UNIVERSITI TEKNOLOGI MALAYSIA

Chapter 5

Monitoring of SF_6 Insulation Systems

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1 Introduction

- Aims
  - To review
    - basic ionisation processes which occur in SF_6
    - **Streamer** mechanism which controls breakdown under relatively **uniform field** conditions
    - The influence of **electrode roughness** on breakdown at high pressure
  - To study PD (corona) phenomena which occur under the non-uniform field conditions associated with certain types of defect
  - To study PD diagnostic techniques

2 Ionisation phenomenon in SF_6

- Why SF_6 has larger dielectric strength compared to other gases?
- Electron attachment property/ electronegativity

$$SF_6 + e \rightarrow (SF_6)^-$$

- Competes with collisional ionisation which is mainly responsible for the breakdown in gases

$$SF_6 + e \rightarrow (SF_6)^+ + 2e$$

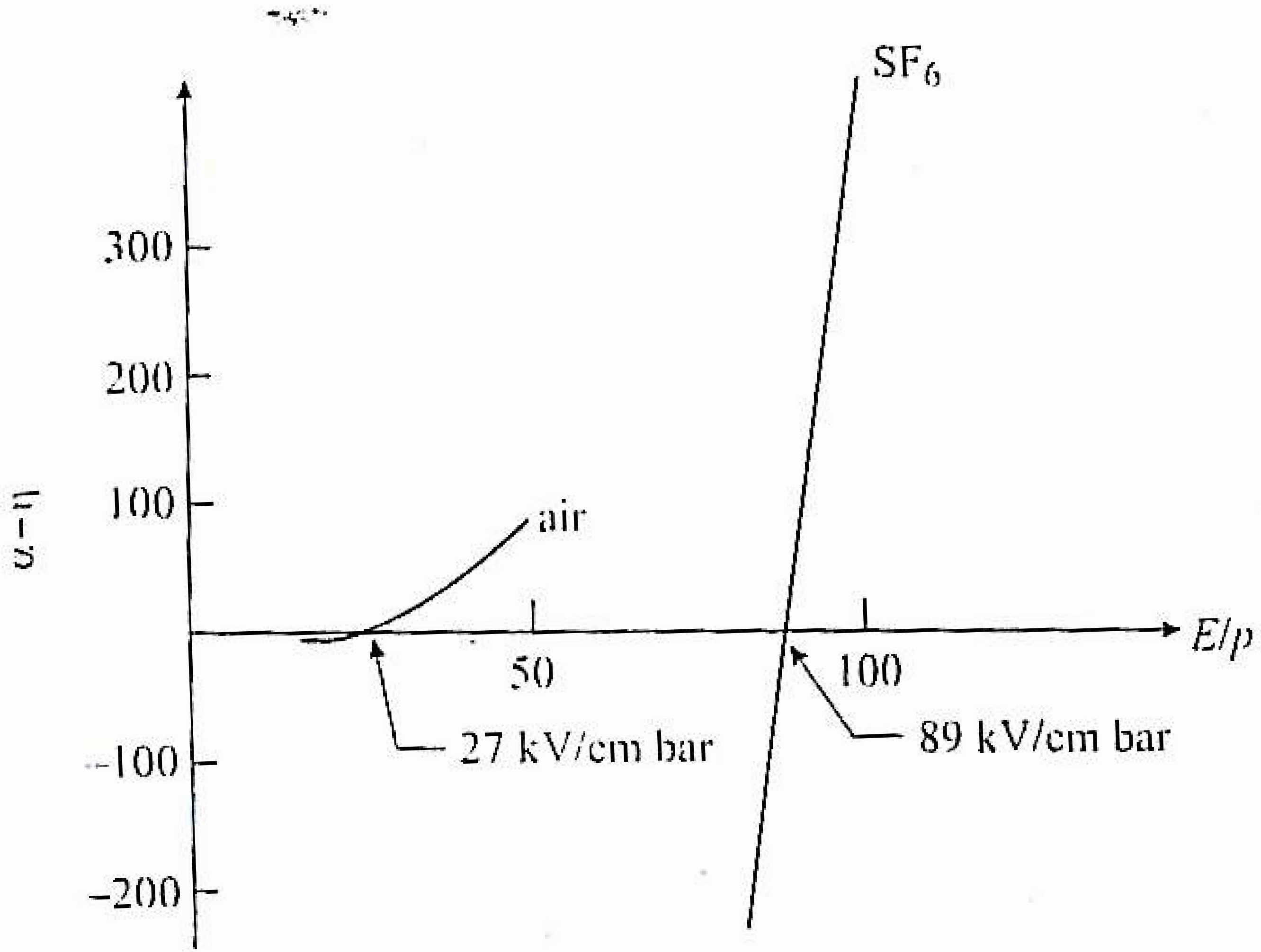
- Compare the $(SF_6)^-$ and e and describe how the attachment process actually make the breakdown more difficult to occur
- Compare SF_6 with other gases such as nitrogen, hydrogen and argon. Also oxygen and CO_2.
- How does the (net) rate of electron production in SF_6 depends on the gas pressure and the applied field?

- Two coefficients are significant, α and η.

$$\frac{\alpha}{p} = f_1\left(\frac{E}{p}\right)$$

$$\frac{\eta}{p} = f_2\left(\frac{E}{p}\right)$$

- The net ionisation depends on the values on α and η.
- Fig. 2.1 shows the net (pressure-reduced) ionisation coefficient $(\alpha-\eta)/p$ as a function of E/p for air and SF_6.
- It can be seen that the critical reduced field strength at which $(\alpha-\eta) = 0$, is about 89 kV/cm bar in SF_6 relative to air as no build-up of ionisation can occur until the reduced field exceeds the critical value $(E/p)_{crit}$.
- The steep slope of the curve of $(\alpha-\eta)/p$ versus E/p in SF6 shows that SF6 is a relatively brittle gas in that, once $(E/p)_{crit}$ is exceeded, the growth of ionisation is very strong.



Effective ionisation coefficients in air and SF_6

- This is significant in situations where stress-rising defects are present in GIS as intense ionisation activity will occur in the region where $E/p > (E/p)_{crit}$ and this may initiate complete breakdown of the insulation.
- Also, the net ionisation coefficient can be represented by

$$\frac{\alpha - \eta}{p} = A\left(\frac{E}{p}\right) - B$$

- At critical value,

$$\left(\frac{E}{p}\right)_{crit} = \frac{Bp}{A}$$

- Substituting know constant A = 27.7 kV^{-1} and B = 2460 $bar^{-1}cm^{-1}$, we get

$$\left(\frac{E}{p}\right)_{crit} = 88.8\ kV/cmbar$$

Quiz

1. Describe the ionisation process in a gaseous medium.
2. Describe the differences in the ionisation process in SF_6 gas and in air.
3. Describe
   - basic ionisation processes which occur in SF_6
   - **Streamer** mechanism which controls breakdown under relatively **uniform field** conditions
   - The influence of **electrode roughness** on breakdown at high pressure

3. Breakdown mechanisms in Uniform field low divergence fields

- The build-up of ionisation in SF_6 is possible only under conditions where the (pressure-reduced) field exceeds a critical value $(E/p)_{crit}$ of ~ 89 kV/cm bar.

- For highly divergent fields (as, e.g., for the case of a sharp protrusion on a high voltage conductor) ionisation will be confined to a critically-stressed volume around the tip of the protrusion. In this situation localised PD, or corona, will be the first phenomenon observed as the applied voltage is increased. Breakdown under these conditions is a complex process, because of the effects of the space charge injected by the prebreakdown corona. As any stress-raising defect in gas-insulated equipment will result in PD activity, it is important to understand non-uniform field discharge mechanisms.

- However, GIS are designed for relatively low field divergence and it will be useful first to consider the simple case of breakdown in SF_6 under uniform field conditions, before reviewing the phenomena associated with particulate contamination or other defects.

3.1 Streamer Breakdown

- For a perfectly uniform field (plane-plane electrode geometry), **no ionisation activity can occur** for **reduced fields less than the critical value**.

Above this level, ionisation builds up very rapidly and leads to complete breakdown of the insulation (formation of an arc channel).

- The first stage of the breakdown involves the development of **an avalanche of electrons.** The **growth** of this avalanche from a **single starter** at the **cathode** can readily be found by computing the net electron multiplication.

Considering a swarm that has grown to contain n(x) electrons at position x in a gap of width d; then, in travelling a further incremental discharge dx, these will generate a net new charge:

$$dn(x) = (\alpha - \eta)n(x)dx = \bar{\alpha}n(x)\,dx$$

where $\bar{\alpha}$ is the net ionisation coefficient.

- Integration over the interval 0 to x gives the number of electrons in the avalanche tip at that stage in its growth:

$$n(x) = \exp\left(\int_0^x \bar{\alpha}\, dx\right) = \exp(\bar{\alpha}\, x)$$

- In crossing the whole gap, an avalanche of exp(〈 d) electrons is created.

- 〈 **increases very quickly when the reduced field exceeds $(E/p)_{crit}$**

- At a **critical avalanche size** (exp(〈 x) = N_c), the space charge field is high enough to generate **rapidly moving ionisation fronts** (**streamers**) which propagate at ~10^8 cm/s towards the electrodes.

When these bridge the gap, a highly conducting channel is formed within a few nanoseconds.

- For pressures used in technical applications (p > 1 bar), the **streamer process** is the accepted breakdown mechanism in SF_6 under relatively uniform field conditions.

- The **critical avalanche size** for streamer formation is found to be that for which the streamer constant ***k* = *ln* N_c is approximately 12. The** breakdown voltage can then be calculated using

$$\frac{\bar{\alpha}}{p} = A\left(\frac{E}{p}\right) - B$$

- A = 27.7 kV^{-1} and B = 2460 $bar^{-1}cm^{-1}$

- **The minimum streamer inception or breakdown level will occur when the critical avalanche size is achieved at the anode. Thus**

〈 d = AEd – Bpd = k

- The breakdown voltage Vs (=Ed) is then

$$V_s = \frac{B}{A}(pd) + \frac{k}{A} = 88.8\,(pd) + 0.43 \quad (kV)$$

where pd is in bar cm

- Note that the breakdown voltage is a function only of the product (pressure x spacing). This is an example of the similarity relationship (Paschen's Law) which allows gas-insulated equipment to be made more compact by increasing the pressure above atmospheric.

