Chapter 2

Advances in partial discharge measurements

MKEP1543 ZAM Nov 2020

Synopsis

In this chapter, we will learn the techniques used to measure partial discharges in high voltage equipment.

Content

1. Introduction
2. Partial discharge degradation mechanism
3. Basic partial discharge measurements
4. Case studies
5. Partial discharge modelling

Chapter Outcomes

At the end of this chapter, you are able to:

1. Professionally explain various partial discharge degradation mechanisms
2. Verbally and by writing, demonstrate how basic partial discharge measurements can be made
3. Carry out simple simulation work on partial discharge modelling

1. Introduction

Revision on mechanism of air breakdown

- Avalanche development
- Critical avalanche and critical volume
- Streamer formation
- Corona
- Leader

- Localised gaseous breakdowns within any plant system when conditions are met

  Local-> partial

- Why is PD activity important?

  -both **symptom of degradation** and a **stress mechanism**

- Correlations among the **measurable parameters** need to be understood for effective maintenance

2. Partial discharge degradation mechanisms

- The **electrons, ions, atoms, radicals and excited molecular specie**s produced in a **partial discharge <u>move</u>** under the influence of the following forces:

  - thermal excitation
  - the electric field
  - electrostatic forces
  - the electric wind (generated by the collision of the ionic species, moving under the influence of the electric field, with the molecules of the surrounding gas)

- The distribution of the **reactive species** within the gas discharge, and their resulting impact at the discharge surfaces, will be complex.
- Different prevalent **stress mechanisms**:
  - Particle impact stress
  - Thermal stress
  - Mechanical stress
  - Chemical stress
  - Electrical stress
  - Synergetic interaction of stresses

2.1 Particle impact stress

- A gas discharge consists generally of electrons, positive and negative ions and photons
- In relation to PD, when these particles impact on a surface at the ends of the discharging channel, they may cause degradation at that surface
- Any of these particle types may contain sufficient energy to cause bond scission, often with an associated electron release

- An impacting ion at an insulating surface may result in local molecular changes as a result of either an electronic interaction between the incoming charged particle and the shell electrons of the molecules of the insulating material or through a tight interaction between the ionising ion and one (or more) ions of the surface lattice.

- The interaction which occurs when an electron collides with a molecular surface will depend upon the structure and energy state of the impacted species and upon the electron energy.

- An energetic **electron** impacting upon an **uncharged molecular species** can interact in four ways:

1. Without being attached

   $e(v_1) + M \rightarrow e(v_2) + M^*$

2. Attached

   $e + M \rightarrow M^-$

3. Collision ionisation

   $e + M \rightarrow e + e + M^+$

4. Attached followed by division (neutral and charged subspecies)

   $e + M \rightarrow M_1 + M_2^-$

- An energetic **electron** impacting upon **an ion** can interact in three ways:

1. Deionisation (for negative ion resulted in 2 e)

   $e + M^- \rightarrow e + e + M$

2. Ion become doubly negatively charged (for –ve ion)

   $e + M^- \rightarrow M^{2-}$

3. Deionisation (plus photons from +ve ion)

   $e + M^+ \rightarrow M + hv$

- A **photon** impacting upon a **molecule** can interact in four ways:

1. Ionisation plus e plus photon

   $hv_1 + M \rightarrow M^+ + e(v_1) + hv_2$

2. Split into subspecies (+ve and –ve)

   $hv + M \rightarrow M_1^+ + M_2^-$

3. Split into neutral, +ve subspecies, and electron

   $hv + M \rightarrow M_1 + M_2^+ + e$

4. Free radical subspecies (2 neutral but higher energy)

   $hv + M \rightarrow M^*_1 + M^*_2$

- A **photon** impacting upon an **ion** can interact in four ways:

1. Deionise a negative ion plus e

   $hv + M^{-} \rightarrow M + e$

2. Release an e from a +ve ion (become double +ve)

   $hv + M^{+} \rightarrow M^{2+} + e$

3. On negative ion into +ve sub, neutral sub, and 2e

   $hv + M^{-} \rightarrow M_1^{+} + M_2 + 2e$

4. On positive into neutral sub and +ve sub

   $hv + M^{+} \rightarrow M_1 + M_2^{+}$

- The **photon** energy and the energy state of the molecular or ionic species involved in the reactions given above will determine which of the reactions will occur.

- Particle impact has been attributed variously as the mechanism of PD degradation.

- Also, the synergetic nature of discharge degradation mechanisms cannot be overstressed.

- Particle impact damage is dependent on the chemical bond energies associated with eg epoxy resin

2.2 Thermal stress

- The energy injected into the gaseous environment by the discharge will increase the temperature of the gas in the local vicinity.

- In turn this thermal differential will cause the gas molecules in the hotter region to migrate to the cooler regions.

- Thermal stress may be sufficient to cause damage to **polymeric** materials but not to **other solid** forms of insulating materials

- May not be significant **even** for polymeric compared to other stresses

- The reaction of polymeric materials to a purely thermal stress is dependent on the structure of the material

- For example, simple structures, such as polyethylenes, degrade by random chain scission:

$$-CH_2-CH_2-CH_2-CH_2-CH_2-CH_2- \rightarrow -CH_2-CH_2-CH_2-CH_2-CH_2 + CH_2-$$

- The application of heat to a polymeric insulating system will produce a number of reactive sites and species given the application of sufficient heat

2.3 Mechanical stress

- A **vibrational** mechanical stress will be set up in a solid insulating material subject to PD stressing under normal AC operating conditions due to the interaction of **trapped charge** in the **solid matrix** from the discharge interacting with the **applied AC electric stress field**

- Particle impact from a PD can also result in **bond breakage** and the production of ionic and radical species, which in turn may react with the gas and solid to produce, for eg, extra cross-links – hence stiffer polymer section-> less resistant to shear, tensile and compressive forces induced in the polymer by the electric stress/trapped charge effects

2.4 Chemical stress

- Previous stresses can results in changes to the chemical structure of a solid insulating system

- Species generated in the gaseous environment of the discharge may also interact chemically with the solid material when they impinge at its surface

- Air (nitrogen, oxygen, argon, water vapour, oxides of carbon) is the most common atmospheric medium through which PDs propagate- ionic species formed from air content (O^-, O_2^-, N^+, O_2^+)

A	B	C
CO_2^-	O^+	H^+
CO_3^-	O_2^+	N^+
O_2^-	N^+	NO^+
O_3^-	NO^+	N_2^+NO
NO_3^-		NO_2^+
		NO^+NO

Ionic species formed in DC coronas:

- A – negative HV electrode
- B – positive HV electrode (not hydrated)
- C – positive HV electrode (hydrated)

- Chemical reactions will occur on the material surface
- The production of reactive oxygen species and oxides of nitrogen in the discharge atmosphere is particularly important when considering degradation processes.
- O_3 (oxidising agent) and HNO_3 (nitric acid).
- Reactions are based on the specific materials and gaseous environment in use. Different mechanisms for air and nitrogen environments

2.5 Electrical stress

- The superposition of an **electric fiel**d due to charge deposition from a PD at a solid insulating surface will result in both **local microscopic** and **macroscopic** effects which may cause degradation

- Electric fields can be responsible for **dissociation** and **transport** of ionised and ionisable **by-products** resulting in increased **losses** and **local stress enhancements**

- Charge trap filling and other forms of charge capture will result in local field effects. In turn, these may result in local electronic breakdowns around the stress enhanced site

2.6 Synergetic interaction of stresses

- It is the synergetic interaction of the above stresses which results in degradation

- Different materials, gaseous atmospheres, contamination levels, discharge magnitudes and orientation, all will result in a unique combination of stress effects at a discharging surface

Quiz

1. In 150 words, explain how partial discharges can cause degradation in insulating materials.

2. In 50 words, indicate various transducing techniques can possibly be used to make a PD detection or to measure PD signal.

3. Basic partial discharge measurements

- Various techniques that can be applied, either **directly** or **indirectly**, to determine the **presence** of, and **characterise**, partial discharge activity

- Categorised as:
  1. Electrical detection
  2. Acoustic detection
  3. Thermography and other camera techniques
  4. Chemical detection

3.1 Electrical detection

Three distinct approaches:

1. Individual discharge pulse measurement
2. Measurement of total loss
3. Measurement of electromagnetic effects

3.1.1 Individual discharge pulse measurement

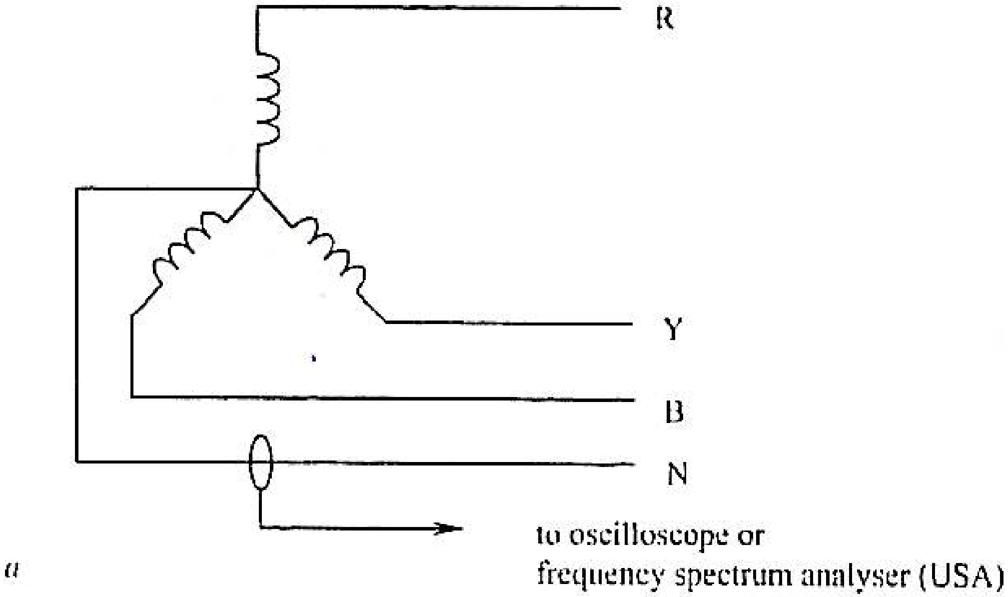
There are **two** broad approaches to making this kind of measurement, i.e.

