Why PD Interpretation For Electrical Rotating Machines is Different From Other Types of Equipment

Greg Stone

gstone@irispower.com

Outline

- Insulation systems in different types of equipment
- How PD causes insulation aging: treeing and tracking
  - Impact of PD on organic insulation
  - Impact of PD on organic/inorganic composites
- Inductive versus capacitive test objects
- Interpretation for insulated equipment using only organic material
- Interpretation for inorganic (mica) insulated equipment (stator windings)
- PRPD patterns – unique types of defects versus many defect types
- Conclusions
- References

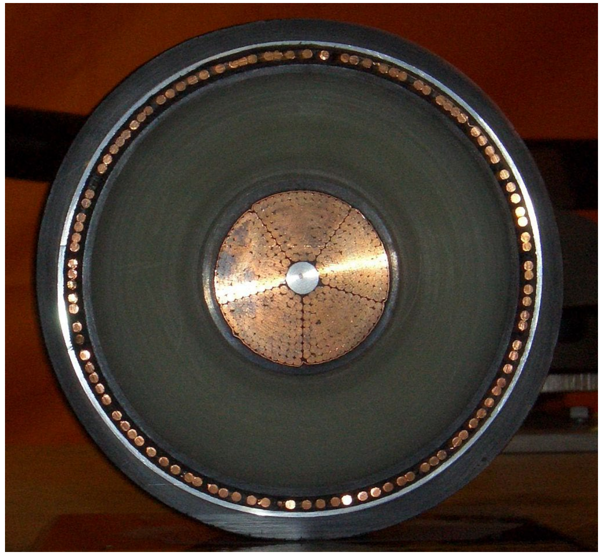
Equipment that is PD tested

- Power cables
- Power transformers
- Dry-type transformers
- Distribution class switchgear (AIS)
- Gas-insulated switchgear (GIS)
- Components in the above
- Stator windings

Inverters and inverter connected equipment are not covered here

Power cables

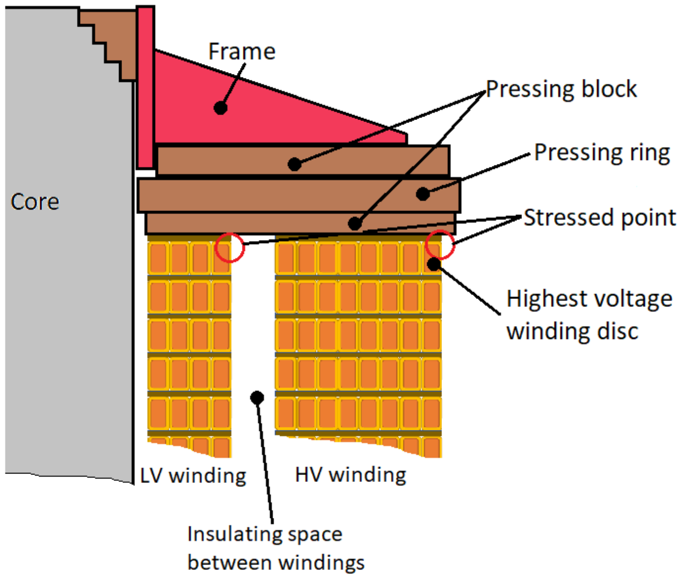
- Distribution class - use polyethylene (PE), cross-linked polyethylene (XLPE) or synthetic rubber (EPR) as insulation
- Transmission class - XLPE or oil-impregnated kraft paper
- Cable systems also have terminations, sealing ends and joints where control of electric stress is needed
- Failure due to defects or aging will lead to electric treeing or tracking at tape or termination interfaces