3.2 Quasi-uniform fields (coaxial cylinders)

- Similar equation in terms of inner and outer radius is available.

$$\frac{E(r_0)}{p} = 89[1 + (0.07\sqrt{pr_0})]$$

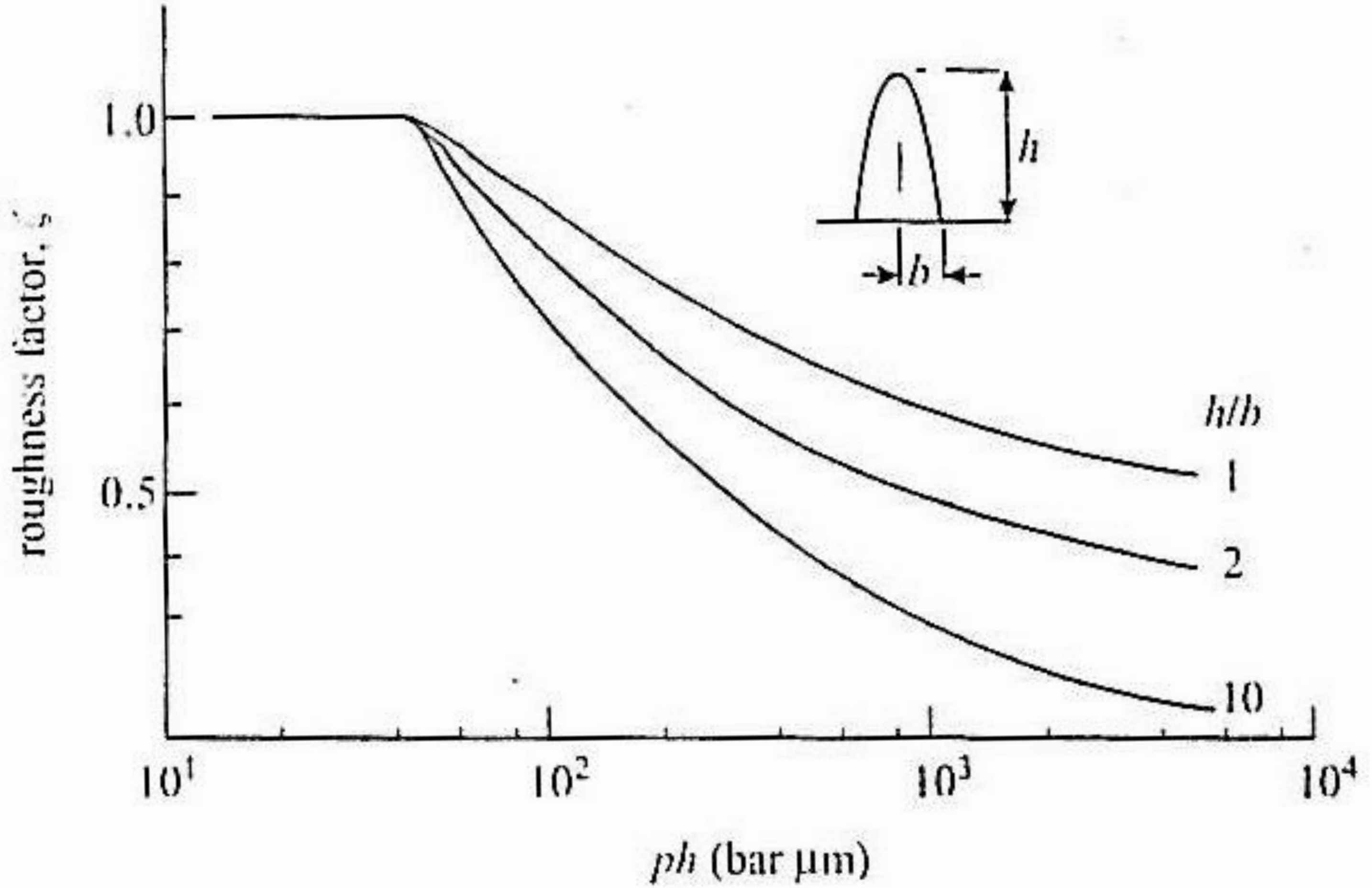
pr_0 in bar cm

3.3 Effect of surface roughness (uniform fields)

- Breakdown strength is reduced by a factor (**roughness factor**)
- One reason for this is the fact that increased ionisation occurs in the vicinity of **microscopic surface protrusions** (surface roughness)
- This results in **reduction of the breakdown field strength** by a factor ξ
- Fig. 2.2 shows calculated values of the factor as a function of the product **ph** (pressure x protrusion height) for a range of spheroidal protrusions.
- It can be seen that

  (a) the breakdown voltage can be reduced to a low level and

  (b) that there is a critical protrusion size for the onset of roughness effects



Roughness factor for uniform field breakdown in SF_6

- With a good technical surface finish, streamers **should not** form in a clean coaxial electrode system (field much lower than the critical field)

- Further, if a local defect does cause streamer formation, the streamer should not be able to propagate into the low field region of the gap.

- The fact that breakdown can occur, even at the lower reduced field associated with AC working stress (~15 kV/cm bar) indicates that an additional mechanism is operative (**non-uniform field breakdown**) (hence one must design the GIS such that the existence of non-uniform field is avoided)

4. Non-uniform field breakdown in SF_6

- **Highly divergent** fields, or **non-uniform** fields, can exist in GIS under certain conditions as, for example, when a needle-like free metallic particle is attracted to the inner conductor or is deposited on the surface of an insulator.

- Such defects can result in very low breakdown levels and, with large defects (e.g. particles several mm long), failure can occur even at the working stress of the equipment.

- For this reason, there have been many **laboratory studies** of the breakdown characteristics of highly non-uniform field gaps in SF_6.

- These studies have shown that there are **two** distinct types of breakdown, depending on the **rate at which the voltage is applied** to the gap.

- When the stress is applied relatively slowly, as with alternating voltage or long rise time switching surges, corona space charge plays an important part in controlling the field distribution by the so-called corona stabilisation process.

- With shorter rise time surges (lightning impulse or fast transients), breakdown occurs directly by a stepped leader mechanism.

- For both cases, the breakdown voltage is lower when the high field electrode is **positive** and most attention has therefore been given to breakdown under positive point conditions.

- As previously mentioned, the breakdown strength of SF_6 under non-uniform field condition is much lower than 89 kV/cm.

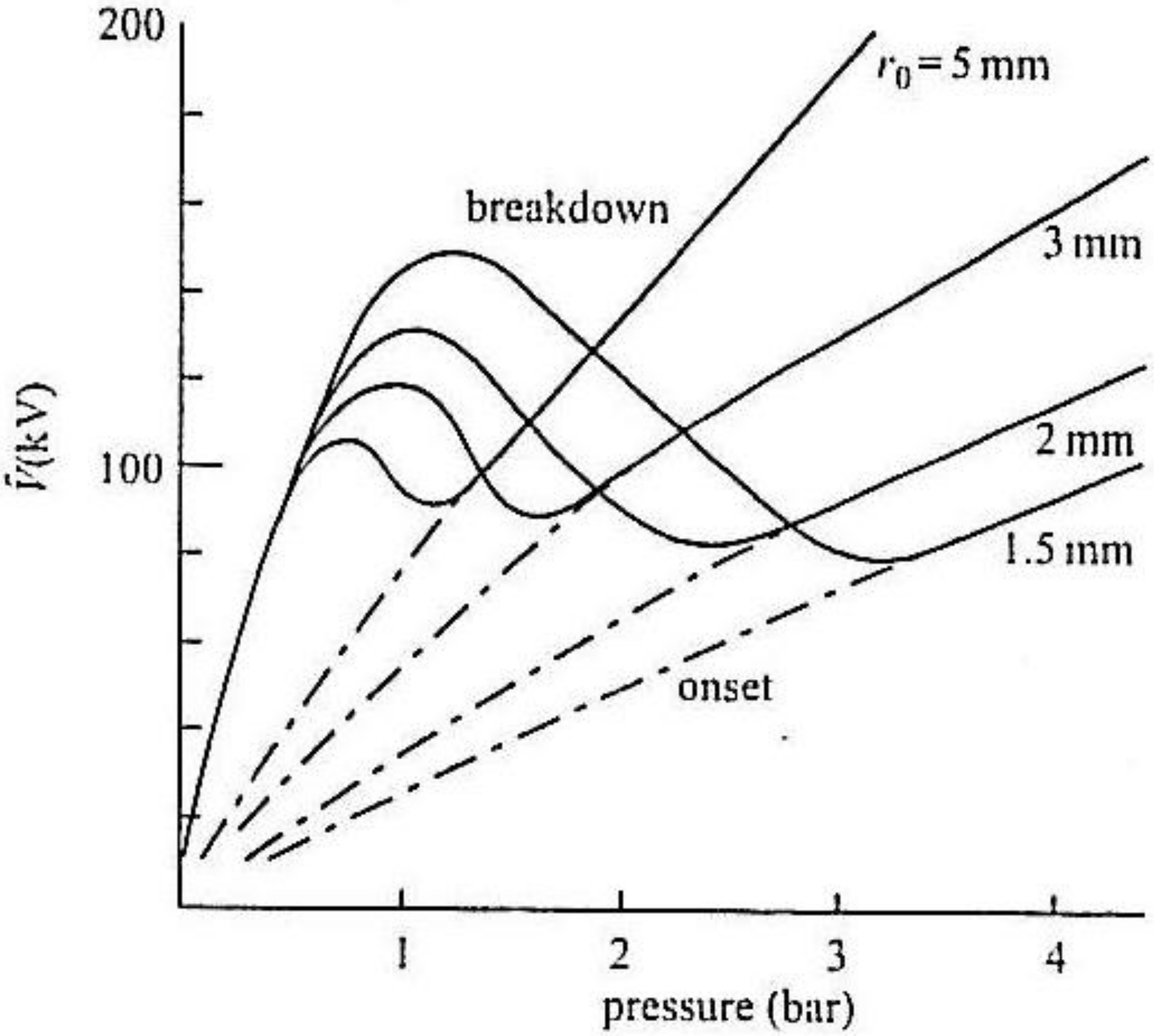
4.1 Corona stabilised breakdown (Slow wave)

- Figure 2.4 (r_o is the inner radius) shows AC voltage-pressure characteristics for point-plane gaps in SF_6.
- The shape of these curves is typical of all non-uniform field gaps with slowly varying voltage applied, in that there is

  (a) a broad pressure region over which the **breakdown voltage** is much **higher** than the (**streamer** corona) **onset voltage**, and

  (b) a **critical** pressure at which breakdown occurs directly at onset (i.e. the first streamer leads directly to breakdown).

- The peak in the mid-pressure range is due to the effects of space charge injected by streamer activity around the point



AC corona onset and breakdown characteristics for a 40 mm rod–plane gap in SF_6 [4]

- The **discharge** at the **critical pressure** has been shown to be **identical** to the **stepped leader discharge** which is found to occur in **non-uniform field gaps under fast pulse conditions.**
- **The breakdown mechanism and breakdown strength of SF6 under non-uniform field condition is dependent on:**

➢ **Electrode configuration**

➢ **Type of applied voltage**

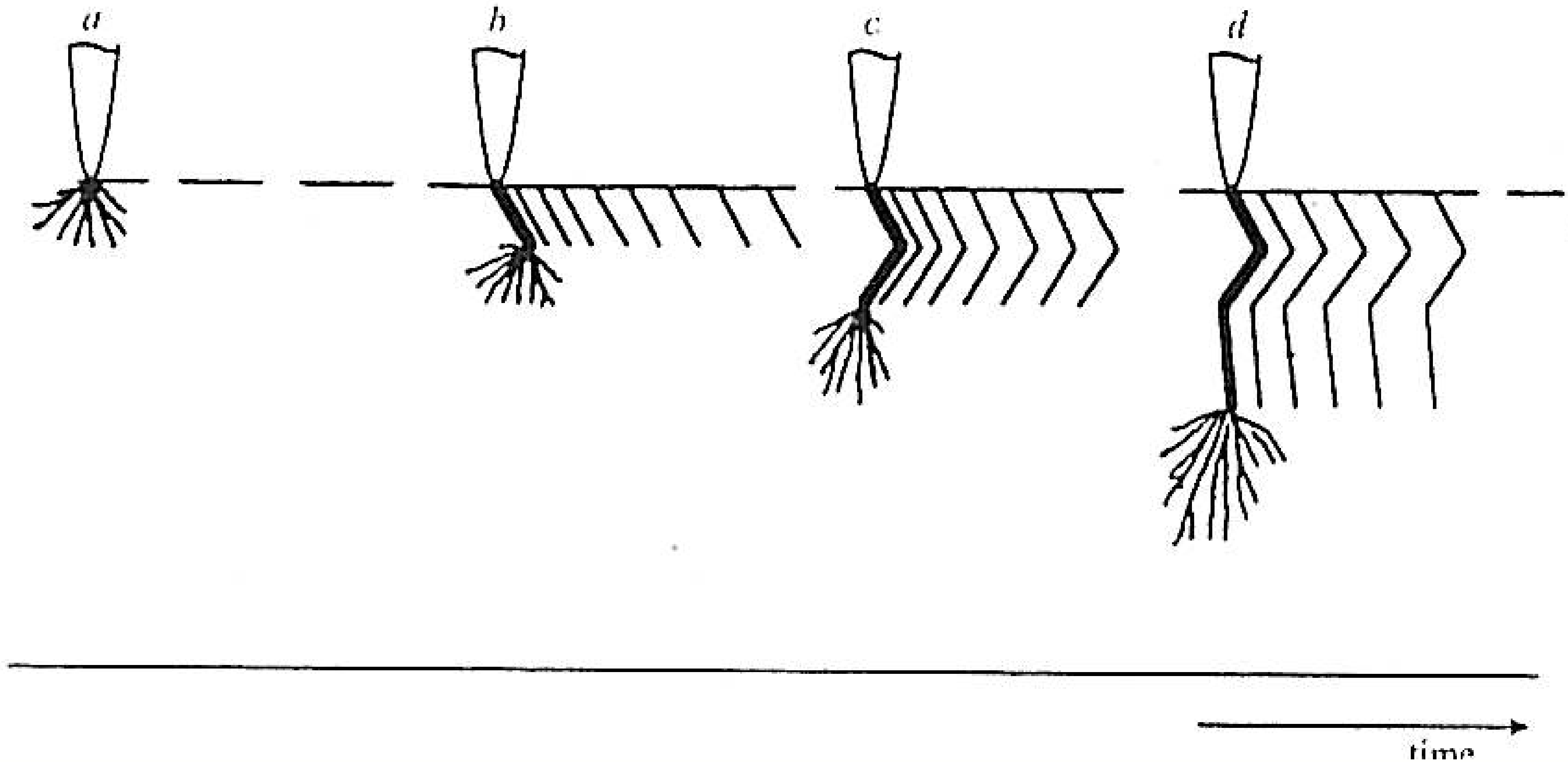
➢ **Polarity of applied voltage**

➢ **SF6 Pressure**

4.2 Leader breakdown (Fast wave)

- With fast-fronted surges (an example of fast wave), where the **voltage passes rapidly through the theoretical streamer onset level**, the **initial streamers can be very intense** and may lead to the formation of a **highly ionised leader channel before there is time for space charge stabilisation** of the **field at the tip of the protrusion**.