- connecting a clamp-on **current transformer** (CT) to the **neutral** strap of the plant item and taking the output to an oscilloscope or similar-recording instrument

or

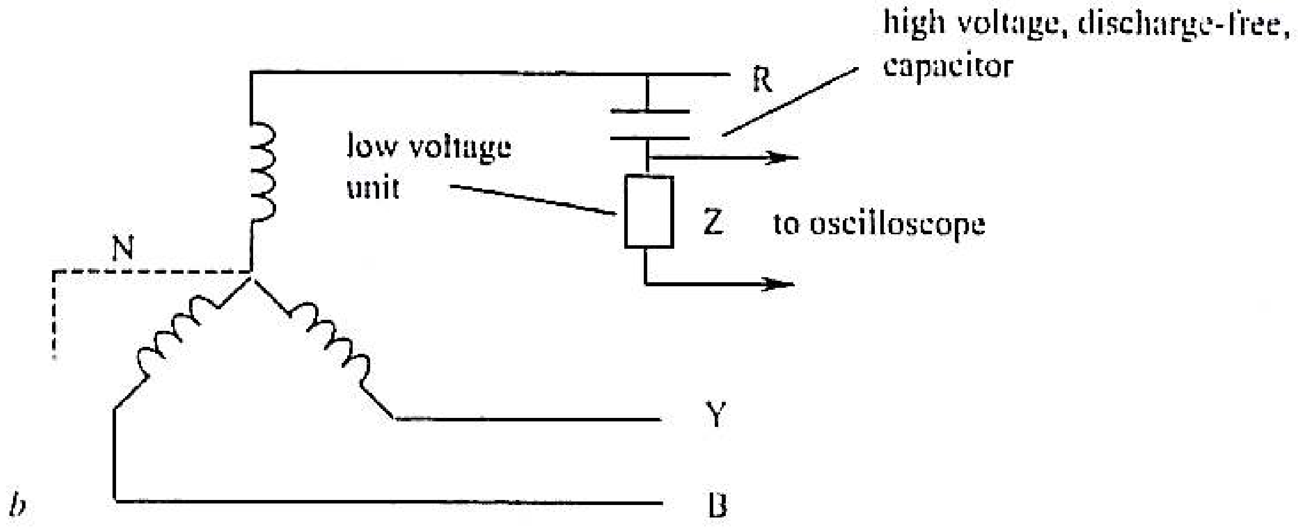
- connecting a **suitable transducer** (typically a **capacitor divider type assembly or Rogowski coil**) to the **high voltage terminals** of the plant item and measuring the output in a similar way to the CT approach

1. CT on neutral approach

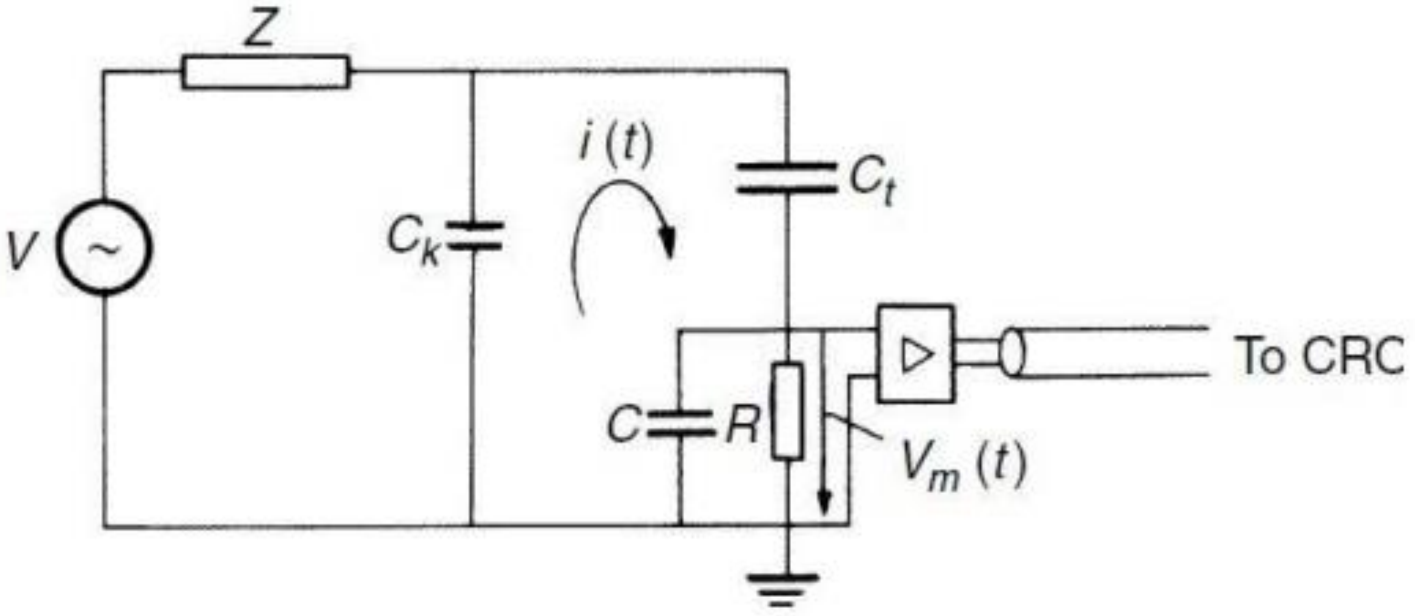


PD pulse measurement on 3-phase motors
CT connected to motor neutral
- Individual discharge measurement

2.a Divider on HV terminal approach

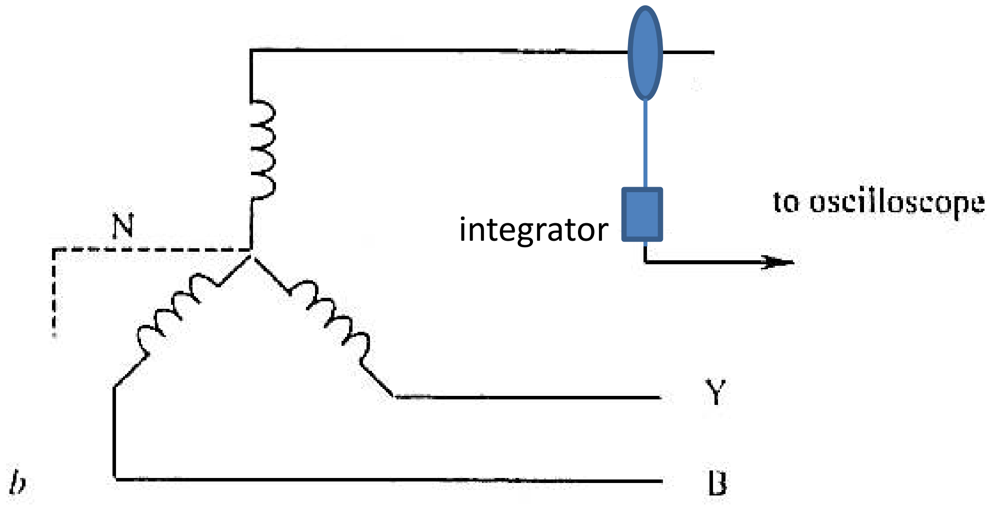


PD pulse measurement on 3-phase motors
Capacitor coupler connected to high voltage phase terminal (each measured in turn)



Measurement of PD currents – high sensitivity circuit

2b. Rogowski coil at HV terminal approach



PD pulse measurement on 3-phase motors
Rogowski coil connected to high voltage phase terminal (each measured in turn)

PD Pattern Interpretation

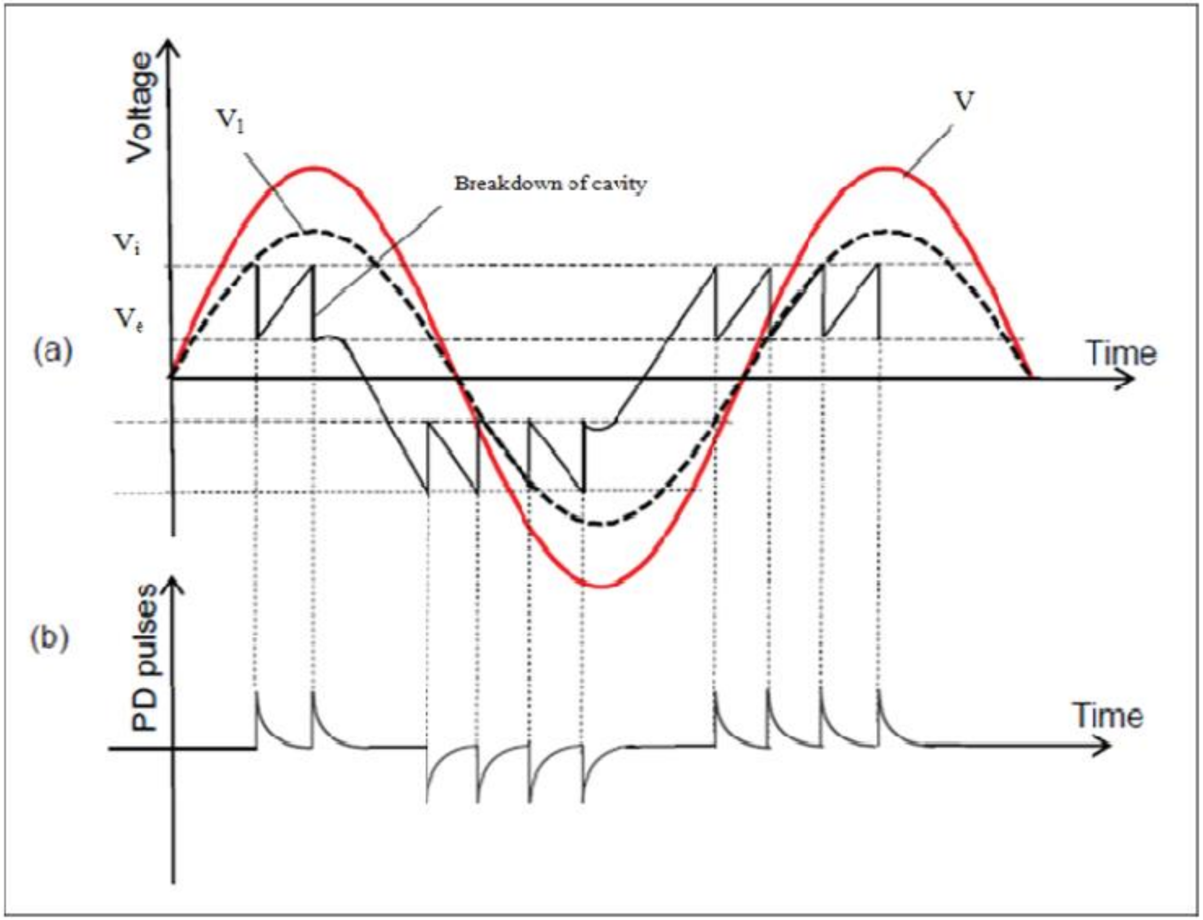
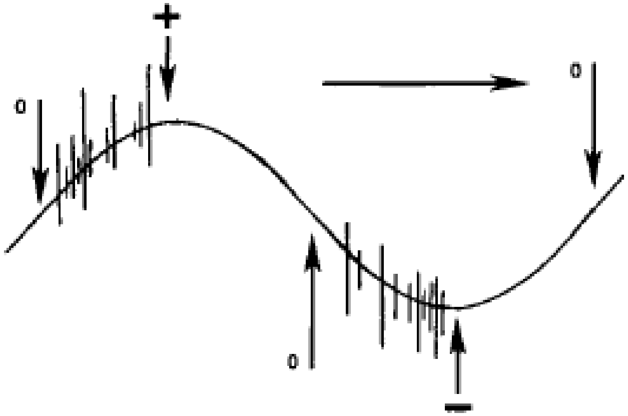
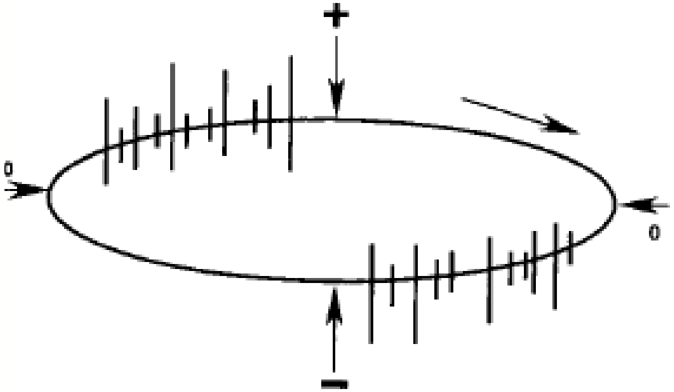


