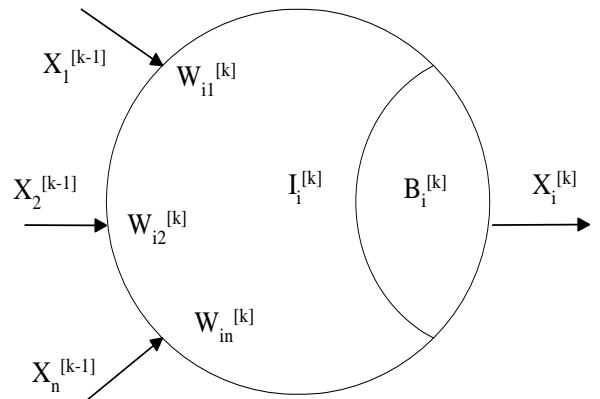
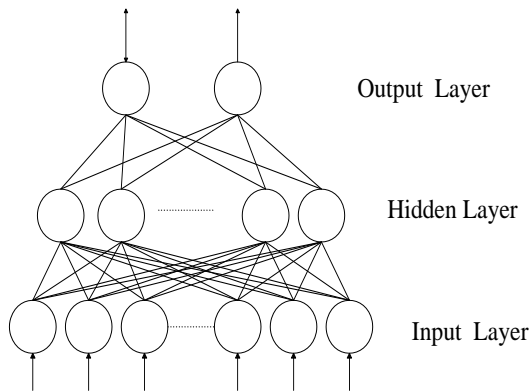
The ANN pattern recognition consists of the learning or training process and the testing process. During the learning or training state, a set of decision rules is developed. The ANN is supplied with a set of representative signals from each source to be classified. It is considered to be trained when it can use the decision rules to identify an input signal correctly. To test the ANN performance, sample signals not used during the training process are presented to the system that will

identify the class to which each unknown signal belongs. Successful identification of input signals is a good indication of a properly trained system.

In most ANN approaches to partial discharge pattern recognition, a multi-layer feed forward network architecture is applied in which training is carried out by means of the back propagation algorithm. [43]

### 3.4.3.2 Back propagation (BP) neural network

The BP neural network consists of the input layer, at least one hidden layer and the output layer, as shown in Figure 38. Each layer is fully connected to the succeeding layer. The main purpose of the hidden layer is to extract features of the different PD sources and pass its knowledge to the output layer or the succeeding hidden layer if there is more than one. The number of processing elements in the hidden layer usually ranges between the number of elements in the input and the output layer. However, it tends to be larger for more complex problems.



**Fig.38 BP network with three layers      Fig.39 Typical BP processing element**

The typical BP processing element (pe) is shown in Figure 39, where  $X_1^{[k-1]}$ ,  $X_2^{[k-1]}$ , ...,  $X_n^{[k-1]}$  are  $n$  outputs from the preceding layer,  $w_{i1}^{[k]}$ ,  $w_{i2}^{[k]}$ , ...,  $w_{in}^{[k]}$  are weight connections between the  $(k-1)$ -th and  $k$ -th layer,  $B_i^{[k]}$  is the threshold

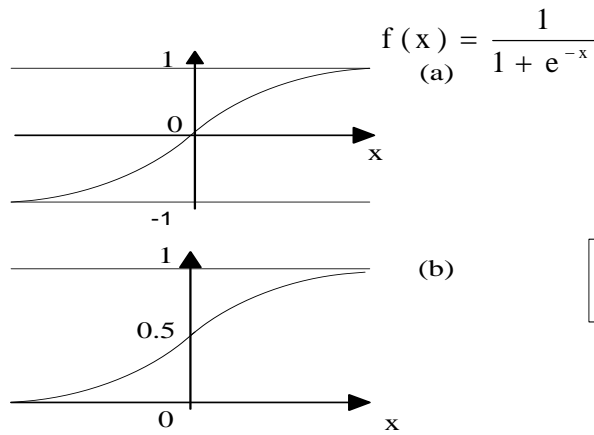
vector of the k-th layer and  $X_i^{[k]}$  is the output of the i-th pe in the k-th layer. The pe transfers its input according to [40]

$$X_i^{[k]} = f\left(\sum_{j=1}^n \omega_{ij}^{[k]} X_j^{[k-1]} - B_i^{[k]}\right) = f(I_i^{[k]}),$$

Where f can be hyperbolic tangent function (Figure 40a )

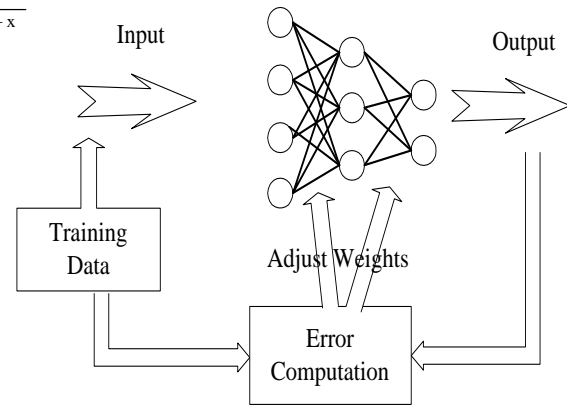
$$f(x) = \frac{e^x - e^{-x}}{e^x + e^{-x}}$$

or a sigmoid function (Figure 40b)



**Fig.40 BP network transfer functions**

**(a) Hyperbolic tangent (b) Sigmoid**



**Fig.41 BP learning process**

Using labelled training data the back-propagation algorithm determines the error between the desired and the actual computed value at the output layer. Propagating this error back through the network, the element weights are adjusted in order to reduce it to a minimum. The whole procedure is repeated until the root mean square error at the output layer is smaller than a pre-defined convergence criterion. The learning procedure is shown in Figure 41. During the classification process the BP ANN produces different outputs that are between zero and one (using sigmoid function). The class of the input vector is determined by the neuron that has the largest value. In order to increase the reliability of the identification results, additional criteria can be defined for this study to ensure that the input pattern was clearly identified. For example, the

largest output value must be greater than 0.5; the next largest value must be less than 0.5; and the difference between these two values must be greater than 0.3.[43]

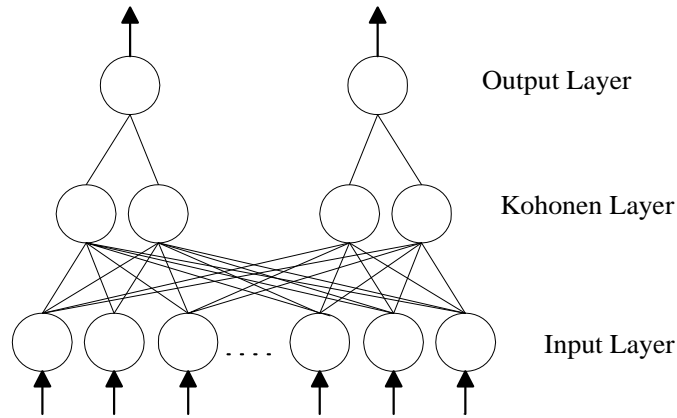
### 3.4.3.3 Learning vector quantization (LVQ) neural network

The basic structure of the LVQ neural network is shown in Figure 42. It also consists of the input, the hidden and the output layers but the hidden layer or Kohonen layer has an identical number of neurons for each class of output. During the learning process, the Euclidean distance  $d_j$ , between the input vector and weights of each neuron at the Kohonen layer is calculated [43].

$$d_j = \sqrt{\sum_{i=1}^n (x_i - w_{ij})^2}$$

Where  $x_i$  is the  $i$ -th input vector;  $n$  is the number of inputs;  $w_{ij}$  is the weight from the  $i$ -th input to the  $j$ -th Kohonen neuron.

The neuron having the minimum distance is selected as the winner. If this neuron is in the class of the learning vector, then the weight of the winning neuron is altered towards the learning vector, decreasing its distance to that class. This increases the probability of the neuron responding more strongly to a similar learning vector in future rounds. If the winning neuron is not in the class of the learning vector then its weight is altered to increase its distance from the learning vector. Having trained the ANN, during the classifying process, the distance of the unknown input vector to each neuron is computed and again the nearest neuron is declared as the winner. The final classification of the input signal is made according to the class associated with the winning neuron.



**Fig.42 Structure of the LVQ neural network**

### 3.4.3.4 PD features for pattern recognition

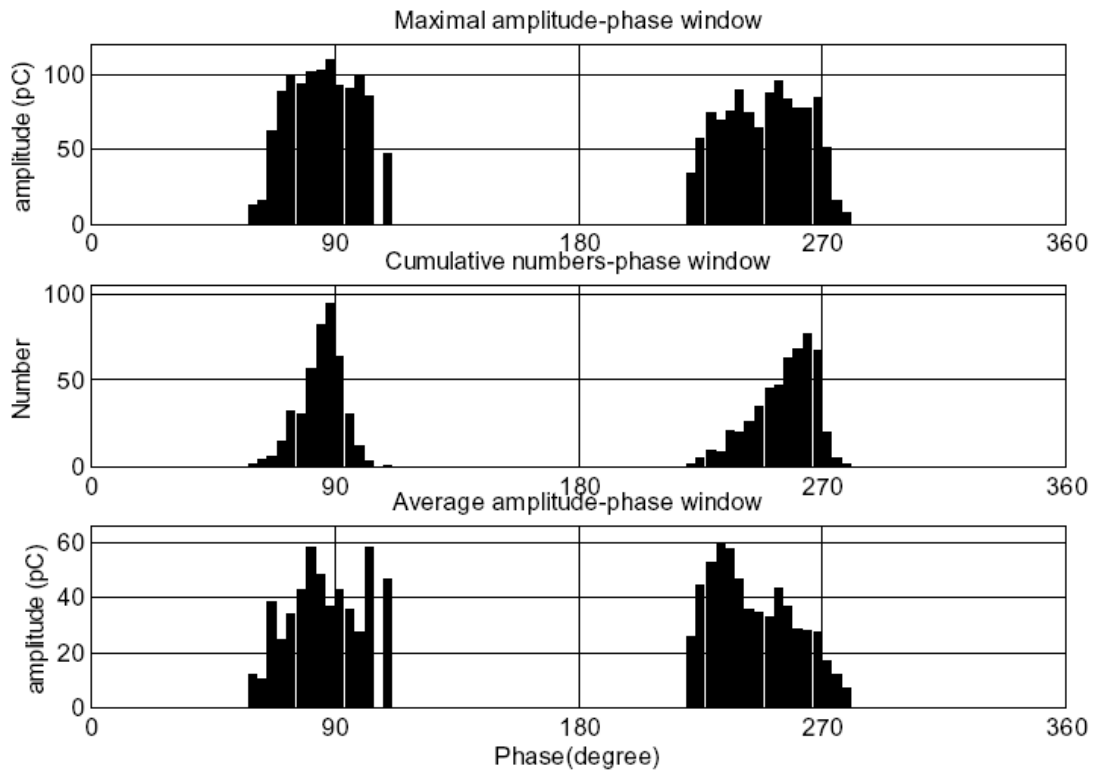
To apply the above artificial neural networks to partial discharge pattern recognition, the ANN data input is important. The input data should be able to fully represent different patterns in an effective way.

#### ▪ Two-dimensional statistical patterns

PD phenomena that occur in a dielectric medium is an inherently complex stochastic process, it is therefore very helpful in analysis to take the statistical characteristics into account. By measuring pulse distribution as a function of the phase angle, it is possible to obtain information about the phenomena that cause the pulse distributions. The following phase-position quantities need to be studied: the pulse count distribution  $H_n(\varphi)$ , which represents the number of observed discharges in each phase window as a function of the phase angle;  $H_{qmax}(\varphi)$ , which represents the maximal discharge amplitude in each phase window; the mean pulse height distribution  $H_{qn}(\varphi)$ , which represents the average discharge amplitude in each phase window as a function of the phase angle.  $H_{qn}(\varphi)$  is derived from the total discharge quantity in each phase window divided by the total number of discharges in the same phase window.[40]

The time dependence of the pulse count phase distribution  $H_n(\varphi)$  and the mean pulse height distribution  $H_{qn}(\varphi)$  can provide a good description of changes in

discharge patterns. The  $H_n(\varphi)$  quantity contains information of the intensity of discharges as a function of their phase angle. The  $H_{qn}(\varphi)$  quantity allows noise reduction due to the difference between the statistical characteristics of the discharge pulses and that of noise pulses as a function of phase angle. The resolution on the phase angle axis is determined by the number of phase windows. This number should be as large as possible to give higher precision, but this would decrease data processing speed and increase the computer memory required. It has been found that 200 phase windows can give reasonable and sufficient resolution. The number of magnitude windows is selected in the same way and 50 is found to be a reasonable quantity to give sufficient resolution.[40] Figure 43 shows the two-dimensional statistical pattern  $H_{qmax}(\varphi)$ ,  $H_n(\varphi)$  and  $H_{qn}(\varphi)$ , for discharge signals from XLP cables under test, collected over 500 continuous power cycles.[45]

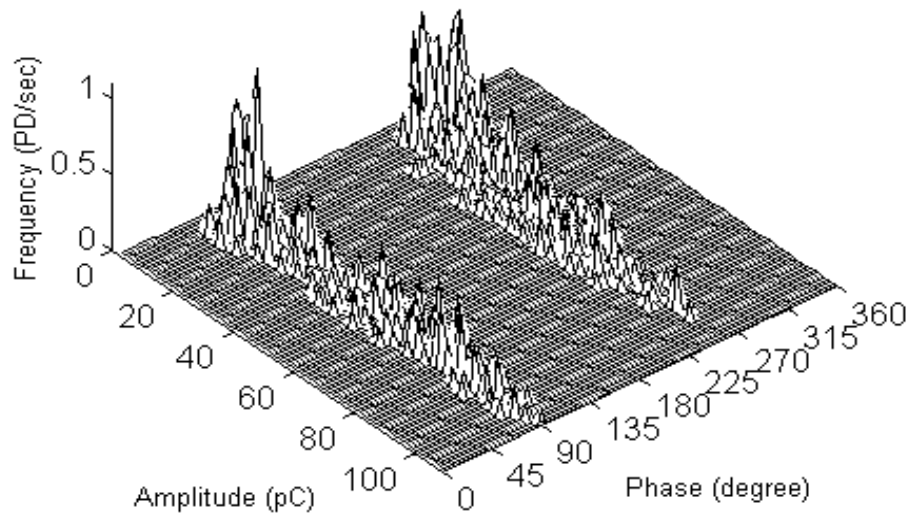


**Fig 43 PD two-dimensional patterns**

- **Three-dimensional  $\varphi$ -q-n patterns**

In addition to the two-dimensional phase-related patterns, three-dimensional Phase-Charge-Number ( $\varphi$ -q-n) patterns may be used to analyse discharge signals.

This is the characterization of the partial discharges by their angular position on the AC cycle ( $\phi$ ), their relative magnitude ( $q$ ) and their frequency per unit time ( $n$ ). These three parameters may be used to construct a three-dimensional surface from which important features may be extracted.[45] Rather than the accumulative signal numbers and average signal amplitudes in each phase window, for PD measurement,  $\phi$ - $q$ - $n$  represents the number of PD signals  $n_{ij}$  having both phase position  $\phi_i$  and amplitude  $q_j$ .  $\phi$ - $q$ - $n$  and is considered to be the most complete form of graphical PD presentation.[45] Figure 44 shows the three-dimensional  $\phi$ - $q$ - $n$  patterns for discharge signals obtained over 500 power frequency cycle.



**Fig 43 PD three-dimensional  $\phi$ - $q$ - $n$  pattern**

The downside to this approach is the number of phase and magnitude windows required to give reasonable and sufficient resolution. The number of windows needs to be limited so that the calculation times for the ANN are not unreasonably long.

#### ▪ Statistical operators

In reality, the discharges occur during a voltage cycle in two sequences and for each half of the voltage cycle separate discharge patterns can be measured. But in



the case of similar inception conditions for each half of the voltage cycle, equal discharge patterns may be expected. Therefore the  $H_n(\varphi)$  and  $H_{qn}(\varphi)$  quantities are characterised by two distributions: for the positive half of the voltage cycle  $H_{qn}^+(\varphi)$ ,  $H_n^+(\varphi)$  and for the negative half of the voltage cycle  $H_{qn}^-(\varphi)$ ,  $H_n^-(\varphi)$ . [45] To study the difference between the distributions  $H_{qn}^+(\varphi)$  and  $H_{qn}^-(\varphi)$  in both halves of the voltage cycle the following statistical operators may be used:

*Discharge asymmetry* is the quotient of the mean discharge level of the  $H_{qn}(\varphi)$  distribution in the positive and in the negative half of voltage cycle:

*Phase asymmetry* is used to study the difference in inception voltage of the  $H_{qn}(\varphi)$  distribution in the positive and negative half of the voltage cycle:

*Cross-correlation factor* is used to evaluate the difference in shape of distribution  $H_{qn}^+(\varphi)$  and  $H_{qn}^-(\varphi)$ .

Thus, the differences between the distributions  $H_{qn}^+(\varphi)$  and  $H_{qn}^-(\varphi)$  are described by three independent parameters: phase asymmetry, discharge asymmetry and cross-correlation factor. A cross correlation  $CC=1$  means 100% shape symmetry and a value of 0 indicates total asymmetry. However, CC tells nothing about the height of the distribution. For that purpose the discharge asymmetry or phase asymmetry are used. Both these variables are defined in such a way that they are equal to 1 in the case of fully symmetric distributions and smaller than one in the case of asymmetric ones. Thus several asymmetry factors can be easily combined by multiplication. Therefore the operator MCC is introduced as follows:

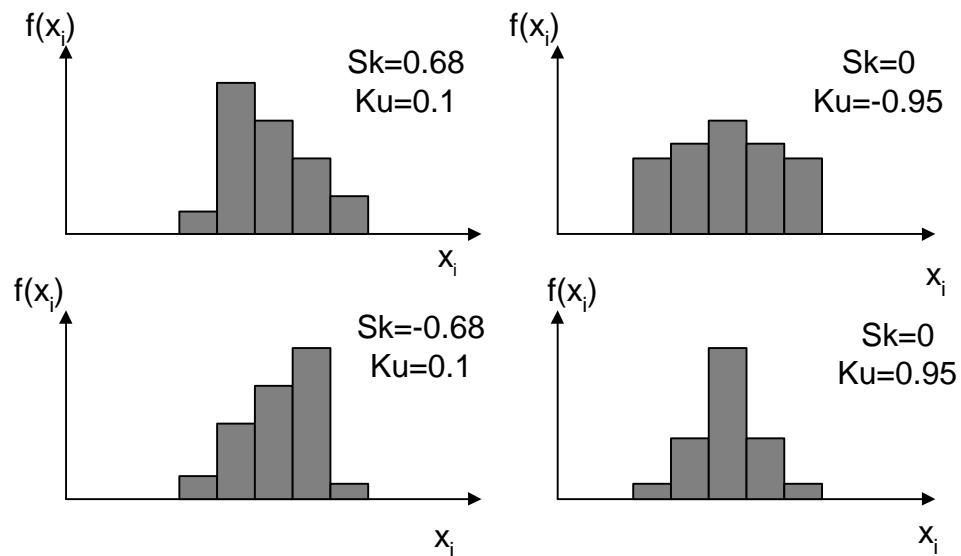
*The modified cross-correlation factor* is used to evaluate the differences between discharge patterns in the positive and the negative voltage cycle. This is defined as the product of phase asymmetry, discharge asymmetry and cross-correlation factor. It is known that in the case of a single defect, discharge parameters can be fairly well described by a normal distribution process. Therefore to get a better evaluation of  $H_n(\varphi)$  and  $H_{qn}(\varphi)$  quantities, several statistical parameters typical for normal distribution can be used:

*Skewness* (Sk) is an indicator for the asymmetry of a distribution with respect to a normal distribution. Sk is zero for a symmetric distribution, positive when the distribution is asymmetric to the left, and negative when the distribution is asymmetric to the right.

*Kurtosis* (Ku) is an indicator for the sharpness of the normal distribution. Ku is zero for a normal distribution. For a sharper than normal distribution it is positive, and if the distribution is flatter than the normal distribution Ku is negative.

Figure 44 shows an example for the above relationship. If the above statistical operators are used as the ANN input parameters, the scale of the input data for pattern recognition reduced to a few values. In a practical application, a number of tests for each defect would have to be carried out and several observations made for the same type of PD source to estimate the statistical operators. For each of the statistical operator the mean value would then be calculated and used for pattern recognition. The effectiveness of using statistical operators for PD pattern recognition needs further proof. [45]

**Fig. 44 Distribution with different Skewness and Kurtosis**



## Chapter 4

# SYSTEMS AND SOLUTIONS

### *4.1 Plant Condition Monitoring*

Condition monitoring on all types of electrical plant is being increasingly used to support asset management programmes with a view to implementing condition-based maintenance regimes. If the large volume of raw data captured is presented to engineers, this leads to a number of problems:

- The data volume is onerous for engineers to deal with.
- The relationship between the plant item, its health and the condition monitoring data generated is not always well understood. Therefore, the extraction of meaningful information from the condition monitoring data is difficult.
- The translation of the health of the plant item into an estimate of its lifetime expectation is not always apparent.

An approach to address these issues is suggested below

#### **4.1.1 Condition Monitoring Architecture**

The following key requirements for a condition monitoring system have been identified:

Raw sensor data, from various sensors, must be conditioned and tested for any significant deviations (such as the exceeding of certain limits and unexpected rates of change).

When significant deviations are identified, diagnosis of the failure must occur through interpretation of the data.

It must be ascertained whether there is a sensor failure or an actual plant failure.

This is achieved by corroborating the interpretation results and sensor data with other relevant data sources.

Once diagnosed, key information and remedial advice must be presented to the relevant engineers.

An additional requirement, which is essential for longevity and practical implementation, is that the architecture must be scalable and support the introduction of new sensors, data sets and interpretation techniques as they become available. This suggests that each of the required functions should be stand alone, with the ability to co-operate and exchange data/information as required.

This leads to the design of a 'layered' condition monitoring system, where functional modules are grouped by their overall goal. Architecturally, the condition monitoring system uses distributed modules that have no constraints on their physical location. This allows data handling modules to be on the plant or close to it. Importantly, modules are designed such that only relevant data and information enters the telecommunications system, thereby avoiding the current practice of sending all data to a central point [49]

The layers are:

- data monitoring layer
- interpretation layer
- corroboration layer
- information layer.

The modules in each layer require fundamental knowledge of how the plant behaves and fails, and how this is exhibited through the sensor data captured. The resulting system would integrate various monitoring technologies and data sources.

**The data monitoring layer** functions as a gatekeeper, the first line of defense in the effort to stop engineers from being overwhelmed by masses of unintelligible data. This first layer in the architecture is intimately associated with the front-end hardware used to monitor physical phenomena relating to plant operation,

and is therefore the most plant-specific of the four layers. Raw data from the sensors and associated monitoring systems is received and all necessary preconditioning (such as Fourier transforms, feature extraction etc.) takes place. Most importantly, this layer is responsible for identifying any significant changes in measurands that may indicate abnormal plant operation. For this reason, a module would be specifically tuned to each sensor or data type.

**The interpretation layer** begins the process of turning the data into information that is of greater use to the plant operator, using plant models. In addition, the modules in this layer use advanced intelligent system techniques, coupled with codified knowledge and expertise in the area of plant monitoring, to diagnose problems, provide remedial advice and offer a prognosis. A key aspect of the architecture is that it would support more than one interpretation technique. Research over the past decade suggests that no single data interpretation method can completely automate condition monitoring and diagnostic tasks. Instead, the combination of a powerful suite of techniques is required, resulting in a hybrid system [50] Currently, the expertise and knowledge concerning fault identification from PD signals is being captured and deployed within knowledge based modules. Data interpretation is also being achieved through the use of techniques such as Kohonen classification and K-means clustering [49]

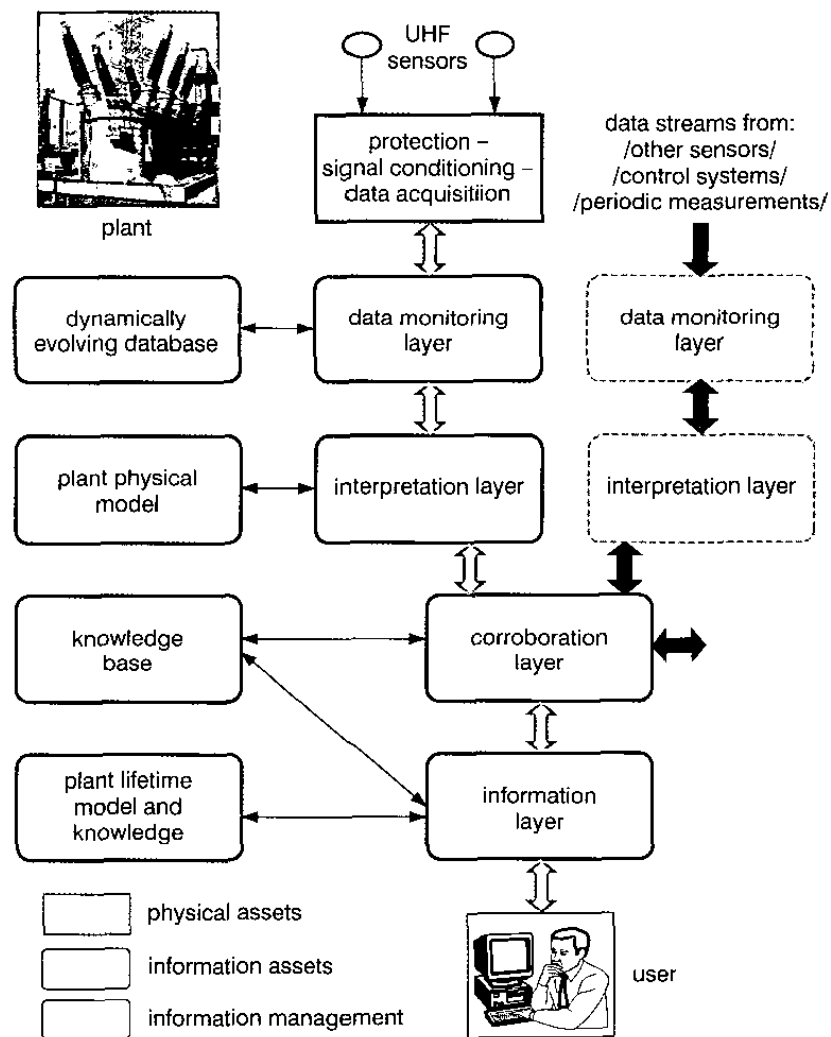
**The corroboration Layer** takes a wider view of the interpretations that it receives, with the aim of piecing together a picture of what is happening based on the widest possible range of available information sources. At one level, the corroboration layer will identify suspicious diagnoses that might be a consequence of sensor failure. For example, suppose the interpretation layer indicates that a particular UHF sensor is detecting regular large bursts of signal that are not detected elsewhere. The corroboration layer does not discount this signal immediately as invalid, but looks for any evidence that something exceptional is happening:

- Are the loading or weather conditions unusual?
- Are temperatures at normal levels?