- Fig. 2.5 summarises the mechanism of the stepped leader.



Schematic of leader development

- During the dark period a—b which follows the **initial corona**, **charge separation** in the **streamer filaments** generates a **succession of ionising waves which build-up their conductivity.**

- Eventually, **one of the streamer filaments is transformed into a highly conducting leader channel step**; this behaves essentially as an **extension to the point electrode** and a **new corona burst immediately occurs at its tip b.**

- The range of this second corona determines the length of the second channel step c.

- During each streamer's dark period, there are regular reilluminations of the leader channel, probably associated with the relaxation processes which are occurring in the streamer filaments.

- The **leader propagates into the gap in steps** typically of a few mm until the streamer activity is too weak for further channel steps to form.

- If the voltage is high enough, the **leader can cross the gap, resulting in breakdown.**

- As the field along the leader channel is much lower than that in the streamer filament, breakdown can occur by the stepped leader process at much **lower** voltages than would be required for streamer breakdown (**notice the difference between streamer AC/DC solid line and impulse dotted line**- also idpdt of p)

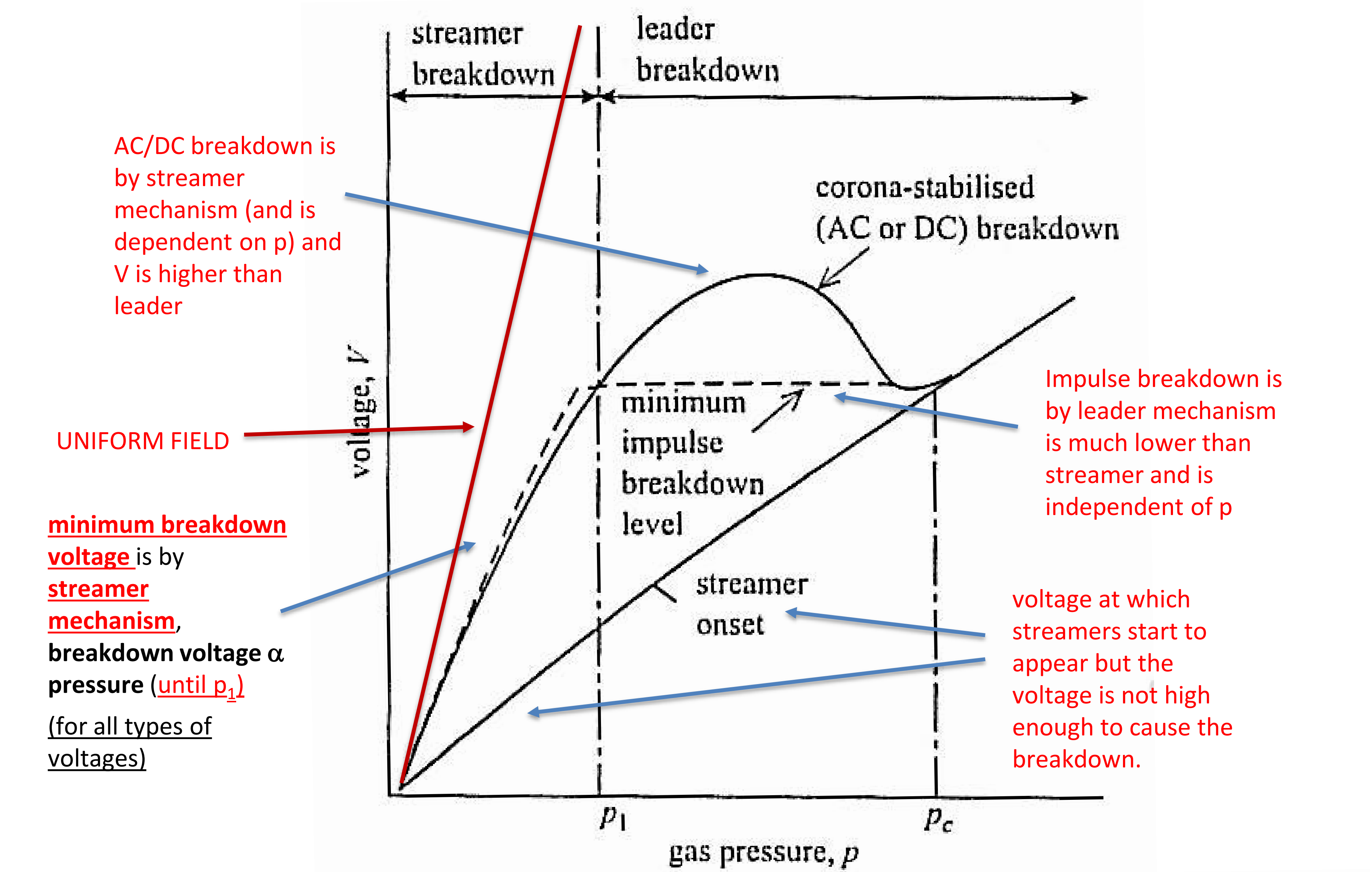
- **For point-plane gaps**, the **minimum** leader breakdown voltage is found to be almost independent of pressure and average breakdown fields of **~25kV/cm** are typical of short (20-50mm) gaps (compared to 89 kV/cm for uniform field).

- In configurations where the background field in the low field region is falling less steeply (eg particle fixed to inner conductor), **leader breakdown can occur at average fields of only ~15kV/cm (compared to 89 kV/cm for uniform field).**

- Figure shows **Vp characteristics** in SF_6, for **corona-stabilised breakdown and** for the **minimum breakdown voltage under impulse** conditions.

- As **p_1 is typically only about 0.5 bar**, the **minimum** breakdown voltage in **non-uniform fields** at pressures **typical of GIS** is determined by the conditions for **leader propagation** in the absence of preexisting corona space charge.

- As can be seen in the figure (showing breakdown voltage versus pressure), for pressures above p1, the minimum breakdown voltage (setting the strength of typical GIS) is determined by the leader breakdown mechanism. For pressure less than p1, the mechanism in operation is the streamer (uniform field) breakdown.



Idealised V–p characteristics for minimum impulse (direct leader) breakdown and corona-stabilised (AC or DC) breakdown in a point-plane gap in SF_6 [7]

The **effect of wave speed / type of applied voltage** can be described as below:

- The dotted lines describe the **minimum impulse voltage to cause breakdown.**
- Two mechanisms are in play: streamer (**uniform field**) and leader.
- For **low pressures**, the **minimum breakdown voltage** is determined by **streamer mechanism**, **the higher the pressure, the higher the breakdown voltage**, until a certain pressure (p1) where the **breakdown is now occurring according to leader process**.
- The **streamer onset voltage** is the voltage at which streamers start to appear **but the voltage is not high enough to cause the breakdown**.

- With fast-fronted surges (an example of fast wave), where the **voltage passes rapidly through the theoretical streamer onset level**, the **initial streamers can be very intense** and may lead to the formation of a **highly ionised leader channel before there is time for space charge stabilisation** of the **field at the tip of the protrusion**.

- As the pressure is increased further, the impulse voltage to cause breakdown is more or less constant, in other words, not influenced by the pressure.

- The difference between breakdown voltage and the theoretical streamer onset is **reducing** as the **pressure is increased** until a point where the difference is zero, ie an onset streamer leads right away to breakdown (critical pressure p_c).

- The reason for a peaking process is due to the corona stabilisation effect, ie larger voltage is required at the peak condition pressure due to the corona appearing at the onset streamer/corona voltage followed by space charge stabilisation.

5 Breakdown in GIS

5.1 Streamer-controlled breakdown

- The design stresses used in GIS are low (<50% E_{crit}) and hence streamer inception will not occur even at full rated impulse level (if purely based on the design)

- However, scratches or other small defects on the inner electrode surface may result in streamer formation (V at much lower than the uniform field case)

- The breakdown voltage can then be predicted on the basis of the streamer criterion (k = 12)

$$exp\left[\int_0^x (AE(x) - Bp)dx\right] = N_c$$

5.2 Leader breakdown

- For **large defects**, such as needle-like particles of several mm length attached to the high voltage conductor, the **onset voltage** for **streamer corona (streamer onset voltage)** will be low.

- This means that the onset voltage is lower than the leader propagation voltage and breakdown is preceded by corona.

5.3 Particle-initiated breakdown

- **Free conducting particles** (**FCPs**) are the most common cause of failure in GIS, and long, thin particles are most dangerous because of the **strong field enhancement** associated with such defects.

Describe what do you think will occur to a FCP under DC and AC voltages/stress?

- For normal working stresses, particles of length less than ~4mm should not be able to cause breakdown.
- However, smaller particles may be scattered onto the surfaces of insulating barriers or spacers, where they may cause breakdown under subsequent impulse stresses.

- It is important, therefore, to ensure that FCPs of significant size (>1mm) are not present in GIS under working conditions.

6 Possible improvements in SF_6 insulation

6.1 Use of **additives** or **gas mixtures**

- The dielectric properties of SF_6 can be significantly improved by using **leader-suppressing additives** such as Freon 113, although the use of such additives in GIS would require confirmation that they have no effect on the solid insulation in the system.

- **Gas mixtures** containing **buffer gases** such as N_2 in concentrations of up to 80 per cent have dielectric strengths which are not much below that of SF_6 under clean conditions and may be less susceptible to particulate contamination.

- SF_6/N_2 mixtures are particularly attractive for use in gas-insulated transmission lines because of their **lower cost** and **reduced environmental impact**.

6.2 Improved spacer formulation and construction

- There is continual progress in the development of **resins and fillers** with improved properties in terms of **mechanical strength**, **resistance to tracking** and **compatibility with SF_6 discharge products**.

6.3 Particle control

- Although every effort is made to ensure that FCPs are removed during preassembly cleaning of GIS, particles can be produced during operation, for example as a result of abrasion of sliding contacts.
- Simple slotted trays in the outer conductor make very effective **particle traps** and their use in the vicinity of solid spacers can offer useful protection.
- Other proposals for particle control have included techniques for covering FCPs with a **sticky insulating coating** by post-assembly polymerisation of an appropriate additive to the SF_6.

7 Partial discharge diagnostic techniques for GIS

7.1 Introduction

- So far the main objectives of GIS diagnostics have been to detect whether there is any defect in the GIS, to identify it as a particle, floating shield and so on, and to locate it so that it can be repaired.

- Various diagnostic techniques have been demonstrated in the laboratory, and with some of them several years' experience on site, both during commissioning tests and with the GIS in service, has been gained.

- The results of the on-site work have been very promising, and have shown the need for these further **developments**:

  i. 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 and its significance assessed.

ii. Continuously monitoring one or more GIS can produce very **large quantities of data**, and it is important not to overburden the engineer with its interpretation.