Fig. 1. Sequence of cavity breakdown under alternating voltages: (a) voltage waveforms and (b) PD Pulses [13]

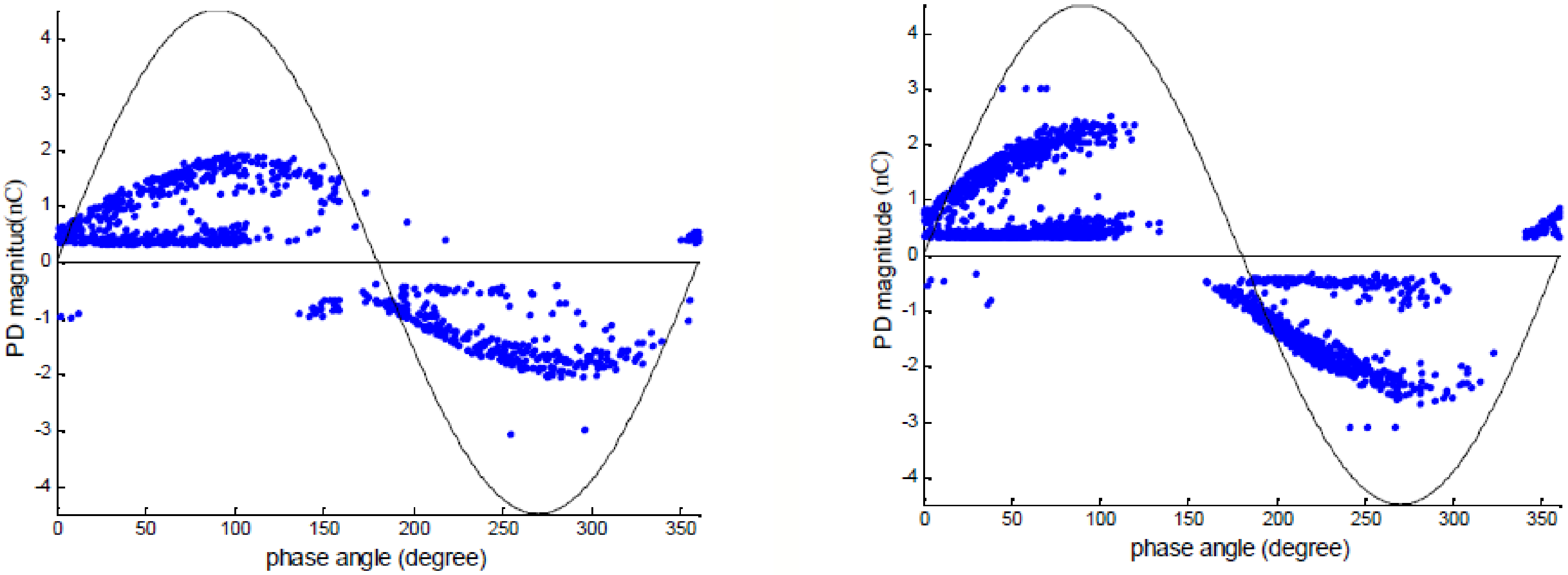
Typical PD signals within an AC cycle



Sinusoidal form



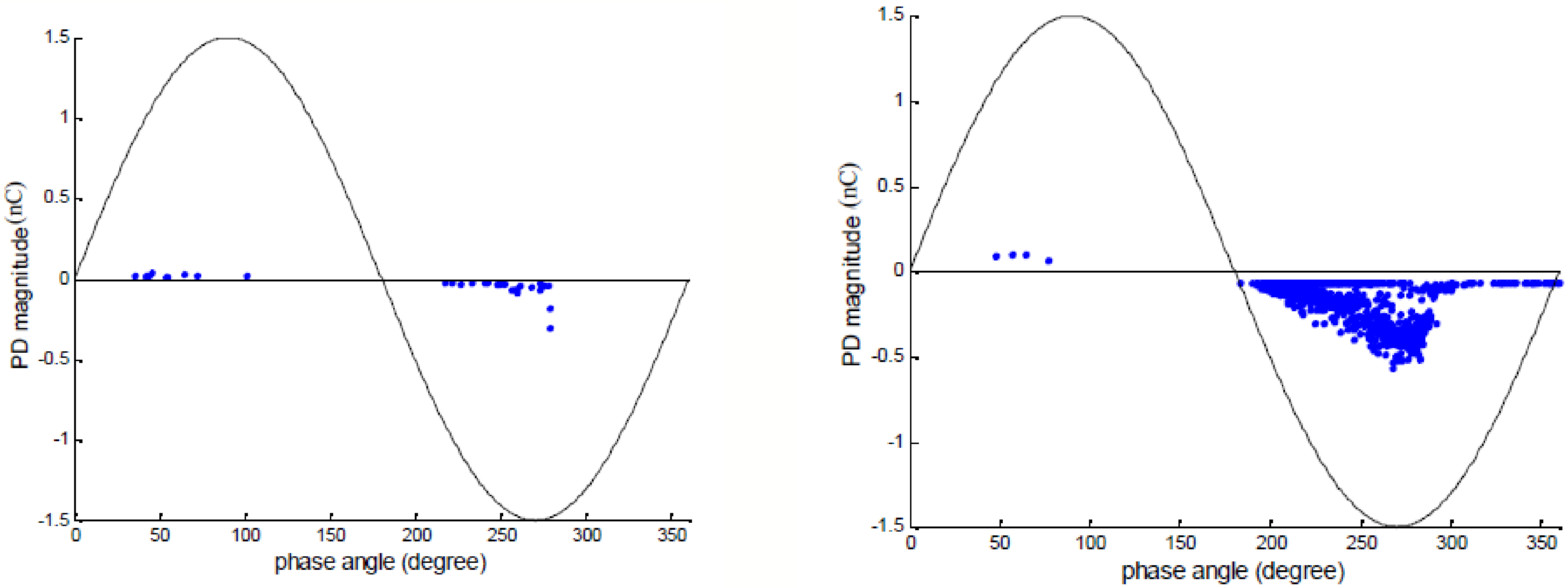
Elliptical form



(a) 18 kV applied voltage

(b) 24 kV applied voltage

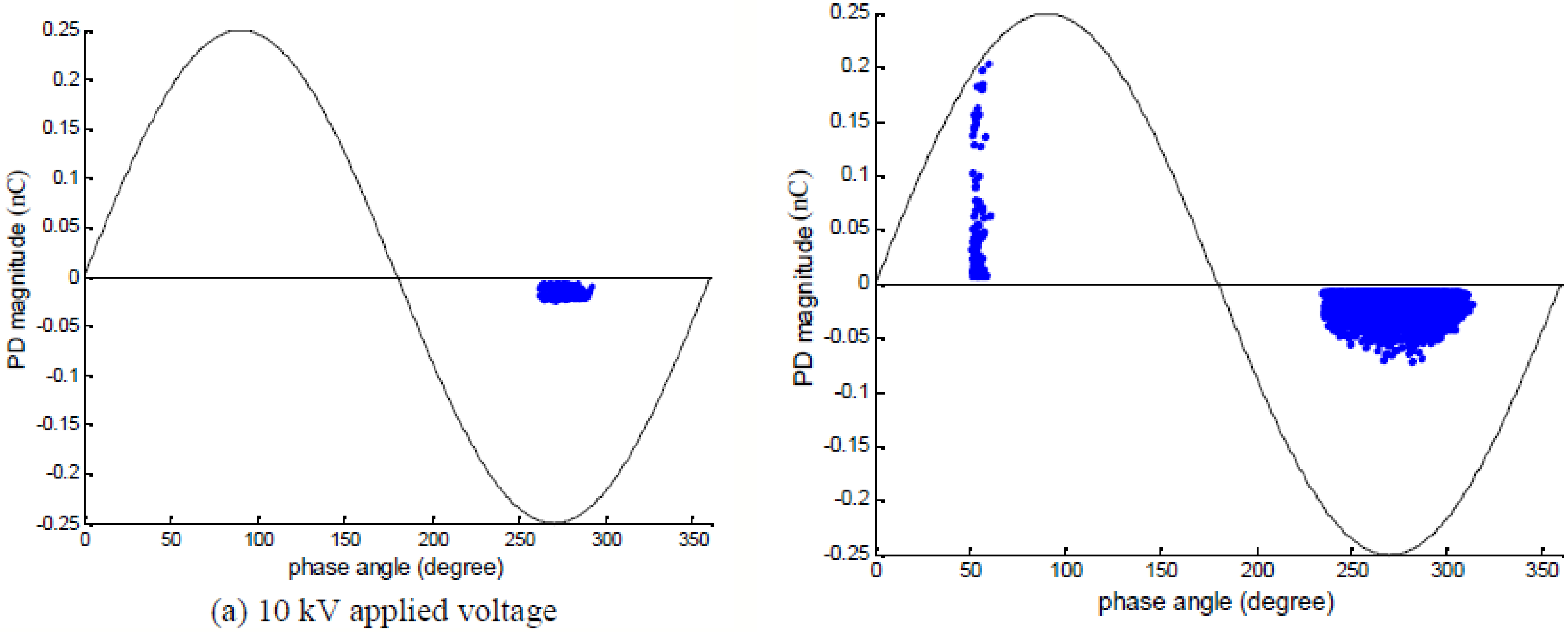
Figure 5. PRPD patterns of void discharge