Just as an expert would rarely make an instant diagnosis, the interpretation layer might take some time to observe trends, thereby improving confidence and refining the eventual interpretation [49]

**The Information Layer** is the intelligent interface that provides high-level information to managerial, engineering and maintenance staff as appropriate. Considering the engineer as the information recipient, an individual piece of plant will be one of a large number of assets for which an individual has responsibility. He/she can access full details of the plant's operational history at any time by delving into the information layer. However, the plant itself will only demand attention when sufficient evidence exists to warrant the request. The engineer can be alerted to urgent requests for attention through a pager or may receive cautionary e-mail messages generated by the information layer. Access to more detailed information could be provided by linking to a web page containing a graphical interface. As well as summarising the reasoning used by the corroboration layer in reaching its conclusion, the graphical interface allows the engineer to drill down through the layers, even accessing the raw data if necessary. During this process, the information layer retains the function of a gateway to the other layers, providing the framework for visual presentation of underlying interpretations and data streams [49]

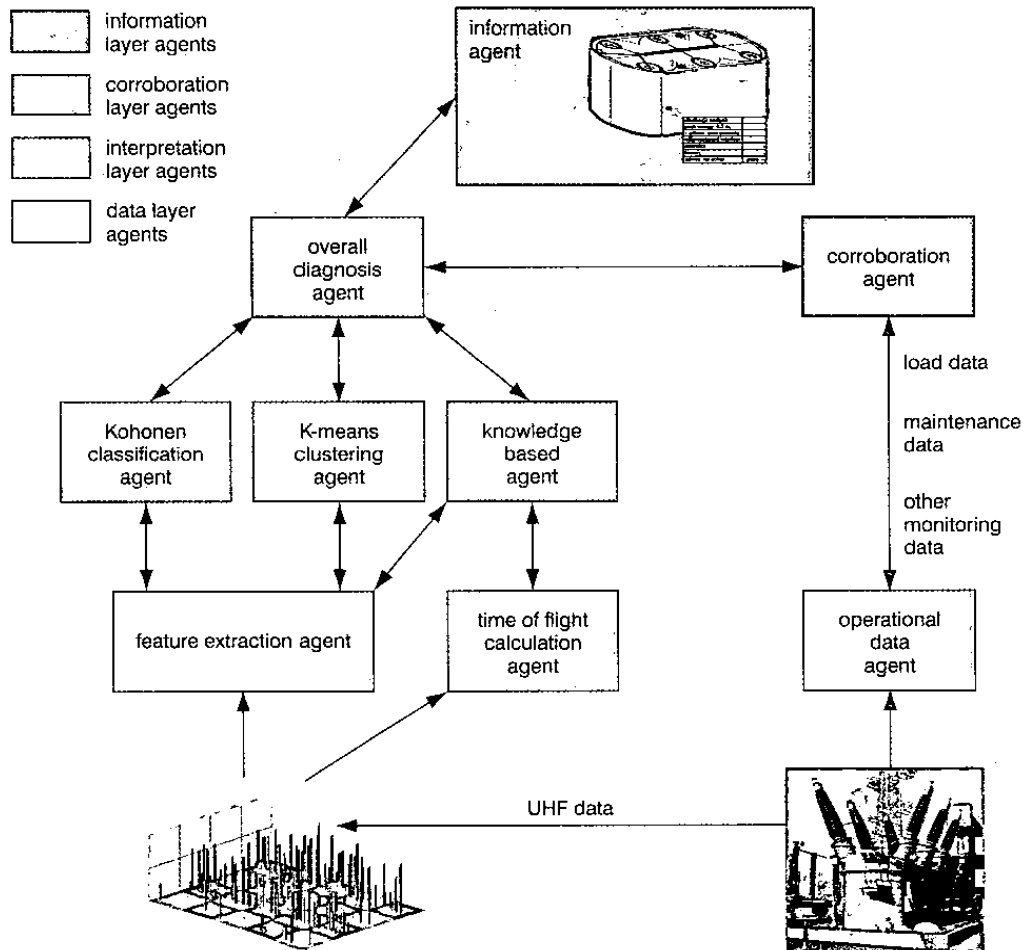
**Implementation of the condition monitoring architecture** is illustrated in Fig. 45 and, relies heavily on co-operating software modules which are able to exchange data and information.



**Fig. 45 Condition Monitoring Architecture**

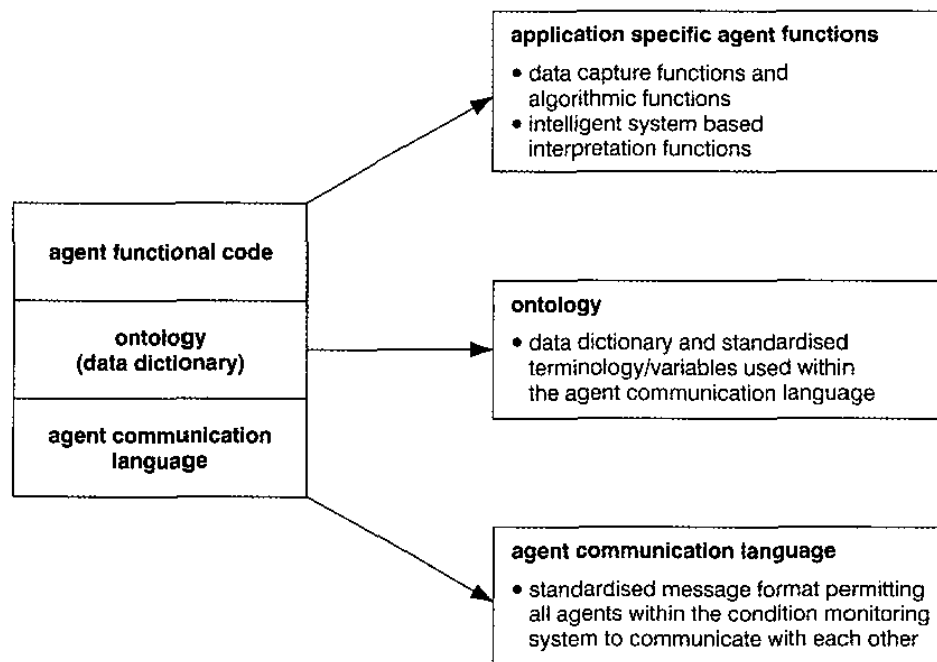
Fortunately, a technology exists to support such a requirement. Agent-based systems have received widespread attention in recent years. While this technology is not a condition monitoring panacea, in engineering terms it provides a system integration technology to support all the aforementioned requirements. Importantly, it also permits the easy integration of further modules (in any of the layers) in the future. Each module described is implemented as an agent, which is a self-contained functional software module having its own goals to achieve. However, agent technology provides a standardised Agent Communication Language (ACL) that permits the easy exchange of information and supports co-operation among the independent

modules. Figs. 46 and 47 provide a diagrammatic representation of the agent-based condition monitoring architecture, and more detail concerning the functions within a single agent [49]



**Fig. 46 Agent -Based Condition Monitoring Architecture**





**Fig. 47 Functional Blocks within a Single Agent**

## **4.2 Circuit Modelling**

In order to fully understand the characteristics and interactions of the various components that form part of a continuous PD monitoring scheme, modelling using finite difference time domain (FDTD) techniques provides a sound solution.

### **4.2.1 Finite difference time domain (FDTD) methods for electromagnetics – introduction.**

FDTD is part of a three- tier hierarchy consisting of:

Computer science, which uses the mathematics underlying algorithms as well as the structure and development of the algorithm.

Computer Engineering, which is concerned with hardware architecture and capabilities including parallelism and fault tolerance.

Computational Engineering, which explores various engineering problems taking numerical solutions to systems of equations describing the phenomenon or process in question

The FDTD technique offers many advantages as an electromagnetic modelling, simulation, and analysis tool. Its capabilities include:

- Broadband response predictions centred about the system resonances
- Arbitrary three-dimensional (3-D) model geometries
- Interaction with an object of any conductivity from that of a perfect conductor, to that of a real metal, to that of low or zero conductivity
- Frequency-dependent constitutive parameters for modelling most materials
  - Lossy dielectrics
  - Magnetic materials
  - Unconventional materials, including anisotropic plasmas and magnetized ferrites
- Any type of response, including far fields derived from near fields, such as:
  - Scattered fields
  - Antenna patterns
  - Radar cross-section (RCS)
  - Surface response
  - Currents, power density
  - Penetration/interior coupling

The advantages of FDTD can be summarized as its ability to work with a wide range of frequencies, stimuli, objects, environments, response locations, and computers. To this list can be added the advantage of computational efficiency

for large problems in comparison with other techniques such as the method of moments, especially when broadband results are required. Further, the FDTD code, while inherently volumetric, has successfully treated thin plates and thin wire antennas. Its accuracy, using a sufficiency of cells, can be made as high as desired. Conversely, engineering estimates of a few decibels' accuracy can be made with surprisingly few cells. Finally, powerful visualization tools are being developed to enhance the user's understanding of the essential physics underlying the various processes that FDTD can model, simulate, and analyse [46]

The basis of the FDTD code is the two Maxwell curl equations in derivative form in the time domain. These equations are expressed in a linearized form by means of central finite differencing. Only nearest-neighbour interactions need to be considered as the fields are advanced temporally in discrete time steps over spatial cells of rectangular shape. The equations shown below have been recast into the form used for FDTD calculations

$$\partial \mathbf{H} / \partial t = -\frac{1}{\mu} (\nabla \times \mathbf{E}) - \frac{\sigma^*}{\mu} \mathbf{H}$$

$$\partial \mathbf{E} / \partial t = \frac{-\sigma}{\epsilon} \mathbf{E} + \frac{1}{\epsilon} (\nabla \times \mathbf{H})$$

Where  $\mathbf{H}$  and  $\mathbf{E}$  are the electromagnetic fields,  $\mu$  is the permeability,  $\epsilon$  the permittivity,  $\sigma$  the conductivity of the medium and  $\sigma^*$  the conductivity term to enable magnetic loss to be taken into account. [46]

### ***4.3 Modelling of system components***

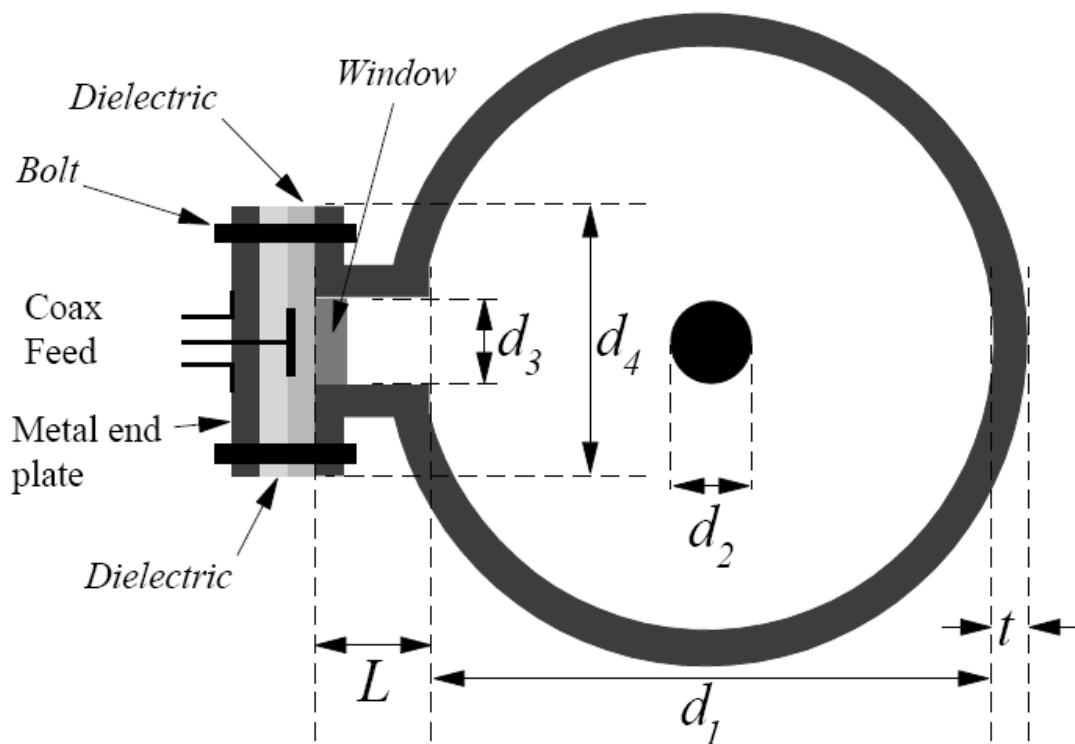
During 2007, using capacitor models and FDTD techniques, The University of Bath carried out a series of investigations to determine the characteristics of possible designs for transducers for use in PD monitoring schemes, to be retrofitted to gas insulated switchgear. The initial work at Bath concentrated on

modelling window and garter transducers and later on PD sensor interference and 50Hz reference studies.

Following the teams excellent research efforts led by Drs. Steve Pennock and Miles Redfern the results outlined in section 4.3 have been included with their agreement. The authors involvement together with colleagues at EA Technology Limited was in the provision of SF6 switchgear design details, the interpretation of the study results and their application to the design of a practical system. The author wishes to record a vote of thanks to the teams at Bath and EA Technology Limited for their constructive contributions.

#### 4.3.1 Window Transducers

Fig 48 shows the cross section of a typical window PD sensor mount. Both eight and twelve inch flanges were studied with different dielectric types and thicknesses



**Fig. 48 Cross section of window sensor**

The dimensions used in the studies for the eight (186mm) and twelve-inch (300mm) flanges are shown in tables 4.3.1.1 and 4.3 1.2

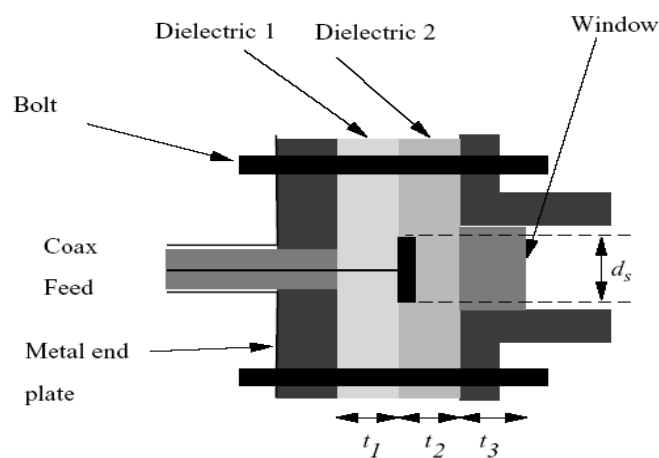
Wall Thickness	t	10mm
GIS tube inner diameter	d1	500mm
Centre conductor diameter	d2	20-30mm
Sensor mount throat diameter	d3	108mm
Flange diameter	d4	186mm
Sensor mount length	L	50mm

**Table 4.3.1.1 Dimensions of PD sensor mount with eight-inch flange**

Wall Thickness	t	10mm
GIS tube inner diameter	d1	500mm
Centre conductor diameter	d2	20-30mm
Sensor mount throat diameter	d3	200-250mm
Flange diameter	d4	300mm
Sensor mount length	L	50mm

**Table 4.3.1.2 Dimensions of PD sensor mount with twelve-inch flange**

An outline of the PD sensor mount is shown in Fig.49 and table 4.3.1.3 gives the internal dimensions.



**Fig. 49 Outline of PD sensor mount**

Dielectric 1 thickness	$t_1$	A=3mm, B=6mm, C=9mm
Dielectric 2 thickness	$t_2$	a=5mm, b=10mm, c=20mm
Window thickness	$t_3$	a=5mm, b=10mm, c=20mm
Sensor conductor diameter	$d_s$	2=20mm, 4=40mm, 6=60mm, 8=80mm

Table 4.3.1.3 Internal dimensions of PD sensor mount

### 4.3.2 Capacitance Coupling Model

In order to determine the sensitivity of the window transducer, an initial approach using a two-capacitor model was considered, this is shown in Fig. 50.

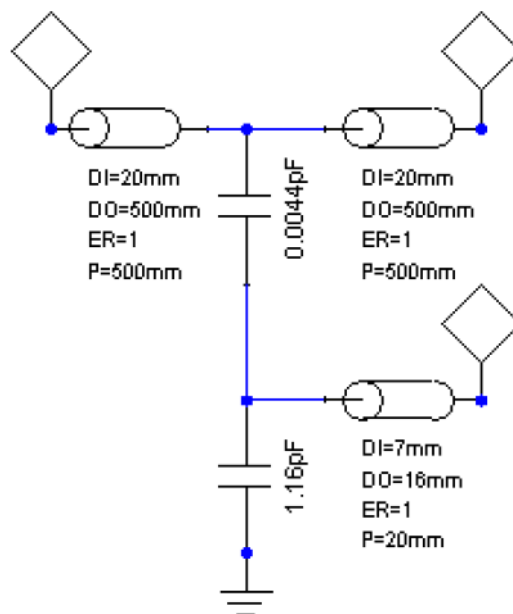


Fig. 50 Two capacitor model coupling main busbar (2cm, 0.5m) coaxial line and 50Ω sensor port

The model considers the sensor to have a shunt capacitance to the local ground plane and a series capacitance to the main busbar. In the case where the busbar diameter is 2cm and the diameter of the busbar chamber is 50cm this coaxial line has a characteristic impedance of about 180Ω. The sensor feed line has an assumed characteristic impedance of 50Ω. Considering the sensor 'plate', this has an approximate parallel plate capacitance to ground of

$$C_p = \frac{\epsilon \pi (d_s/2)^2}{d_1}$$

Where  $\epsilon$  is permittivity,  $d_1$  is the diameter of the cylinder and  $d$  is the diameter of the sensor plate. [48]

The capacitance from the centre conductor to an area  $d\Delta L \times d_s$  on the wall of a cylinder of diameter  $d_1$  can be approximated from the capacitance per unit length of the coaxial line,  $C_0$  as:

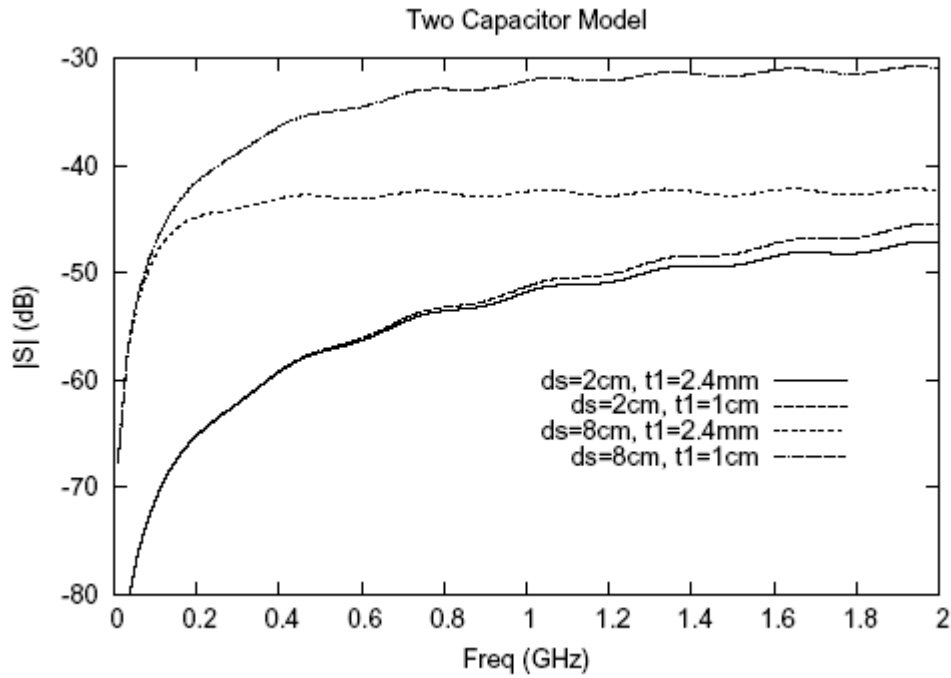
$$C_s = C_0 \Delta L \frac{d_s}{\pi t_1} \approx C_0 d_s \frac{d_s}{\pi t_1} \quad \text{where} \quad C_0 = \frac{2\pi\epsilon}{\log_e(d_1/d_2)}$$

[48] For the case where  $d_1 = 0.5\text{m}$ ,  $d_2 = 0.02\text{m}$  we have  $C_0 = \epsilon_r \times 17.3\text{pF/m}$  and  $C_s$  varies between  $4\text{fF} \times \epsilon_r$  and  $70\text{fF} \times \epsilon_r$  over the range  $d_s = 0.02\text{m}$  to  $d_s = 0.08\text{m}$ .

For  $C_p$  we have the ranges:

	$t_1 = 2.4\text{mm}$	$t_1 = 1\text{cm}$
$d_s = 2\text{cm}$	$\epsilon_r 1.16\text{pF}$	$\epsilon_r 0.28\text{pF}$
$d_s = 8\text{cm}$	$\epsilon_r 18.5\text{pF}$	$\epsilon_r 4.5\text{pF}$

Using these values in a simple capacitor divider network the results in Figure 51 show the expected coupling to the coaxial output port on the sensor. The larger sensor shows greater sensitivity, particularly when it is placed further away from the 'local' ground plane [48]

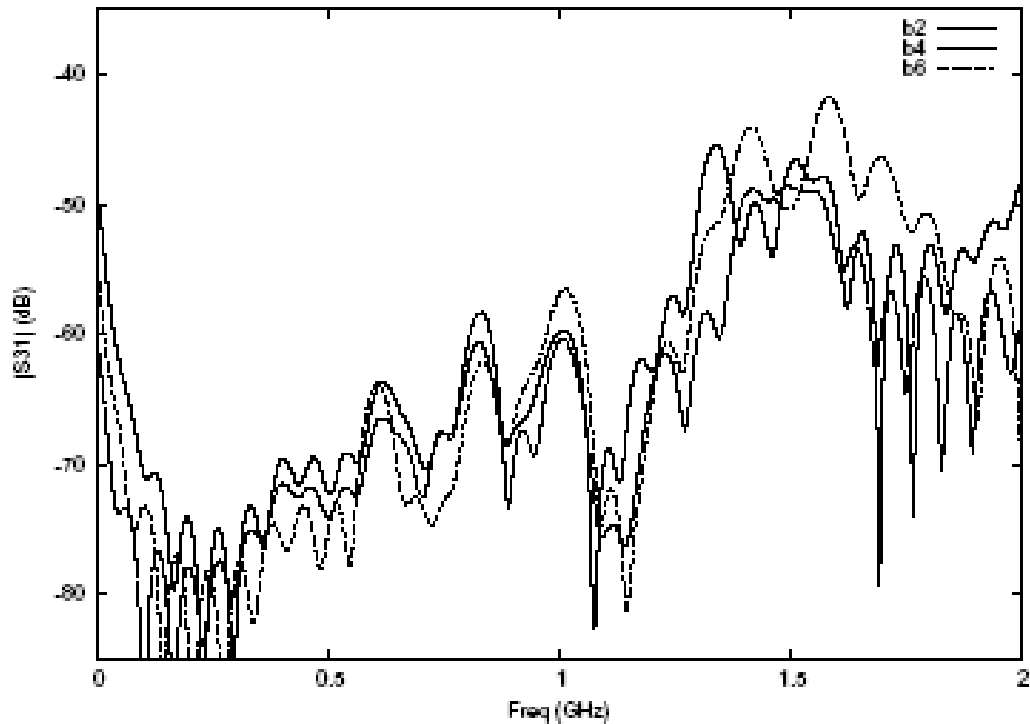


**Fig.51 Coupling to the output port from the “busbar” coaxial mode for the two-capacitor model**

### 4.3.3 FDTD Analysis of Sensor Position

A number of studies were carried out with circular sensor plates of radius 2, 4 and 6cm at various distances between the backing plate and the sensor. Fig.52 shows the response to the output port when the sensor plate is close to the ground plane at the coaxial sensor output. These responses did not match well with the predictions of the simple two-capacitor model. The relatively rapid variation with frequency were most likely to have been caused by the complicated multi-mode propagation, and the fact that various ‘resonances’ must be possible between the sensor plate and its surroundings. The influence of the size of the circular sensor plate was not that great [48]





**Fig. 52 PD Sensors of radius 2, 4 and 6cm, mounted 0.5cm from backing plate**

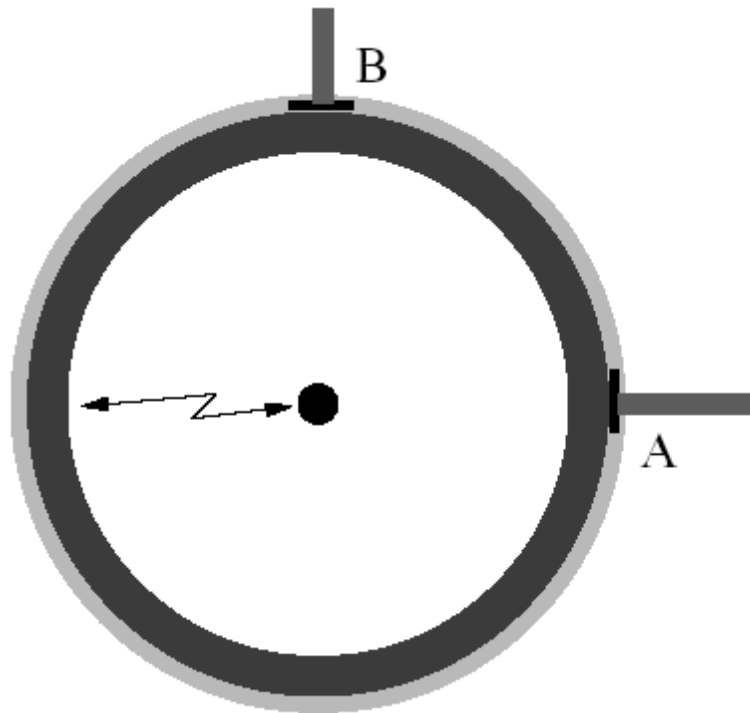
Further studies were carried out to determine the excitation from a coaxial sensor feed, connected to an infinite cylindrical tube which was filled with PTFE and then SF6. The model was used to study the influence of the length of the sensor from the junction with the coaxial cable. The responses showed that for with PTFE around the sensor for distances to the sensor between 1 and 20cm the signal propagated well above 1.5 GHz, the circular waveguide cut-off attenuating signal transmission at lower frequencies. For separations above 6cm there was considerable frequency dependence. The best sensitivity over the 500MHz – 1.5GHz band occurred with separations of 2/3cm [48] When the dielectric around the sensor was replaced with SF6 the better frequency responses were seen when using a slightly longer sensor. The longer section was required to produce the same electrical length between the junction and the sensor in comparison to the case where it was loaded with dielectric. The inclusion of a typical glass window of thickness 4mm and relative permittivity of 6 showed only a slight improvement in response.