The discharge data needs to be analysed by an expert system, and the engineer informed only when some condition arises which needs attention.

iii. 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 plant, and so provide a **complete diagnostic system** on which predictive maintenance of the GIS can be based.

7.2 The range of diagnostic techniques for PD detection

7.2.1 Fundamental processes

- The statistics of GIS reliability show that the most common cause of electrical failure is a **free metallic particle**, which can become **attracted** to the **high voltage conductor** and produce a **microdischarge** which triggers breakdown.

- Other causes of failure are discharges from any stress-raising protrusion, capacitive sparking from an electrode which is not properly bonded to either the high voltage conductor or earth, and so on; and the common feature of all these defects is that they generate PD activity in advance of complete breakdown.

- With the exception only of the mechanical noise from a bouncing particle, **PD detection** is the basis of all dielectric diagnostics in GIS.

- The PD has many effects — physical, chemical and electrical — and in principle any of them could be used to reveal the presence of the discharge.

7.2.2 Light output

- 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**.

- The radiation is primarily in the **UV band**, and since this is absorbed strongly both by glass and SF_6 it is necessary to use quartz lenses and a reasonably short path length.

- Although this is a powerful laboratory tool for finding the onset of activity from a known corona point, there are many **difficulties** in using it to detect a discharge which might be anywhere in a GIS.

7.2.3 Chemical byproducts

- This approach initially appears attractive because chemical decomposition is immune to the electrical interference which is inevitably present in the GIS, and with any steady discharge the concentration of the **diagnostic gas** should **rise in time to a level where it can be detected** (this assumes, of course, that an absorbing reagent is not used in the chambers).

- The main decomposition product of **sulphur hexalluoride** is **sulphur tetrafluoride** (SF_4), but this is a highly reactive gas.

- It reacts further, typically with traces of water vapour, to form the more stable compounds thionyl fluoride (SOF_2) and sulphuryl fluoride (SO_2).

- These are the **two most common diagnostic gases**, and, by using a gas chromatograph and mass spectrometer, they may be detected with sensitivities down to 1 p.p.m.

- As a simpler but less sensitive alternative, chemical detection tubes can be used.

7.2.4 Acoustic emission

- Acoustic signals arise both from the pressure waves caused by **partial discharges** and from **free particles bouncing on the chamber floor**.
- The latter is the only instance of a diagnostic signal not coming from a PD (although of course the particle generates a PD as well).
- The signals in GIS have a broad bandwidth, and travel from the source to the detector by multiple paths .
- The different propagation velocities of the wave as it passes through various materials, and the reflections occurring at boundaries between them, give rise to a **complex acoustic waveform**.
- This signal can be picked up by **accelerometers** or acoustic emission sensors **attached to the outside of the chamber**.
- One advantage of acoustic measurements is that they are made non-intrusively, using **external sensors** which may be moved from place to place on the GIS.
- The acoustic technique is not suited to a permanently installed monitor, because too many sensors would be needed.

7.2.5 Electrical methods

- There are **2 approaches** to detecting the electrical charge in a partial discharge; in the **external circuit** by **a conventional PD measurement system**, and **internally** by **detecting the resonances set up in the GIS chambers**.

(i) Conventional method (External circuit)

- The test circuit is that given in IEC Publication IEC 60270, and the **charge flowing through a coupling capacitor** fitted in parallel with the GIS is measured using a detector.

- The PD current pulse at the defect has a duration of less than 1 ns, and propagates as a travelling wave in each direction along the chambers.

- The pulses are attenuated and undergo multiple reflections, but do not appear immediately in the external circuit.

- After about a microsecond or so, the pulses die away and the GIS appears to the external circuit as a lumped capacitor with a depleted charge.

- From then, a replacement charge flows into the GIS, and is measured by the detector.

- ***Quiz**: draw the equivalent circuit diagram of the whole setup.*

(ii) UHF antenna method

- The **current** at the PD site **rises in less than a nanosecond**, and can **radiate EM waves** with **energy spectra extending to frequencies of 2000 MHz or more**.

- **This excites the GIS chambers into various modes of electrical resonance**, which because of the low losses in the chambers can persist for up to a microsecond.

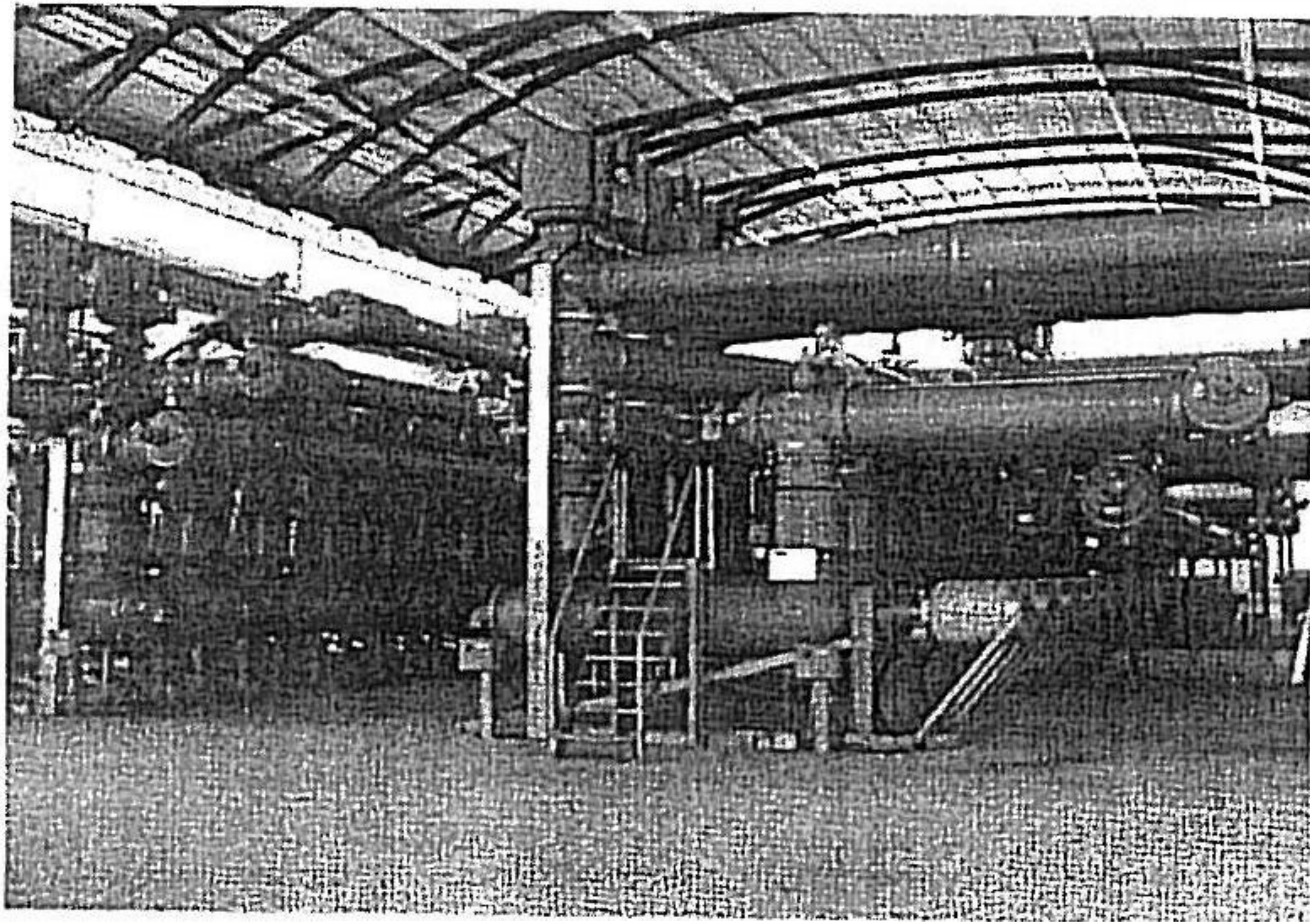
- The **resonances** are indicative of PD activity, and if they are **picked** up by **couplers** installed **in the GIS** may be displayed on a **spectrum analyser**.

- UHF technique has **high sensitivity**, **locates discharge accurately by time of flight**, can readily be used in a continuous and remote CM system

7.3 Comparison of the techniques

The general conclusions of investigations carried out were that:

- All techniques, namely, the acoustic technique, the IEC 60270 electrical method, and the UHF technique, show good sensitivity
- acoustic measurements are non-intrusive and can be made on any GIS, but the attenuation of the signal across barriers and along the chambers is rather high
- conventional PD (IEC 60270) measurements need an external coupling capacitor, and cannot be used on GIS in service
- the UHF antenna technique is suitable for in-service monitoring.



A modern 400 kV GIS


UTAMAKAN KESELAMATAN
PE61
UTM
PENCAWANG MASUK UTAMA 132/22kV
PMU UTM
KOLEJ PERINDU
Universiti Teknologi MARA
24.11.2016


=E03+S1
BUS SECTION
ALSTOM
=E03
BS
ON


=E05+S1
SDAI / SLNG
=E04+S1
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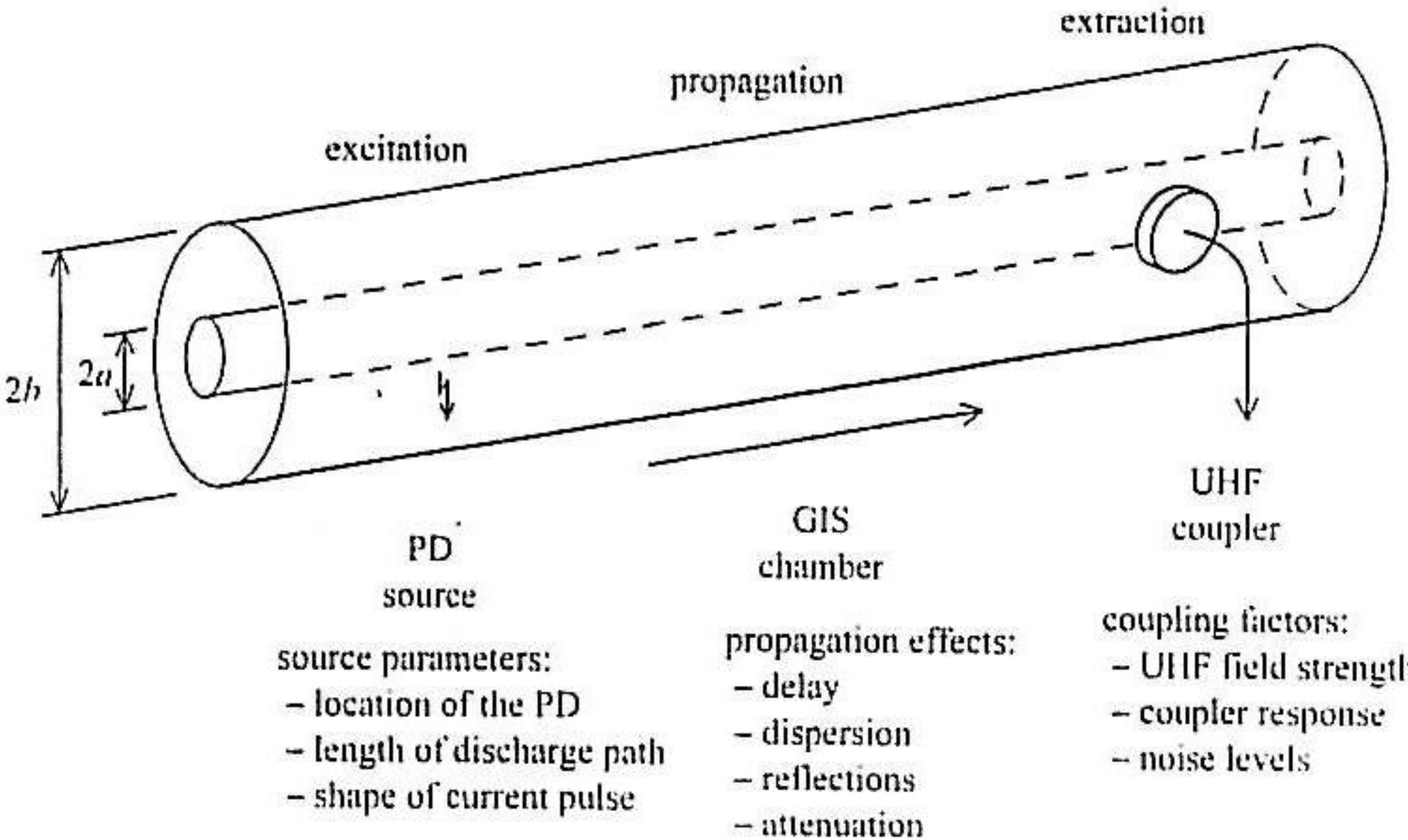


Transfer functions involved in the UHF antenna detection of PD in GIS

8 The generation and transmission of UHF signals in GIS

- Detection of PD by the UHF antenna method involves the stages of energy transfer (excitation, propagation, and extraction)

Excitation

- The **shape** of the streamer current pulse **i(t)** at the PD source is most important in determining the characteristics of the UHF signal.