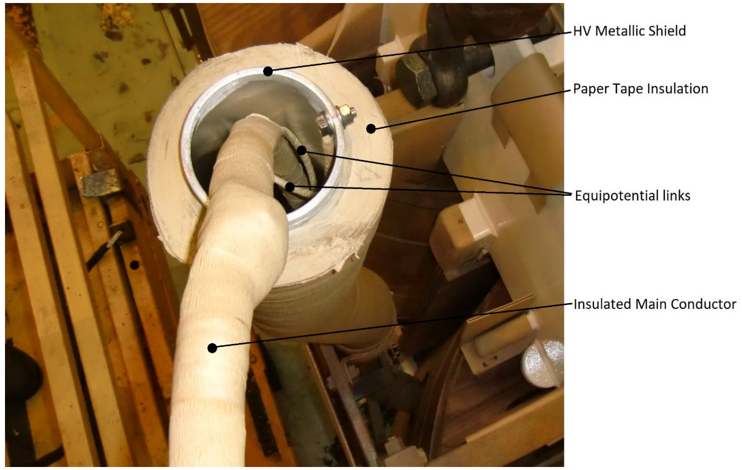


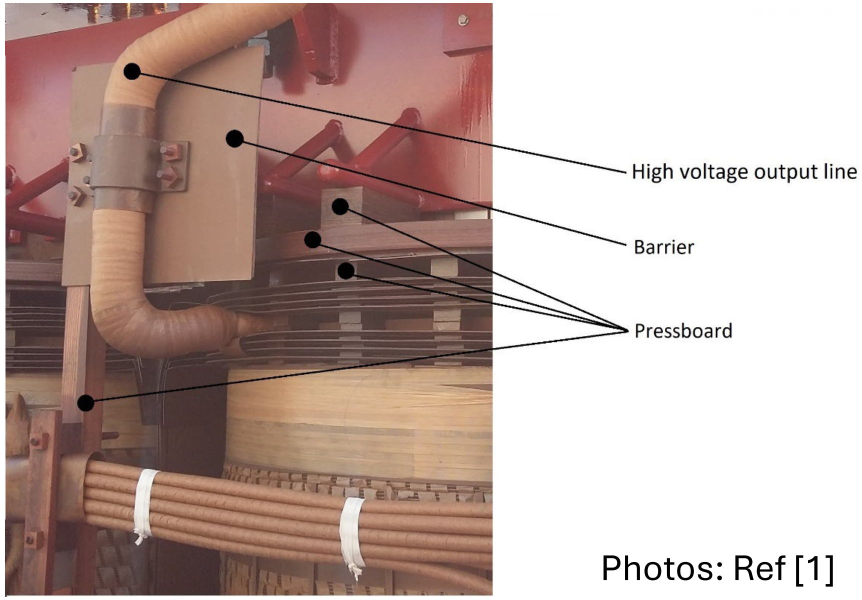

Photos: Ref [1]

Power Transformers

- Conductors wrapped in kraft paper and impregnated with oil
- Barriers made of pressboard
- In addition there are bushings normally insulated with oil and paper
- Failure due to defects or aging will lead to tracking at interfaces and PD within gas bubbles







Photos: Ref [1]

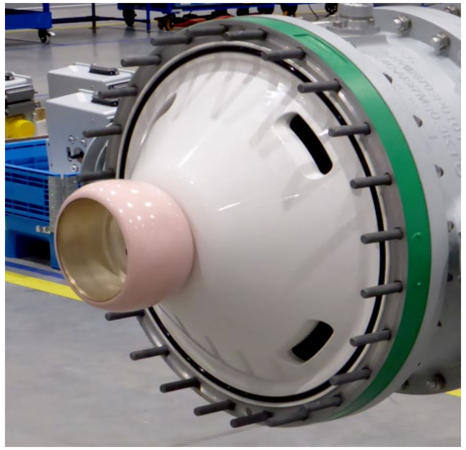
Air Insulated Switchgear

- Air is the main insulation
- Pre 1970s, busbars supported by ceramic insulators
- Modern AIS uses fiberglass reinforced polyester boards to support busbars and act as barriers between cubicles
- Failure due to contamination will lead to electric tracking

Photos: Ref [1]