#### 4.3.4 Study Results – Widow Transducers

Overall the studies showed that a major factor influencing the sensitivity of window sensors is the cut-off frequency of the circular wave-guide that forms the window. It would be difficult in practice to produce a sensor with the desired frequency range (500 – 1500MHz) bearing in mind the usual diameters of inspection windows in typical SF6 switchboards and the requirement to load the inspection window with a dielectric of relative permittivity greater than 11 [47]. Significant differences were observed between the simple capacitance coupling model and the full-wave FDTD model. The FDTD calculation included the propagation of higher order modes in the GIS chamber. This has shown that the position and polarisation of the PD event in the GIS chamber has a significant effect on the output from the sensor, particularly in the frequency response range 500MHz-1500MHz. Whilst the frequency content seen at the sensors was shown to depend on the position of the PD event, the effect on the magnitude of the envelope of the PD signal should be less noticeable [47]

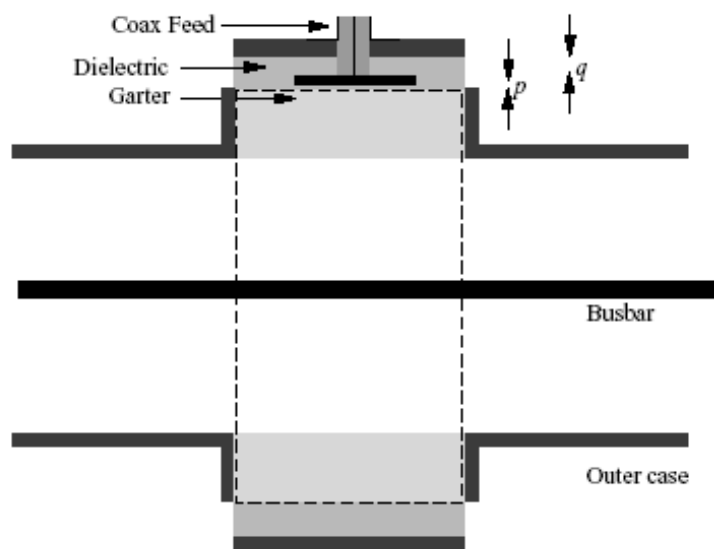
#### 4.3.5 Garter Transducers

Fig 49 shows the cross section of a garter transducer with circular disc sensors sitting at positions A and B with respect to the location of the PD event, on a 5cm wide PTFE flange with an assumed relative permittivity of 2.08.



**Fig. 49 Cross section of Garter Transducer**

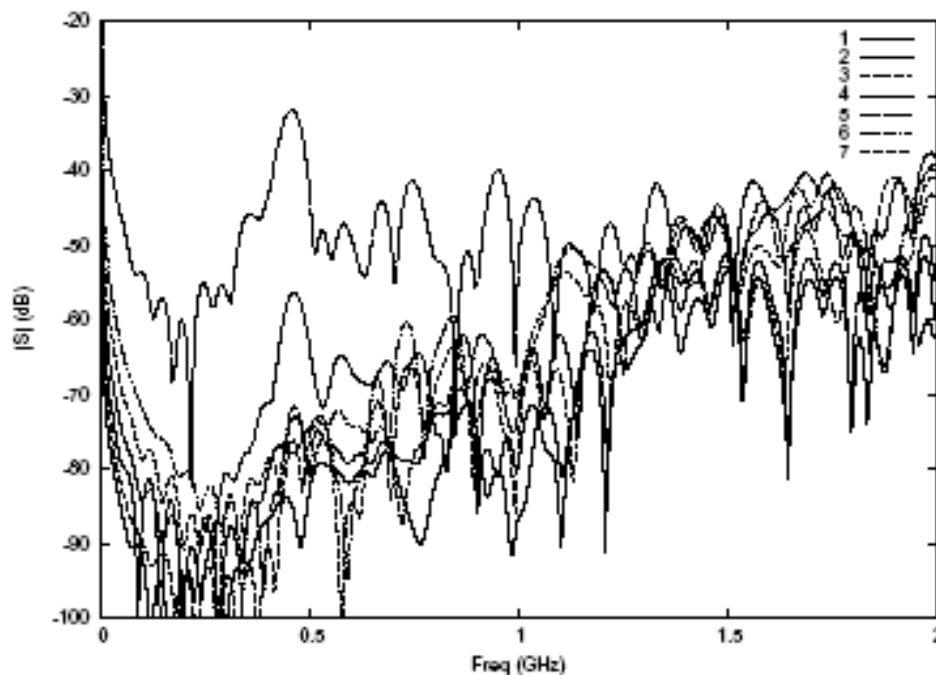
Various combinations of thickness of the disk and distance to the garter band were examined. In the example sensor shown in Figure 50 there was a  $3\text{mm}$  thick circular disk sitting at a distance  $p = 3\text{mm}$  away from the GIS chamber outer conductor, with a spacing of  $q = 4\text{mm}$  to the garter band. The total distance  $s$  between the garter band and the GIS chamber outer conductor was therefore  $1\text{cm}$ .



**Fig. 50 Disc sensor sitting on garter band**

Figure 51 shows the responses when the sensors were at position A, while Figure 52 shows the responses when the sensors were at position B. The greatest response was noted when the diameter of the disk was 5cm, the width of the flange. Wider disks had a greater capacitance to the outer conductor of the GIS chamber, while smaller had a lower capacitance to the central busbar.

The greatest response occurred when the disk was the same diameter as the width of the flange. The response at position A was generally much greater than at position B resulting in the location of the sensor being sensitive to the polarisation of the PD excitation. The 1cm disk was least sensitive to polarisation, as shown in Figure 53, but this is also the sensor that was least sensitive. This arrangement would not therefore provide a practical solution [47]



**Fig. 51 PD sensor response at position A with  $s$  between 1 and 7cm**

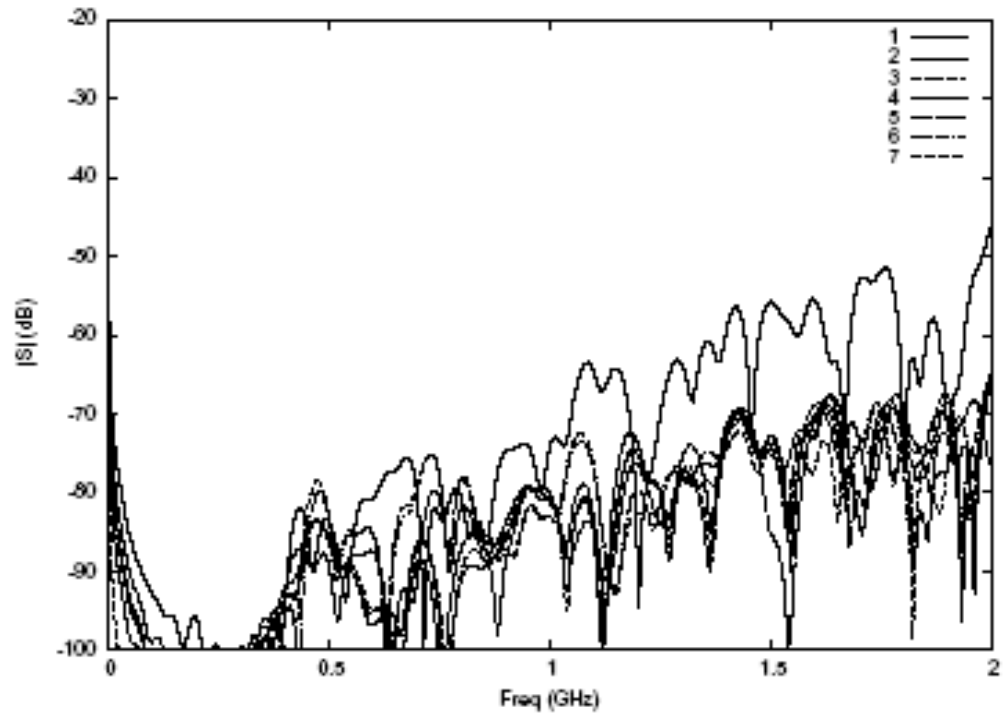


Fig. 52 PD sensor response at position B with  $s$  between 1 and 7cm

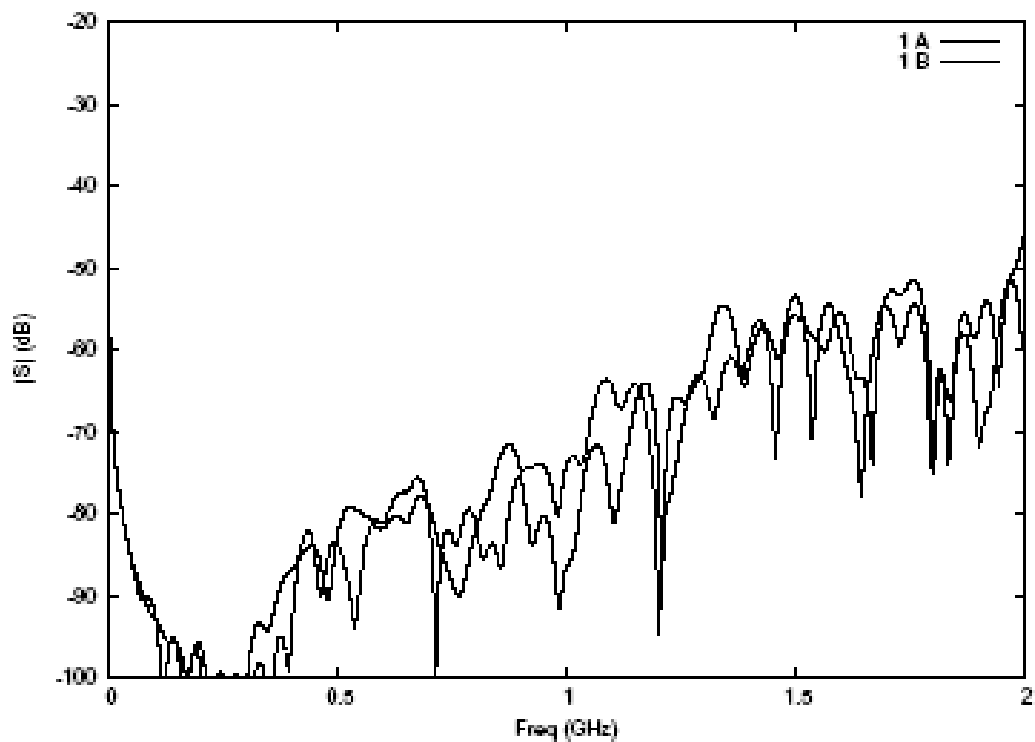
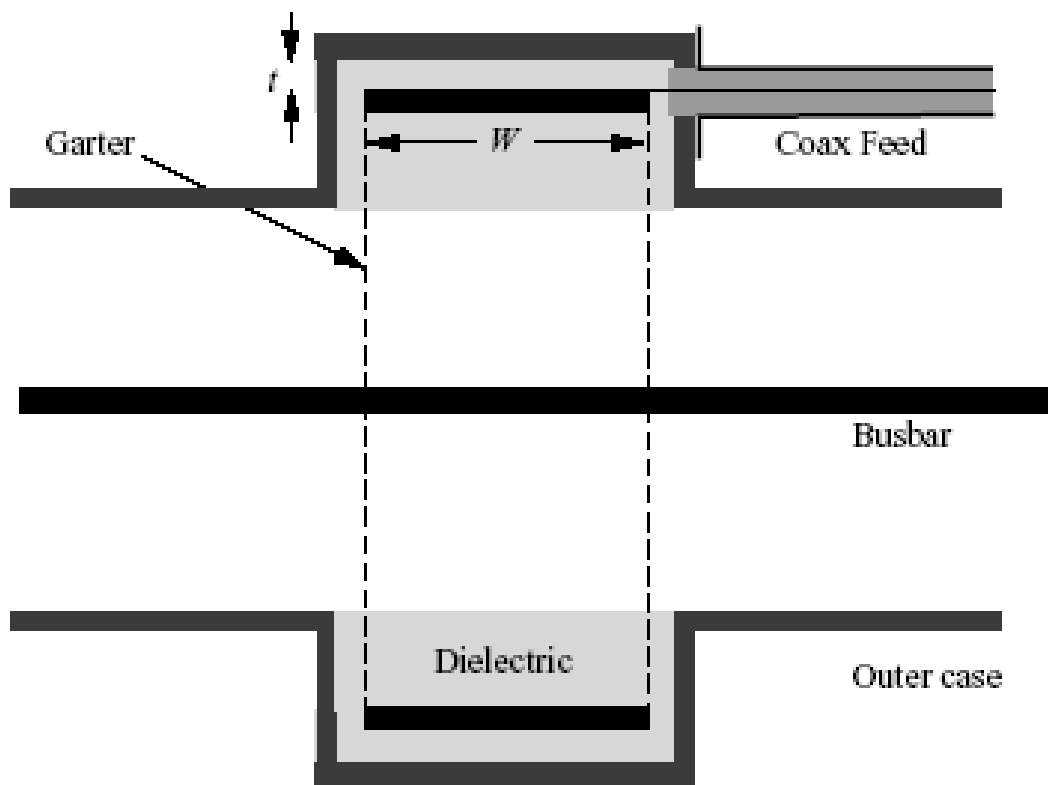


Fig. 53 PD sensor response,  $s = 1$ cm with 5cm wide flange, both outputs

Other garter transducer arrangements were modelled including a garter edge sensor, a side fed disc on the flange surface, a single split side fed garter using various garter widths both open and enclosed. Fig. 54 shows a configuration where the garter electrode was fed by a coaxial cable at the side of the garter. The center conductor of the coaxial cable extended onto the garter electrode, whose width was varied. The dielectric in the flange extended from the inner surface of the GIS chamber to the enclosing back conductor and was 7cm.



**Fig. 54 Enclosed flange PD sensor**

Fig.55 shows the responses for the garters of widths  $w=1\text{cm}$ ,  $w=2\text{cm}$ ,  $w=3\text{cm}$  and  $w=4\text{cm}$  when the separation between the garter and the backing conductor was  $t = 1\text{cm}$ . The wider garter generally gave the higher response, and in all cases the response fell at frequencies below 650MHz.[48]

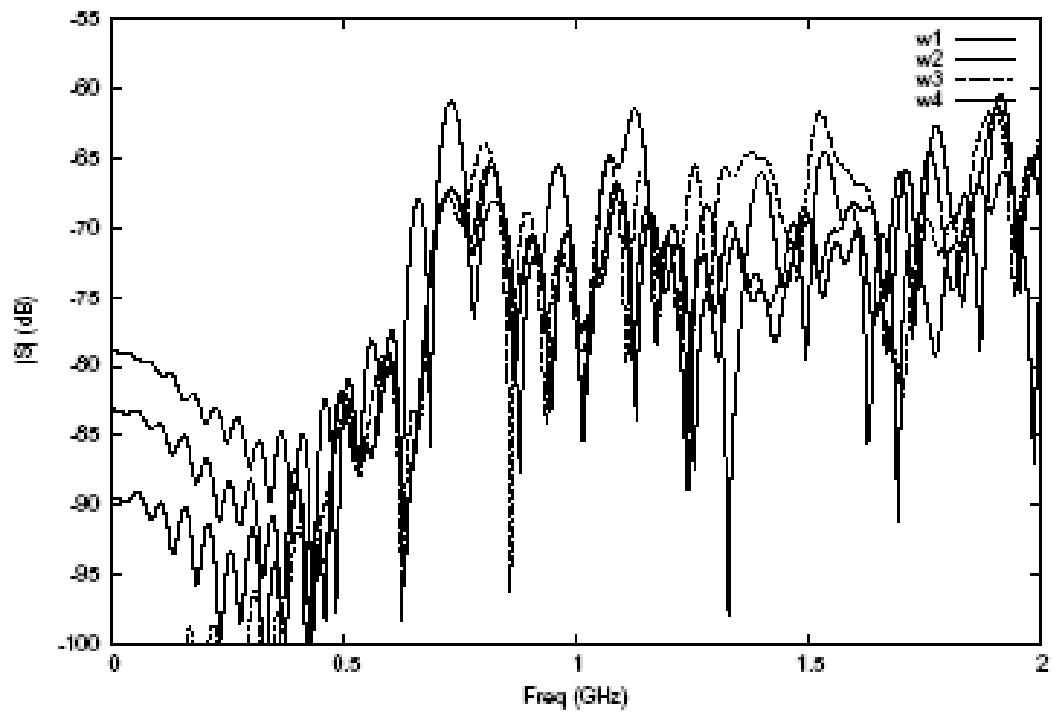


Fig. 55 Enclosed PD sensor response at position A for  $t = 1\text{cm}$

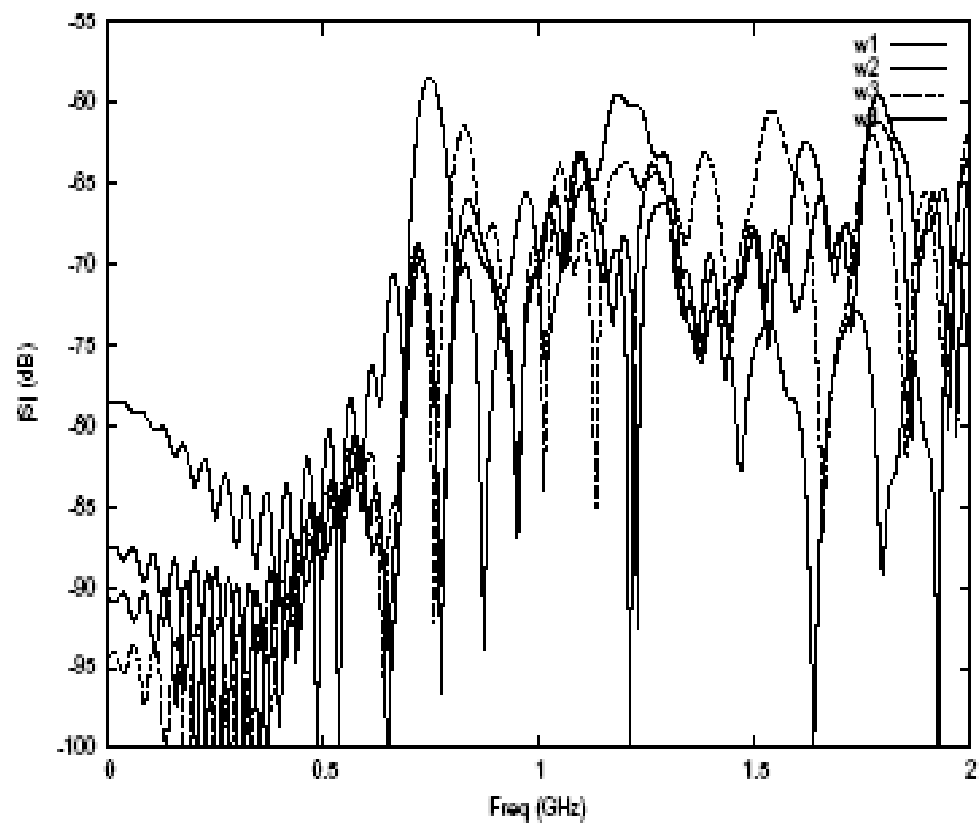
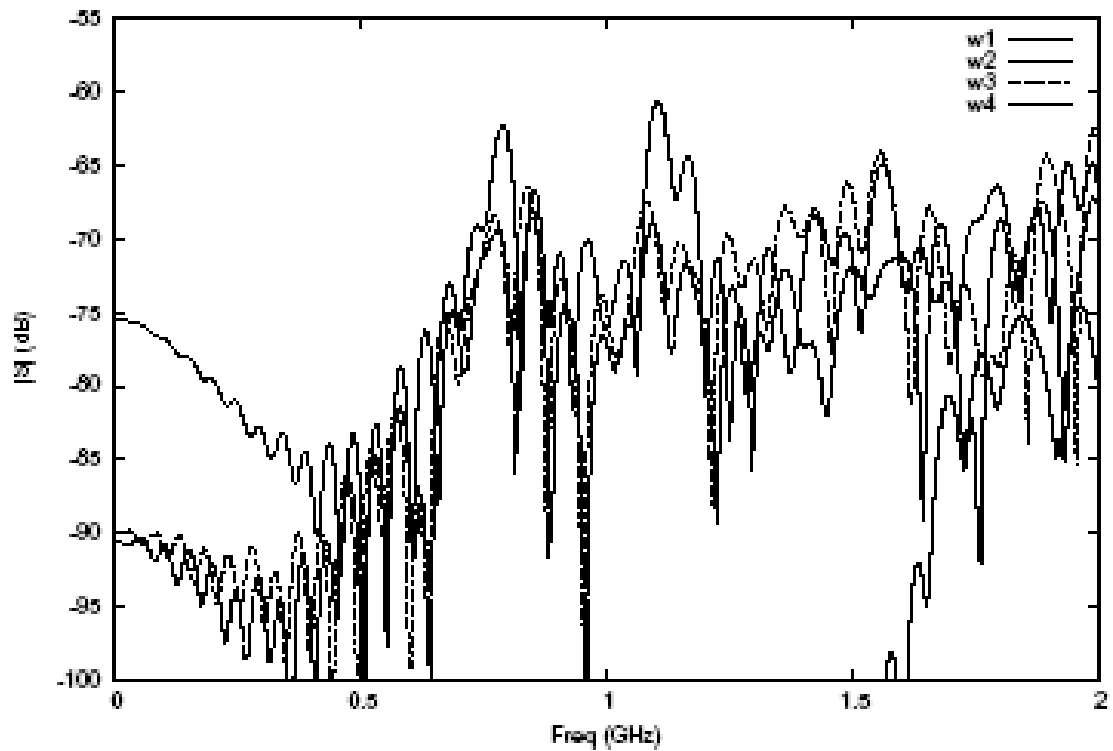


Fig. 56 Enclosed PD sensor response at position A for  $t = 2\text{cm}$

Figure 56 shows the responses for the case where the garter was 2cm from the backing, while Fig. 57 shows the responses when  $t = 0.6\text{cm}$ . The wider garters where  $w = 3\text{cm}$  and  $w = 4\text{cm}$  gave the greater response.[48]



**Fig. 57 Enclosed PD sensor response at position A for  $t = 0.6\text{cm}$**

#### 4.3.6 Study Results – Garter Transducers

The results of the FDTD studies indicated that the disk sensor with a backing garter resulted in a quite poor sensitivity and was dependent on the polarisation or direction of the PD event. The side fed disc with no backing garter was more sensitive but rather frequency and polarisation dependent. Better sensitivity was achieved with a side fed garter when the garter width was slightly wider than the flange. A practical application with this arrangement would be possible with careful choice of garter width and some compromise between sensitivity and frequency selectivity [47].



### 4.3.7 PD Sensor Interference and 50Hz reference studies

Further studies have been carried out at The University of Bath to investigate:

- Cross coupling between adjacent open-garter flange sensors on GIS chambers
- Interference induced in open-garter flange sensors by external RF sources in the vicinity of GIS chambers
- The sensitivity of garter sensors to 50Hz signals for synchronisation when there is a single busbar in the GIS chamber
- The sensitivity of broken garter sensors to 50Hz signals for synchronisation when there are a three phase busbars in the GIS chamber

The studies were based on FDTD analysis, equivalent circuit and radio link modelling. They were initiated to determine the response seen at sensors to PD activity within SF6 switchgear, 50Hz signals obtained from power conductors and externally generated RF signals.

### 4.3.8 Study Results – Sensor Interference and 50Hz reference

The studies showed that the flange mounted garter sensor is more sensitive to 50 Hz signals than the window mounted sensors. The 50Hz analysis of the garter transducer highlighted the potential hazard condition when the transducer is open circuit. Analysis has shown that the output voltage may exceed 550 V for a 33 kV application. Properly loaded with a typical instrumentation system, this reduces to 5 V. Both on health and safety considerations and the need to protect the transducer circuitry, the design should ensure that the garter transducer is shielded and permanently resistively loaded [48]

Further analysis revealed that the effects of fringe fields on the capacitance of the garter sensor structures are significant. The capacitance can be 34% to 100% greater than simplified mathematical predictions in the case of the non-

symmetric and partially enclosed parallel plate structures. The analysis did however show that a simple correction factor could be applied. Where the garter occupies a sector of the circumference of the GIS chamber, for example where the circumference is divided into three for three separate transducers, the effects of the fringe fields were predicted to have an even greater effect. In the cases where the garter opening angle lies between 60 and 120 degrees the correction factor is between 2 and 5. In the case where there are three busbars in the GIS chamber, the busbars are displaced from the central symmetric location. In this case the correction factor has been shown to vary between 4 and 6. [48]

The use of three garter sensors offers the opportunity to pick out the three individual phases in a tri-busbar configuration. The natural cancellation or balancing effect on a sensor reduced the voltage developed in normal operation. Loss of voltage on one busbar produced a very significant change in the sensor voltage. The voltage on each of the three sensors had a greater signal from the busbar closest to it, it consequently made the most sensitive measurement from that busbar. With three such transducers, the amplitude and phase for each of the busbar voltages could be identified. [48] The UHF performance of the tri-sensor configuration had similar characteristics to that of the single whole flange garter sensor. The multimode propagation that exists in the GIS chamber at these frequencies showed that the relationship between recorded PD voltages and the position of the PD event is complicated. This will require sophisticated signal processing to determine the position and characteristics of the PD event.[48]

The analysis of externally radiating signals between open garter sensors has shown that this can produce a similar response to the “intended” path through the GIS chamber. As such this could interfere with the proper operation of the flange mounted garter sensors, and produce a susceptibility to changes in the environment near the GIS equipment. Shielding the garter sensor would eliminate the problem.

The analysis of the response of the garter transducer to an external signal indicated that interfering devices that might typically be encountered, such as a mobile telephone or a radio transmitter which is fairly close by, could produce

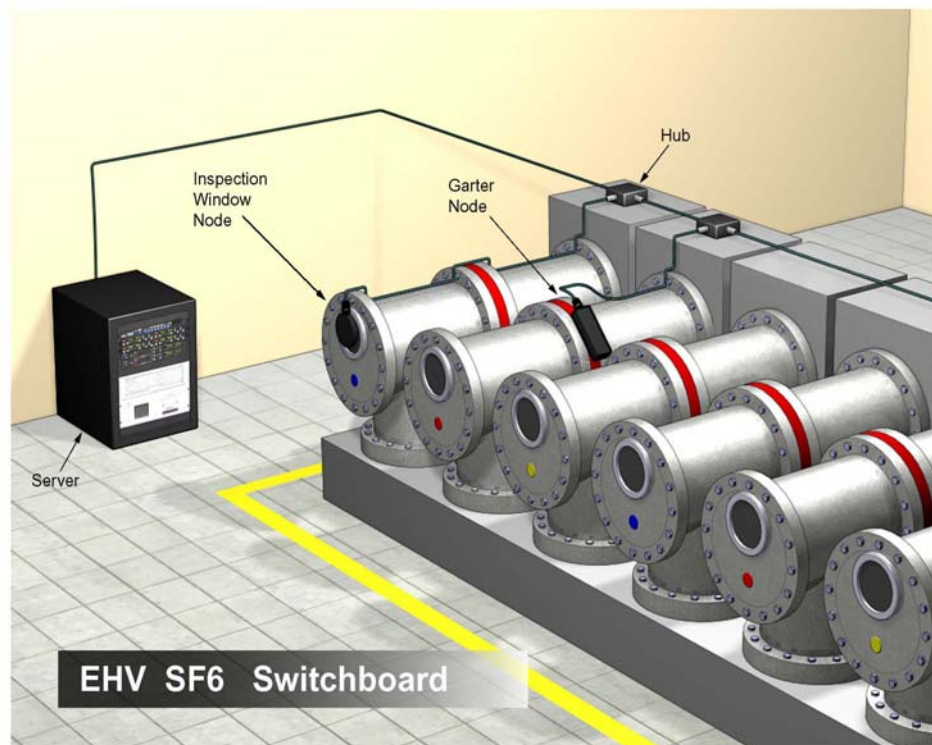
signal levels of the same order of magnitude as the envisaged PD signals in open flange mounted garter sensors. A practical solution would be to enclose the garter configuration to eliminate susceptibility to such interference. Overall the studies showed that the performance of garter transducers were superior to the window mounted units [48]

#### 4.4 System Operation

A UHF multi-node EHV partial discharge monitoring scheme should, ideally, be capable of detecting the amplitude, type, severity (number of pulses per second) and location to within 100mm of discharge activity within the SF6 switchgear. In order to identify the type of discharge source the discharge signals require a power system phase reference.