(a) 3 kV applied voltage

(b) 6 kV applied voltage

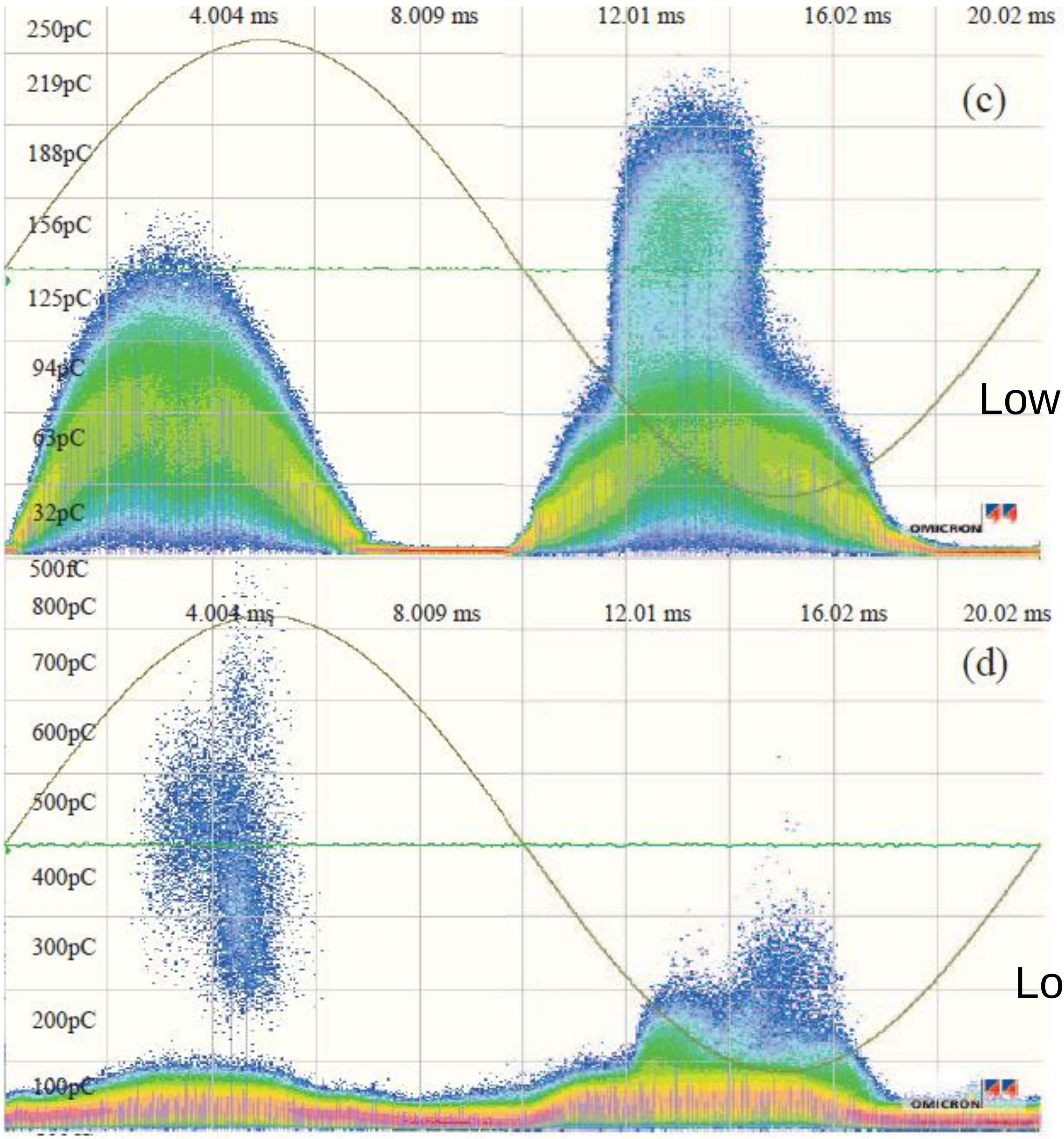
Figure 6. PRPD patterns of surface discharge



(a) 10 kV applied voltage

(b) 14 kV applied voltage

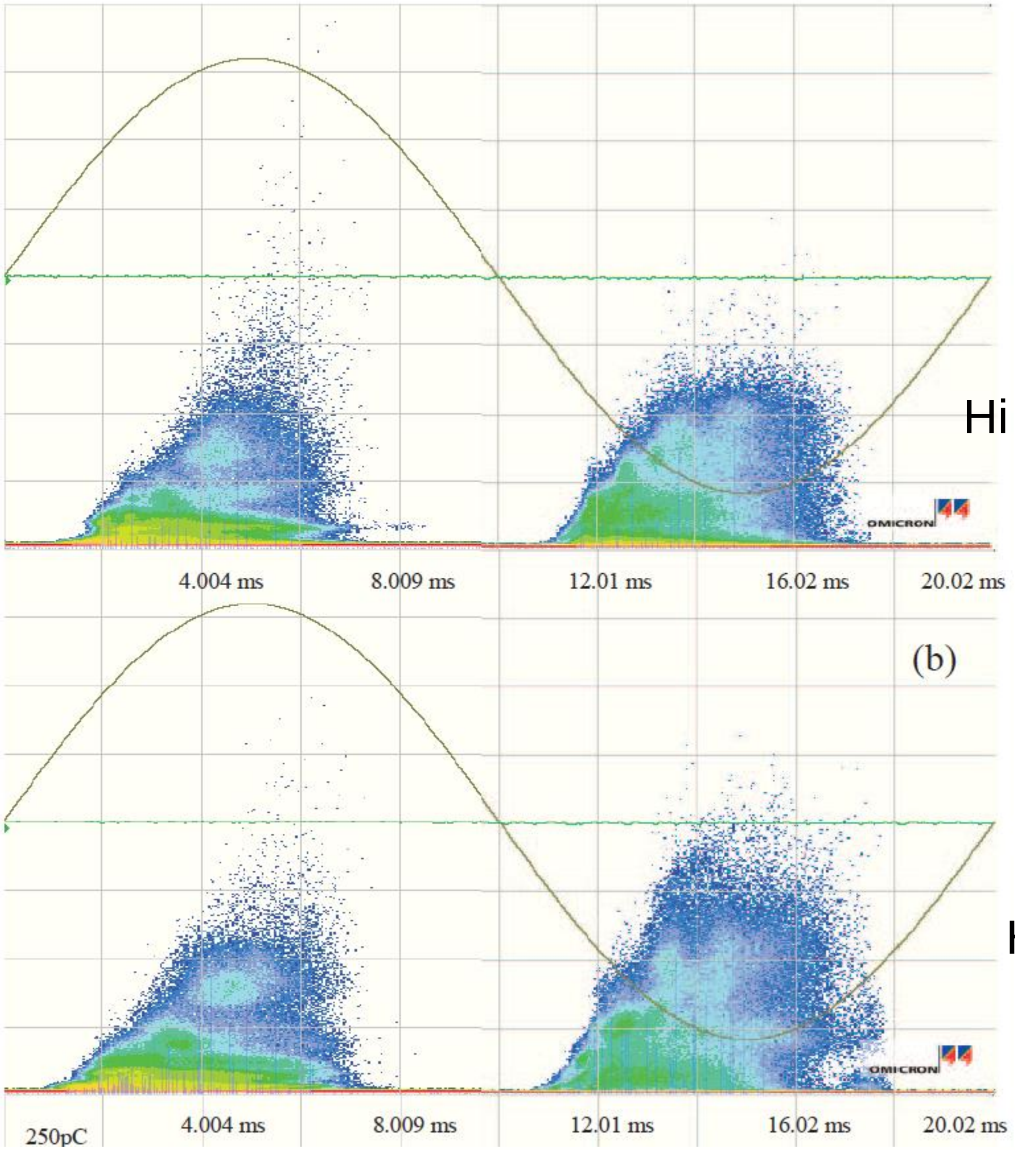
Figure 7. PRPD patterns of corona discharge



Low pd low noise

Low pd with noise

x-axis: time (ms) y-axis: discharge magnitude (pC)



Hi pd low noise

Hi pd with noise

Individual discharge pulse measurement-comparison

CT approach advantages

- Extremely cheap
- Simple (may use spectrum analyser and establish **trend**)
- Safe to use

CT approach Disadvantages

- Cannot be effectively calibrated (cf. HV terminal approach)
- Prone to interference from external sources (‘empty’ CT or plant deenergised to determine interference)
- No effective phase information (no HV measurements)
- Subject to neutral availability

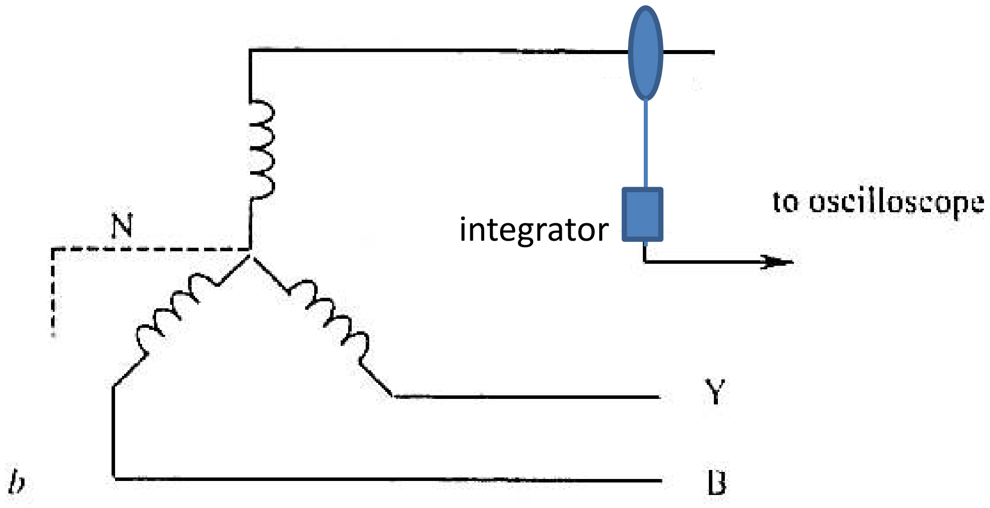
HV terminal approach advantages (divider / Rogowski)

- Individual pulses can be displayed superimposed on the AC power cycle voltage
- Can be calibrated by injecting a discharge-simulating pulse of known magnitude into the detector circuit
- For transformers with bushings containing tapping points, the bushing can act as the HV coupling capacitor (divider)

HV terminal approach disadvantages (divider / Rogowski)