- The energy radiated in the UHF range is highly dependent on the rate of change of PD current.

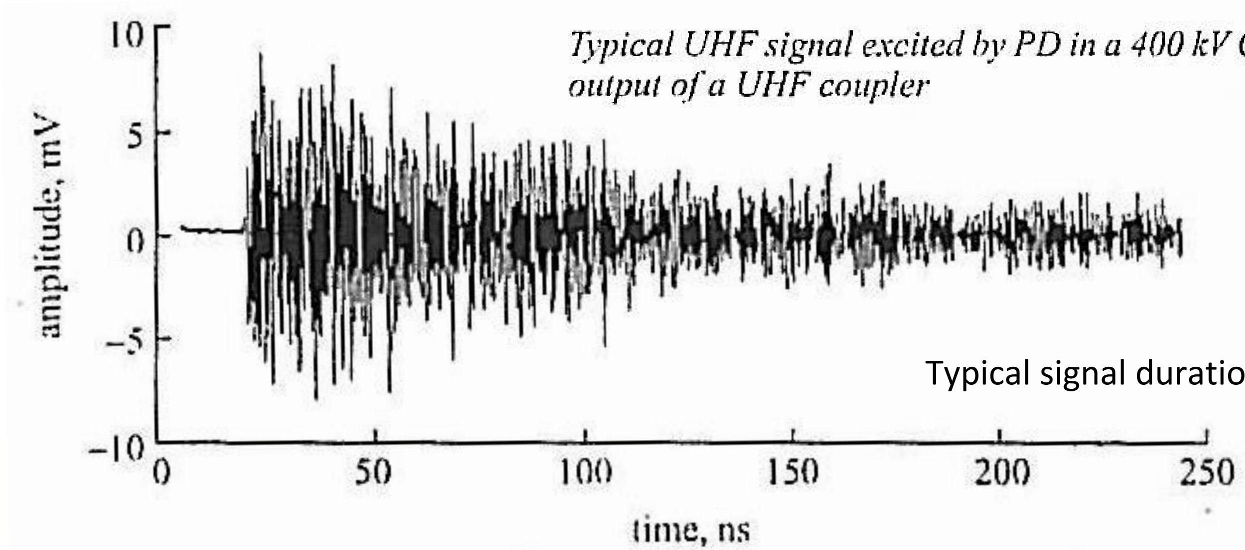
For a given pulse shape, the **UHF signal amplitude scales linearly with the current flowing at the defect**.

- The UHF amplitude is proportional to q x l when the pulse shape is constant (q charge in PD and l = length over which it flows)

- The **position of the defect** also influences the UHF signal detected because the **coupling coefficients** to each of the waveguide mode **vary** across the coaxial cross-section of the GIS

8.2 Propagation

- Generated EM waves propagates in the chamber
- Different frequency components of the PD pulse propagate at different velocities, causing dispersion of the pulse
- The overall dispersion effect is to cause the signal to appear as a long, oscillating waveform with random appearance



Typical UHF signal excited by PD in a 400 kV GIS, as measured at the output of a UHF coupler

Typical signal duration: 100-1000 ns

- **The relative arrival times of the waveforms at antennas/couplers on either side of the PD source can often be used to locate the defect**

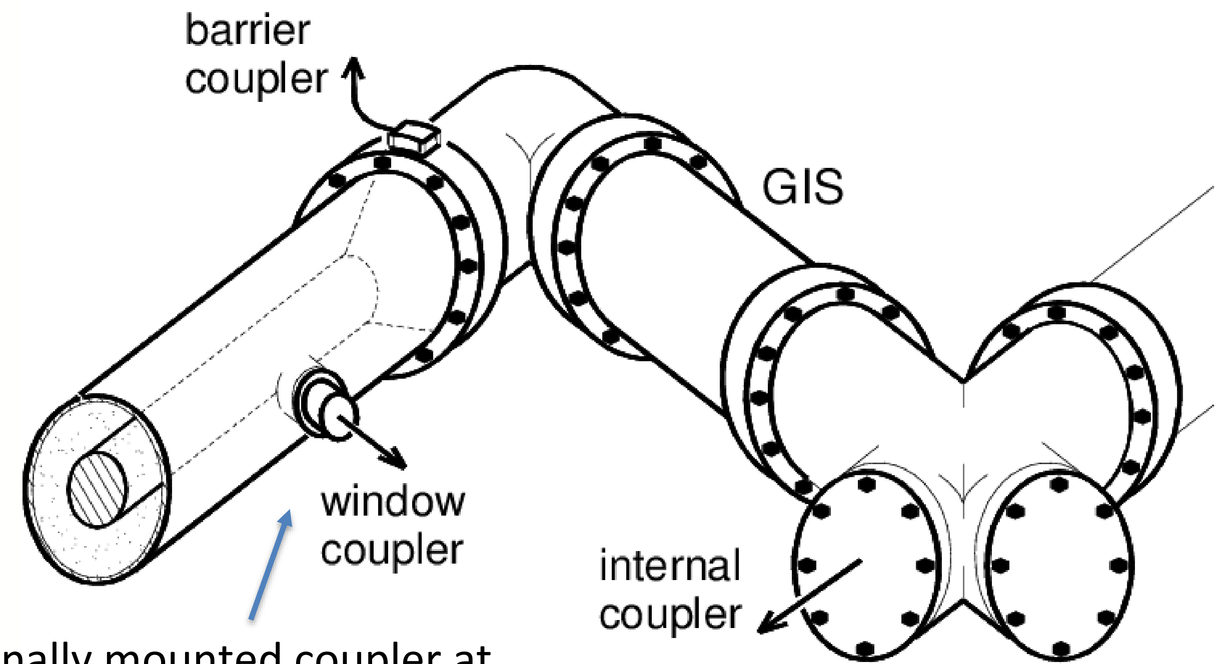
- Any non-uniformities in the GIS will cause partial reflections of the UHF signals

- Most discontinuities inside the GIS have a complicated reflection pattern.

- Numerical techniques and experimental measurements give some guideline figures for the attenuation caused.

8.3 Extraction

- UHF antennas/couplers are normally mounted as shown to measure radial E



Externally mounted coupler at inspection window

8.3 Extraction

- The radial component of electric field is predominant
- Internal couplers are best as the noise level is low.
- Externally mounted will be affected by the field patterns in the structure on which they are mounted.
- The mounting arrangement should be considered part of the coupler.
- The coupler's function is to maximise the output voltage for a given radial component of UHF electric field.
- The frequency response of the coupler should be suitable for the frequency range of the UHF signal (500-1500MHz).

8.4 Waveguide modes and UHF propagation

A **transverse mode** of electromagnetic radiation is a particular electromagnetic field pattern of radiation measured in a plane perpendicular (i.e., transverse) to the propagation direction of the beam.

Transverse modes occur in radio waves and microwaves confined to a waveguide, and also in light waves in an optical fiber and in a laser's optical resonator.[1]

Transverse modes occur because of boundary conditions imposed on the wave by the waveguide.

For example, a radio wave in a hollow metal waveguide must have zero tangential electric field amplitude at the walls of the waveguide, so the transverse pattern of the electric field of waves is restricted to those that fit between the walls.

For this reason, the modes supported by a waveguide are quantized.

The allowed modes can be found by solving Maxwell's equations for the boundary conditions of a given waveguide.

Transverse electromagnetic (TEM) modes

- Neither electric nor magnetic field in the direction of propagation.

Transverse electric (TE) modes

- No electric field in the direction of propagation.
- These are sometimes called H modes because there is only a magnetic field along the direction of propagation (H is the conventional symbol for magnetic field).

Transverse magnetic (TM) modes

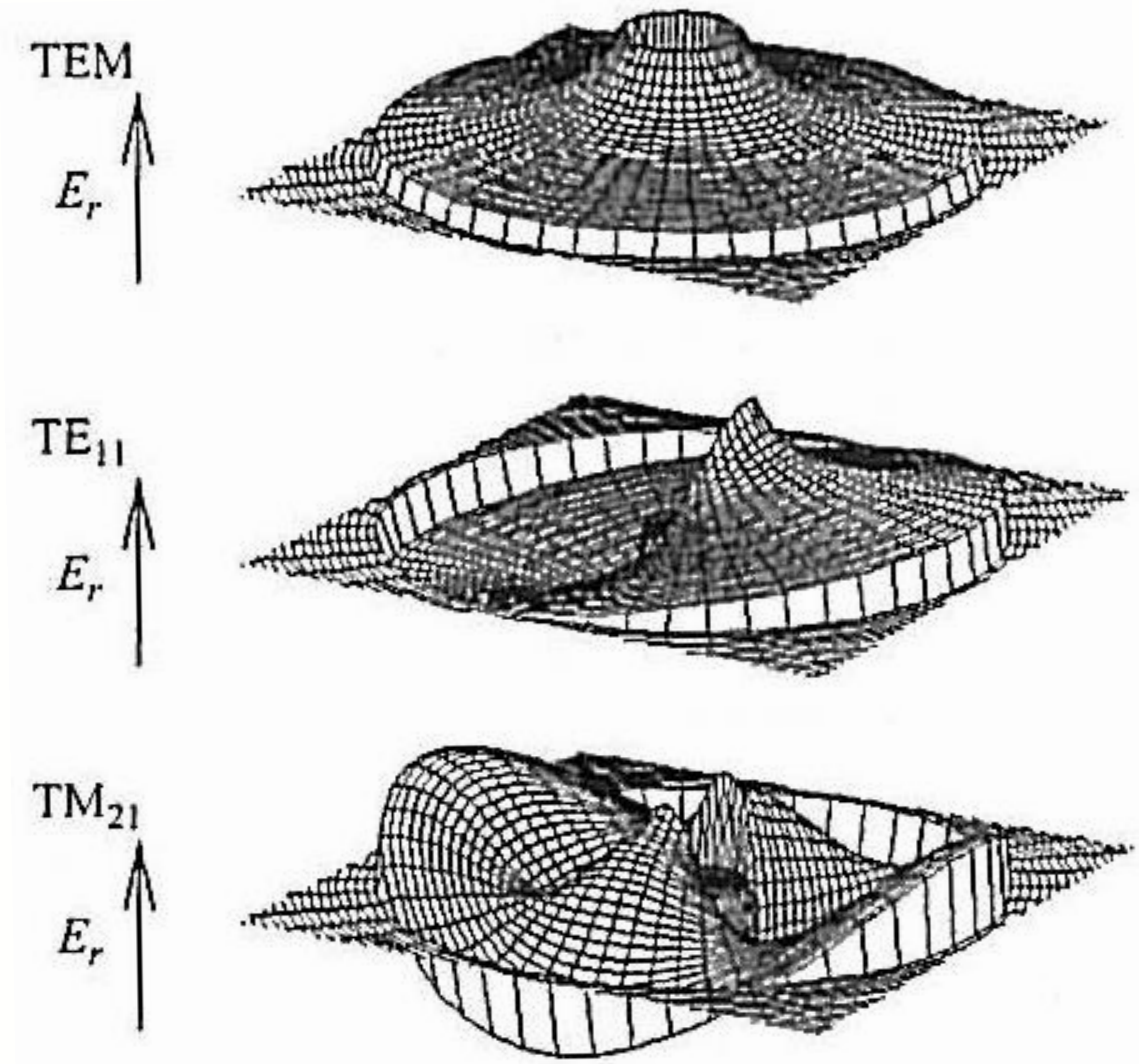
- No magnetic field in the direction of propagation.
- These are sometimes called E modes because there is only an electric field along the direction of propagation.