Three essential modules for an EHV system would be required:-

- PD Monitor Node
- PD Monitor Hub
- PD Monitor Server



**Fig. 58 Layout arrangement for Nodes, Hubs and Server**

A typical scheme suitable for retrofitting to, say, a 30 panel SF6 EHV switchboard would comprise garter sensors installed along the busbar at barrier joint positions some two to three meters apart, depending on the geometry of the gear, together with associated hubs and a server. The hubs would be connected in a daisy chain fashion.

The Node is a single channel probe/aerial interface unit designed for logging the magnitude, count and precedence of partial discharge signals. Since the PD activity within the switchgear would be sensed with a UHF envelope detector, the design and method of initiation of the precedence circuitry would require careful consideration if location accuracies of the order of 100mm are to be realised. Nodes would be connected to the Hub via communications and power cables. The Hub would pre-process the data received from the nodes and then pass a data packet to the Server.

The Hub would provide the central synchronisation of the Nodes as well as the data storage and processing and external communications interfacing. The unit would consist of a high speed PC linked via an RS232 port to the Hub that has an RS485 communications port, a 1kHz onboard clock and a data-processing/stripping function.

The Server suite would essentially control and interface with the Hub and the user and be menu driven. Menus would include installation, node set up, communications set up, alarms and reports, display diagnostics and administration. It would comprise software designed to operate on an IBM compatible PC, running with Windows or other platforms that allows access and control of the PD Monitor EHV via local serial access, Ethernet access, remote modem access and Internet interfacing. The software would include a facility, using pattern recognition techniques, to enable individual PD disturbances which have been resolved down to the nearest node, to also indicate the signature of the event. The software suite would allow the alarm threshold settings to be reconfigured and for data logging and download [51]

### **4.4.1 Functional Requirements**

The EHV PD Monitoring Scheme would comprise a number of Nodes attached to the switchgear to be monitored via one of three different types of coupling methods. The coupling methods are: internal sensor fitted at manufacture, window type sensor or a insulated garter type sensor. The preference for retrofitted schemes in the absence of internal sensors would be the garter type sensor. Each node would be required to detect measure and count the number of discharge pulses arriving at it's input, it will also establish the phase reference for it's sensor.

The system should provide the capability of monitoring a large number of partial discharge sites in a complete switchboard. The number of nodes would be limited mainly by 3 parameters: the addressing capability of the system, the time taken to download data from each node and finally the amount of memory available in the Hub. The Server system software should utilise the latest browser based graphical user interface, to facilitate simplicity of use and ease of integration with off-the-shelf packages such as Windows NT, Windows 2000, Internet Explorer, etc. [51]

## ***4.5 Arrangements for Demonstrations***

A 220kV metal clad test rig comprising three single bus-bar and two end cap sections together with a composite EHV bushing was made available in the Test Section at EA Technology Ltd. Chester.

The rig contains three small glass inspection windows, five insulated barrier joints (one gas tight), three bus-bar end caps and two gas injection nipples. Under normal operation the rig would be filled with SF<sub>6</sub> at a maximum pressure of 4 bar. Fig 59 shows a picture of the rig layout. Fig.60 shows a barrier joint and Fig. 61 shows a diagram of the test gear layout



**Fig. 59 EHV Test Rig**



**Fig. 60 Barrier Joint**

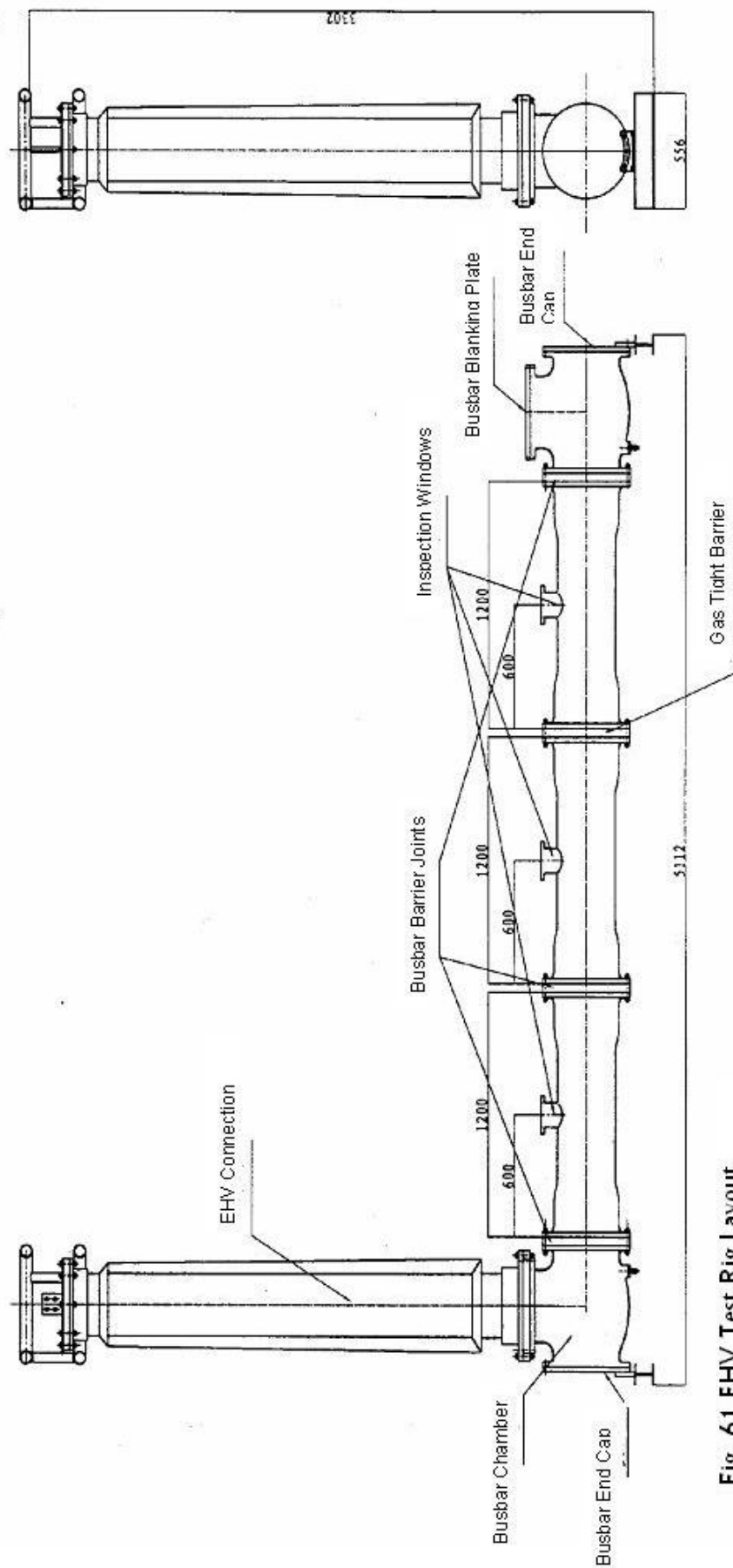


Fig. 61 EHV Test Rig Layout

## Chapter 5

# EVALUATION

### *5.1 Tests and Trials*

An EHV SF6 Test Rig made available by EA Technology Limited was used to test the various components required for a practical online PD detection scheme outlined in Chapter 4.

The author is a Non Executive Director serving on the Board of EA Technology Limited and operates as an independent Consultant. He was personally charged to work with the Team Leader on the technical and marketing aspects of the project to ensure the timely development of the PD detection scheme.

The author was personally involved with the development team in carrying out the tests listed below to verify the modelling work carried out at the University of Bath, together with making recommendations on the practical suitability of the components tested.

The intellectual property rights resulting from this experimental work are vested in EA Technology Limited to whom sincere appreciation is expressed for their permission to include the results in this chapter. Also special thanks to the Team Leader and members of the development team for their valuable contributions.

The full series of tests intended to be carried out included:

- Assessing the test rig frequency response (Transfer function)
- Determining garter sensor outputs using a spark gap mounted in the busbar chamber.
- Determining the energy content of the spark gap to enable the output from the sensors to be calibrated.
- Introducing typical types of discharge activity into the busbar chamber and detecting the outputs at the sensors.



- Building a prototype instrument and producing typical types of PD activity within the rig to confirm the functionality of the total scheme.

The above tests were arranged to be carried out with the test rig operating at normal atmospheric pressure and then pressurised initially with dry compressed air and, later with SF<sub>6</sub>, both at 4.0 bar.

## ***5.2 Results and explanations***

### **5.2.1 Test Rig frequency response**

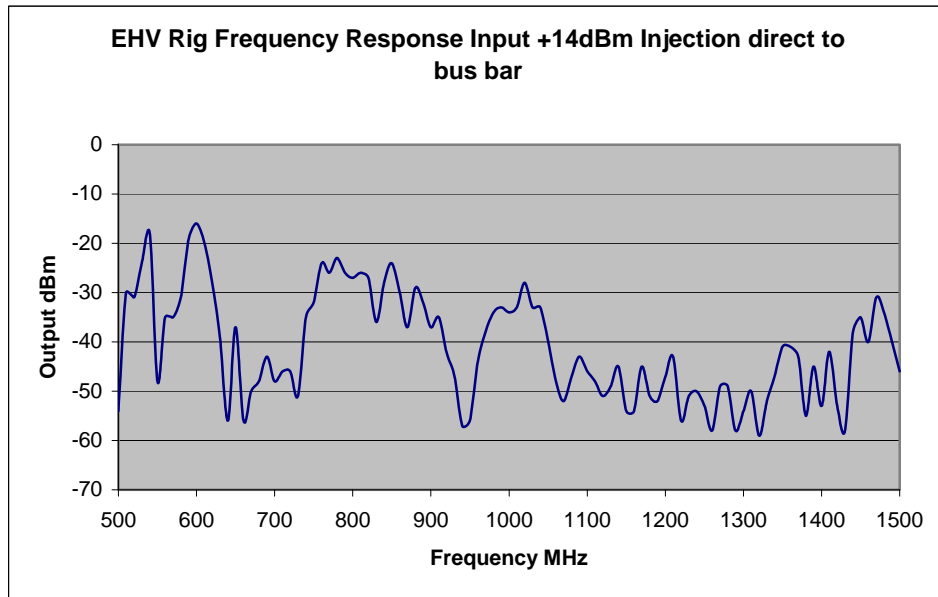
A side entry connected garter sensor was installed on an insulated flange on a section of the rig as shown in fig 62.



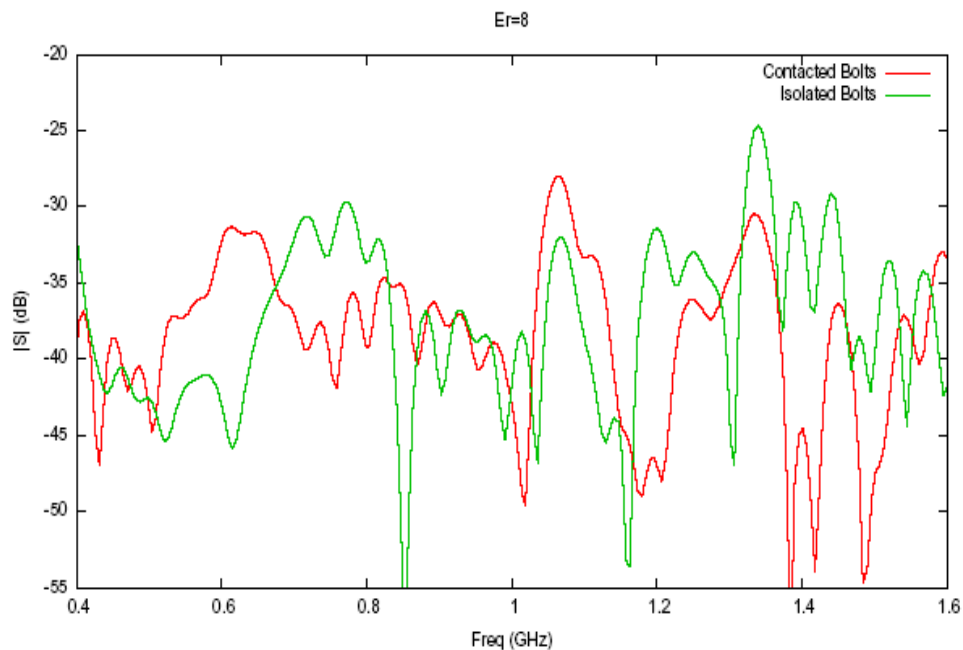
**Fig. 62 Ouput Garter Sensor Installed on Insulated Flange of Test Rig**

Fig. 63 shows the output from the sensor with the busbar being directly injected with a +14dBm sinusoidal wave form over the frequency range 500-1500 MHz.

The response was generally in the  $-30\text{dB}$  to  $-40\text{dB}$  range with deeper reductions over some frequency ranges. The result compared favourably with a simulation exercise carried out by the University of Bath. Fig. 64 shows their results for the spacer flange with a similar relative permittivity to those in the test rig with bolts both in contact with, and isolated from the flange. The effect of the bolt connections were not considered severe on the overall trend across the whole frequency range.



**Fig 63 Output from Garter Sensor**



**Fig. 64 Output from Sensor using Simulation Exercise**

### 5.2.2 Garter sensor outputs

With the test rig set up as shown in fig. 65 operating at normal atmospheric pressure, the spark gap device shown in fig 66 was installed directly into the busbar chamber and connected between the busbar and earth.



**Fig. 65 Input and Output Garter Sensors Installed on Test Rig**



**Fig. 66 Spark Gap Device Installed in Busbar Chamber**

The spark gap was set to flash over of 7kV ac RMS and thin band, side connected garter sensors with TNC connectors, one of which is shown in fig 67, used to detect the resulting output signals.



**Fig. 67 Thin Band, Side Connected Garter Sensor**

Fig. 68 shows the outputs from the two sensors. Channel 1 was closest to the spark gap, about one busbar section away (1.2m) and channel 2 was two sections away. The waveform separation between the outputs from each channel was 4.4ns with a clear indication that the pulse was received first by channel 1.

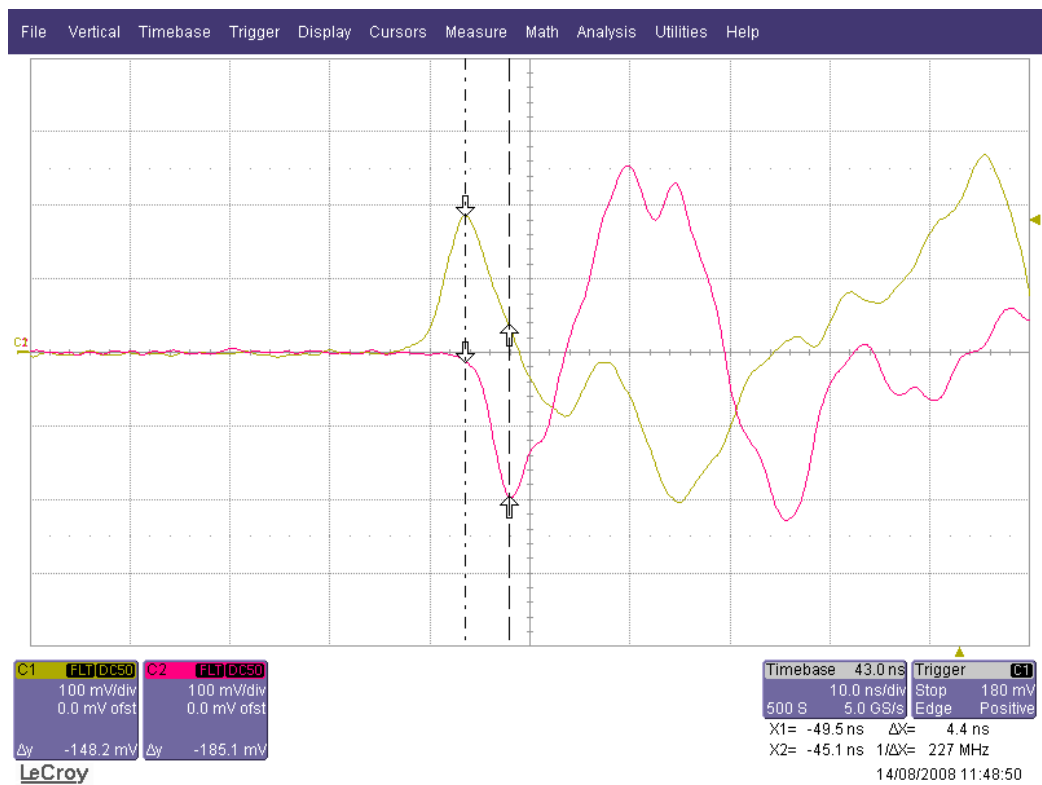


Fig. 68 Outputs from Garter Sensors

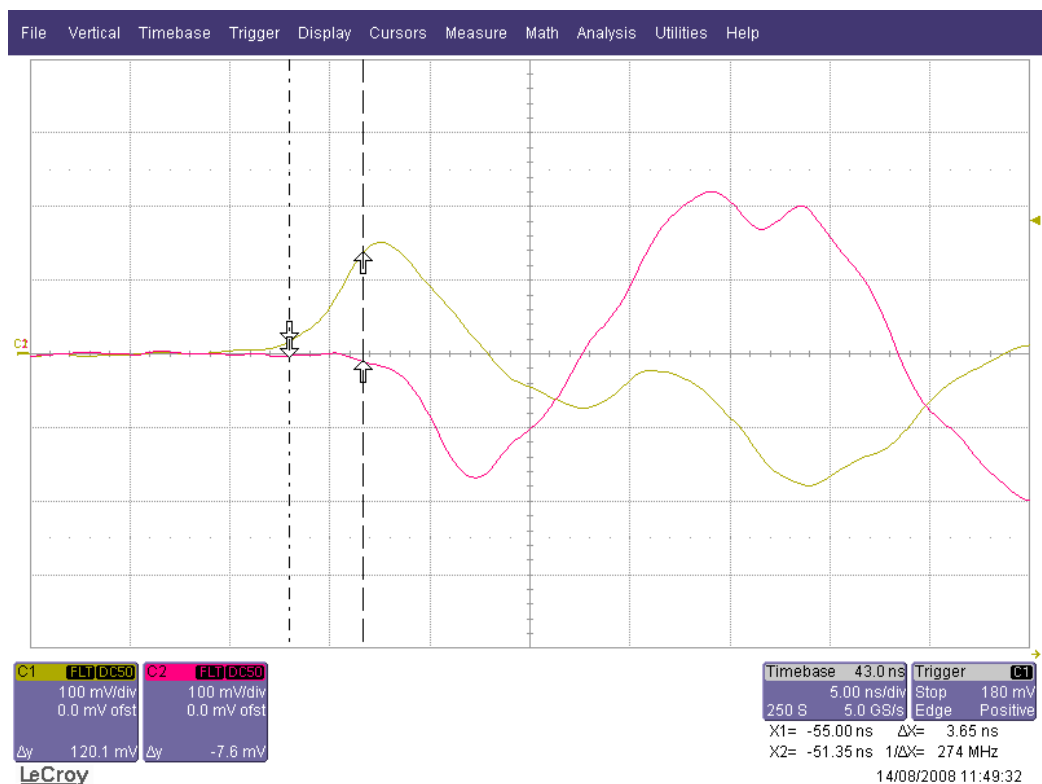


Fig. 69 RF Rise Time for Pulses on each Channel



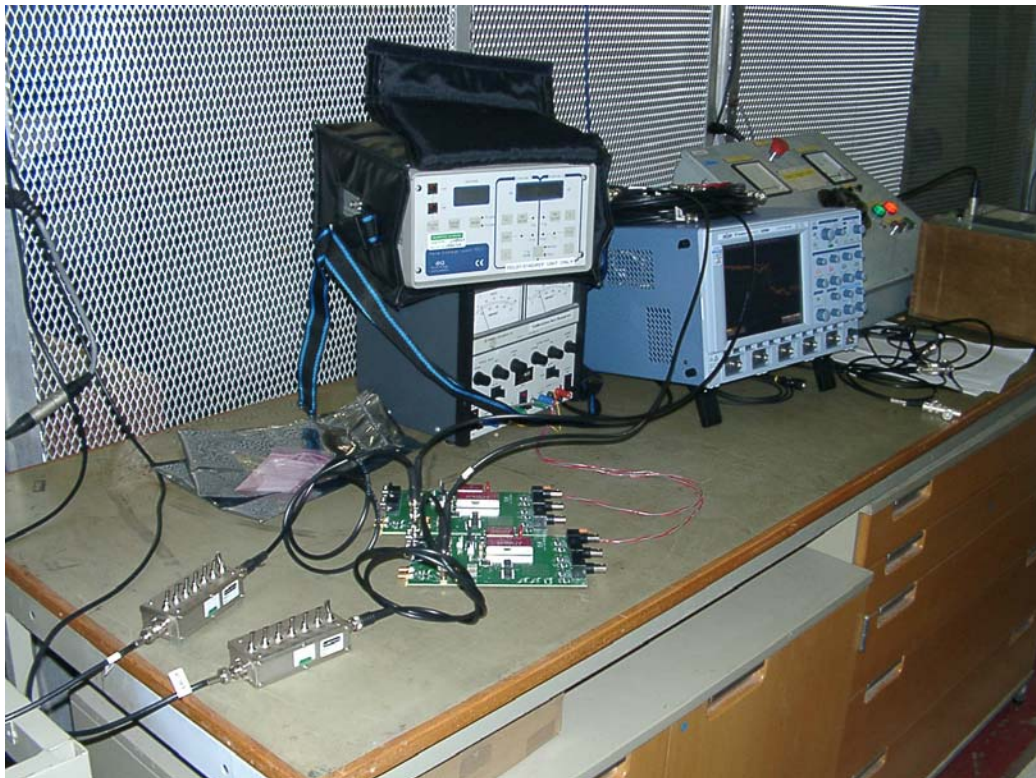
Fig 69 shows the rise for the first radio frequency (RF) discharge pulse on each channel. The time to reach 0.9 of peak was some 3.6ns, a very fast rise time.

### 5.2.3 Sensor Calibration

In order to determine the spark gap discharge level an online Robinson discharge set was connected to the test rig and the above tests repeated. The spark gap was adjusted to flash over at 7kV ac RMS and this resulted in a 3000PC discharge. The peak to peak level of the channels was 1.3v

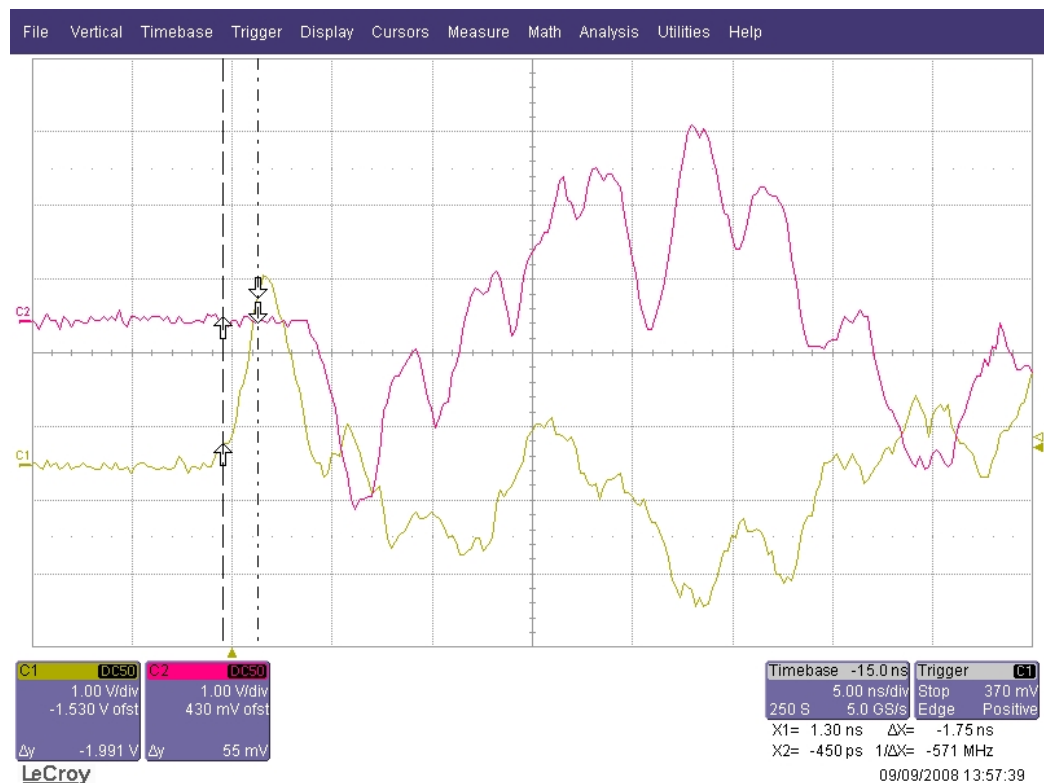
### 5.2.4 Garter Sensor Outputs – Pressurised Rig

With the test rig set up as shown in Fig. 65 the rig was pressurised at 4 bar with dry compressed air. The spark gap device shown in fig 66 was installed directly into the busbar chamber and connected between the busbar and earth. The distance between the spark gap contacts was the same as for the tests at atmospheric conditions, but now required 12.5kV ac RMS to flash over. The side band connected garter sensors used previously were used to detect the output signals.



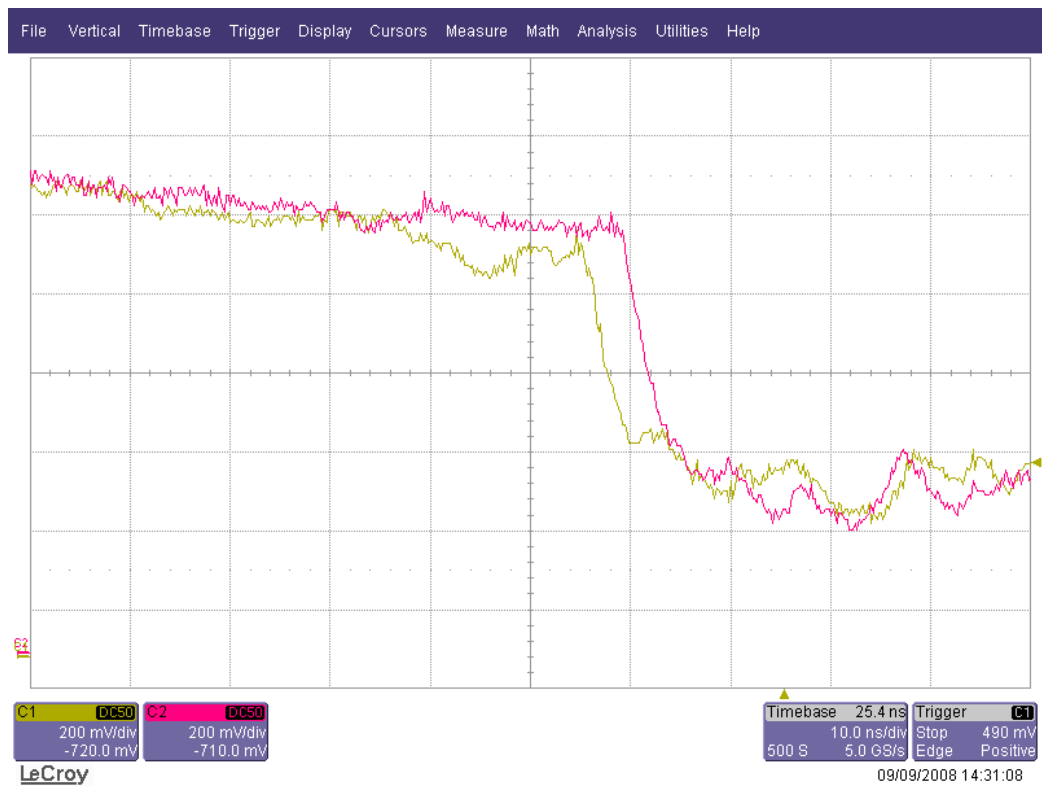
**Fig. 70 Amplifier boards and attenuators**

Fig. 70 shows the leads from the two sensors connected to the amplifier boards via switched attenuators set at 20 dB laid out on the test bench. The outputs from the amplifiers were fed on matched cables via dc blocking capacitors directly into a two channel PD instrument. The waveforms recorded from the sensor outputs are shown in Fig.71. The rise times for each channel were about 1.7 ns, clearly much faster than when the rig was operating at atmospheric pressure due to the changed permittivity of the air within the rig.