EHV Gas Insulated Switchgear

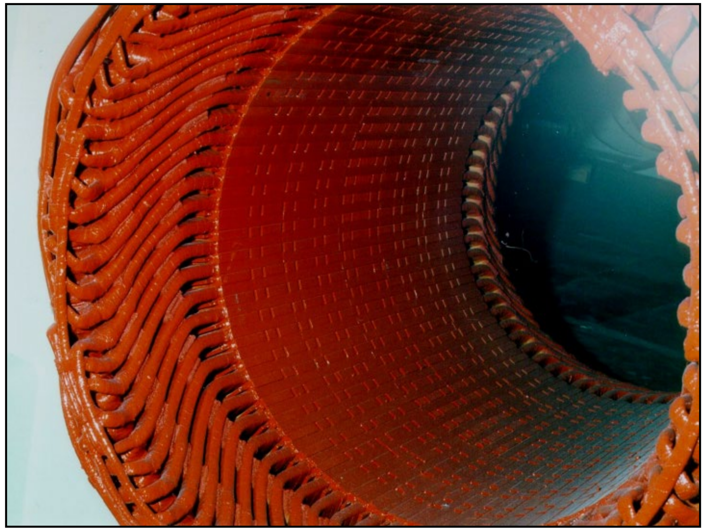
- SF_6 is the main insulation
- Busbars supported by cast epoxy ‘spacers’
- Failure due to electric treeing from voids in spacers; tracking over spacers initiated by small metal particles

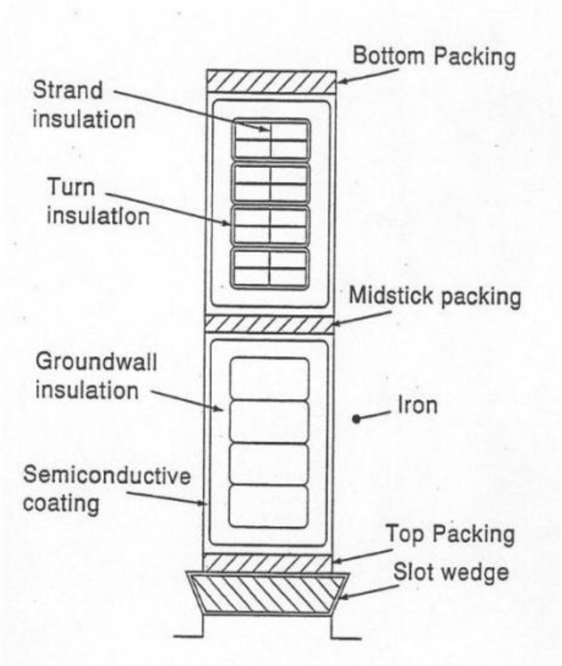


Photos: Ref 1

Stator Windings

- Main insulation is inorganic mica tapes bonded together by epoxy
- Manufacturing defects may lead to PD, but very slow failure process
- More commonly, aging creates voids or stressed insulation surfaces leading to PD