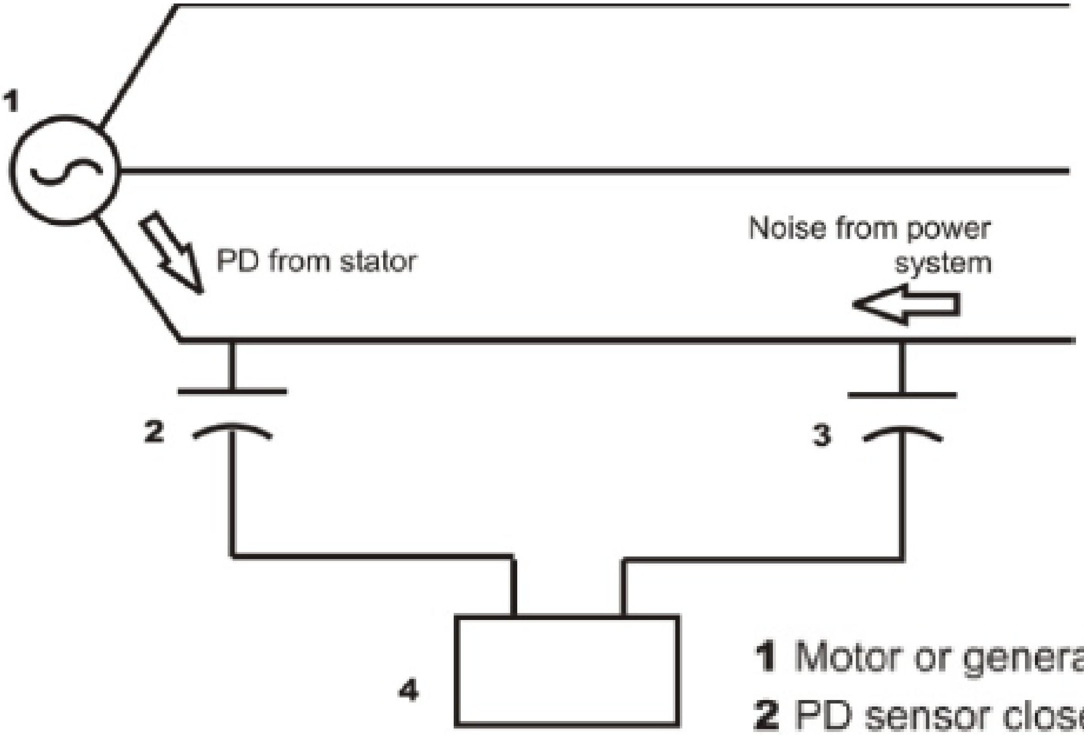
- Requires deenergisation of supply unless sensors are already pre-installed
- Subject to noises which can not be differentiated for the case of capacitive coupler option (Rogowski coil ables to discriminate)

Rogowski coil is signal direction sensitive



Noise from right side will be seen as a negative signal

Capacitive divider technique of discriminating noise



1 Motor or generator stator winding
2 PD sensor close to stator
3 PD sensor remote from stator
4 Dual input detector

1: VHF capacitive coupler method to separate PD from the stator winding from disturbances from either between the sensors or from the power system.

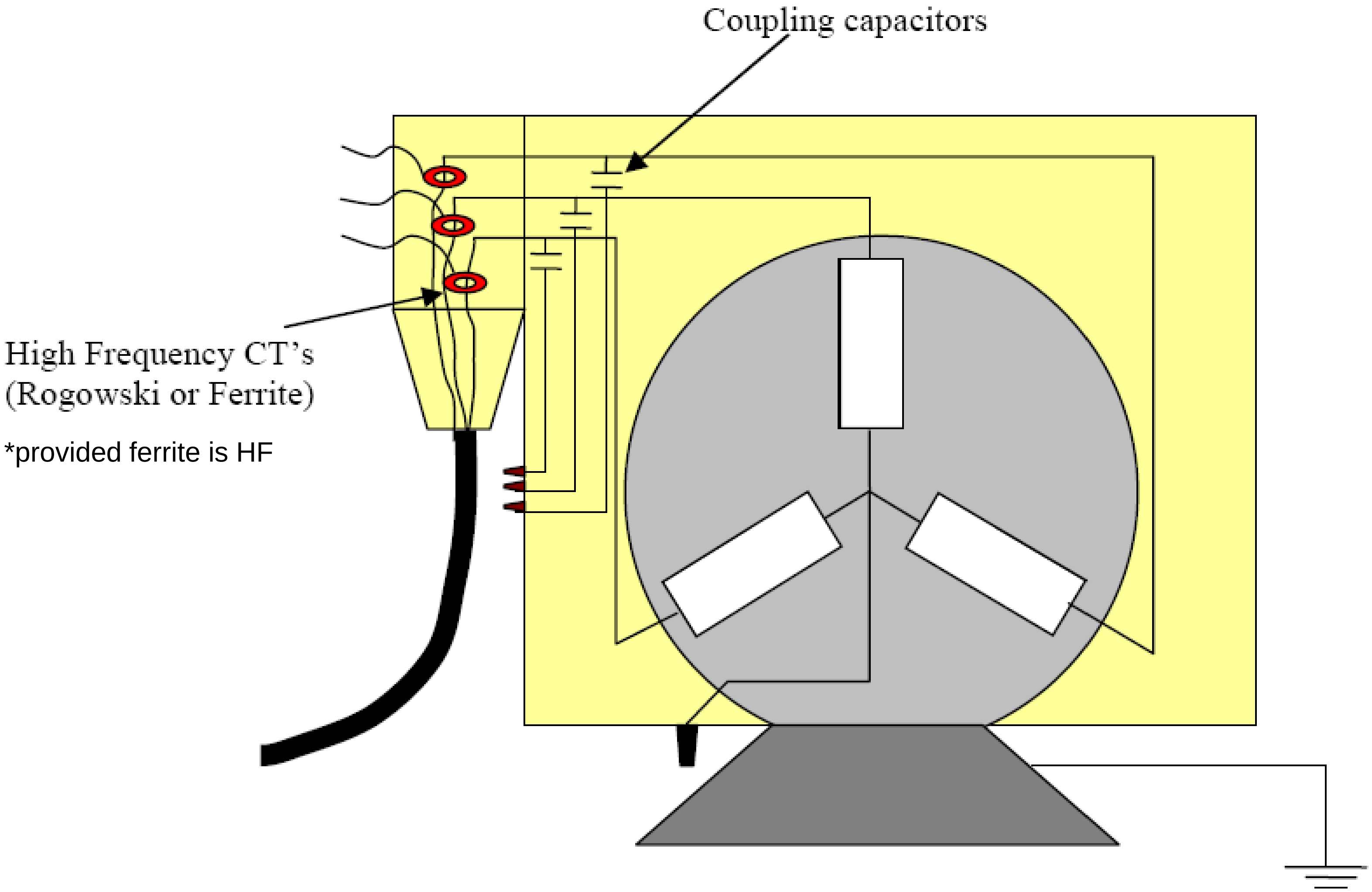
Rogowski coil

  - Rogowski coil concentrates the magnetic flux more effectively (cf. a standard CT)
  - Based on Ampere’s Law rather than transformer concept
  - Air-cored
  - Needs integrator

- **Advantages**
  - Light
  - Flexible
  - Easy to connect to terminals (open and closed)
  - Gives an indication of **pulse direction / direction sensitive**

- **Disadvantages**
  - Less sensitive than the capacitive coupler/divider

Typical applications - machines

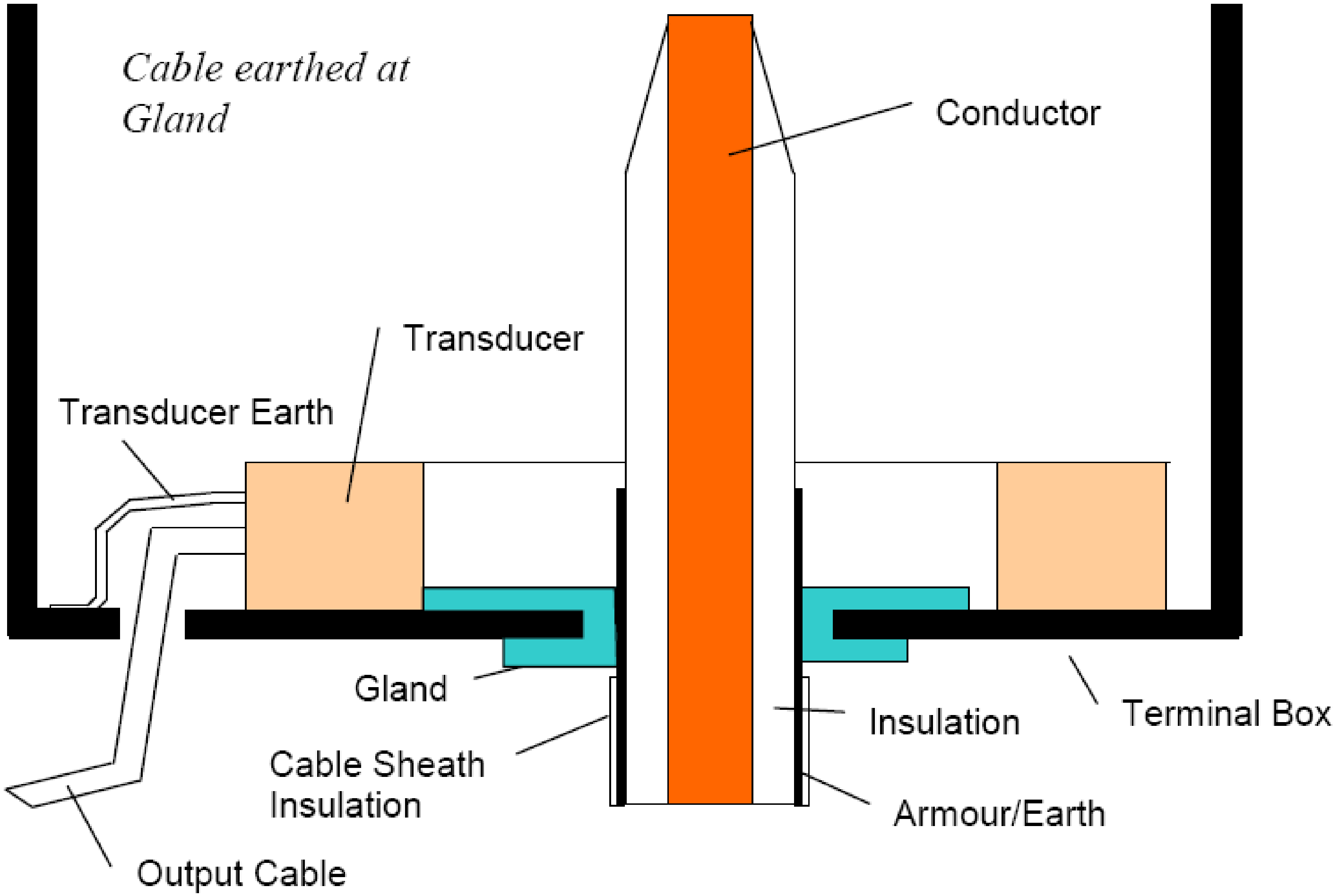


Coupling capacitors

High Frequency CT’s (Rogowski or Ferrite)