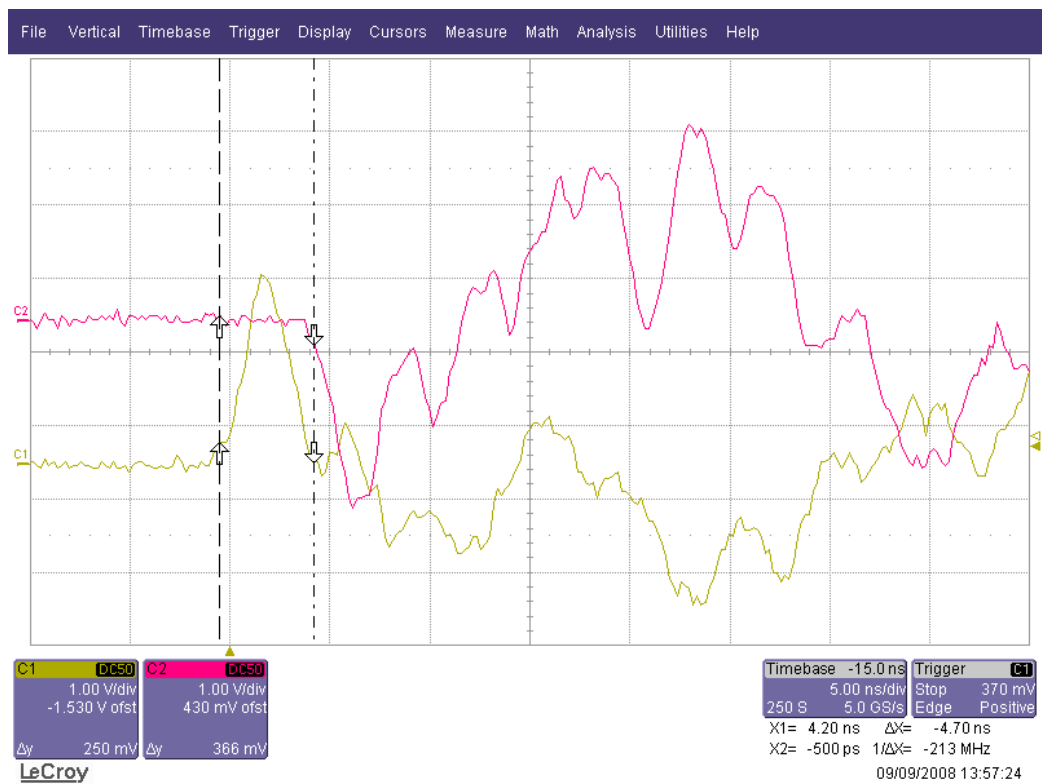


**Fig.71 Output pulse rise times from Garter Sensors – Pressurised Rig**

Fig. 72 shows output traces from the amplifiers fed from the two sensors . There was a 4ns time interval between the two. It was considered that with careful design it may be possible to use this fast speed of operation feature in a precedence detection circuit. The two channel PD instrument was able to detect the pulse from channel 1 before channel 2, adding confidence to this approach.



**Fig. 72 Amplifier outputs fed from two sensors**



**Fig. 73 Outputs from Garter Sensors – Pressurised Rig**



A further view of the output pulses from the two sensors are shown in Fig 73. The traces clearly show that although the rise time of each pulse has significantly increased the delay between the two of some 4.7 is the same for the atmospheric and pressurised tests and would permit the approach mentioned earlier to precedence detection. The delay equates reasonably to the physical separation of the two sensors at 1.2m.

### **5.2.5 Further Tests**

The remaining tests outlined at the beginning of this chapter are expected to be carried out over the next few months. These will require the production of a prototype instrument and bespoke software package capable of recognising the various types of PD activity likely to be encountered in SF6 EHV switchgear. The initial tests demonstrate quite conclusively that the design of the basic components enable them to operate well together as a functional non-intrusive PD detection scheme.

## **5.3 *Assessment and comments***

The test rig provided an excellent facility to enable practical live tests relating to the FDTD studies carried out by the University of Bath together with a whole range of systems components to be examined.

The initial test on the de-energised rig to determine the transfer function of the set up provided a graph showing the frequency response between two adjacent sensors used as inputs and output sources. A simulation exercise carried out by the University of Bath using similar parameters produced a similar trace and was largely as expected. The frequency spread was 500-1500 MHz, this being the most likely range over which PD sources are expected to produce their maximum energy.

The energised test rig results using the spark gap provided vital information on the effectiveness and sensitivity of side connected garter sensors. The tests

demonstrated that it was quite feasible to determine which sensor was closest to the PD source. With a typical EHV switchboard it would be unlikely for busbar sections to be less than 1.5m long enabling the PD source to be located to a particular section.

The very fast rise time of the initial RF pulse from a PD source, some 1.7ns for pressurised gear would, using fast comparators, enable this to be used to measure precedence quite accurately between adjacent sensors. More work is required to refine this feature, it would need to be used in conjunction with an automatic level detector set at just above the noise floor of the installation

The calibration test provided important information on the sensitivity of the garter sensors referencing the magnitude of the pc discharge to the peak value of the sensor outputs.

Experience will need to be gained on the PC discharge levels in switchgear which will merit generating an alarm. It is suggested that levels very much lower than 3000pc, probably in the range 20/30pc would be used to trigger an alarm. This points to the necessity to have a UHV amplifier with envelope detector associated with each sensor. In addition to using the detector to measure the peak value of the PD activity it may be possible to determine the energy released from the PD source by measuring the area under the output curve. The final tests are planned to be carried out with the rig pressurised with SF<sub>6</sub> but since there is little difference between the permittivity of compressed air and SF<sub>6</sub>, no surprises are expected.

## Chapter 6

# SUMMARY, CONCLUSIONS AND FUTURE WORK

### 6.1 *Summary*

Partial discharge is the most prominent indicator of electrical insulation degradation. The principal methods of detection and location using electrical and acoustic methods have been researched for both HV and EHV plant and their relative merits assessed.

The focus of the research has concentrated on gaining an in depth appreciation of partial discharge phenomenon in the components which make up switchgear. This has enabled the development of ideas for a commercially viable scheme capable of detecting the electromagnetic waves generated when a PD source is active. Finite Difference Time Domain modelling of the switchgear environment and various components required for a scheme together with their compatibility and susceptibility to external interference have been studied.

The results from FDTD studies used in combination with theoretical analysis and an extensive literature search have enabled a conceptual design to be outlined for a non-intrusive PD scheme suitable for retro fitting to a wide variety of EHV SF6 switchgear. An SF6 EHV test rig has been used to run tests on various components to correlate theoretical with practical results.

The FDTD studies have proved to be a very powerful technique to enable a wide understanding of the behaviour of partial discharge activity in switchgear and the methods of sensing and identifying the resulting UHF waveforms.

## **6.2 *Core Research Findings***

### **6.2.1 MV Equipment**

The history and development of PD testing on MV switchgear together with the techniques and range of instruments available has been outlined.

PD surveys on MV gear are normally carried out using hand held instruments which detect electromagnetic (EM) or ultrasonic disturbances and give an instantaneous reading of their amplitudes and number of pulses over, typically, a two second period. The transient earth voltage technique (TEV) is fully detailed and the principles, including high frequency skin effects and wave-guide cut off effects are explained. Simpler instruments provide only a visual indication of the state of the equipment – essentially a “go/no go” test. When PD activity is suspected or detected instruments are available to carry out short term monitoring on the effected switchboards. The results are stored, usually, on a compact flash memory card and they may be analysed using bespoke software. Hand held instruments that are specifically designed to detect lower frequencies in the ultrasonic range (20-40 kHz) are also used to compliment the EM tests.

Fixed PD alarm monitoring schemes using TEV principles are presently being developed for application to older installations in order to constantly assess their integrity.

### **6.2.2 EHV Equipment**

Present approaches and technologies used to detect PD activity on EHV switchgear have been researched. The two basic technologies used in assessing the condition of GIS in service are high frequency electromagnetic wave detection and lower frequency ultrasonic pulse detection, from the PD activity. The EM wave detection method is considered to be the primary method of detection.

Both of the above approaches have been studied and the relative merits of schemes using each have been discussed. New installations may be offered with a UHF permanent monitoring scheme or be equipped with internal sensors, ready for later use. In general schemes provide only limited information on the nature and actual location of the PD source. More work to refine the outputs from such schemes is required

Retrofitted schemes normally rely on external ring antennas or inspection window sensors. Schemes have been developed which use narrowband and broadband detectors placed at suitable positions along the switchboard. The design of such sensors and analysis of the waveforms there from has formed a critical part of this work.

Acoustic methods for detecting PD activity have been studied in depth and fully outlined. Besides emitting electrical signals, partial discharge activity also produces ultrasonic signals. The detection and analysis of acoustic waves generated by PD sources can be extremely complex. The acoustic wave may be distorted by a variety of factors including division due to multiple pathways, transmission losses in different media and at their interfaces and frequency dependent velocity effects. Generally, such ultrasonic signals undergo a much stronger attenuation than the UHF signals. Especially, ultrasonic detection of partial discharge activity of embedded voids (spherical gas cavities) in epoxy resin material is hampered by this attenuation. Additionally, the sensitivity strongly depends on the position of the sensor. However, detecting ultrasonic signals on gas-insulated equipment can be performed on-line, does not involve any modification of the GIS, and is comparatively easy to apply, though the results, particularly the characterization of the waveform, often require analysis by an expert.

### **6.2.3 Circuit Modelling and Test Rig Facilities**

In order to fully understand the characteristics and interactions of the various components that form part of a continuous PD monitoring scheme, modelling

using finite difference time domain (FDTD) techniques proved to be a reliable and powerful tool. A considerable number of studies were carried out at the University of Bath to determine the characteristics of different antennas with a range of connection arrangements in order to select the most suitable sensors for use in a retrofit scheme. The likely influence of external noise in various frequency bands on the overall sensitivity of PD detection together with methods of providing phase reference, to enable PD signatures to be established, was also studied.

The EHV SF6 test rig facility made available by EA Technology was invaluable for carrying out practical confirmatory tests on a whole range of components that would form part of a PD scheme. Tests on this rig were essential in order to verify the modelling and provide a facility for future modifications to scheme components in the light of on site experience.

#### **6.2.4 Switchgear Survey**

A survey of the different types of plant on Network Operators systems in England has been carried out in order to determine their suitability for the application of PD schemes. Switchgear replacement and new schemes included in the survey provided very useful information on the trends to replace older oil and air blast technology with SF6 indoor and outdoor equipment. Failure statistics highlighted the types of gear most likely to benefit from a retrofitted PD scheme.

### ***6.3 Contribution to the Electricity Industry***

There are large quantities of both MV and EHV switchboards in use on distribution and transmission systems around the world. Much of the plant is at least 30 years old and carries substantial loads, often to highly sensitive geographical areas. Over the years fault current levels have tended to rise and if a particular piece of plant fails during service the effects on the overall operation

of the network can be catastrophic. In addition both company staff and the public may be subjected to a hazardous situation and the costs of repair or replacement can be enormous and the outage times very protracted. Companies usually face financial penalties for lengthy supply interruptions.

Partial discharge activity in electrical plant that is not detected and remedial action taken is the most likely cause of catastrophic failure. MV switchboards provide the backbone of most distribution systems around the world. Their integrity may be readily checked with the range of hand held and monitoring instruments now available and listed in this thesis, the majority of which enable non-intrusive detection.

PD detection on EHV switchboards is more complex, but for all the reasons mentioned above is compelling and prudent. Indeed failures on EHV plant usually results in very large numbers of customers suffering loss of supply for long periods. The costs to commercial and industrial customers, particularly those operating continuous process plants, can be enormous and the economic consequences dire.

This thesis outlines the nature of PD activity and the fundamental principles associated with its detection. Since the privatisation of the UK electricity industry in the early seventies, companies have sought to “sweat” their assets in order to maximise the utilisation of all plant on their systems and defer capital expenditure. In order to achieve this safely it is imperative that arrangements are implemented to determine the condition of all plant and cables. Asset management should now form an integral part of company’s business plans, partial discharge detection provides a fundamental input to this process.

## **6.4 *Future Work***

### **6.4.1 Technological Advances and Understanding the Economic Consequences**

Technological advances in the fields of computing and communications continue apace and will have a dramatic impact on the level of integration that can be achieved in the monitoring of complex systems like the power transmission network. Software techniques and intelligent system paradigms required to implement sophisticated integrated condition monitoring schemes are in existence. The hardware costs associated with advanced monitoring techniques such as UHF PD detection are decreasing rapidly due to developments in low cost data-storage devices and the technological advances driven by mobile telephony operating in the UHF band. Bringing them together into a fully integrated condition monitoring system will result in the more effective operation of electrical energy systems.

A challenge currently being addressed is how our understanding of the economic consequences and impact on plant lifetime of the monitored parameters can be improved. Experience and records of historical data are vital inputs to this process. A comprehensive monitoring framework can therefore be regarded as a prerequisite if effective interpretation is to be achieved.

### **6.4.2 PD Pattern Recognition**

Reliable PD pattern identification is very difficult to achieve and in many schemes relies on the use of Artificial Neural Networks (ANN). The consistency of such schemes has not really been fully demonstrated, they certainly demand a considerable amount of experimental work and programming. Various experimental conditions need to be simulated, not just various PD types (in GIS, protrusions on the busbar; floating particles; voids within spacers etc.), but also various voltages, and time effects. PD is stochastic, it may vary between being active and quiet, and the way in which PD activity develops is also complicated.



For example. PD within a void may be self extinguished due to the PD-related pressure increase inside the encompassed void. More work on these aspects is required.

An alternative approach to pattern recognition using PD Classifier software may provide a less complicated but viable option. With this approach each captured cycle is divided into phase windows and each window characterized using parameters such as magnitude, pulse count, severity etc. The results would be displayed as bar graphs for each type of PD activity detected together with their probability. Work on this approach is at an early stage, for meaningful, repeatable results it would be necessary to sample large quantities of actual data from site.

### **6.4.3 Precedence Detection**

PD schemes connected to EHV switchboards should ideally be able to locate the source of the activity to within a maximum of 0.5m. The method of location usually involves measuring the time of flight of the electromagnetic waves, travelling in the insulating medium, between adjacent nodes.

PD events are expected to produce their maximum energy in a broad band, covering 0.5 to 1.5 GHz. Sensors are invariably fitted with an amplifier and envelope detector to cover the above frequency range. Due to the geometry of typical EHV switchboards the output from the envelope detector will consist of complicated waveforms containing both the initial effects from the PD pulse, plus multiple reflections from within the gear. This makes choosing an amplitude trigger point and a reliable point on the waveform to start timing, very difficult. Use of the RF portion of the first PD pulse for timing purposes looks very promising, more modelling work on these aspects is required.

#### **6.4.4 Functional PD Scheme**

The specific additional tests outlined in 5.2.5 need to be carried out in order to complete the full testing programme for the practical online PD detection scheme outlined in chapter 4.

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## APPENDIX

Technical Papers published in the period leading up to and during this research work.

- Cost effective Asset Management for Electricity Companies by Peter Jones and **Graham Dennis**. Presented at 12 CEPSI 1998 Pattaya, Thailand.
- Asset Management Data Collection and Decision Support by **Graham Dennis** and Mike Lees. Presented at CEPSI 2000 Manila, Philippines.
- The Evolution of Non-Intrusive Partial Discharge Testing of MV and EHV Switchgear by **Graham Dennis**, Miles Redfern and Steve Pennock. Presented at CEPSI 2004 Shanghai, China.
- The Development of Non-Intrusive Techniques for Partial Discharge Detection on MV and EHV Switchgear by **Graham Dennis**, Miles Redfern and Steve Pennock. Presented at UPEC 2006 Newcastle UK.
- Condition Based Risk Management (CBRM ) by **Graham Dennis**. Presented at CIRED Asia 2006 Petaling Jaya, Malaysia

## **COST EFFECTIVE ASSET MANAGEMENT FOR ELECTRICITY COMPANIES**

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### **Abstract**

*In many countries of the world, electricity companies have recognised the importance of asset management as a key business driver. The planning, procurement and maintenance of assets is becoming a vital differentiator, with effective asset management having a profound impact on shareholder value, regulatory perception and customer service. Many electricity companies have made a significant investment in collecting and collating relevant data associated with their existing assets. In common with any IT system, the investment in the creation of the data will only be of value if the information is accurate, up to date, complete and accessible, so that the knowledge inherent in the system can be used to enhance decision making and business performance.*

*Effective asset management is critically dependent upon the following key elements:*

- *A clear and well formulated policy with the Asset Owners and Operators adopting a strategy to ensure the optimum balance across a number of business drivers including improving share,older value and enhanced customer service.*
- *Objective, accurate and relevant information regarding the condition of key assets.*
- *Techniques for the collection of data in a timely and cost effective manner.*
- *Powerful software tools for the modelling of the business to enable decisions concerning assets to be made quickly and with a real understanding of the risks involved.*

*This paper will review key issues and highlight practical and cost effective solutions. A range of tools, techniques and methodologies will be described which can enhance decision making and improve business performance.*

### **1 POLICY AND STRATEGY FORMULATION**

The rapidly changing business climate around the world has meant that the senior managers in the electricity sector have to manage their assets with differing business drivers. The objectives are now much more to do with managing risk and customer expectations and meeting regulatory requirements in a fast changing world. The development of strategy in these fields is thus the optimisation of several business options set against a number of key electricity industry criteria, whose weights can change both rapidly and significantly depending on political, regulatory and financial circumstances (including mergers and take-overs).

The importance of being able to assess options and evaluate the sensitivity to major business drivers cannot be over stressed. Complex and often conflicting requirements must be assessed with the optimum policy being adopted to achieve strategic business objectives. These objectives will vary from company to company with each organisation attempting to gain competitive advantage based upon different business drivers.



The relationships between cost, risk and benefit for a wide range of investment options and the variables that surround them can be weighed and judged by teams of managers and experts with the help of experienced facilitators and sophisticated computer software.

The impact of changes in risk profiles, investment levels and even organisational culture can be accommodated and rapidly built into a strategy decision model.

### **1.1 An Approach to Policy and Strategy Formulation**

To ensure success in the formulation of an asset management strategy a number of key elements have been adopted:-

- Definition of the scope and assimilation of current business strategies and decision making processes
- Team review of organisational Strengths, Weaknesses, Opportunities and Threats
- Definition of the status quo for asset management area by area
- Development of a team view of the overall vision for the long term future of the organisation in relation to asset management
- Establishment of a strategy decision model involving agreement on the structural elements and development of decision criteria
- Assessment of the implications for different investment levels in each element of the business and the range of creative options available. A team consensus can be reached by scoring the different benefit scales
- Creation of weighting factors to relate the importance of the different elements one to another and the relative significance of the different benefit criteria
- Production of computer generated graphics to illustrate the optimal solution for each element and the combined risk return curve for the resulting strategy
- Testing of the resulting strategy by applying various sensitivities including different levels of overall resource availability
- Firm conclusions as to the optimum asset management strategy for maximum benefit for any particular level of expenditure or resource

## **2 ASSET CONDITION ASSESSMENT**

Having an accurate and relevant record of asset condition is of fundamental importance to any effective asset management programme.

Many companies have information and records of data associated with asset age, maintenance history etc. However to be of real value any data-base must also contain information regarding current asset condition so that important decisions can be made regarding asset replacement, refurbishment or retention and for effective condition based maintenance programmes.

Condition monitoring and assessment and diagnostic testing all provide information concerning the "state of health" of a network asset. In general, the information can provide a measure of the integrity of specific components, parameters or capabilities of the asset. Where measurements are involved they are usually viewed against some benchmark level e.g. the manufacturer's original specification or other predetermined level of acceptability. Condition assessment of an asset is generally a "one-off" activity aimed at providing information

to assist the decision making process. It may or may not include diagnostic testing. Condition monitoring is an ongoing process that measures certain parameters against a benchmark and looks for significant changes and trends. Condition monitoring may form part of a preventative maintenance strategy. Both condition monitoring and condition assessment can therefore include diagnostic testing.

Condition assessment techniques are seen as providing key information for both the operational management and safety management of network assets. In addition condition assessment information can provide a valuable input to the financial decisions that are associated with asset replacement, retention and refurbishment.

### **3 ASSET CONDITION ASSESSMENT TECHNIQUES**

Objective information regarding the condition of key network assets is of fundamental importance to determine:

- priorities for capital investment
- asset life prediction
- safety and reliability issues
- enhanced customer service/reduced customer minutes lost
- targeted maintenance requirements
- enhanced network operation

An extremely wide range of techniques are available to determine asset condition. Many of the techniques use non-invasive technologies (e.g. partial discharge measurement, ultrasonic measurement, oil sampling etc.) to enable important operation criteria to be measured without disrupting supply.

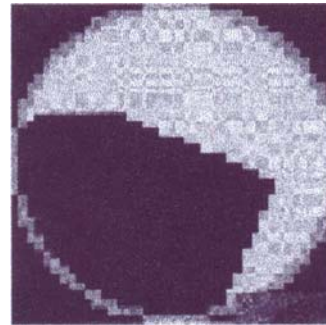
The information gained from detailed analytical and forensic examination, provides invaluable insight regarding the safe and reliable operation of other assets of the same type. This is of particular importance in predicting residual asset life.

#### **3.1 Overhead Lines**

Large sums of money are spent annually on the maintenance, refurbishment and rebuilding of overhead lines in order to maintain a safe and reliable system. To optimise these activities, it is vital to have information on the condition of components that make up an overhead line. Assessments of tower foundations, tower paint work, fittings, conductors and wood poles (Figure 1 Pole Rot Assessment ) all provide vital condition information. Use of some or all of these techniques can make a major contribution to undertaking a refurbishment scheme or when developing strategic policies for the management of either wood pole or tower lines.



Method of Location



Computer Model of Rot Cross Section

Figure 1 Method of Rot Location and Computer Generated Representation

### 3.2 Cables and Accessories

Underground cable networks represent massive capital investments.

The areas of assessment include:

- Examination of cables and accessories recovered from service in order to establish cause of failures and likely future performance
- Cable discharge mapping: a non-destructive technique for assessing the condition of a cable in-situ
- Laboratory testing of cables and accessories including partial discharge testing, breakdown tests, life tests, loss angle measurements, impulse tests and thermal runs
- Cable fluid leak location using proprietary equipment and methodology. The system provides a very effective approach to the management of fluid filled cables providing an increased speed of leak location, together with major labour and cost savings
- Sheath testing and sheath fault location.

### 3.3 Substation Plant and Equipment

A range of assessments are available which are specifically aimed at maximising the utilisation of existing equipment, detecting critical signs of deterioration, optimising maintenance procedures.

The assessments include:

- Monitoring and location of partial discharge activity in electrical switchgear (Figure 2 Partial Discharge Measurement On Live Switchgear)
- Thermal assessment of transformers to provide an enhanced rating
- In-situ diagnostic testing of outdoor 33kV and 132kV bushings
- Condition monitoring of transformers via specialised oil analysis
- Measurements of PCB levels in oil, and advice on the technical, environmental and legal implications
- Location of discharge sites in transformers using ultrasonic techniques

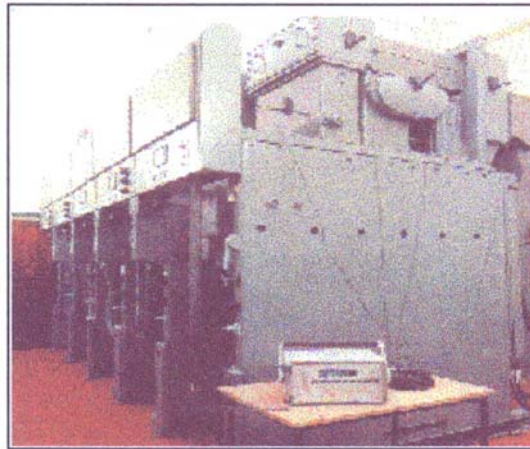


Figure 2. Partial Discharge Measurements on In-Service Switchgear

#### 4 ASSET DATA GATHERING

Data is an essential ingredient to cost effective asset management. The asset management process adds value to converting this data into knowledge which is the basis for decisions on reducing the overall life cycle costs of the network[1]. Accurate and reliable data significantly reduce the risk exposure of business decisions.

Data gathering solutions must be cost effective to implement and operate, and fully integrate with existing legacy and new IT systems. Typical systems are highly user friendly with intuitive interfaces suitable for staff who are not computer literate.

The key issues associated with Asset Data Gathering are:

(a) Primary and Secondary Plant Maintenance

If staff are equipped with the relevant information to undertake a wide range of plant maintenance operations their flexibility is increased. By giving them the ability to access clear, concise and specific information relating to a particular plant item, problems can be resolved on-site and the work done recorded.

(b) Integration with Work Management

Network operations can be co-ordinated and resource utilisation improved. By integrating business process support tools, such as knowledge based solutions, with work scheduling and management systems staff workload can be handled more efficiently and effectively.

(c) Support of Condition Assessment

An organisation which quantifies the condition of its assets can optimise its maintenance strategies. Capturing asset condition in a consistent and intuitive manner allows asset replacement and maintenance strategies to be based upon information of high quality.

(d) Upskilling of Staff

The expertise of more experienced staff can be captured and made accessible throughout an organisation. This valuable information resource can be used to enhance the skills of less experienced staff, allowing them to broaden their skill base.

#### (e) Consistent Asset Data Collection

If asset data is recorded in a consistent manner its value is greatly enhanced. By using a structured, intelligent system, asset data can not only be captured but validated in the field, turning it into relevant information for the business.

#### 4.1 Typical Data Gathering Software

An example of such a system is ProMEX, a decision support tool for undertaking protection relay maintenance operations in the field. The first implementation was targeted at the maintenance of 11kV protection equipment but the architecture and concepts are relevant for virtually any inspection and maintenance operation[2<sup>1</sup>].