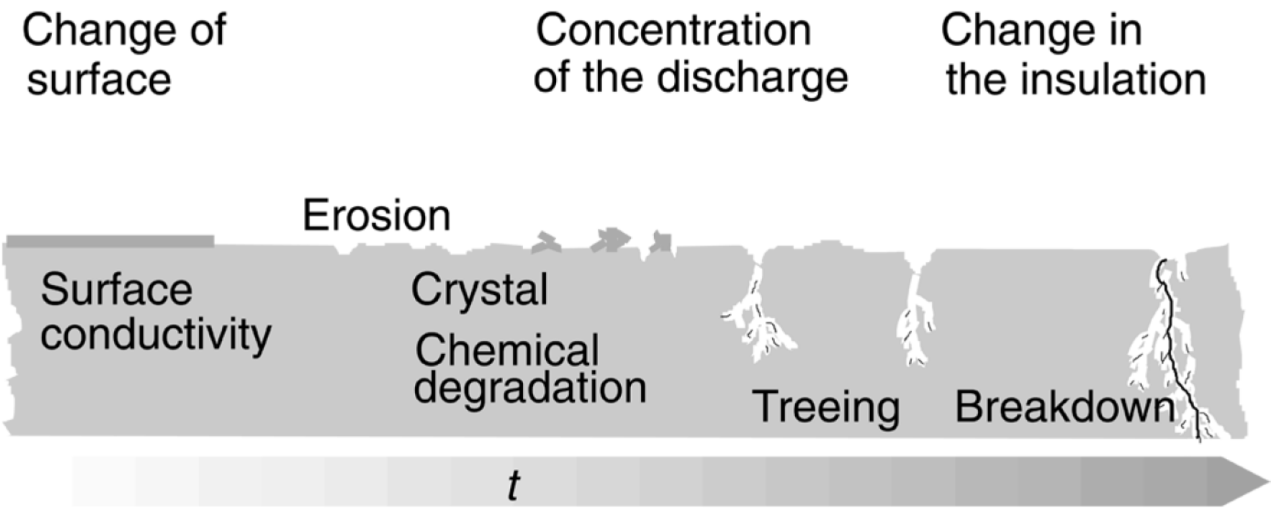




Electric Treeing

- PD mainly occurs in gas-filled voids or in a gas adjacent to an insulation surface that is under high electric stress exceeding the gas breakdown strength
- PD is a spark where electrons and ions bombard the solid or liquid insulation surrounding the defect
- Electrons travelling through the gas gaining energy from electric field
- Typically a high percentage of electrons gain enough energy to break the carbon-carbon chemical bond of organic materials (paper, XLPE, epoxy, oil)
- ‘Bigger’ discharges have more electrons (more pC) which may break more bonds
- Eventually sufficient bonds are broken to extend the size of the defect and bore (erode) holes through the organic insulation – called ‘electric treeing’
- The branches of the tree are often partly conductive due to free carbon
- If purely organic insulation, treeing may cause failure in hours or days

Electric Treeing in Organic Polymers



Stages of tree growth [1]

Electric tree in epoxy leading to failure

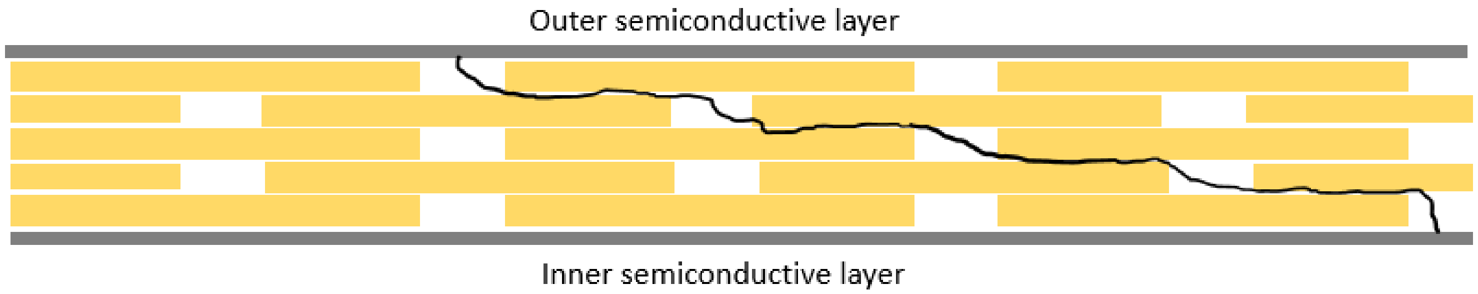
Electric Treeing in Organic Polymers with an Inorganic Barrier

- Mica and glass are inorganic materials
- The chemical bonds and crystalline structure of mica are stronger than those in polymers
- Discharges do not break the chemical bonds of mica
- Thus mica flakes are very resistant to electric treeing
- In most cases electric trees grow around mica barriers, rather than through mica
- If mica content is high, treeing may take tens of years to cause failure