- **Basic field patterns** that can exist in a **coaxial waveguide (with different cut-off frequencies)**

  - **Transverse electromagnetic** (TEM) mode
  - **Transverse electric** (TE) mode

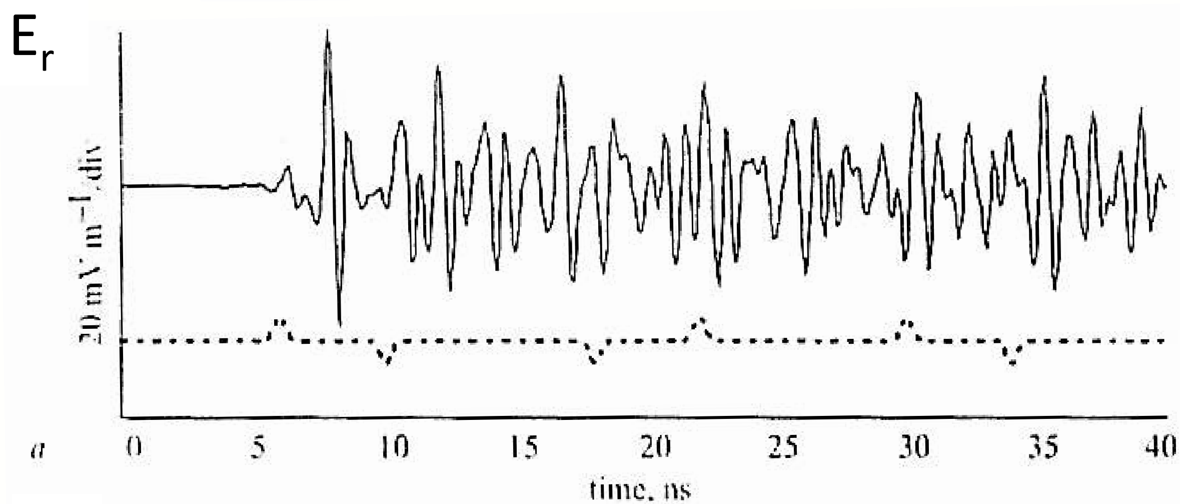
    TE modes have Er and Eθ components to their electric fields
  - **Transverse magnetic** (TM) mode

    TM modes have Er, Eθ and Ez components to their electric fields

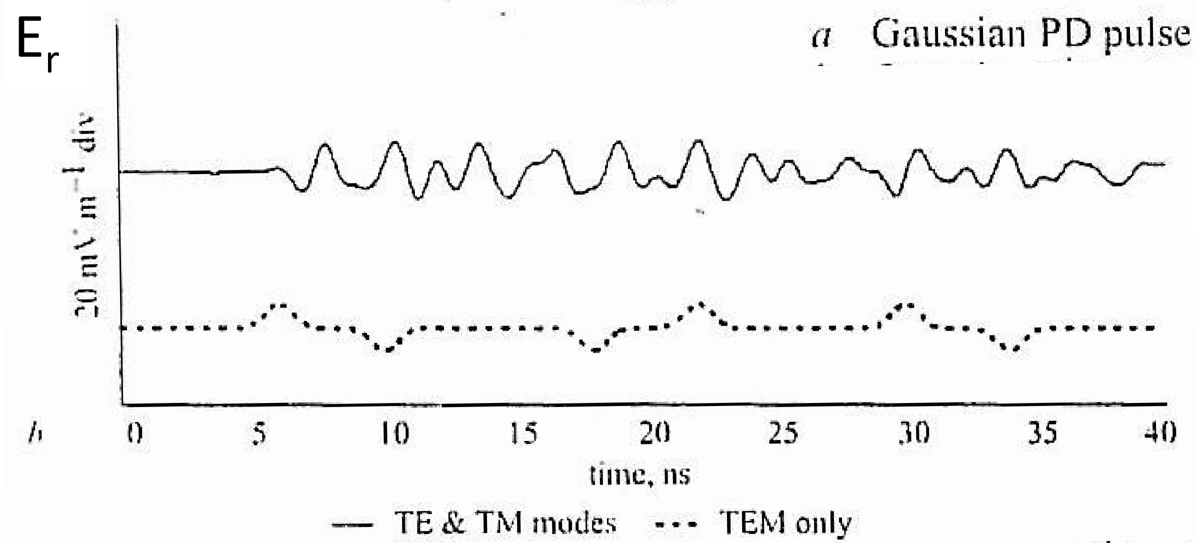


Patterns of the radial electric field over the GIS cross-section for some coaxial waveguide modes. The rectangular plane represents the position of zero electric field

Simulation results comparing the mode contributions to the radial electric field E_r at 1.2 m from a PD source. The PD current has a path length of 10 mm and the peak current is 2 mA.



a Gaussian PD pulse of half-amplitude width 500 ps



b Gaussian PD pulse of half-amplitude width 1.25 ns

8.5 Attenuation of UHF signals

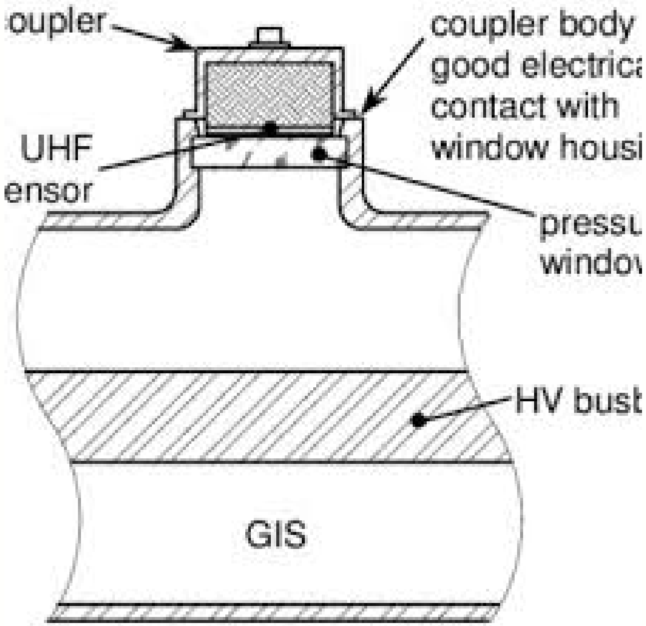
- The GIS can be considered as a series of loosely coupled chambers in which the UHF resonances occur.
- Over the shorter timescale (10-100 ns), energy is transferred between adjacent chambers, with those nearest the PD source maintaining the higher energy levels.
- Dissipation losses (skin effect) become significant in the longer timescale (100-1000 ns), and are the reason for the ultimate decay of the signal.

9. Application of UHF Antenna techniques to PD detection in GIS

- For radially-directed PD currents, the majority of the energy available to an electric field sensor (coupler) is in the radial component of the electric field.

- The purpose of a coupler is to provide the maximum transfer of energy from the incident radial electric field to the 50 ohm input of the monitoring system.

- Internal couplers must be fitted to the GIS during construction.
- Couplers often take the form of a metal disc insulated from the GIS enclosure by a dielectric sheet.



Antenna/Coupler calibration system

- Couplers are calibrated by measuring their transfer function in terms of their output voltage in response to a defined incident electric field.
- A standard measurement scheme has been developed which is independent of the GIS in which the coupler is to be used.
- The calibration system (see Figure) measures the frequency response of the coupler and its mounting arrangement when subjected to a known electric field normal to the ground plane in which the coupler is mounted.
- The incident field is first calibrated using a monopole probe having a known frequency response.

- **The probe is then replaced by a mounting plate suitable for holding the coupler to be tested.**

- **A digitiser records the signal from the coupler under test, and a continuously updated display of the coupler gain is provided by the signal processing unit.**

- **The coupler sensitivity has units of length and is represented by an effective height h.**

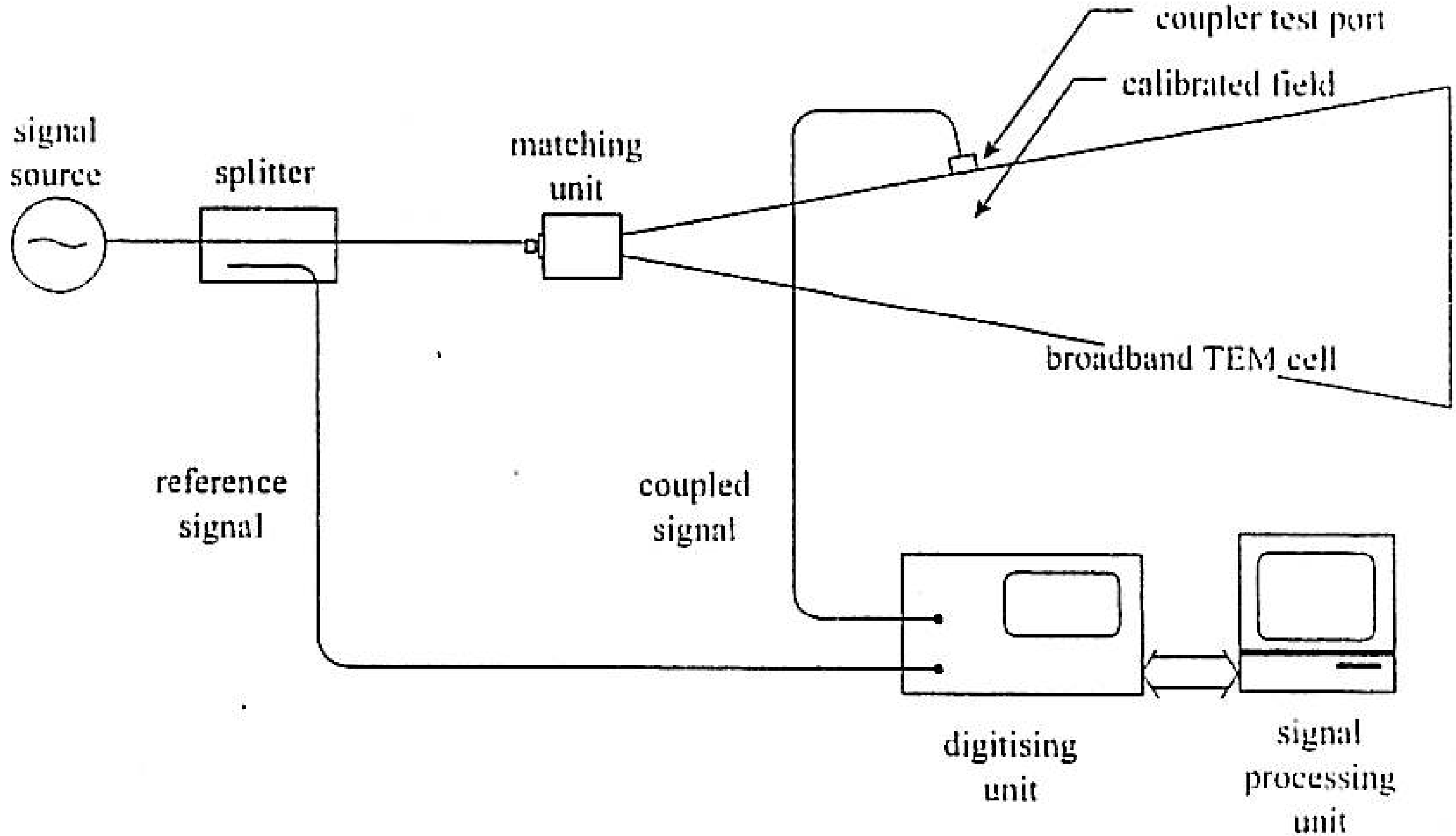
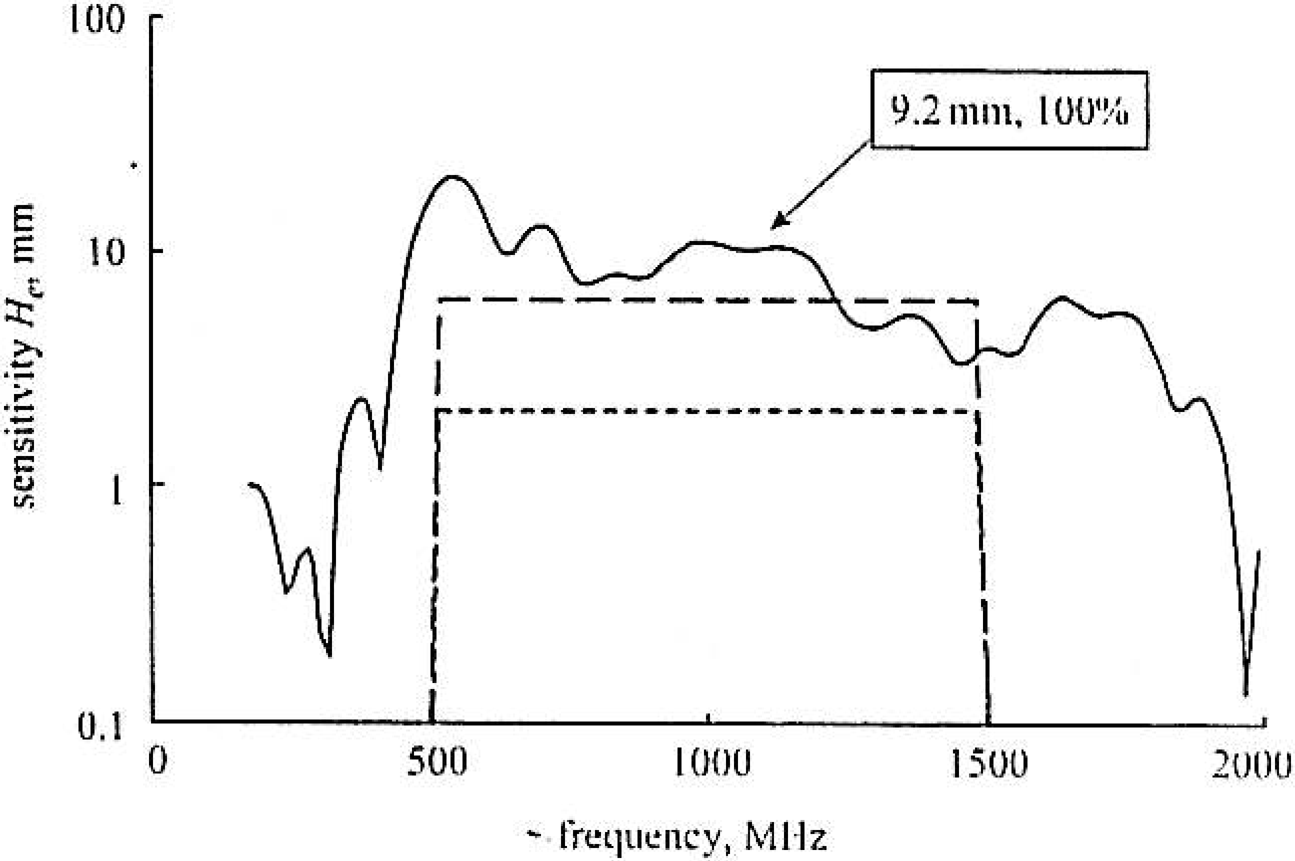