The system is pen-based and guides a user through inspection, condition assessment and maintenance, as required. It carries data extracted from the relevant corporate database and enables both the data held in this database to be corrected and the condition of equipment to be recorded in a precisely prescribed manner. This makes it straightforward to subsequently use the data for producing a quantitatively based condition-based maintenance scheme. Figure 3: ProMEX - An example of a decision support and data entry tool for field staff

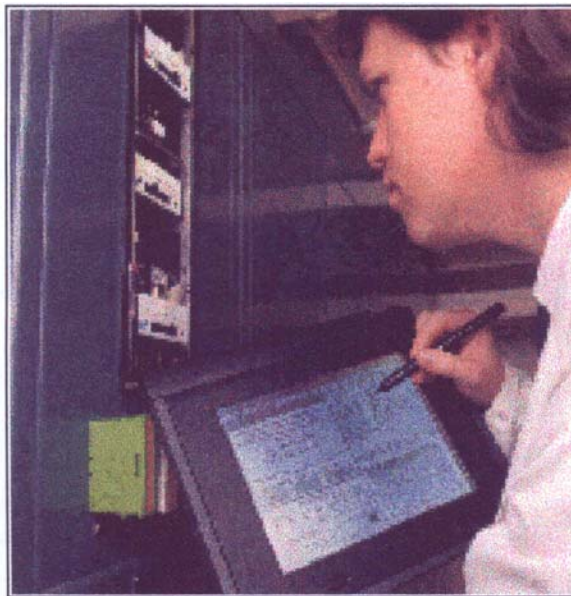


Figure 3. Field Data Gathering Combined with Decision Support at the Point of Work

### 5 ASSET MODELLING AND ANALYSIS

Modelling the performance of assets and networks using powerful desktop software can greatly speed up business decisions and significantly reduce the associated risk. Modelling provides the insight as to how network performance through re-design or targeted capital investment will convert into standards of performance.

Modelling also identifies assets that can be pushed harder and the impacts to be expected.

The collection of information and data concerning the operating conditions and performance indicators of electricity distribution assets, leads to large, sparse data sets. Specialist analysis and modelling techniques are required to extract useful condition information from such data sets. Analysis and modelling techniques can be given three broad classifications:

- Analysis of operational data to determine equipment loadings and to predict future operating conditions
- Analysis and modelling of site measurement data to determine asset conditions and establish safe operational ratings
- Modelling of networks to establish operational scenarios and planning to satisfy predicted future loading.

These three areas naturally fit together, the first establishing current and future loading, the second establishing current condition, and the third to formulate future plans to handle loads. Between these categories, various other analysis and modelling techniques can be employed such as analysis of demand-side options to control demand and business analysis of refurbishment options.

### **5.1 Asset Modelling and Analysis Tools**

#### **Analysis of Operational Data**

- SCADA data collection and 'cleaning' prior to analysis
- Disaggregation of demand curves by sector and load classifications
- Scenario analysis for demand based on market trends and intervention in end-use loads (Load Management, Energy Efficiency, DSM)
- Analysis of effects of renewable and embedded generation and second tier trading arrangements
- Modelling of end-use loads to predict network demand

#### **Network Simulation Models**

The purpose of Network Simulation Models are to provide a decision support tool to compare and evaluate a wide range of policy issues which depend upon the capacity and performance of the distribution network<sup>[3]</sup>. In accordance with the priorities set by the companies, the most highly developed aspect is the capability to evaluate the specific Regulatory customer performance indices.

The models typically include a capability to calculate network losses and provides elementary economic assessment. The models have the capability to become the major tools for the analysis of network policy relating to customer performance issues, to provide:

- Network reliability modelling
- Network losses modelling
- Investment planning modelling
- Automation policy modelling
- Maintenance policy modelling

#### **Benefits:**

- Lower risk business decisions
- Policy and strategies tested before implementation
- Rapid response to changing business / regulatory environment
- Understanding of assets performance behaviour

## Thermal Assessment of Transformers

Models exist to represent power transformers without requiring knowledge of the internal construction. The quality of the models is such that the hot spot temperature, as given by the winding temperature indicator, may be predicted to within 3°C.

Transformer loading guides such as BS 7735, for bulk supply point (BSP) transformers and primary transformers, are based on the assumption that all transformers of the same voltage, capacity and cooling type, have the same thermal performance. However, each manufacturer's design is different and changes from year to year. Models enable the capacity of transformers to be individually assessed which will determine whether they can be operated at loads above nameplate rating.

Benefits:

- Rating for individual transformers
- High utilisation of transformers
- Expenditure saving through deferment of transformer reinforcement
- Assists in outage planning

## 6 CONCLUSIONS

There is a new paradigm in the UK in the utilisation and maintenance of electricity distribution assets. The UK form of regulation is forcing companies to justify expenditure on quantifiable benefits in reliability, quality and security of supply while simultaneously minimising the costs to the customers and growing the return to shareholders. There is therefore an urgent need to put in place cost effective systems for simultaneously optimising the utilisation and management of assets ..

Investments are being made in the following areas:-

- Company-wide asset databases, which are capable of being use to assist strategic asset management;
- Hand-held electronic field data collection systems;
- Maintenance analysis techniques, and choosing RCM as a common route to identifying critical areas;
- Condition-monitoring techniques, to build a database of asset ageing and failure modes;
- Sophisticated analysis techniques, to extract maximum value for assets employed with in the electricity distribution businesses.

Practical tools utilising the latest hardware and software technology are now addressing the major business issues associated with asset management and hence bringing to the market place cost effective tangible solutions to an increasingly critical core activity of electricity companies.

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## **Asset Management Data Collection and Decision Support**

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### **ABSTRACT**

*The goal of Asset Management is to manage the asset base to yield maximum business value. Detailed knowledge on the assets is essential to minimise risk and maximise benefit and this requires accurate and reliable data and tools to support the decision making process. If properly specified and designed, portable computer applications can be quicker to complete than comparable existing paper forms and systems, enabling efficiency gains on-the-job as well as in the back office. They can achieve better adherence to common work practices and accurate and consistent data collection than training or education exercises. The provision of decision support tools to field workers “upskills” staff and enables more flexible working. There is an increasing movement away from traditional time based maintenance regimes to condition based maintenance regimes. In an increasing cost conscious environment, it is essential that asset managers have objective measures to rank equipment when prioritising asset maintenance activities. Where strategic asset replacement programmes are being undertaken asset managers need to be able to rank individual assets in order of priority for replacement in order to minimise risk and maximise benefit to the business. This paper highlights initiatives that a number of UK companies are undertaking based on both the InMEX field system and the PARM decision support systems which have been developed by EA Technology. It stresses the requirement for flexible, easily adapted systems that do not require development by programmers, but can be maintained and adapted by asset managers. Examples will be given where this approach has been successfully applied. The paper give examples where decision making in the field has been devolved to industrial staff, supported by portable knowledge-based systems.*

### **1. INTRODUCTION**

The planning, procurement, operation and maintenance of assets has a major impact on the operation of a business. The drivers for Asset Management are increased business benefit from the assets. Careful attention to management of the assets maximises the value to an organisation of those assets, or in other words, produces a greater return on the investment which is put into the asset base. This can be achieved both by reducing the overall cost to an organisation of any given asset and by increasing its utilisation. Utilities are now focusing upon Asset Management as a core business skill. If the costs of ongoing operational costs such as inspection &



maintenance activities can be significantly reduced then there are major reductions in the whole life cost of an asset and an equivalent increase in the return, to the business, from the asset.

Good, reliable information for individual assets is essential to ensure that resources are deployed efficiently and that work is targeted effectively. Accurate allocation of operational costs against asset-related activities and objective assessments of the benefits resulting from changes in, for example, maintenance work practices also require accurate reliable data on the assets and the work carried out.

Utility businesses differ from other types of asset-based businesses, for example manufacturing and production-based industries. The assets are geographically dispersed, rather than being reasonably accessible and concentrated on one site. The system is composed of many discrete components, many of which are of low cost. It is therefore not normally cost effective to monitor on-line the condition of most distribution system assets. The assets are in the field, the assets are operated and maintained by field staff. Much of the information on which decisions are taken is reliant on accurate, up-to date and relevant data gathered in the field by field staff. Good, reliable information for individual assets therefore relies heavily on the accuracy and timeliness of inspection and maintenance activities. This requires quality data capture as an integral part of these activities.

## **2. ASSET MANAGEMENT DRIVERS**

The drivers for Asset Management are increased business benefit from the assets. Careful attention to management of the assets maximises the value to an organisation of those assets, or in other words, produces a greater return on the investment which is put into the asset base. This can be achieved both by reducing the overall cost to an organisation of any given asset and by increasing its utilisation.

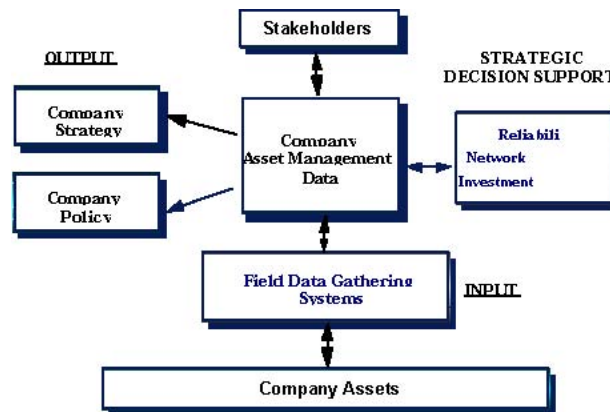
Improved business performance results from the understanding and careful management of risk. Historically there has been a significant degree of redundancy in networks, with assets operating well within their designed operating limits. The drive for increased utilisation of assets necessarily reduces the degree of redundancy in the network. However, this must be accomplished whilst standards for supply are being improved. A greater understanding of the assets, which reduces the degree of “randomness” in their behaviour is therefore needed.

It can be argued that the business of the distribution side of a utility is the successful management of its assets, that is selecting, operating and replacing assets in the manner which maximises benefit. In a business based on engineering technology, there are continuing improvements both operating practices and in the price and performance of available equipment, which can be used to replace existing assets. The assets have a finite lifetime, but this is not known exactly for individual pieces of equipment.

A distribution utility also has statutory obligations to meet both in terms of continuity and quality of supply and in terms of the health and safety of both its workforce and the public at large. The environment that a utility operates in today ensures that there is less investment money available for large reserve margins. It is not a viable option to replace all assets over a given age in order to

“guarantee” reliability. Indeed, replacement in this manner is highly unlikely to guarantee reliability. In order to maximise the benefit of an asset or group of assets to a business in a changing environment there is a need for reliable, speedy decision making to:

- . ☐ enable the best choice to be made when selecting and procuring an asset
- . ☐ advise the most effective manner of operation of an asset, balancing reliability, availability, performance and cost
- . ☐ advise when maintenance or replacement of an asset is required.



**Figure 1: Asset Management**

High quality decisions require high quality data. In order to maximise the benefit to the organisation, it is crucial that information which could influence the asset management strategy is recorded accurately and is made available in a form which can readily be used to support decision making. In many organisations, particularly those that utilise engineering assets, routine inspection and maintenance provides the most cost effective source of performance data. This data can be used in establishing compliance against operational targets, whether internal or externally imposed.

The take-up of new asset management processes has not only been hindered in the past by the cost and performance of computer systems, it has also been hindered by the cost of collecting and maintaining data to the required level. It is essential that these activities form an integral part of the inspection and maintenance function, and do not introduce inefficiencies in the normal duties of the staff that carry out inspection and maintenance. Any field system, which is introduced to acquire and maintain asset data, must be easier to use than any manual data collection systems that it replaces.

### 3. ASSET CONDITION ASSESSMENT

Having an accurate and relevant record of asset condition is of fundamental importance to any effective asset management programme. Many companies have information and records of data associated with asset type, commissioning date, maintenance history etc. However, to be of real

value any data-base must also contain information regarding current asset condition so that important decisions can be made regarding asset replacement, refurbishment or retention and for effective condition based maintenance programmes.

Condition monitoring and assessment and diagnostic testing all provide information concerning the "state of health" of a network asset. In general, the information can provide a measure of the integrity of specific components, parameters or capabilities of the asset. Where measurements are involved they are usually viewed against some benchmark level e.g. the manufacturer's original specification or other predetermined level of acceptability. Condition assessment of an asset is generally a "one-off" activity aimed at providing information to assist the decision making process. It may or may not include diagnostic testing. Condition monitoring is an ongoing process that measures certain parameters against a benchmark and looks for significant changes and trends. Condition monitoring may form part of a preventative maintenance strategy. Both condition monitoring and condition assessment can therefore include diagnostic testing. Typically, enterprise scale asset management systems enable automatic scheduling of remedial work which is triggered by an "out of scale" value for a single condition indicator. More typically when experts assess distribution network assets, they consider a wide range of indicators rather than relying on one single measurement..

EA Technology has developed a range of systems for data gathering and decision support to the asset management process which enable the move to condition based maintenance. The decision tools extend a condition based approach into business risk based maintenance where the business risk is derived from the condition of an individual asset and its value to the business. These tools enhance the functionality of existing work management systems to automate day to day scheduling of maintenance based on business risk.

#### **4. EXAMPLES OF DATA COLLECTION AND DECISION SUPPORT INITIATIVES:**

**Eastern Electricity** are introducing an Asset Management Process which is based on the inspected condition of distribution network equipment. Key parts of this system are the streamlining of the process of gathering the inspection information and the relation between the observed condition of equipment and its maintenance need.

Eastern's network is one of the largest in the United Kingdom. The Network covers East Anglia and reaches westward into Oxfordshire and Buckinghamshire and southwards into London's suburbs -a total area of 20,300 sq. km. supplying electricity to over three million customers. The Network includes some 61,000 substations connected by 51,000 km of underground cable and 35,000 km of overhead lines distributing, transforming and controlling electricity at 132,000, 33,000, 11,000 and 415/240 volts. Together these carry a peak load of over 6,000,000 kilowatts.

As part of its asset management strategy, Eastern Electricity recognised the value of condition based monitoring. The application of such techniques can provide valuable information on the condition of network assets, leading to the implementation of more focused maintenance and replacement strategies. Sub-station inspection is carried out for a variety of reasons. The frequency of maintenance of equipment requires judgement based on experience of the assets and increasingly, their condition. The aim of Condition-Based asset management is to apply the measures necessary to prevent loss of function in a scheduled manner "just in time"; that is prior to the loss of function (in the P-F interval).

It has been established that large populations of similar plant can be managed by a strategy of invasive inspection and maintenance of a statistically-derived sample, in conjunction with data derived from “forensic” examination of units taken from service randomly, annual noninvasive inspection of the entire population, and other data derived opportunistically. Substation inspection is an opportunity to gather information in order to assess the condition of the electrical plant and perhaps perform some maintenance tasks or gather general asset information.

To gain the maximum benefit from undertaking sub-station inspections and condition based monitoring in particular, it is imperative that on-site measurements and assessments are recorded and analysed in a consistent and efficient manner. The efficient acquisition and effective use of data are the biggest challenges contained in the new asset management strategy. The concept is that data flows through a hierarchy of levels to provide relevant information to a number of different users.

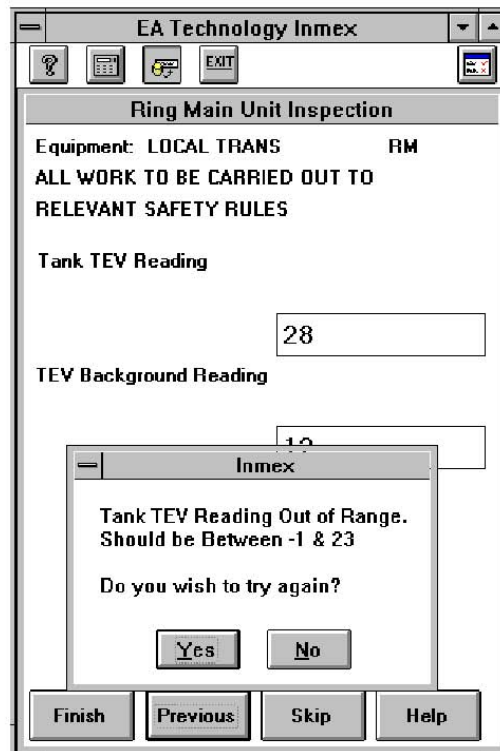
Eastern Electricity’s Network Business started work in 1995 to develop an asset management system to facilitate the future management of maintenance principally on the basis of condition data. The continuing development and improvement of this system links the identification of key asset condition indicators, inspection procedures and techniques and data acquisition and analysis. In the course of implementing its asset management strategy, Eastern Electricity has adopted a phased approach to reduce risk and confirm business benefit before committing to major expenditure. This approach includes the selection and trial of products which fulfil the requirements for the system before adoption.

EA Technology have developed a flexible data gathering and decision support system known as InMEX which can be used for any task which involves systematic inspection and action based upon the information gathered. An efficient and cost-effective asset inspection system can readily be achieved using InMEX. Eastern Electricity selected this system for a trial of data gathering for substation inspection because of its flexibility (applications can be produced and changed quickly and easily) and because it is simple and easy to use with a clear and intuitive user interface. EA Technology have also developed the Partial Discharge Monitor (or TEV). This measures the level of partial discharges within switchgear housings and terminations and is an important non-invasive diagnostic technique. The InMEX inspection system interfaces with the TEV condition based monitoring database to provide on-site indication of potentially unsafe conditions.

The Substation Inspection System was delivered on a pen based computer in the field. User interaction is by means of menus, buttons, drop-down lists and tick boxes with restricted use of alphanumeric input aided by character recognition. User experience and feedback shows that this way of working requires only a few minutes of learning and then is very easy to use. The pen approach has been found to match the user input requirement in an on-site environment where input is needed whilst standing in front of a piece of equipment.

The following types of plant were supported by the trial system:

- . ☐ Transformer
- . ☐ Switch Fuse
- . ☐ Oil Switch
- . ☐ Circuit Breaker
- . ☐ Ring Main Unit
- . ☐ Extensible Board
- . ☐ LV Fuse Board



**Figure 1: Example screen showing context sensitive drop-down menus. of “actual” with “expected” value**

A generic inspection template for each of these types was developed rapidly, using a selection of generic screens and logic. This has been found to lend itself readily to this class of activity. Moreover, because the inspection applications are flexible and easily adaptable they were amended during the trial based on user feedback. Example screens from the application are shown in figures 1 to 3.

Condition data that was collected included TEV partial discharge measurements and oil levels. These were compared against safe limit values and exceptions flagged up in the field when the measurements were taken.

The system guides users through the inspection activity, stores test results obtained on-site and if required, analyses and suggests the appropriate course of action. Structured access to help

documentation guides the user in carrying out the tests. Data is transferred to and from a central database for trend analysis, degradation modelling and the production of management reports and provides a uniform reporting procedure, an audit trail and history for each asset.

For each specific item in the field, where required, the system provides the functionality to compare the condition as measured or observed with a predetermined value or state. This, for example, may be a statistically derived upper limit value based on measurements of a large population of equipment, or may be derived by a model from the relevant data already in the condition database for the plant item concerned, based on age, environment, duty and other identified criteria. As the actual data is entered, the system compares “actual” with “expected”. This comparison achieves two principal objectives:

- The entered data is immediately verified at the point of entry and excursions from the expected condition will be immediately queried.  
Data entry errors can be readily trapped and efficiently corrected.
- Real excursions from the predicted values can be assessed to validate the robustness of the sampling strategy. Additional sampling requirements will be identified if necessary.

The screenshot displays the 'MDI Readings' application window. It features a title bar with a minus, maximize, and close button. The main content area is titled 'Enter Phase readings (Amps)' and contains instructions: 'If the reading is off the low end of the MDI scale then enter the low end scale value and select Underscale' and 'If the reading is off the high end of the MDI scale then enter the high end scale value and select Overscale'. Below these instructions are three rows for 'Red', 'Yellow', and 'Blue' phases. Each row has a text input field for the reading and two checkboxes for 'Overscale' and 'Underscale'. The 'Red' phase has a reading of 700, while 'Yellow' and 'Blue' both have readings of 600. Below the phase readings is a 'Multiplier' section with a text input field containing the value 1. At the bottom left is an 'OK' button. Overlaid on the bottom right is a smaller 'MDI Readings' window titled 'Rating'. This window contains an information icon (i) and displays the following calculated values: 'Unbalance factor: 1.105', 'Load: 471 kVA', and 'Utilisation factor: 94%'. It also includes the text 'Select OK to continue, or Cancel to re-enter' and 'OK' and 'Cancel' buttons.

**Figure 3: Example Screen showing calculation of derived values from entered data**

Existing asset register data and limited condition data for the assets in the selected substations were extracted from the mainframe plant database. The central database for the trial was populated with this data. The availability of this data on the field machines provided a useful mechanism for checking the accuracy and completeness of the data held in the central register.

Condition-Based inspection had been carried out on the assets previously using a paper-based

system. Therefore some paper records on the condition of the assets at the previous inspection were available. In carrying out the inspections, data on each asset was entered into the system from the paper records, before carrying out the new inspection. Hence the trial allowed the capture electronically of inspection data from two inspection cycles for the assets selected for the trial.

Productivity using the system was initially low due to unfamiliarity with hardware & system. As the users gained experience the productivity, in terms of number of substations inspected per day, was as good as, and occasionally better than the current paper-based procedure. Added to this, four times as much condition information was collected in each inspection compared with the current practice. Hence in terms of amount of data collected per day there was a four-fold increase in productivity. This was because data entry was quicker (point rather than write) and some data was already present from previous inspections where relevant. Feedback from the users improved the inspection sequences and this fed back into improved productivity.

Entering data only once (in the field) rather than entering on paper and then subsequently entering from paper into a central computer system not only saved time but assisted in the acceptance of the system by the users.

Minimal training was found necessary for the trial users and full familiarity with the system was achieved after a few weeks of use. It is felt that this lead time could be shortened by targeted training during the roll out.

Although some revisions and enhancements to the inspection applications were identified, in general the applications were found to be sensible, helpful and promoted efficient and effective inspections. The use of template scripts for the inspection assessment process was found to promote objective assessment and constrain subjective judgement. This in turn assists in the objective comparison of inspections carried out by many different people in a wide range of environments and backgrounds.

**Hyder** own and operate both the water and electricity distribution networks of South Wales. They recently identified a need to identify the location and type of all LV pillars in the electricity network and at the same time collect information on their condition. The driver for this was to increase safety of staff working on the network. Hyder wished to confirm that it was safe to maintain the LV pillars and identify those that needed remedial work to bring them to the same level of safety as the majority of the LV pillars.

Safety is taken very seriously by Hyder and therefore a solution was required which could be quickly implemented and introduced into the normal inspection routines. Hyder have in excess of 3450 LV pillars and the exercise would generate a large quantity of condition data. Manual identification and prioritisation of the remedial work was therefore not feasible, however, Hyder wished to avoid a large data transcription exercise to populate the asset database. They selected the EA Technology InMEX system because of its flexibility, the speed at which applications

could be created and the ease of interface with the asset database. The full inspection system was specified, designed, produced, delivered and rolled out within three weeks of order. The Casiopea E15 had very good screen visibility in both bright sunlight and poor lighting and was originally selected. Unfortunately it was not available in sufficient numbers because Casio had stopped producing this machine and therefore the HP Jordana 430SE was used.

The system is enabling Hyder to collect the data without undue impact on the normal work carried out by inspectors. The main problem that has been identified is the poor screen visibility in bright sunlight of the HP Jordana 430se.

**London Electricity** is responsible for the electricity distribution network of most of the capital city of the UK. The 19,000 mile network serves about two million customers, including the critical financial and business district of the City. London Electricity is increasing the efficiency of its condition-based asset management systems by adopting EA Technology's InMEX field data gathering solution to provide field staff with a simple but powerful method for recording the condition of assets. The system has been integrated with the existing MP5 work management system which is provided by Datastream.

The system enables investments for replacing and upgrading assets to be prioritised on the basis of the asset condition, reliability and quality of supply. This is clearly a more effective solution than wholesale replacement of equipment, which inevitably involves unnecessarily high costs. The attraction of InMEX is that it is very easy for field personnel to use in a wide range of applications across the business, whilst providing extremely sophisticated information in a form which is vital for effective asset management. The gathered information is transferred to the central asset management database via InMEX's "middleware" which translates it into reports which can be read and acted upon by managers.

**Meridian Energy** are the largest generator in New Zealand. Their generating capability is predominantly Hydro Electric. Meridian manage their assets using Maximo provided by PSDI but find that the data entry screen are not tailored to the activities carried out by the maintenance staff. They are currently evaluating InMEX to facilitate data gathering at the remote power station locations. The attraction of InMEX is the speed with which applications can be developed. The demonstration applications were produced with just two man days effort.

A recent development in the UK electricity distribution sector is the formation of the joint venture company **24Seven**. This company, formed by Eastern Electricity and London Electricity, is responsible for managing and operating the networks of London Electricity and Eastern Electricity. 24Seven has placed a contract with EA Technology, which was won by competitive tender, for a significant role out of the InMEX system and integration of the PARM prioritisation system with the MIMS asset management system, supplied by AMT Sybex. This system will not only provide a flexible data gathering solution throughout the area operated by 24Seven, but it will also provide added value to the data gathered before passing information on to the asset register.

Both London and Eastern have undertaken assessments of their assets and have worked with EA Technology in developing a detailed understanding of degradation processes and condition based risk assessments. The knowledge and understanding which has been accumulated by EA Technology in these and other exercises, provide weightings onto condition point and condition



state attributes based on the significance of the components being inspected. A single maintenance index which is representative of a particular aspect of the overall condition of the plant will be passed onto the asset register for each item of plant. These indices will then be used by the asset register to reschedule maintenance and emergency remedial work by 24Seven based on derived condition measures rather than simple defects alone. Previous risk assessment work [refs 1,2] has determined that this approach provides lower risk of failure and higher safety at significantly lower operating costs, however to date IT system which automates this approach have not been an available. PARM satisfies this need.

## **5. SUMMARY**

The restructuring of the regulatory framework in the UK has led to a recognition by Distribution Network Operators that their core competence is the effective and efficient management of network assets. Increasingly asset managers are looking to place commercial, performance related contracts with out-sourced service providers in order to drive costs down. Progressive companies are finding that InMEX and PARM reduce the business risk by facilitating the transfer of skills to the service provider, maintaining quality and consistency of information, whilst improving the asset manager's knowledge and understanding of the assets.

## **6. ACKNOWLEDGEMENTS**

The authors would like to thank the Companies named in this paper for allowing their experiences to be reported.

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## THE EVOLUTION OF NON-INTRUSIVE PARTIAL DISCHARGE TESTING OF MV AND EHV SWITCHGEAR

Graham DENNIS, Miles REDFERN and Steve PENNOCK  
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### INTRODUCTION

*The trend for extending maintenance periods for MV switchgear brings with it a need for interim non-intrusive diagnostic techniques to give confidence in the continuing safety and reliability of the equipment. This paper will look at recent developments in equipment available for partial discharge testing of switchgear operating in the 3.3kV–33kV range.*

### BACKGROUND

The most successful and practical method employed for the non-intrusive detection of partial discharge activity in MV switchgear is through use of both electromagnetic and ultrasonic detectors [1]. The process of surveying switchgear using this equipment is well established and the equipment now has a proven track record in identifying defects and eliminating possible catastrophic failure due to breakdown of insulation.