Photo from Ref. [1]

Electric Tracking

- Occurs within polymers at interfaces (e.g. oil-paper tapes in power cables and transformers)
- Occurs on insulation surfaces (e.g. GIS epoxy spacers and stator endwindings)
- Discharges driven by electric field that is not perpendicular to conductors
- Discharges at defects/contamination on the surfaces
- Tracking may take a short or long time to cause failure depending on the creepage distance



Tracking between interfaces in oil-paper cable [1]

PD Testing of equipment with purely organic insulation – Factory tests

- In purely organic insulation, PD can lead to electric treeing or tracking failure quickly
- Thus OEMs recognized that a factory PD test is essential to make sure equipment does not fail in service (or at least before the warranty expires)
- Led to many IEEE and IEC standards for off-line PD tests before equipment enters service – standards for each type of equipment
- In all cases OEM must show that PD does not occur at a specific test voltage that is 10% to 400 % higher than operating voltage

PD Testing of equipment with purely organic insulation – Equipment in service

- Any PD occurring at operating voltage can be expected to rapidly cause failure
- For PD detection with on-line monitoring, and if the false positive indication rate is low – it is usually recommended to remove equipment from service as soon as possible to avoid in-service failure, limit consequential damage and minimize disruption to service
- On-line continuous monitors more effective to maximize warning time – which may only be hours/days, compared to periodic on-line testing
- Alternatively perform off-line/on-site PD test where apply a voltage that is above operating voltage. The greater the difference between the PD inception voltage (PDIV) and operating voltage – the less likely an in-service PD failure will be – this approach gives a better assessment of risk of failure
- PD of any magnitude is ‘bad’, there is no safe level of PD activity in organic insulation
- The trend in PD activity in on-line testing is not an indicator of time to failure

PD Testing of equipment with a high inorganic content – Factory and Commissioning tests

- Most commonly mica in stator insulation
- Essentially every stator rated 3 kV and above will have voids/defects that will cause PD during normal operation
- Within reason this does not imply the stator will fail, even after 100 years of operation – because mica acts as a barrier to PD
- Even large defects in stators causing high PD will not fail within the warranty period, or perhaps for many years (if ever)
- Although there are standards for PD testing stators, there are no requirements recommending minimum PDIV or acceptable PD magnitudes in factory or commissioning tests

PD Testing of equipment with a high inorganic content - Equipment in service

- PD is expected during normal operation
- The question is if it is ‘high’ and/or increasing
- If the PD activity increases over time, it implies aging is occurring and defects are growing bigger
- Since PD rarely causes significant aging – PD testing mainly determines if other aging processes are occurring: thermal, thermomechanical, mechanical, contamination
- In almost all cases, all the aging processes are slow (years to tens of years)
- Thus the trend in on-line PD activity over the years is the most important indicator
- Continuous PD monitoring is convenient, but not essential
- “Alert” PD levels based on comparison to other similar machines with same type of PD detector, where the aging has been verified by other methods

Relevance of PD Magnitudes

Organic insulation, non-inductive equipment:

- How rapidly organic insulation degrades depends on the number of electrons in the discharge – this is quantified in terms of Coulombs
- IEC 60270 facilitates calibrating mV (what is actually measured by all conventional PD detectors) into pC (about 10^7 electrons) or nC
- Since its creation, IEC 60270 has always indicated the calibration process is only valid for capacitive test objects and simple transmission lines like power cables and GIS
- For such equipment pC, nC are absolute, and can be compared between different PD detectors and different test objects

Stator windings:

- Since stators are complex inductive-capacitive networks – one can obtain almost any calibration factor to convert mV to pC using IEC 60270
- Thus for stators – interpretation only valid by comparison to similar machines or the same machine over time measured by the same method – the units are not important

Relevance of PD Magnitudes

Organic Insulation:

- Any PD is bad, since electron bombardment will increase volume of defect and eventually PD will cause failure
- Since such equipment is designed to be ‘PD-free’ in operation, PD test comes down to knowing the sensitivity of the PD test set-up in terms of pC – i.e. the minimum PD pulse one can detect above the noise floor
- Sensitivity mainly depends on electrical interference in factory or at site
- Thus cable OEMs can get a few pC sensitivity since shielded rooms are used, similar for GIS since inherently shielded
- AIS PD sensitivity mainly around 100 pC, because testing is done in a factory without a shielded room

Relevance of PD Magnitudes

Stator Windings

- Actual PD magnitudes depend on the volume of defects, and also the measurement method and frequency, distance between PD site and PD sensor
- Calibration can be done, but it conveys no information
- A 30 to 1 difference in PD magnitudes possible among brands of detector, and the measurement frequency range
- Since all stators have PD, it is the peak PD magnitude Qm (together with other indicators) that are interpreted (not whether PD is present of not)

Relevance of pulse count rate

Organic Insulation:

- In factory testing there may be many defects (and thus many pulses per second - pps) due to multiple defects – these are normally corrected before shipping
- For equipment in service, only aging (or undetected manufacturing flaws) will create PD – there are normally few PD sites (and thus a relatively lower pps rate)

Stator Windings:

- Even great windings will have hundreds of small defects creating PD – thus relatively higher pps rate
- Some aging mechanisms produce thousands of PD sites (bad semicon) and others produce few (semicon/grading coating interface)
- Since so many sites, the pps is less relevant for stator insulation

Trend in PD Activity

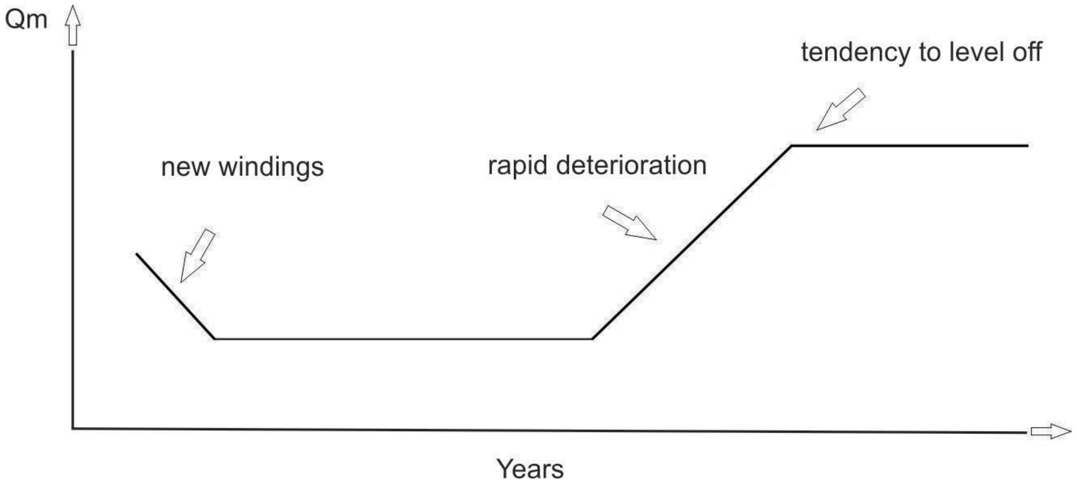
Organic Insulation

- PD will normally not be present
- Then it starts abruptly and increases in magnitude, pulse count rate
- But it can also be intermittent – disappear for long periods of time
- In erratic fashion it may increase until failure occurs since PD is the cause of failure