Diagram of the UHF coupler calibration system



Frequency response plot for an external, window coupler as measured by the calibration system

An external window coupler on a 500 kV GIS

9.2 Partial Discharge Monitoring system for GIS

- **The general arrangement of one particular partial discharge monitor (PDM) is shown.**
- **The monitoring system consists of the following basic parts:**

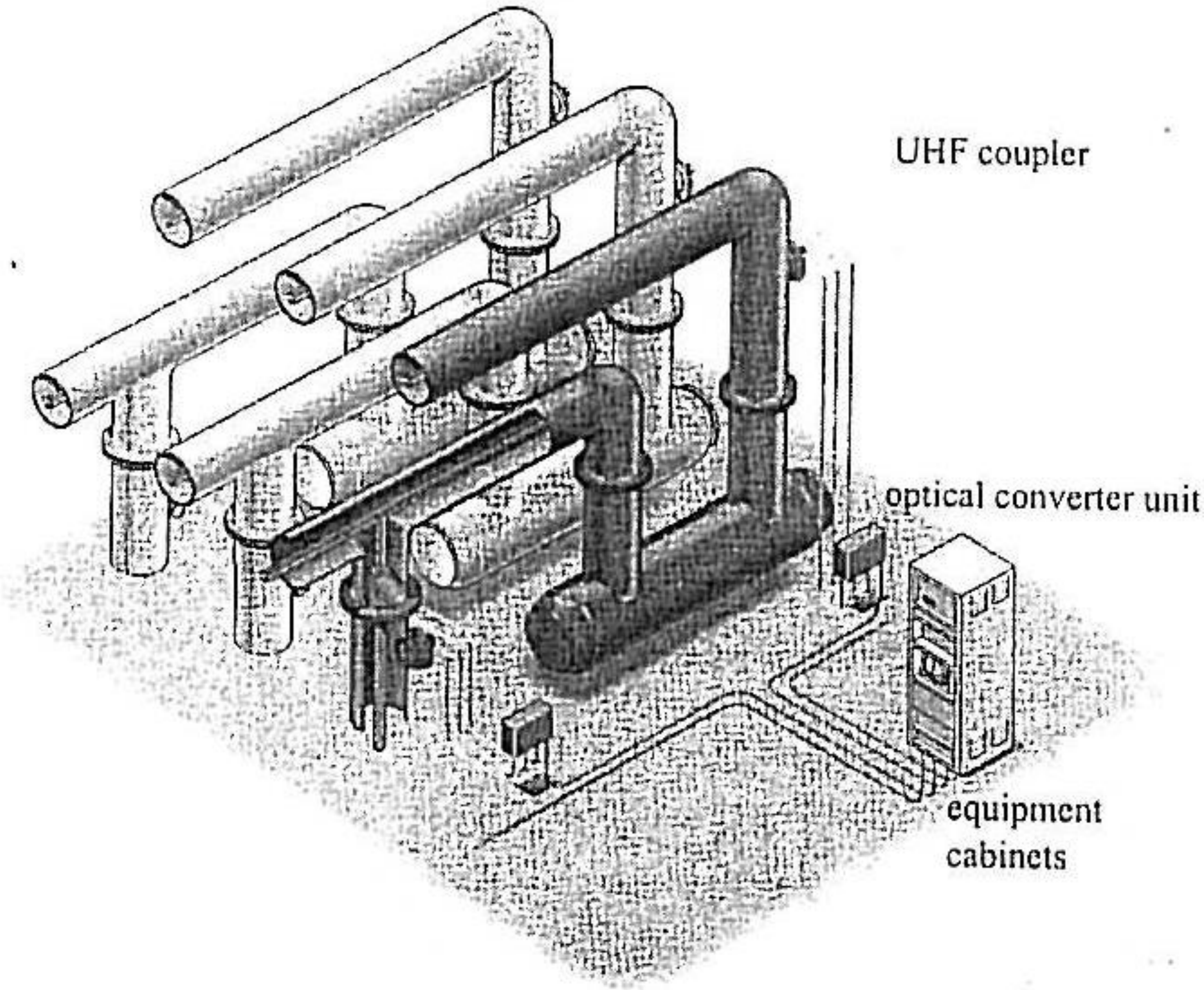
  - **UHF couplers — to take the UHF signals from the GIS.**

  - **Optical converter units (OCUs) — each OCU contains circuitry to detect and process the UHF signals from one three-phase set of couplers.**

    The UHF data is then transmitted via an optical fibre link back to the equipment cabinets, which are located in a central place.

- **The central data handling, processing, storage and display are carried out within equipment cabinets located in the relay room.**

The racks contain the electronics to receive and handle the streamed data from the OCUs, the PC and control unit for data storage and display.



General arrangement of the PDM system

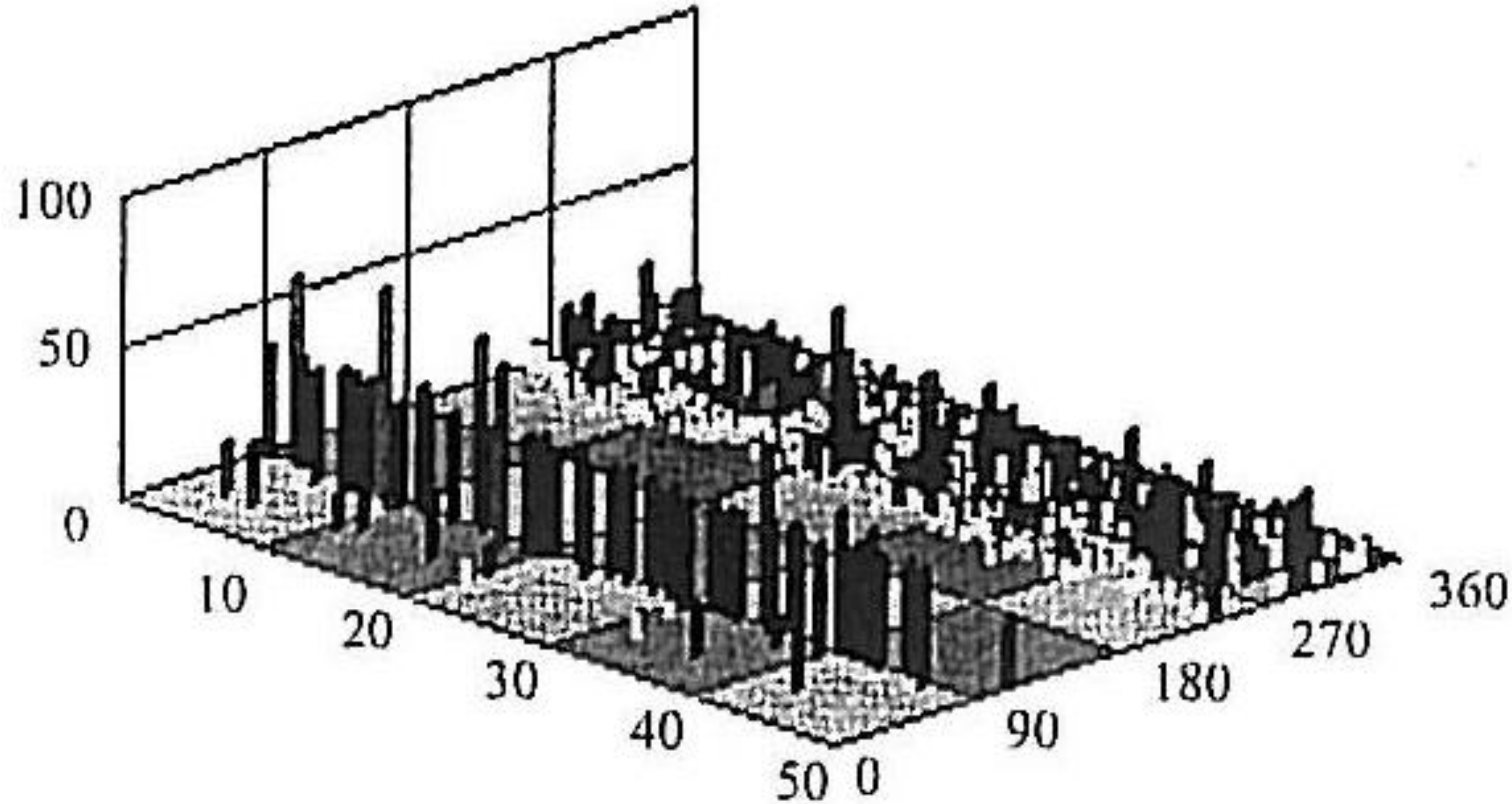
9.3 Display and interpretation of PD data

- The features of the UHF discharge pulses that are most useful for interpretation purposes are their amplitude, point on wave and the interval between pulses, T.