For networks with large numbers of switchboards surveying using hand held equipment can be successfully employed for the detection of continuous partial discharge activity. When the switchboards are critical to the operation of the network or fewer in number then it is often desirable to install monitors onto the switchboards for a period, e.g. a week, to detect intermittent sources of discharge activity. For very critical switchboards, permanent monitoring can be installed to provide early warning of any partial discharge problems developing within the switchgear [2].

### REQUIREMENT FOR PARTIAL DISCHARGE ASSESSMENT

The number of catastrophic failures of MV electrical switchgear is small in relation to the installed population. However, when a failure does occur, the consequences are often serious with respect to injury to personnel, damage to equipment and loss of availability of electrical supply.

Analysis of failure statistics has shown that a high percentage of failures can be attributed to breakdown of solid insulation. This insulation breakdown is often preceded by partial discharge activity and therefore non-intrusive detection of this activity is an effective tool for the detection of deterioration in the insulation.

The use of condition monitoring for the detection of partial discharge activity becomes increasingly important with the

trend within electricity companies towards the adoption of condition based, rather than time or age based maintenance. Bodies such as the UK Health and Safety Executive are now including the use of condition monitoring tools within their guidance documents as an illustration of good practice in the use, care and maintenance of switchgear [3]. Therefore, the use of condition monitoring is also becoming more widespread by owners and operators of switchgear within industrial and commercial organisations.

For these reasons, the development of equipment suitable for widespread use by personnel that are not necessarily highly trained in the use of condition monitoring tools but nonetheless provides beneficial and meaningful results is essential.

### Transient Earth Voltage Instrumentation

When partial discharge activity occurs within medium voltage switchgear, electromagnetic waves in the radio frequency range are generated. These waves escape from the inside of the switchgear through openings in the metal casing. When the electromagnetic wave propagates on the outside of the switchgear they also impinge on the metal cladding generating a transient earth voltage on the metal surface. The Transient Earth Voltage (TEV) has a nanosecond rise time and an amplitude which varies widely from millivolts to volts.

The TEV is measured (in dBmV) with a capacitive probe placed on the earthed metalwork of the switchgear.

A range of equipment has been available for a number of years that can detect TEV signals. The Partial Discharge Locator (PDL) enables users to measure and through use of two probes and precedence detection circuitry, locate sources of partial discharge activity. The Mini TEV is a single probe device that provides an indication of the magnitude and rate of discharge activity during a survey of switchgear. The Partial Discharge Monitor (PDM) is a 12 channel instrument capable of monitoring discharge activity on a switchboard for a week or more and is able to mask out external sources of electromagnetic activity and is also particularly effective at detecting intermittent sources of discharge activity.

### The MicroTEV

A recent development within the range of TEV equipment is the MicroTEV. This instrument has been developed as a first pass tool that provides an indication of the level of partial discharge activity within switchgear through use of a simple coloured LED display. The unit has three distinct levels – green, amber and red. The probe of the instrument is placed on the metal surface of the switchgear and the unit will continuously measure the discharge activity and display the

results on the LED (Figure 1). At least two discharges above the amber and red thresholds are required within a 2 second period to be displayed on the LED.



**Figure 1 MicroTEV on a cable box**

The discharge levels at which the thresholds have been set were carefully chosen based on measurements held within EA Technology's extensive partial discharge measurements database. This database contains over 9500 records of discharge surveys on switchgear operating at 3.3kV to 33kV in 14 different countries around the world.

The amber threshold equates to readings that are within the top 25% of PDL records within the database. The red threshold equates to readings that are within the top 10% of PDL readings. It should be noted that there may be electromagnetic activity in the vicinity of switchgear that is not the result of partial discharge activity. This can be overcome when using the PDL or PDM, which have multiple probes and precedence detection circuitry. Whilst the Micro TEV does not have this facility, analysis of the records held within the database has provided confidence that minimum numbers of "false alarms" will be experienced. The data shows that when the red threshold is detected, 90% of the surveys had readings on the switchgear greater than 10dB above background noise thus positively indicating that there was a source of discharge internal to the switchgear.

The remaining 10% of the surveys had very high levels of background electromagnetic noise within the vicinity of the switchgear. This activity may have effectively masked out potentially serious discharge sources and therefore, surveying using a PDL or preferably monitoring using a PDM would be warranted for these cases anyhow.

Therefore, in all cases when a red level is detected, it is recommended that a further survey be carried out using some of the more sophisticated instruments to provide additional information on the magnitude, severity and location of the discharge source(s).

The situation is slightly different when the amber level is

detected. Analysis of the database has shown that when the amber threshold is detected, 50% of the surveys had readings on the switchgear greater than 10dB above background noise thus positively indicating that there was a source of discharge internal to the switchgear. For this 50% it should be straightforward to determine that the discharge is internal to the switchgear by carrying out spot measurements on metalwork in the vicinity of the switchgear but not connected to it e.g. on a metal substation door. For these locations, the background readings would always indicate green and only measurements on the switchgear would produce an amber reading.

For the remaining 50% of the instances where an amber light was indicated, the background would also be indicating amber. This would have the effect of possibly masking out amber levels of discharge present within the switchboard. The decision on what to do about this will largely depend upon the criticality of the switchgear. At the very least surveys should be carried out more frequently to give early warning should any internal discharge increase above the red threshold. If the switchboard were considered critical then the way forward to positively determine whether there were internal sources of discharge would be to again use a PDL or preferably a PDM.

It should be remembered that historically only 15% of all surveys would indicate amber on the switchgear and only 50% of these i.e. 7.5% of the total would have an amber background also which would leave uncertainty on whether internal sources of discharge have been detected.

## PARTIAL DISCHARGE MONITORING

Partial discharge sources, particularly in their early stages of development, may be intermittent in nature and lie dormant for extended periods until initiated by a voltage surge or changes in temperature or humidity. The discharge site may then remain active for minutes or several hours before becoming dormant again. This sort of discharge source is very difficult to detect during a partial discharge survey, which may only take an hour for a switchboard survey.

For this reason, the original Partial Discharge Monitor (PDM03) was developed. The instrument has 8 probes that are magnetically clamped onto different components of the switchboard and 4 aerials that are positioned around the switchboard to effectively mask out external sources of electromagnetic activity.

### The Importance of Precedence Detection

The use of precedence detection within the instrument is very important for 2 reasons. Firstly this is what enables external sources to be filtered by determining that signals are detected by the aerials around the switchboard before they are detected by probes on the switchgear. An example of this is shown in Figure 2. In this instance the PDM was installed on a 33kV GIS switchboard. A survey using the PDL had shown levels

of activity in the region of 21 – 26dB recorded on all panels of the switchboard and other metalwork within the substation. This was of some concern as the switchgear was recently installed and was very critical to the local network.

The results of the monitoring shown in Figure 2 reveal that nearly 17 million pulses were detected by the monitor during 1 day. Due to the precedence circuitry these were all allocated to one of the aerials and the switchboard could be given a clean bill of health. Measurements through amplitude alone would not have been able to determine whether there were internal partial discharge sources or not.

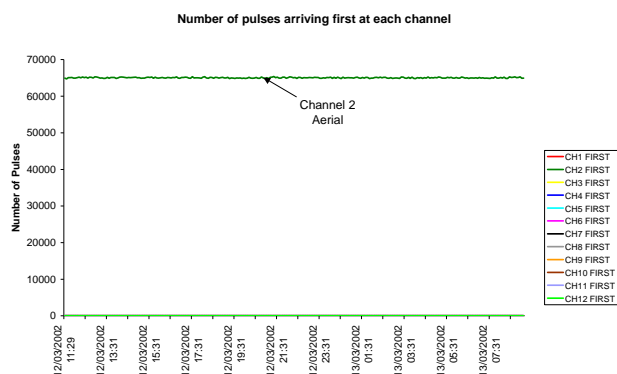


Figure 2 Activity detected by PDM installation on 33kV switchboard

Secondly it also enables discharge sources to be located as well as magnitudes to be detected. Although the amplitude of the signal generally decays away from the source, internal reflections and the attenuation of several possible paths makes location based purely on amplitude uncertain. Therefore, location is determined by which probe detects the discharge signals first. This also enables multiple discharge sources to be more readily detected by the monitor.

### Use of the PDM in Semi-Permanent Installations

Although the PDM was initially designed for temporary installations of around a week, developments in the instruments functionality have enabled the units to be used in longer term installations. This has proved particularly useful in instances where new switchboards have been installed and circuits have been commissioned over extended periods of time. An example of this was on a unit installed on a 33kV SF6 insulated switchboard.

As part of commissioning, Partial Discharge Mapping was carried out on all the installed cables. In order to test the cables, test prods needed to be inserted through a gas seal to make the connection and disconnect the Voltage Transformer from the circuit. The cable testing was carried out successfully, the test prods were removed and the circuit re-energised. Figure 3 shows the plot of severity (function of discharge magnitude and rate of discharge) for the PDM probe that was installed on the panel in question. The newer versions of the PDM have alarm functionality based on the severity levels on each probe. The alarm level was set at 100 and was wired in to the substation SCADA system.

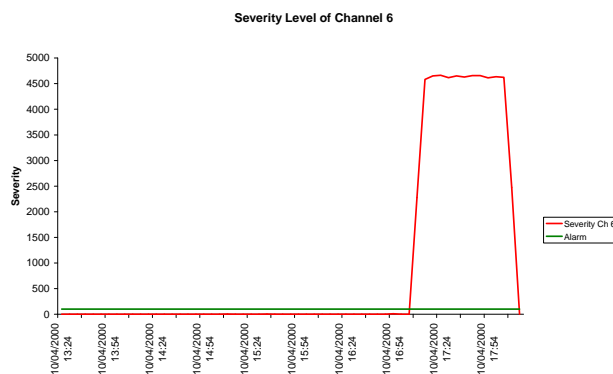


Figure 3 Severity Level of Discharge Initiating Alarm

Figure 3 shows that the alarm level was greatly exceeded when the circuit was re-energised. This enabled the local engineers to take the decision to switch the circuit out within an hour. The chamber was subsequently de-gassed and upon inspection, it was found that the VT contact spring had not correctly re-made when the test prods were removed and evidence of discharge activity was seen despite the short period between energising and switching out.

Without the installed PDM, in all likelihood such swift action to remove the potentially serious discharge source would not have been possible.

A similar situation is shown in Figure 4 where the discharge activity on a probe located on a cable termination went through a step change in severity and exceeded the alarm level. Again this enabled the component to be de-energised and removed from service before failure. Examination of the termination showed there to be a defective component that affected the stress relief within the termination thus causing the partial discharge activity.

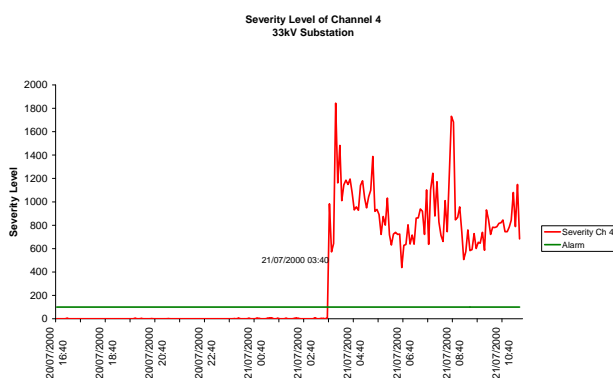


Figure 4 Severity Level of Discharge on a Cable Termination

These examples and the experience of installing permanent versions of the PDM onto switchboards in a power station [2] have demonstrated the benefits that can be gained through the installation of permanent monitoring on medium voltage switchboards, particularly when the switchgear is critical to the network.

## THE CONCEPT OF FULL SUBSTATION MONITORING

With the benefits of permanent partial discharge monitoring using electromagnetic TEV probes established for critical switchboards, the question still remains on the practicality and cost effectiveness of such installations. The prevention of failures as shown in the two above examples (Figures 3 & 4) in themselves would justify the expense of installation of this equipment onto the switchboards in question. This is emphasised still further where the switchboard supplies continuous industrial process networks where the loss in production greatly outweighs the component cost of the failure or in the case of electricity companies where large numbers or strategically important customers would be affected.

The cost justification may be enhanced if additional parameters are included in the hardware that enables us to move down the road towards full substation monitoring. With this concept in mind further development has recently been carried out on the partial discharge range of instruments.

### The PDM100

One restriction of the original Partial Discharge Monitor was the limit in 8 probes and 4 aerials. When switchboards with more than 8 panels were to be monitored it either needed to be done in stages or for longer term installations, multiple monitors needed to be installed. This had the drawback in that the monitors could take no account of signals being detected on the other instruments.

### Hardware

The development in the hardware has addressed this problem and enabled any number of nodes up to 100 to be linked together to a central hub in the system. Each node can have a single TEV probe or an aerial attached. The nodes are able to log the magnitude, rate and precedence of partial discharge TEV signals and therefore the location capability is maintained. The modular nature of the new design means that the equipment can be tailored for a particular installation.

Whilst the configuration of the hardware of the "PDM100" is new, the equipment utilises the same measurement techniques as the existing TEV equipment. Therefore, the design of the electromagnetic partial discharge detection circuits is already well proven and the existing extensive database of partial discharge measurement results is directly applicable to the results gained using the PDM100.

With ultrasonic surveying complementing the use of TEV detection, the inclusion of ultrasonic probes was a logical step in the development of the new hardware. Multiple airborne ultrasonic microphones can be included on each node and this provides additional benefit where air insulated component form part of the switchgear - providing that an air path exists between the potential sources of discharge and the outside of the switchgear.

As the ambient conditions within a substation can affect whether discharge activity occurs, particularly in the instance of surface tracking, then the monitoring of temperature and relative humidity is advantageous and therefore can also be included in the PDM100 installation.

Other parameters that can readily be incorporated into the system include on-line cable monitoring through measurement of partial discharge signals on the earth strap of cables and monitoring of auxiliary components such as battery voltage. With this type of flexible functionality the system can soon be configured to be a fully functional remote substation monitor although the primary function is the detection of partial discharge activity on the switchboard.

### Software

A new suite of software, the TEV SoftNET, has been developed which allows access and control of the PDM100 via local serial access, Ethernet access or remote modem access and internet interfacing. The software suite allows the PDM100 settings to be remotely or locally configured dependent upon the user's access rights.

Alarms can be configured for any of the measured parameters. In the case of TEV detection, they can be based on trends or thresholds of the severity measurements and multiple alarm levels can be set. Criteria such as the alarm threshold must be reached 5 times within a 60 minute period can be used to avoid spurious alarms through events such as switching that may cause short bursts of electromagnetic noise. When an alarm is initiated the system can be configured to inform relevant personnel via email and/or SMS. The system can also be set to send data with the email, e.g. the last 24 hours of data prior to alarm initiation. Alternatively, users can dial up the system and display the data in real time via an internet browser.

Powerful graphing facilities are available to enable users to display different parameters such as the amplitude measurements on each probe or plots of the severity level over time. The user can also specify the time period over which the parameter is to be displayed as historical data is stored on the hub.

### Case History

The benefits and functionality are best shown through an actual example from a PDM100 installation. The installation in question was on a 12 panel switchboard with 33kV GIS switchgear. With no air insulated components, the detection of partial discharge within the switchgear was dependent upon the use of TEV probes. An amber alarm level had been set to initiate when any of the probes exceeded a severity level of 10 at least 5 times within any 60 minute period. Whilst this severity level is reasonably low, it should be noted that probes on discharge free switchgear should have severity levels of zero. A further red alarm level was set to initiate when any probe exceeded a severity level of 100.

A few months after installation, emails were received

indicating that both the amber and red alarms had triggered for the installation on one of the probes. The PDM100 was remotely accessed and the online display (Figure 5) showed that the probe was still in the amber alarm state and that a step change in condition had been experienced at approximately 04:20 in the morning.

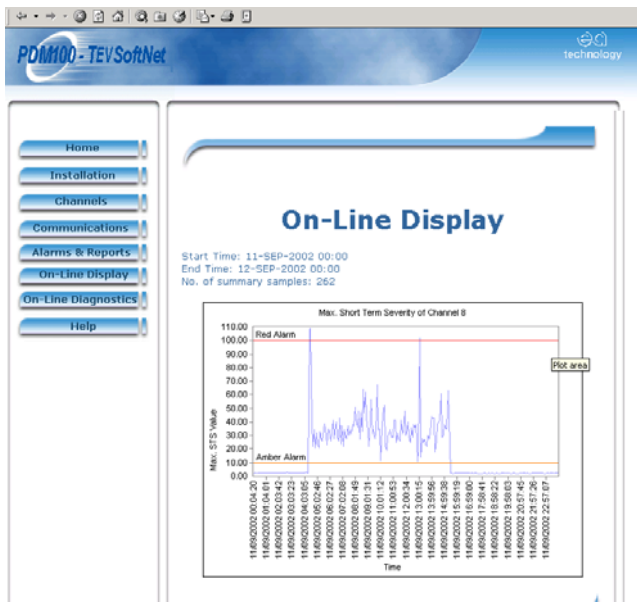


Figure 5 On Line Display of Severity on a PDM100

The time of the discharge initiation coincided with switching being carried out on the local network following some remedial work. Further changes to the network configuration were undertaken to allow the circuit breaker with the probe in the alarm state to be switched out. This was done at approximately 15:20 on the same day and the plot in Figure 5 shows that the discharge activity then fell back down below the amber threshold level.

Therefore, the PDM100 detected that discharge activity had initiated and early warning of this was provided via email. Investigation revealed that the timing coincided with switching on the network and this enabled the discharge source to be switched out later the same day so that further investigation and remedial work could be undertaken.

## CONCLUSIONS

The use of partial discharge detection equipment is expanding as condition based maintenance practices are increasingly adopted within electricity companies and by owners and operators of electrical distribution networks. Recent developments in the instrumentation available for partial discharge detection have provided additional options for widespread use of simple and effective spot check detectors for regular surveying of medium voltage switchgear. This then allows engineers to effectively target the use of the more sophisticated partial discharge location tools.

Where monitoring is justified, either due to excessive levels of background electromagnetic activity or the critical importance of the switchgear, precedence circuitry within the instrumentation is important to ensure external electromagnetic sources are effectively masked out. This also enables better location of discharge sources and multiple sources of discharge to be detected.

New hardware has been developed for permanent monitoring of switchgear that due to its modular nature can be tailored for specific installations and can accommodate even the largest switchboards. The flexibility allows multi parameter monitoring of substations with web enabled access of data and alarms that can be set to send multiple emails or SMS messages when alarm conditions are met.

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## THE DEVELOPMENT OF NON-INTRUSIVE TECHNIQUES FOR PARTIAL DISCHARGE DETECTION ON MV AND EHV SWITCHGEAR

Graham Dennis<sup>(1)</sup>, Miles Redfern<sup>(2)</sup> Steve Pennock<sup>(3)</sup>

(1) EA Technology, Chester, UK (2) & (3) University of Bath, UK

### ABSTRACT

*There is a large population of ageing distribution plant and equipment installed on electricity companies' networks and in many industrial and commercial locations. In order to achieve effective utilisation of these assets and make sound decisions on maintenance strategies, asset refurbishment or replacement, it is necessary to have reliable information on the condition of existing plant. The trend to extend maintenance periods and optimising the availability of switchgear brings with it a need for interim non-intrusive diagnostic techniques to give confidence in the continuing safety and reliability of the equipment. This paper will look at developments in equipment available for partial discharge testing of switchgear operating in the 3.3kV – 400kV range.*

**Keywords:** MV and EHV switchgear, Partial Discharge activity

### INTRODUCTION

The most successful and practical method employed for the non-intrusive detection of partial discharge activity in MV switchgear is through use of both electromagnetic and ultrasonic detectors [1]. The process of surveying switchgear using this equipment is well established and the equipment now has a proven track record in identifying defects and eliminating possible catastrophic failure due to breakdown of insulation.

For networks with large numbers of switchboards, surveying using hand held equipment can be successfully employed for the detection of continuous partial discharge activity. When the switchboards are critical to the operation of the network or fewer in number then it is often desirable to install monitors onto the switchboards for a period, e.g. a week, to detect intermittent sources of discharge activity. For very critical MV switchboards, permanent monitoring can be installed to provide early warning of any partial discharge problems developing within the switchgear [2]. It is common practice with EHV switchgear to include a permanent monitoring scheme in the specification or for schemes to be retrofitted.

### REQUIREMENT FOR PARTIAL DISCHARGE ASSESSMENT

The number of catastrophic failures of electrical switchgear is small in relation to the installed population. However, when a failure does occur, the consequences are often serious with respect to injury to personnel, damage to equipment and loss of availability of electrical supply.

Analysis of failure statistics has shown that a high percentage of failures can be attributed to breakdown of solid insulation. This insulation breakdown is often

preceded by partial discharge activity and therefore non-intrusive detection of this activity is an effective tool for the detection of deterioration in the insulation.

The use of condition monitoring for the detection of partial discharge activity becomes increasingly important with the trend within electricity companies towards the adoption of condition based, rather than time or age based maintenance. Bodies such as the UK Health and Safety Executive are now including the use of condition monitoring tools within their guidance documents as an illustration of good practice in the use, care and maintenance of switchgear [3]. Therefore, the use of condition monitoring is also becoming more widespread by owners and operators of switchgear within industrial and commercial organisations.

For these reasons, the development of equipment suitable for widespread use by personnel that are not necessarily highly trained in the use of condition monitoring tools, but nonetheless provides beneficial and meaningful results, is essential.

### TRANSIENT EARTH VOLTAGE INSTRUMENTATION – MV SWITCHGEAR

When partial discharge activity occurs in the phase to earth insulation of components within medium voltage switchgear, electromagnetic waves in the radio frequency range are generated and a small quantity of electrical charge is transferred due to the capacitance from the high voltage conductor system to the earthed metal cladding. These waves radiate from the inside of the switchgear through non-metallic joints which form part of the switchboard design. When the electromagnetic waves propagate on the outside of the switchgear they also impinge on the metal cladding generating a transient earth voltage on the metal surface. The Transient Earth Voltage (TEV)[1] has a nanosecond rise time and an amplitude which varies

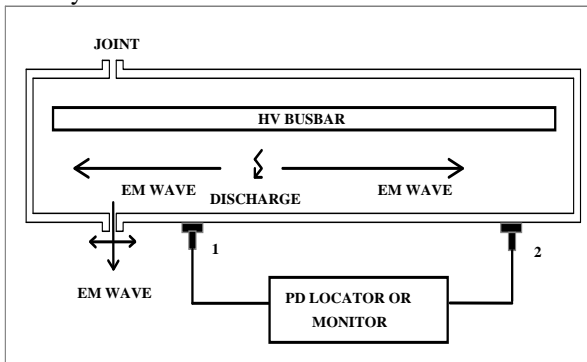


widely from millivolts to volts. The TEV magnitude is a function of the amplitude of the discharge and the attenuation of the propagation path. The TEV signals are measured on a logarithmic scale from 0 to 63dBmV with a resolution of 1dB using a capacitive probe placed on the earthed metalwork of the switchgear.



**Figure 1 PD Locator**

A range of equipment has been available for a number of years that can detect TEV signals[4] The Partial Discharge Locator (PDL) [1]figure 1, enables users to measure and through use of two probes and precedence detection circuitry, locate sources of partial discharge activity.



**Figure 2 Location of PD source**

The source of the partial discharge can be located as shown in Figure2, where the discharge signal will arrive at probe 1 before it arrives at probe 2[5]

The Mini TEV is a single probe device that provides an indication of the magnitude and rate of discharge activity during a survey of switchgear.



**Figure3 PD Monitor**

The Partial Discharge Monitor (PDM)[1] figure 3 is a 12 channel instrument capable of monitoring discharge activity on a switchboard for a week or more and is able to mask out external sources of electromagnetic activity. This equipment is also particularly effective at detecting intermittent sources of discharge activity.

### Combined TEV and Ultrasonic Detection

The UltraTEV is a recent development in the hand held range of detection equipment as shown in figure 4. This instrument has been developed as a first pass tool that provides an indication of the level of PD activity within switchgear by detecting the radiating waves either or both in the electromagnetic or ultrasonic frequency range through use of a single coloured LED display. The unit has three LEDs, one to display the battery status and two to display discharge status, one for TEV and one for ultrasonic. Depending on the level of activity the discharge LEDs will either show red, green or a mixture of red, yellow and green.

To detect TEV activity the instrument is placed on the metal surface of the switchgear and the unit will continuously measure the discharge activity and display the results on the LED display. At least two discharges above the amber and red thresholds are required within a two second period to be displayed. The discharge levels at which the thresholds have been carefully chosen are based on measurements held within EA Technology's extensive partial discharge measurements database. The database contains over 10,000 records of discharge surveys on switchgear operating at 3.3kV to 132Kv in fourteen different countries around the world. The amber and red thresholds equate to readings within the top 25% and 10% of PDL readings respectively within the database. In all cases when a red level is detected, it is recommended that a further survey be carried out using some of the more sophisticated instruments to provide additional information on the magnitude, severity and location of the discharge site. Typically, the PDL1 has two probes and is capable of determining all the above parameters.



**Figure 4 UltraTEV**

### PARTIAL DISCHARGE MONITORING

Partial discharge, particularly in its early stages of development, may be intermittent in nature and lie



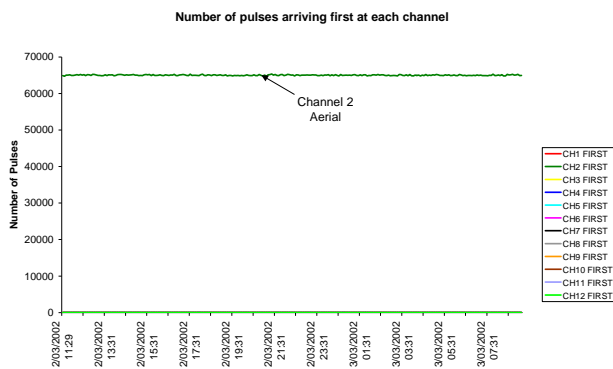
dormant for extended periods until initiated by a voltage surge or changes in temperature or humidity. The discharge site may then remain active for minutes or several hours before becoming dormant again. This sort of discharge source is very difficult to detect during a partial discharge survey, which may only take an hour for a particular switchboard.

For this reason, the original Partial Discharge Monitor (PDM03)[1] was developed. The instrument has 8 probes that are magnetically clamped onto different components of the switchboard and 4 aerials that are positioned around the switchboard to effectively mask out external sources of electromagnetic activity.

### THE IMPORTANCE OF PRECEDENCE DETECTION

The use of precedence detection within the instrument is very important for 2 reasons. Firstly this is what enables the signals from external sources to be filtered by determining that signals are detected by the aerials around the switchboard before they are detected by probes on the switchgear. An example of this is shown in Figure 2. In this instance the PDM was installed on a 33kV GIS switchboard. A survey using the PDL had shown levels of activity in the region of 21 – 26dB recorded on all panels of the switchboard and other metalwork within the substation. This was of some concern as the switchgear was recently installed and was very critical to the local network.

The results of the monitoring shown in Figure 5 reveal that nearly 17 million pulses were detected by the monitor during 1 day. Due to the precedence circuitry these were all allocated to one of the aerials and the switchboard could be given a clean bill of health. Measurements through amplitude alone would not have been able to determine whether there were internal partial discharge sources or not.



**Figure 5, Activity detected by PDM installation on 33kV switchboard**

Secondly it also enables discharge sources to be located as well as magnitudes to be detected. Although the amplitude of the signal generally decays away from the source, internal reflections and attenuation of several possible paths makes location based purely on

amplitude uncertain. Therefore, the location of the discharge is determined by which probe detects the discharge signals first. This also enables multiple discharge sources to be more readily detected by the monitor.