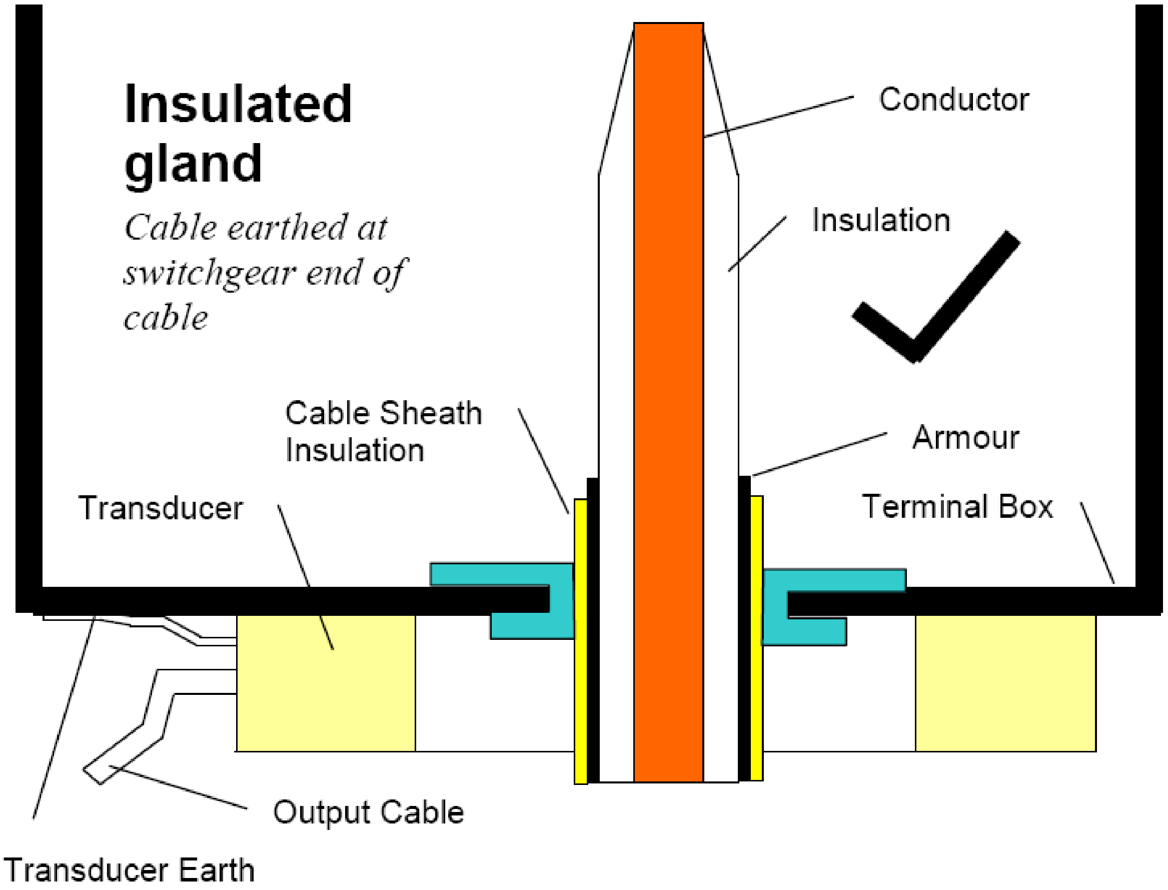
*provided ferrite is HF

Diagram of a rotating HV Machine showing the PD Sensor Options



*Broken earth return through the Rogowski/HFCT

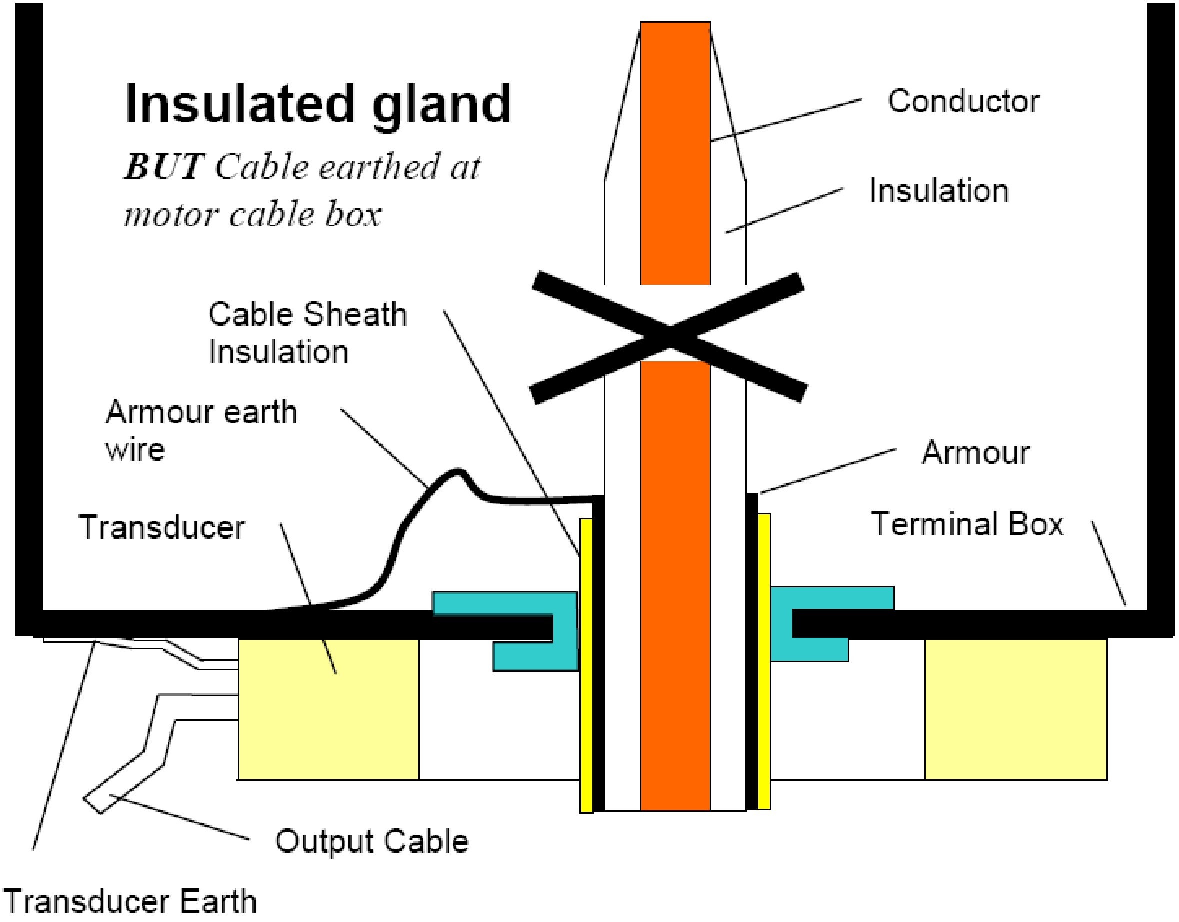
: Correct placement for HFCT Transducer inside cable box.
(This applies for both earthed and unearthed cables)



*Broken earth return through the Rogowski/HFCT

Correct placement of HFCT outside the cable box.

Note: The cable sheath insulates the cable armour/earth screen from the cable box so that no earth exists between the cable box and the cable sheath