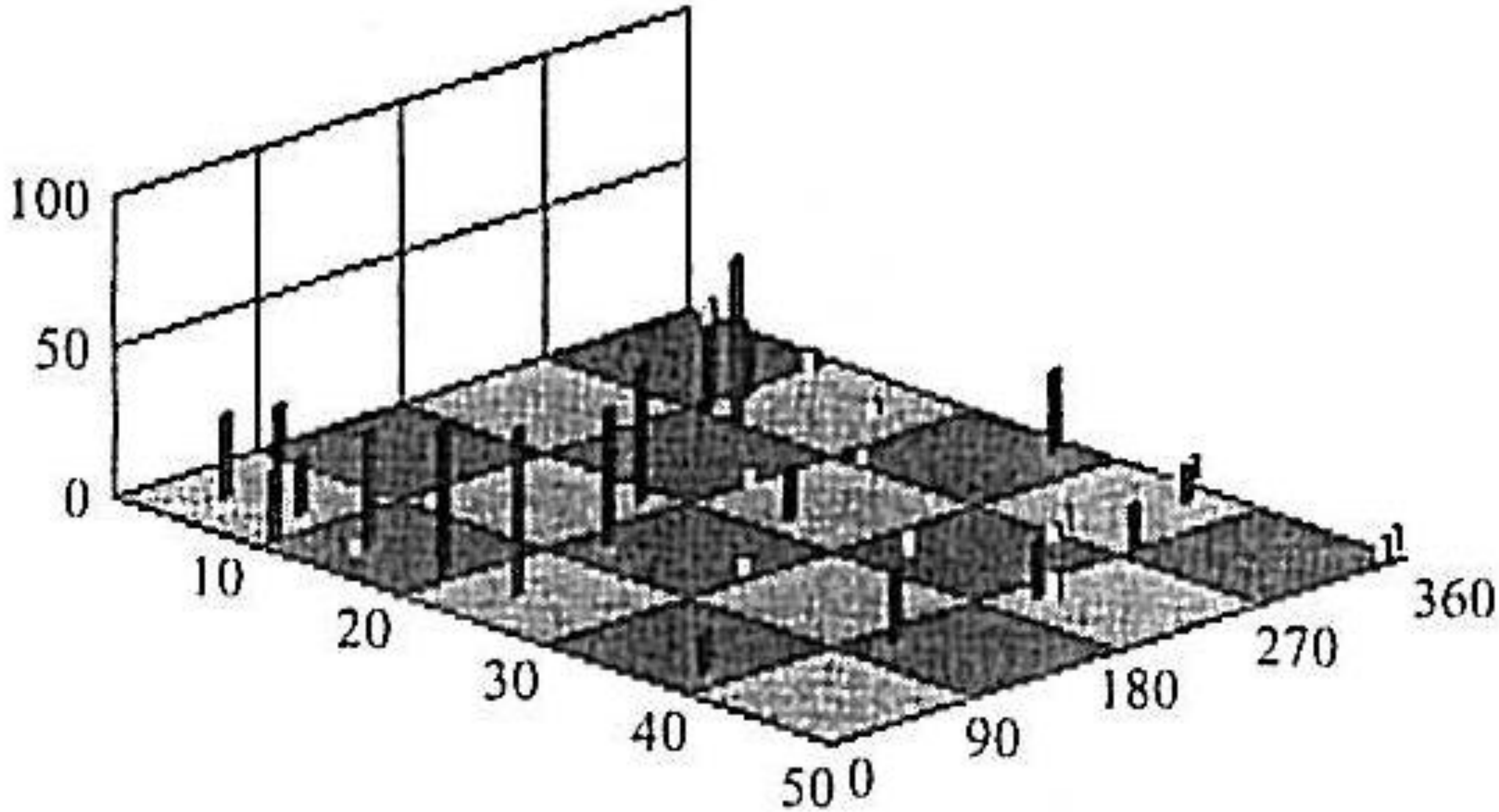
- These parameters enable typical defects such as fixed point corona, free metallic particles and floating electrodes to be identified.

- The UHF data may be displayed in any way which reveals the characteristic patterns typical of the defects causing them, as, for example, in the three-dimensional patterns shown.

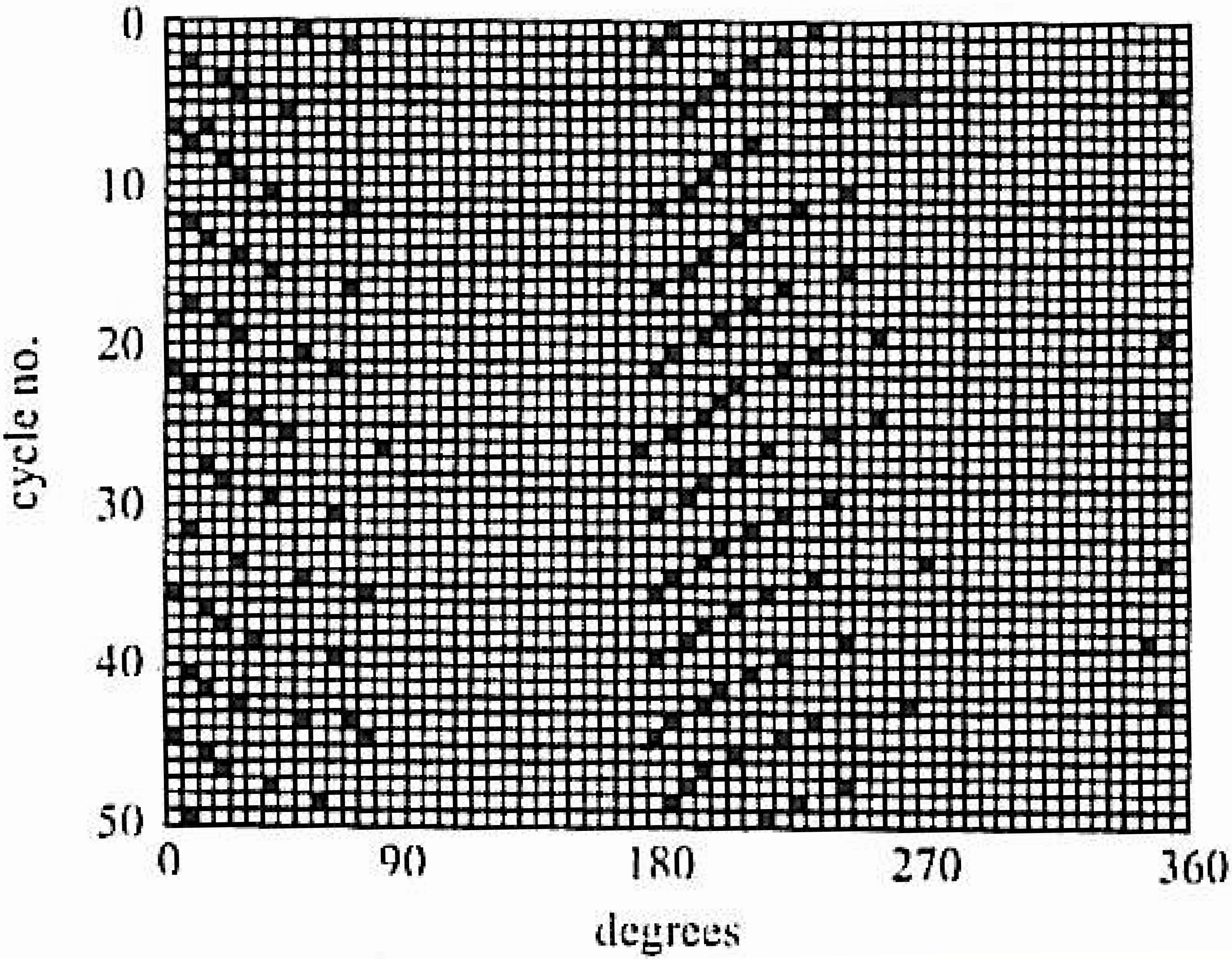
- **Here, the pulses detected in 50 consecutive cycles are shown in their correct phase relationships over the cycle.**
- **In the three-dimensional displays, 0° corresponds to the positive-going zero of the power frequency wave, 90° to the positive peak, and so on.**



Busbar corona, streamers and leaders



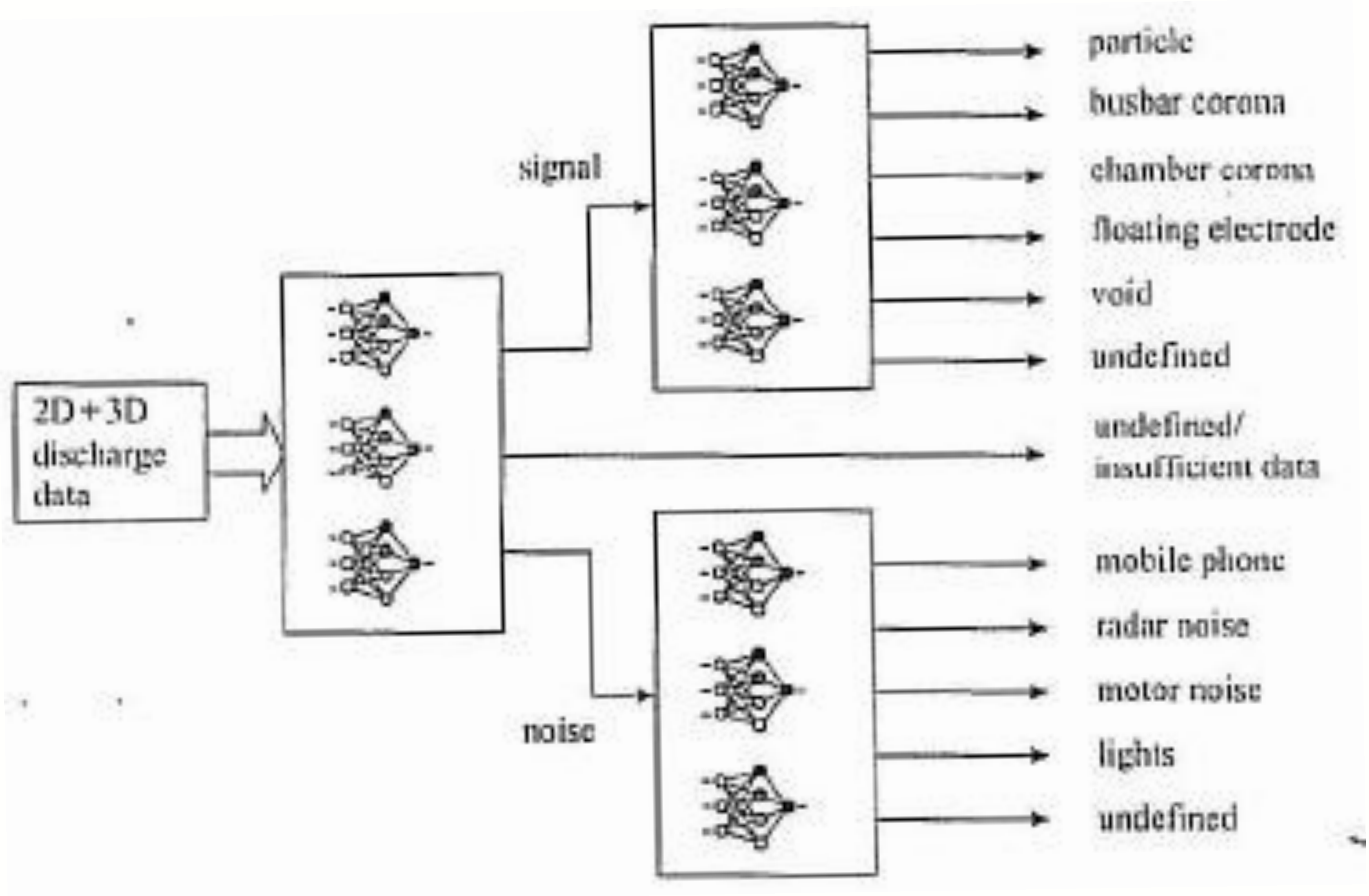
Free metallic particle



Floating electrode, plan view

9.4 Diagnostic techniques

- Classification algorithms
- Trend analysis and alarms



Classification of PD signals by ANNs

The End