### The PDM100

One restriction of the original Partial Discharge Monitor was the limit of 8 probes and 4 aerials. When switchboards with more than 8 panels were to be monitored it either needed to be done in stages or for longer term installations, multiple monitors needed to be installed. This had the drawback in that the monitors could take no account of signals being detected on the other instruments.

### Hardware

The development in the hardware has addressed this problem and enabled any number of nodes up to 100 to be linked together to a central hub in the system. Each node can have a single TEV probe or an aerial attached. The nodes are able to log the magnitude, rate and precedence of partial discharge TEV signals and therefore the location capability is maintained. The modular nature of the new design means that the equipment can be tailored for a particular installation.

Whilst the configuration of the hardware of the “PDM100” is new, the equipment utilises the same measurement techniques as the existing TEV equipment. Therefore, the design of the electromagnetic partial discharge detection circuits is already well proven and the existing extensive database of partial discharge measurement results is directly applicable to the results gained using the PDM100.

Ultrasonic surveying complements the use of TEV detection. The inclusion of ultrasonic probes was a logical step in the development of the new hardware. Multiple airborne ultrasonic microphones can be included on each node and this provides additional benefit where air insulated components form part of the switchgear - providing that an air path exists between the potential sources of discharge and the outside of the switchgear.

As the ambient conditions within a substation can affect whether discharge activity occurs, particularly in the instance of surface tracking, then the monitoring of temperature and relative humidity is advantageous and therefore can also be included in the PDM100 installation.

### Software

A new suite of software, has been developed which allows access and control of the PDM100 via local serial access, Ethernet access or remote modem access and internet interfacing. The software suite allows the PDM100 settings to be remotely or locally configured dependent upon the user’s access rights.

Alarms can be configured for any of the measured parameters. In the case of TEV detection, they can be based on trends or thresholds of the severity measurements and multiple alarm levels can be set. Criteria such as the alarm threshold must be reached 5 times within a 60 minute period to avoid spurious alarms through events such as switching that may cause short bursts of electromagnetic noise. When an alarm is initiated the system can be configured to inform relevant personnel via email and/or SMS. The system can also be set to send data with the email, e.g. the last 24 hours of data prior to alarm initiation. Alternatively, users can dial up the system and display the data in real time via an internet browser.

Powerful graphing facilities are available to enable users to display different parameters such as the amplitude measurements on each probe or plots of the severity level over time. The user can also specify the time period over which the parameter is to be displayed as historical data is stored on the hub.

## EHV SWITCHGEAR

The fundamental problems of deterioration of insulation due to PD activity apply across the whole voltage range of switchgear. Considerable research has been carried out over the past 10–15 years, particularly for GIS, aimed at providing reliable and cost effective PD detection schemes. The most common detection methods available being electrical, acoustical and optical techniques[6]

### Electrical methods for detecting PD activity

Techniques include the use of narrowband and broadband PD detectors placed at suitable positions along the switchboard. The electrical methods outlined for detecting PD sources in MV switchgear generally operate in a condition between 2-80MHz. In order to achieve greater sensitivity UHF detection methods have been developed. PD current pulses in SF<sub>6</sub> can be extremely short with rise times <50ps and the signals contain significant energy at frequencies <3GHz [7]

For new or refurbished GIS internal couplers mounted on inspection plates are used, figure 6. The couplers can play a valuable role during commissioning tests[8] To avoid the operational problems of taking GIS out of service to fit internal couplers, external couplers been developed, figure 7. and can be used to detect UHF signals at electrical apertures.

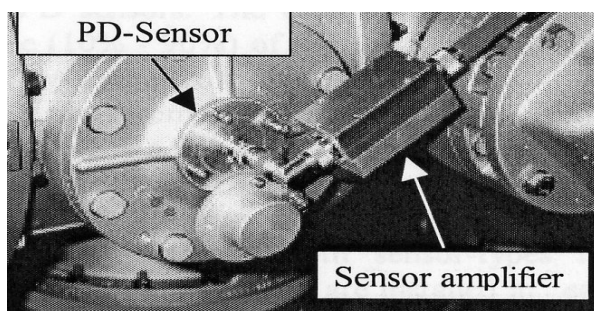


Figure 6 Internal PD Sensor

Typical locations include glass inspection windows and barrier couplers. With careful design, in certain circumstances, the sensitivity of external couplers can out perform internal couplers. They can also be totally screened to eliminate external interference. It is normal practice to fit a wide band amplifier as part of the detector circuit[9]

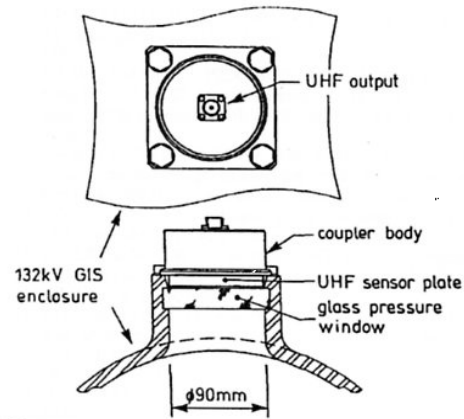


Figure 7 Internal PD Sensor

Well designed couplers are capable of detecting the PD activity from typical discharge sources within the GIS such as free metallic particles, electrode protrusions and floating electrodes all of which may lead to breakdown. The discharge pulses excite the GIS chambers into many modes of resonance at ultra-high frequency. The location of a particular PD source can be accurately located using time of flight techniques applied to the whole installation.

Coupler sensitivity affects the signal output resulting from the transmission of electromagnetic energy from a PD source. Electrical methods of PD detection are now accepted technology for GIS and most manufacturers offer on line systems. The UK specification for UHF couplers requires that the average sensitivity of a coupler over the frequency range 500-1500 MHz should produce an output voltage of no less than the 6mV rms for an incident UHF electric field of 1 volt per m, rms.

### Acoustic methods for detecting PD activity

The detection and analysis of acoustic waves generated by PD sources can be extremely complex. The wave may be distorted by a variety of factors including division due to multiple pathways, transmission losses in different media and at their interfaces and frequency dependent velocity effects. To add to the complications of detection of and analysis there are different wave types (longitudinal, transverse etc) that travel at different velocities and suffer reflections at impedance discontinuities. Even with all the above problems and with a skilled operator using the various equipment available acoustic detection in GIS is widely practiced with reasonable success.

With some instruments it is possible from the analysed waveform to determine the characterisation of the defect. In practice acoustic detection is considered as complimentary to the electrical techniques of primary PD detection in GIS.

### Optical methods for detecting PD activity

Early laboratory work to characterise PD activity and associated mechanisms of degradation using optical techniques looked encouraging, though the application of this invasive technique in the field has been limited[6] Power plant geometry and materials that are not optically transparent tends to produce very poor sensitivity.

As an alternative to the above direct optical approach the use of fibre optic technology is being explored, primarily in the acoustic detection of PD[6] Deformation of the fibre optic structure occurs when acoustic mechanical waves impinge on the cable. This results in a change to its refractive index and fibre length. With a suitable demodulator the resultant phase modulation of the light wave can be determined. The technology has been tried on GIS as a non-invasive technique by wrapping the fibres around enclosures. Acoustic PD waves due to activity within the enclosure cause small displacements that can be detected by the fibres. Calibration and sensitivity are areas requiring refinement.

### CONCLUSIONS

The use of partial discharge detection equipment is expanding as condition based maintenance practices are increasingly adopted within electricity companies and by owners and operators of electrical distribution and transmission networks. Recent developments in the instrumentation available for partial discharge detection have provided additional options for widespread use of simple and effective spot check detectors for regular surveying of medium voltage switchgear. New hardware has been developed for permanent monitoring of switchgear that due to its modular nature can be tailored for specific installations and can accommodate even the largest switchboards. The flexibility allows multi parameter monitoring of substations with web enabled access of data and alarms that can be set to send multiple emails or SMS messages when alarm conditions are met.

New EHV switchboards are invariably fitted with electrical and or acoustic on line PD monitoring schemes. Retrofitting of schemes is also widely practised. In general the schemes available for GIS

provide a reasonably early warning of developing PD activity, though it is often necessary to seek expert advice in order to determine the exact location and characterisation of the PD source. Further development work is required in order to introduce cost effective schemes with the above capabilities. It is universally accepted that undetected partial discharge activity in switchgear is the most common cause of catastrophic failure.

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## Condition Based Risk Management (CBRM), the Practical Application of Intelligent Asset Management to the United Utilities Distribution Network

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### INTRODUCTION

Many electricity company networks consist of large numbers of relatively old assets dating back to the major expansion and refurbishment of networks in the 50's and 60's and early 70's.

Despite the age of the assets in many cases they continue to perform well with a high level of reliability. It is however recognised that over the next 10 to 20 years significant investment to renew much of the network will be necessary.

As the result of privatisation of the UK electricity industry, engineers have been under increasing pressure to reduce costs and particularly to justify investment programmes. Although it is recognised that the age of the assets will necessitate significant investment, age by itself is not seen as an acceptable reason for replacement. Within this context it is therefore vital to define the condition and understand the future performance of the assets on the network in order to provide a sound basis for future investment programmes.

The condition based risk management approach described in this paper is specifically designed to address these issues. The process has been developed by EA Technology working in conjunction with many electricity companies both in the UK and overseas. In this paper the application of the process with United Utilities is described. Not only has the process enabled United Utilities to develop a sound engineering case for future investment plans, it has also provided a framework for ongoing development and application of intelligent asset management processes.

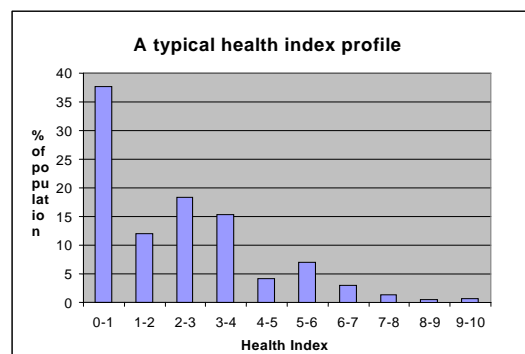
### Condition Based Risk Management

The essence of condition based risk management is defining the condition of the assets and using this to understand future performance so that risks can be identified and addressed in an appropriate and effective manner. The process can be described in a number of distinct stages.

#### Stage 1 - defining the condition of the assets

This is achieved by producing health index profiles for individual asset groups, i.e. grid and primary transformers, 11kV wood pole overhead lines, etc, etc. The aim is to define the condition of assets as a simple number, on the scale of 0 to 10, and display the results as a profile showing the distribution of condition within the asset group. A typical health index profile is shown below.

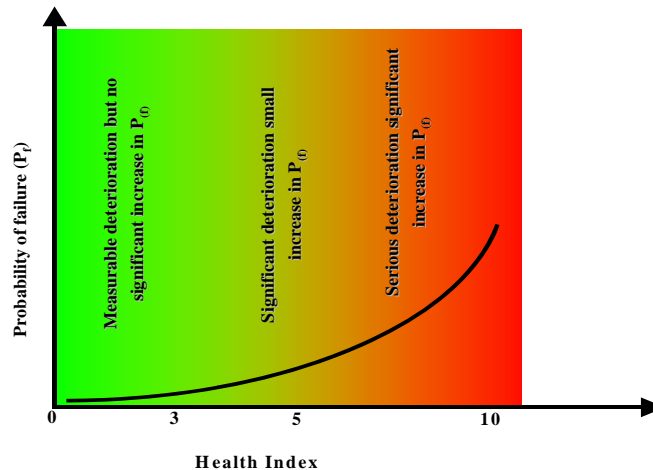
Fig.1 Typical Health Index Profile



#### Stage 2 – relating the health index to performance (probability of failure)

The health index profile are 'calibrated' against a standard shape of probability of failure curve as shown below. By using recent failure rate information the absolute values of probability of failure can be determined by matching the health index profile and the standard probability of failure curve to the actual failure rate.

Fig.2 Health Index



#### Stage 3 – estimating changes in the health index to the future

Using knowledge and experience to the degradation processes and the practical knowledge and experience of the assets the ongoing rate of degradation and therefore the rate of change of the health index can be estimated. In this way the health index profile in 5, 10, 15 or 20 years can be derived from the original health index profile.

**Stage 4 – estimating the future performance**

The future performance by, failure rate, can then be determined by applying the relationship between the health index and the probability of failure, derived in Stage 2, to the future health index profiles.

**Stage 5 – evaluate the effect of potential investment programmes on future performance**

Take the future health index profile, factor in the effect of investment programmes (asset replacement, refurbishment, enhanced maintenance etc) and recalculate the future failure rates.

The key to success of the process is being able to define the current condition of the assets via a health index profile. This may appear to be a difficult process, particularly as in many cases there will be limited condition information available. However, there is a large volume of knowledge and experience relating to the assets with a very good understanding of degradation and failure processes and in most cases a great deal of practical experience. Combining these enables credible health index profiles to be derived in most cases.

An important point to make is that our intention is to utilise existing information and not to require large scale condition assessment in order to determine initial health index profiles.

Having achieved a health index profile and therefore a numerical definition of asset condition provides a very powerful starting point for understanding future condition and performance. This then enables evaluation of the risks posed by the future condition of the assets and the means of evaluating the effect of future investment programmes on these risks.

An essential feature of the CBRM process is that it is based on the best knowledge and understanding of the assets available and therefore the conclusions that are derived are both credible and defensible.

In the following sections of this paper the process and its potential are illustrated by its application to the United Utilities distribution network.

**Application of CBRM to the United Utilities Network**

UUSD carried out an extensive study into the most appropriate method of delivering an improved approach to asset replacement forecasting & prioritisation. This concluded that the joint development of the EATL work on Health Indices into a comprehensive CBRM approach was the optimal solution. Using this approach would also build on the work undertaken in UUSD to introduce a single asset register (Master Asset Management System) and incorporate feedback from Ofgem received following the Asset Risk Management survey in 2002 and perceived infrastructure failures in other industries. CBRM provides a fundamental review both of the data UUE needs to collect about each asset and also what data UUE actually collects. It builds upon the data collected to

define the condition of any asset in a structured auditable way and relates failure data, captured independently of asset data, to condition information to develop the probability of an asset failing. Using CBRM, UUSD builds on the knowledge gained during years of industry R&D to understand how assets degrade and hence how the probability of asset failure varies with time.

**Description of United Utilities Networks**

United Utilities' distribution network covers 12,500 square kilometres in the north west of England, from Macclesfield in the south of the region to Carlisle in the north and from the Irish sea coast to the Pennines. United Utilities provides an electricity network for 2.3 million customers throughout Cumbria, Lancashire, Greater Manchester and parts of Yorkshire, Cheshire, Derbyshire and Merseyside. In general, four major networks are used, operating at extra high voltage (EHV) - 132kV, 33kV, high voltage (HV) 11kV or 6.6kV and low voltage (LV) - 400/230 volts.

This 58,000 kilometre electricity distribution network delivers 25,400 gigawatt hours of electricity annually from the National Grid to the 2.3 million customer premises (domestic and business) in north west England. United Utilities charges supply companies for using our distribution network.

Both underground cables and overhead lines are utilised to distribute the electricity. Underground cables supply dense urban areas. A mix of underground cables and overhead lines is used for smaller towns and semi-urban areas whilst rural areas are predominantly supplied by overhead lines.

This network covers a diverse range of terrain and customer mix from an isolated farm in Cumbria to the areas of industry and dense urban population in Manchester.

**United Utilities Objectives**

When developing the CBRM approach, United Utilities defined the following objectives for the process:

- Identification of all asset types (description and numbers)
- Assessment of a suitable end of life (EOL) description for each asset
- Assessment of the quality and suitability of data already collected and held by the business.
- Condition assessment of all assets (where practicable)
- Assessment of the probability of failure of assets based on condition and relationship to known failures
- Prediction of future failure rates using the probability of failure and an assessment of the rate of degradation.

Using this information the business was able to predict, using

an auditable methodology, what its asset replacement requirements would be in the XD4 review period 2005 to 2010. Going forward, as more information is collected, the process can be used to identify which assets require intervention and thereby more accurately target capital investment.

### Asset Groups

In order to apply the condition based risk management approach the United Utilities asset base was split into 22 main asset groups. These are listed below. The intention at the beginning of the project was to derive health indices for all the A and B assets. It was recognised at the outset that for the assets in Category C it may not be possible to derive a meaningful from the health index from the information that was available. In practice credible health indices were produced for all the assets in the Categories A and B (except protection and telecommunications equipment). In these cases it was concluded that condition was not a major reason for end of life or replacement. Obsolescence or lack of functionality were more important and therefore a condition index was deemed unnecessary. Within the assets in the C categories, a health index was produced for C14, LV mural wiring. For the remaining C assets, although a health index was not specifically derived, an analysis of the background information, knowledge and experience of the asset was used to estimate future condition and performance in a less formal manner.

**Figure 3**

#### UNITED UTILITIES ASSET GROUPS

Group designation	Asset description
A1	Ground mounted distribution trans.
A2	Grid and primary switchgear
A3	Distribution switchgear
A4	Batteries
A5	LV link boxes and feeder pillars
A6	Pole mounted switchgear
B7	Grid and primary transformers
B8	Distribution substations civil
B9	Steel tower OHLs
B10/11	Woodpole OHLs
B12	33 and 132kV cables
B13	6.6 and 11kV cables
B21	Protection
B22	Telecommunications equipment
B23	Grid and primary substations civil
C14	LV mural wiring
C15	LV cables
C16	Pole mounted transformers
C17	LV panels and cabinets
C18	Domestic services
C19	Street furniture
C20	Commercial and industrial cut outs

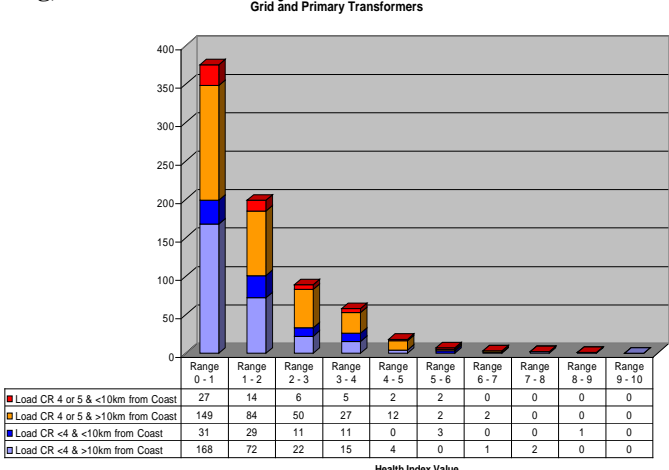
### Examples of Results for Specific Asset Groups

In general the process revealed assets in reasonable condition. However, it did predict that in many cases there would be significant increases in the failure rate unless some asset replacement was undertaken.

### Grid and Primary Transformers

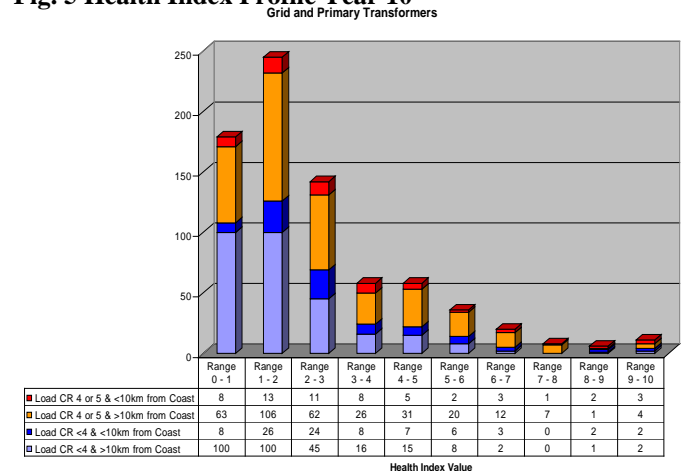
The health index profile below indicates the population of grid and primary transformers in reasonable condition but with a small number of assets in poor condition and a significant number of assets in the mid regions whose performance is likely to be of concern in the medium term.

**Fig. 4 Grid and Primary Transformers Health Index**



By applying the ageing process to the health index profile we derived the following health index profile for year 10. For this asset group we were able to apply different ageing rates depending on the operating conditions (these are represented by different colours in the profile). Applying the probability of failure relationship (derived by matching the current failure rate to the current health index profile) to the 10 year health index profile indicates a significant increase in the failure rate by year 10 unless some investment is undertaken.

**Fig. 5 Health Index Profile Year 10**



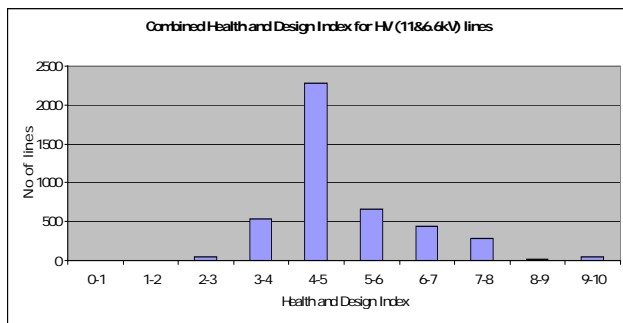
In order to maintain the failure rate at the current low level it will be necessary to replace 1.2% (approximately 90) transformers over the 10 year period or to combine replacement of less transformers with a programme of refurbishment and enhanced maintenance.

### 11kV Overhead Lines



In this case it is recognised that the performance of wood pole overhead lines is a combination of both design and condition. Therefore the health index was derived from factors relating to both. In fact it became clear that while the condition of the lines was generally good a significant proportion of the wood pole overhead lines faults could be related to the design of the lines. A factor that would also make the lines particularly susceptible to severe weather situations.

**Fig.6 Overhead Lines Combined Health and Design Index**



When considering the future performance of these lines it was recognised that the design factors will not change therefore the degradation of the combined index into the future is predicted to be modest. In this case rather than use the results to indicate the level of refurbishment of overhead line necessary to achieve a constant failure rate the results were used to evaluate the extent of overhead line refurbishment necessary to reduce the current fault rate to defined levels.

#### Use of Results in the Regulatory Process

When preparing its Capex application to Ofgem for the 2000 - 2005 price review (XD3), United Utilities used a top-down modelling approach based on the age of assets. Since this review took place accepted best practice, both in the electricity industry and externally, has moved towards condition monitoring and an understanding of deterioration and modes of failure.

In light of this, United Utilities prepared its XD4 Capex submission using the CBRM process to assess and rank assets based on their condition and subsequent risk of failure. A spreadsheet combining predicted fault rates, the proactive replacement rate necessary to maintain or improve on these fault rates and the unit costs of asset replacement was prepared and an overall asset replacement cost calculated. This process enabled the predicted spend per asset to be identified and sense checked with the relevant experts within the business. Building the forecast spend using this bottom up approach highlighted some areas of concern where higher than expected spend was predicted at an early stage. This allowed further investigation to be carried out to verify (or disprove) these predictions. When the detailed Ofgem questionnaires were received by the business this information could readily be used to complete tables and answer specific questions about the businesses spending plans and how they were arrived at.

When Ofgem's representatives and their expert consultants visited United Utilities to discuss the company's spending plans, it could be clearly demonstrated how the replacement figures had been arrived at. A full audit trail of asset numbers, condition assessments, relationship to actual failures etc. was available to justify the proposals.

#### Future Opportunities (Building the Process into Business as Usual)

Fundamental to the application of CBRM is the collection and manipulation of asset condition data. Traditionally, asset inspection in United Utilities has been defect based i.e. the inspectors only report what is wrong with an asset with no indication of deterioration until it actually affects the future performance of a piece of equipment. The application of CBRM requires that an assessment is made of what level of deterioration is apparent in key components of an asset so that a reasonable prediction of its remaining life can be made. This change affects all the inspections carried out by the business including assessments made during maintenance. The business is currently reviewing all its inspection procedures to incorporate the requirements of CBRM. A key component of a revised inspection regime is the manner in which data is captured. Whilst a paper based system would undoubtedly be sufficient to collect information, it is not conducive to accurate and timely data transfer into the corporate asset register (MAMS). To this end, United Utilities is carrying out an evaluation of suitable electronic data capture devices and associated software.

With asset condition information collected, the business can then set about using this information to rank asset types into a prioritised replacement list. However, condition alone is not the only driver when assessing where investment should be made. Other factors such as safety, connected customers and legal obligations all play a part to a greater or lesser extent. United Utilities has already begun to assess the various effects of asset failure against these factors and to identify potential intervention strategies to mitigate the overall risk.

In the medium term, United Utilities aims to completely embed the principles of CBRM into all its inspection and maintenance activities and to routinely use this information to prioritise asset replacement. This prioritised list will then be further refined by an assessment of relative asset criticality against a range of risk criteria as defined in the companies risks & issues database. In this way, investment can be targeted to where it is most needed, both to maintain the condition of the asset base and also maintain, or improve, network performance.

#### Implications and Opportunities for Future Asset Management of Distribution Networks and other Engineering Assets

The CBRM process has been designed to put condition at the

heart of asset management. Its strength is that it is based on combining all available knowledge and experience of the assets to provide a credible definition of condition. Its successful application within United Utilities (and several other electricity companies) relied on the ability to define condition from existing information, despite the fact that for many of the assets there was little specific condition information. Because of the detailed understanding of degradation and failure processes and the extensive practical knowledge of the assets available it was still possible to derive and populate a credible health index.

Our experience, both within United Utilities and in other electricity companies indicates that for assets that make distribution networks this will almost always be the case. It is therefore a practical proposition to define the condition of distribution network assets in this way. The definition of condition in this way then enables a real understanding of the future performance.

We therefore believe that the process is eminently application to the assets of any electricity company. Indeed, in principal the process is applicable to any assets, however, in order to make it work it is essential to have a good understanding of the failure and degradation processes and access to extensive practical knowledge of the assets.

A particular feature of the application of CBRM to distribution networks is that in general we can proceed to initial results and useful output without the need for large scale condition assessment activities. Our aim is always to utilise existing information, knowledge and experience. However, having undertaken the process having carefully analysed the information that is available and how it can be used to define condition inevitably results in clear understanding of the improvements in information that could be obtained. Therefore, one very important bi-product of the process is identification and definition of the future activities to gather condition information that will enhance the ability to define condition in the future.

In general, it would be our intention to define collection of information related to condition that could be undertaken as part of ongoing routine inspection and maintenance activities and therefore would not add significant cost. Indeed, it is our belief that application of this structured approach to defining asset condition may in the end result in reduction in the cost of inspection. A very important issue in this area is the way in which information is collected and managed. One of the major difficulties we have when applying condition based risk management within any utility is accessing and qualifying information then combining it to give a result for a specific asset. In our experience asset management information systems leave much to be desired. An additional benefit of the process is that it clearly demonstrates the potential benefits to the company of rationalising their information collection and management systems.

Overall, the process is capable of providing an immediate result in terms of defining asset condition and using this to

project forward to understand future investment requirements. It also provides powerful justification and guidance for future asset management processes including improvement of information systems.

## Conclusions

The process of CBRM has been successfully developed and applied with a number of electricity companies. It has proved very successful and has enabled for the first time asset condition to be used as the basis of determining future investment programmes.

The application with United Utilities has demonstrated the value of the process providing not only immediate benefits for the current investment cycle, but a framework that will enable the ongoing development and implement of intelligent asset management within United Utilities.

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