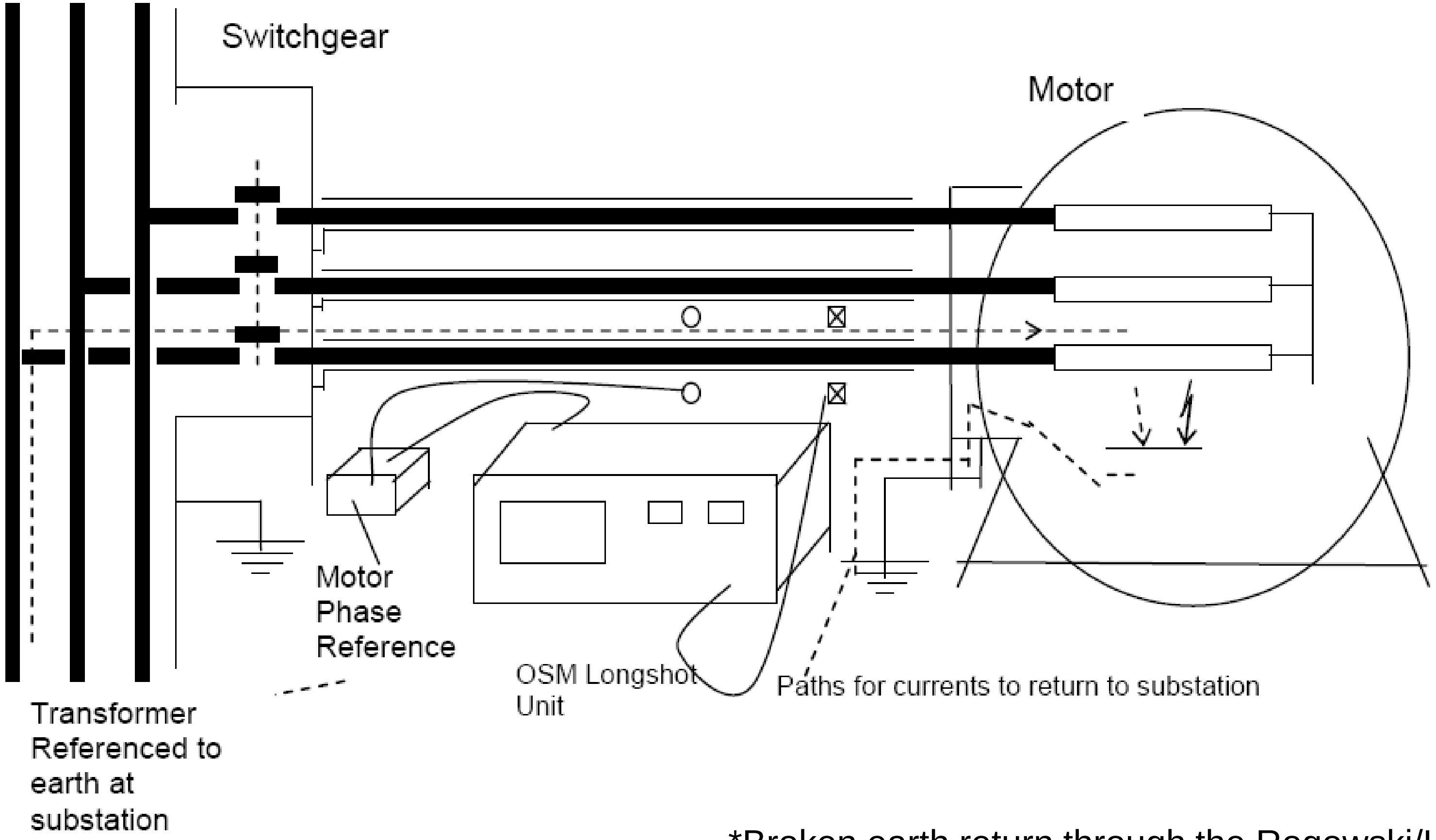


Insulated gland

***BUT** Cable earthed at motor cable box*

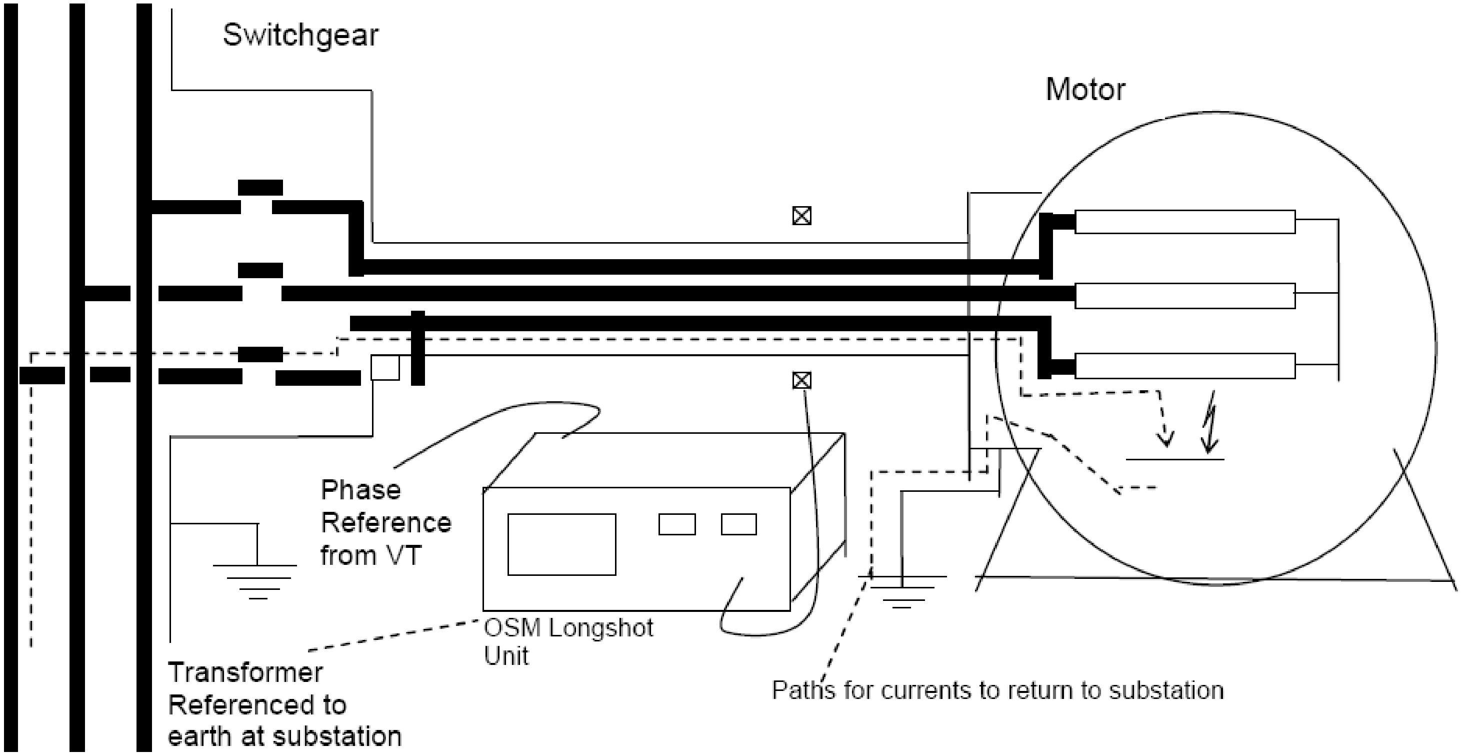
*Unbroken earth return through the Rogowski/HFCT

Incorrect Earthing for HFCT PD Testing outside of the cable box



*Broken earth return through the Rogowski/HFCT

PD Testing of HV Motor connected to Switchgear by an HV Cable



*No earth return through the Rogowski/HFCT

Online PD testing of HV Motors with a 3-core, ‘belted’ cable

Typical Machine PD CM Values

For the case of 3.3kV to 13.8kV machines, there is a generally accepted view (taken from Research studies around the world) that the following **Guideline PD Levels vs. Condition** can be apply to the stator windings.

Assessment	**Colour Code**	**PD in Slot Section**	**PD in End Windings**
New/Excellent	⬜	**<2000pC**	**<2000pC**
Good	🟩	**2000 to 4000 pC**	**2000 - 4000pC**
Average	🟩	**4000 – 10000 pC**	**4000 – 10000pC**
Still Acceptable	🟨	**10000 – 15000 pC**	**10000 - 15000pC**
Probable Inspection	🟧	**15000 – 20000 pC**	**15000 - 30000pC**
Problem/Unreliability	🟥	**>20000pC**	**30000pC**

Individual discharge pulse measurement- external interference

Possible external interference:

1. **PD and corona** from the **power syste**m which can be coupled directly to the apparatus under test (in an online test) or radiatively coupled (in online or offline tests)

2. **arcing between adjacent metallic components** in an electric field where some of the components are poorly bonded to ground or high voltage

3. arcing from **poor metallic contacts** which are **carrying high currents**

4. **arcing from slip ring** and shaft grounding brushes in **rotating machinery**

5. **arc welding**

6. powerline carrier communication systems

7. thyristor switching

8. radio transmissions

Interference checklist

Problem	Source of disturbance	Suggested corrective action
Pickup from external sources	Main interference	Filter in supply leads and/or HV line. Use a balanced detector circuit
	HV Supply	HV filter or check HV terminations for any sharp edges
	Radio signals and electromagnetic waves	Screened room or other shielding
Discharges in test circuit	HV source	Use a discharge0free supply, filter in HV line, toroid, or shielding. Balanced circuit
	Coupling capacitor	Capacitor must be discharge free, use two at a time and check circuit if possible
Contact noise	Noise in test circuit Between foils and terminals in capacitors Noise in bushings, tap changers, trancore	Good connections and grounding, apply current pulse by charging with dc and short-circuit, check all contacts well before testing

- Interferences can be minimised through the use of **inline filters** and some form of discrimination circuit if the problem is in the high voltage line
- Discrimination of pulse source using Rogowski coils
- Airborne interference can be identified/eliminated while deenergised

PD Discharge pattern

- Amplitude
- Number of discharge pulses per power cycle
- Distribution of these pulses within the power cycle (phase relationship)
- Also interested in effects of time of stress and magnitude of stress -> nature of degradation sites and hence insulation integrity

Pattern Interpretation

- Difficult to establish specific site
- The importance of regular measurements on a given insulating system

Ideally, patterns should be obtained at regular intervals throughout the life of the insulating system since there is, no doubt that the trend in the discharge pattern of a given insulating system with time provides far more useful information on insulation integrity than any measurement at only one point in time.

The rate of change is more important!

- In relation to the interpretation of the discharge pattern, the starting point would be the **magnitudes of the discharges** being detected and their **repetition rate**

- Broadly, the larger the discharge magnitude, the larger the site of degradation with which it is associated and the greater the likely rate of degradation

- Similarly, **the greater the repetition rate or number of discharges per cycle or unit time, the greater the number of discharging sites**

- The next aspect for interpretation would be the location of the discharges on the **power cycle waveform**

- Cavity-type discharge sites generally yield a discharge pattern within which **most pulses are in advance of the voltage peaks**, i.e., 0-90^o and 180-270^o of the AC power cycle

- In contrast, discharge sites containing a sharp-metal surface generally produce a pattern with pulses symmetrically spaced on both sides of the voltage peak(s)

- Then, relative **magnitudes** of discharges on the **positive** and **negative** half cycles (quadrants 1 and 3) -> two similar insulating surfaces vs. two different surface topology

- Based on the above, decide whether the discharge site(s) are **insulating-bound**, **insulating-metalli**c or **metallic (corona**).

- Next, see the effects of test voltage, time of application of voltage (both usually possible if off-line)
- If the discharge **magnitudes remain constant with increasing test voltage**, one is observing discharge activity within **fixed cavity dimensions**.
- It means all cavities are of the same dimension or only one cavity is involved.
- In contrast, if the magnitudes change with the applied voltage, it means cavities of different sizes, the bigger ones breakdown later…

- Having decided what one is dealing with- either a **cavity-type degradation** or otherwise, and –either **insulation-bound cavity** or **metallic-insulation bound**, and having determined something of the **cavity size/number distribution**, observing the pattern at a fixed voltage over a period of time may yield still more information

- If the activity **lessen with time**, a **pressure** increase in the cavity is possible – gaseous byproducts effect, a build-up of surface charge within the cavity structure –thus inhibiting further discharges, or a build-up of water or acids within the cavity – increasing surface conductivity and hence allowing charge to leak away.

- Gaps with a sharp metallic boundary situation – same analysis can be made

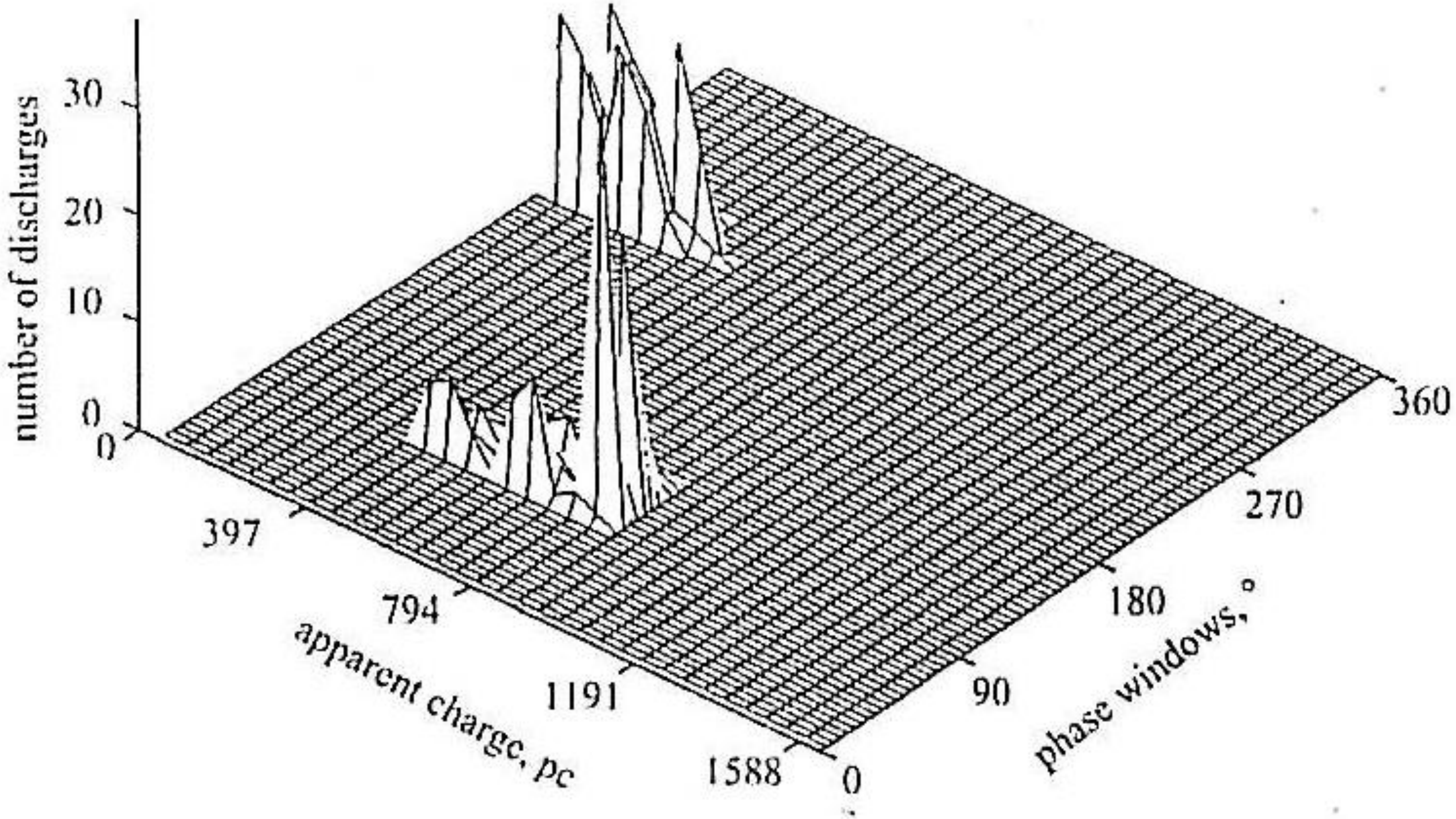
- **There are many conditions that could be discussed relating discharge magnitude, phase distribution, test voltage and time of application to specific conditions.** Look-up table vs understanding