Trend in PD Activity

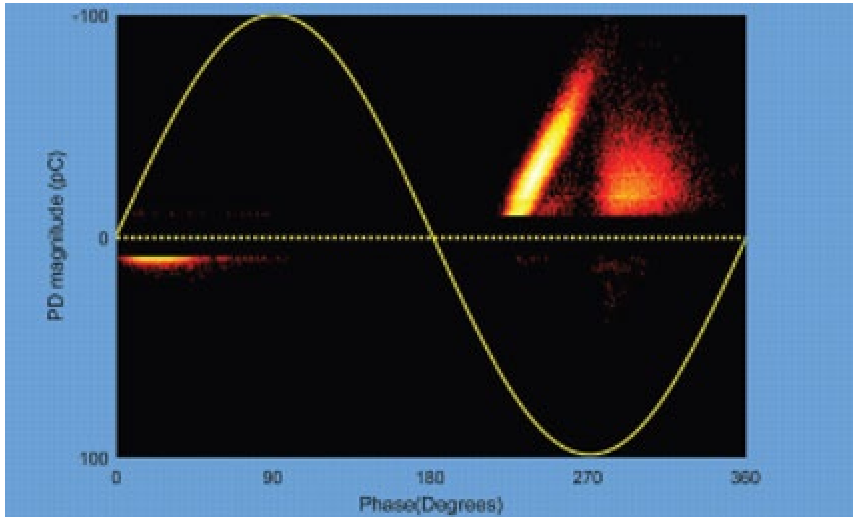
Stator windings:

- PD will always be present
- If Qm doubles every year or so, indicates thermal, mechanical, contamination, etc. aging is occurring since these processes increase the volume of the defects
- How quickly PD increases depends on operating temperature, number of load cycles, how loose coils are in the slot – not on the PD causing aging
- Experience shows PD eventually levels off
- Thus presence of PD can NOT predict when insulation will fail – unlike for equipment using only organic material



Identifying Failure Processes using PRPD plots

- Many PD instrument suppliers and researchers have associated different PRPD patterns with different types of defects or failure processes
- These have been reproduced in the various equipment standards for PD measurement to help determine the root cause of the PD
- With other tools, this has been very helpful in factory testing to find what went wrong if PD is detected



Identifying Failure Processes using PRPD plots – Organic insulation

- Since PD causes relatively rapid failure in organic-insulated equipment, for operating equipment at any instant of time there is only likely to be one PD location/process occurring at a time
- Thus if noise is effectively suppressed, identifying the most likely root cause based on a PRPD fingerprint is reasonably effective
- It is interesting to note that sometimes the same PRPD pattern in two equipment standards points to fundamentally different aging mechanisms
- There is still much to learn and much more blind testing required to find the correct patterns for each mechanism in each type of equipment

Identifying Failure Processes using PRPD plots - Stator windings:

- In a stator there will always be some level of groundwall void PD that is harmless, but easily detected
- As the winding ages, many different processes occur simultaneously since failure processes take years to tens of years to cause failure
- Thus very complicated PRPD patterns involving many processes occur, even if noise is effectively suppressed
- Some processes produce high Qm, yet are very slow processes
- Only AIS and stator windings are likely to have phase-to-phase PD
- To date, in blind testing, AI tools have been no better than 'experts' (and usually much worse) in deconvoluting the mechanisms present
- About 20% of the time the PRPD pattern is not consistent with visual inspection of the winding
- Still better to use the effect of load, winding temperature and humidity to identify failure processes

Conclusions

- The presence of mica in stator windings makes the interpretation of PD tests fundamentally different from equipment that has purely organic insulation
- Unlike other equipment, PD in stator winding insulation is mainly a symptom of aging by other stresses, rather than a cause of failure itself
- All PD tests on stator windings are comparative – not absolute
- ‘Experts’ who mainly are skilled at PD test interpretation on organic-insulated equipment should be wary of interpreting results from stator windings – and vice versa

Reference

1. G.C. Stone, A. Cavallini, G. Behrmann, C. Serafino, “Practical Partial Discharge Measurement on Electrical Equipment”, Wiley/IEEE Press, 2023.
2. There are also dozens of IEEE and IEC standards that cover PD measurement in each different type of equipment. See [1] for lists.