- Again, the importance of establishing a **trend** in the discharge pattern for a given insulating system over its lifetime cannot be stressed too strongly

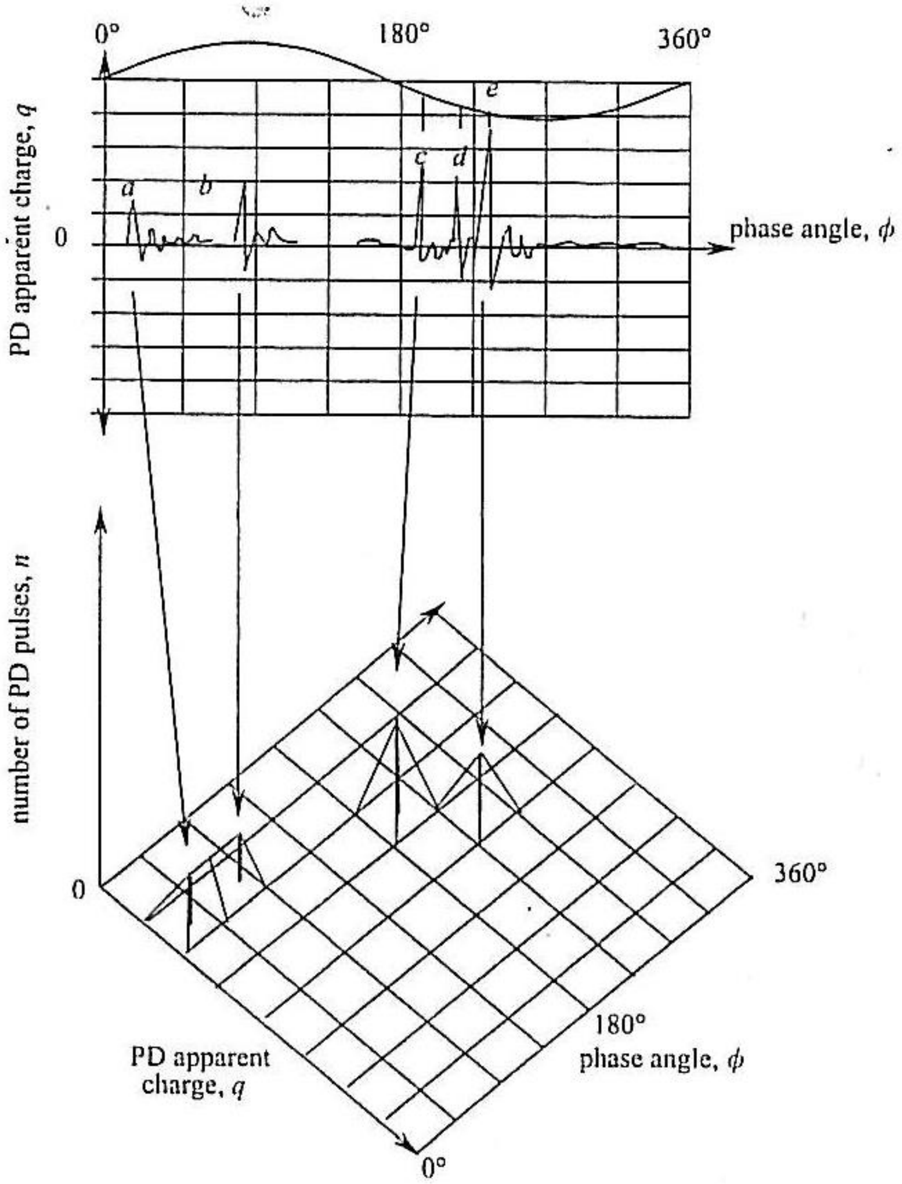
- In general, the particular degradation characteristics are often developed relatively early in the life aim insulating system

- Thereafter, the parameters of primary importance are the **absolute discharge magnitude** and, more importantly, its **rate of rise over given times** — both relative to the values obtained front other insulating systems of similar design and history

- Modern facilities enable 3-D plots: ϕ-q-n (x-y-z) plots; n being number of discharges per unit time (within specific phase-magnitude window)



ϕ-q-n plot of discharge activity



Build-up of ϕ-q-n distribution

- If the PD pattern is relatively stable over the sampling period, a probability distribution of the plot can be obtained – more cycles taken mean more statistically accurate distribution -> sampling rate and memory size issues

- May detect changes in the statistical moments of the distribution – mean, variance, skewness and kurtosis

- Other modern parameters taken (as a function of time or phase angle):
  - The discharge energy (p=qV) V during discharge q
  - The discharge phase inception voltage, Vi (where the discharge pulse sequence starts)
  - The discharge phase extinction voltage, Ve (sequence ends)

- The discharge current
- The discharge power
- The discharge intensity, N (during time T)
- The quadratic rate, D

- More work need to be done to clearly **establish** correlations between them and the nature and extent of PD based on the measurements

- IEC60270 is not immune to inherent errors – eg filter bandwidth and responses/sensitivity

Pulse sequence analysis

- Increasing interest in the nature of the sequence of pulse events – with help of modern memory capacity and digital signal acquisition
- Explores the deterministic nature of PD events
- A PD event terminates when the local voltage drops below some critical value
- Due to macroscopic field as well as local field in the vicinity of the PD event due to space or surface charge effects (distribution and rate of decay play role)
- Pulse sequence provides greater insights
- Change of external voltage between consecutive discharges
- Able to separate several sites

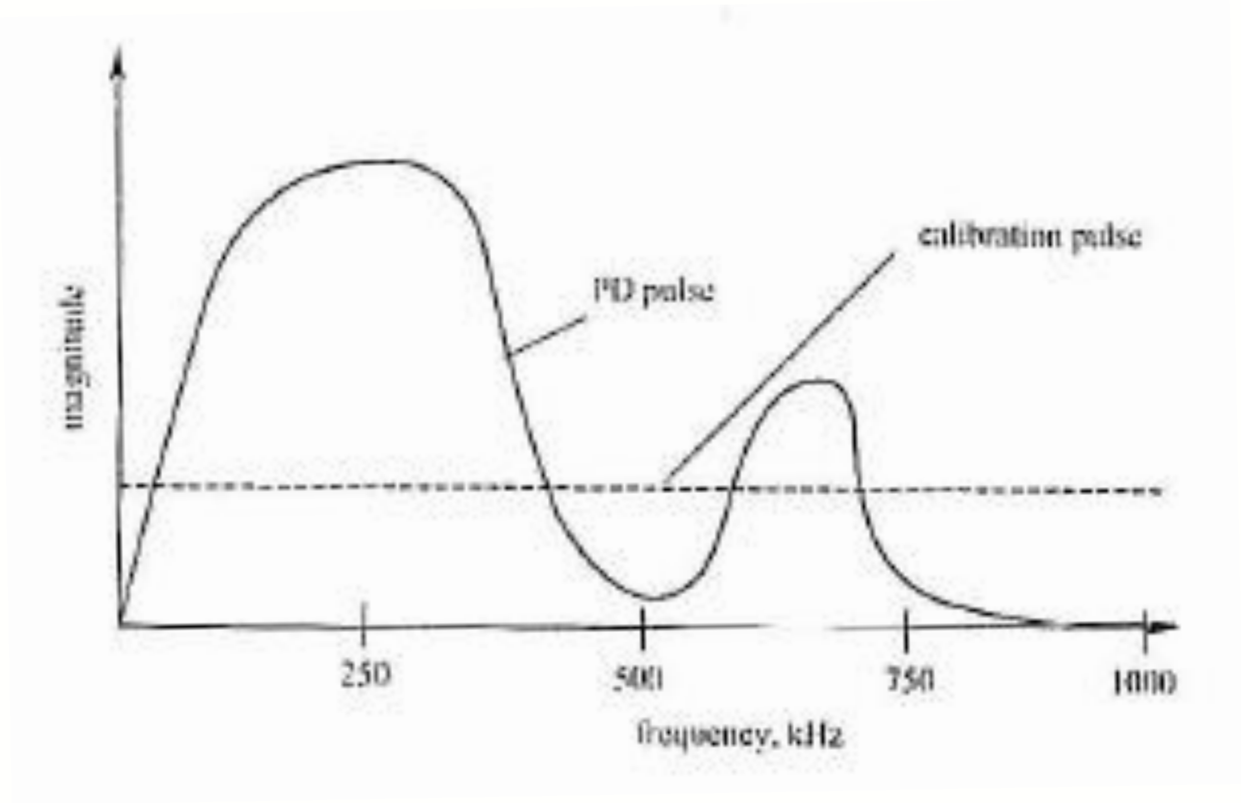
PD Calibration

- Irrespective of detector characteristics (various available bandwidths and sensitivities), an accurate measurement of PD activity is needed
- A discharge simulating pulse of known magnitude (the calibration pulse) is injected into the detector at the point where the real discharge pulse enters the detector
- Hence, irrespective of the modification to the pulse introduced by the detector, the same modification is done to both calibrating and real pulses
- For example, if due to the limited bandwidth (compared to broad band), the magnitude is reduced to half, then the calibrating pulse will correct this
- The above strategy is valid if the discharge site is close to the detector terminals

- However, this strategy does not work for generators, motors, or transformers since the measured pulse magnitude is dependent on the location (at various points through their windings) at which the discharge-simulating pulse is injected (10s of meters from the detector)

- The detected magnitude is a function of both the location of the injected pulse and of the bandwidth of the detector utilized (transmission line effects take place and modify the frequencies of the PD pulse)

- The calibration pulse characteristic compared with PD pulse characteristic following propagation (Fig. 4.4) illustrates the dependent of the PD pulse on the injected location and how the detector (with a given bandwidth if it is not broad band) detects the propagated pulse ie a narrowband detection system around 250kHz would suggest the PD is large whereas that around 800kHz suggest an extremely small PD pulse.



Calibration pulse characteristic compared with PD pulse characteristic following propagation

Noise and wavelet analysis

- Methods of employing discrimination circuits, traditional filtering techniques, neural networks etc. have been designed to suppress noise with limited success.
- However, a new, more powerful tool is now being applied to this problem — wavelet analysis.
- It is likely that this technique will bring radical improvement to noise reduction and suppression.

- It is possible to extract PD pulses from extraneous noise in a way which would be impossible with traditional filtering techniques

- Ability to store needed information only and hence save space!

Noise and wavelet analysis

PD measurement in presence of noise

- a Raw data, PD activity and noise superimposed
- b Processed data to show PD activity