Partial Discharges in Electrical Insulation

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Outline

• What is partial discharge (PD) and under what conditions does it occur
• Examples of PD in power cables, transformers, switchgear and stator windings
• PD measurement as a factory acceptance test of equipment
• Off-line PD testing at site
• On-line condition monitoring of power cables, transformers, switchgear and machines
What is Partial Discharge (PD)

• An incomplete electrical breakdown between two conductors
• Corona is a type of PD, where the PD is occurring on a conductor surface and is the result of a high local (non-uniform) electric stress
• Generally PD is only likely to occur on equipment operating at 3.3 kV phase to phase or above
• PD is known to occur in power cables, stator windings, transformers and switchgear
What is Partial Discharge (PD)

• PD only occurs where there is a gas (air, SF6, hydrogen) between the two conductors
• The conductors must have a high voltage between them, creating an electric stress
• If the electric stress in the gas exceeds 3 kV/mm of spacing (for most dry gases at 100 kPa), then electrons are stripped from the gas atoms
• The electric strength of most solid and liquid insulations is 50 to 100 times higher than most gases
• The (negative) electrons move through the air (toward the more positive conductor) and bombard the solid or liquid – causing aging of the insulation
• Electrons moving through space and time create and electric current \(i = dq/dt\)
Potential difference (voltage) builds across an air-filled void due to capacitive voltage divider.

PD occurs if \( E = \frac{V}{d} > 3\text{kV/mm} \) (i.e., electrical stress exceeds electrical breakdown strength of gas).

The larger the void, the larger the discharge.
Partial Discharges

- Once the electric stress in the void exceeds 3 kV/mm (at 100 kPa), electric breakdown (a “discharge” or flow of electrons) will occur in the gas.
- When the electrons hit the edge of the void, any organic material (polyethylene, epoxy, oil) will be gradually decomposed – aging.
- A discharge in air also creates ozone (O3) and nitric acid.
- PD is very dependent on voltage.
Examples of individual PD current (voltage) pulses
PD Pulse Characteristics

- Extremely short rise-time current pulse
- Rise-time at discharge origin ~ 2-5 ns at 100 kPa, and <1 ns at higher gas pressures
- Using Fourier transform – each PD pulse creates frequencies from 0 to 250 MHz or higher
- Measure PD in high frequency spectrum
- PD usually creates both positive and negative pulses
PD Testing

• PD is bad – it is an important cause of failure in equipment using pure organic insulation

• Where the insulation is a organic/inorganic composite (stator windings), PD may not cause failure, but is a symptom of poor manufacturing or certain aging processes

• Measure PD current pulses to detect PD
Types of PD Testing

• Off-line testing (equipment disconnected from power system) – factory testing for quality and in-situ for condition assessment

• On-line testing – equipment is connected to the power system and usually in normal operation – used for condition assessment

• Test methods, pass-fail criteria, standards are different for each type of power equipment
Basic Off-Line PD Test Equipment

- Transformer to energize test object to rated voltage or higher
- Sensor is normally a high voltage capacitor – blocks high voltage 50/60 Hz while a short circuit to the high frequency PD pulses
- Display PD pulses with respect to the AC cycle on an oscilloscope or PD detector
PD Detection with Capacitive Sensor

50/60Hz
83MHz

80pF

83MHz

1.5kΩ

50/60Hz Micro-amps

PD Pulse Counter

System
Off-line PD Test Set
PD Display: Phase Resolved PD (PRPD) Plot

Phase position vs Pulse count & Magnitude (color)
PD in different types of power equipment

- Power cables
- Medium voltage switchgear
- Power transformers
- Stator windings
Insulated Power Cables

Many types of power cables:

- Oil paper insulated (PILC-paper insulated, lead covered, LPOF-low oil pressure, HPOF high pressure oil filled), both distribution and transmission class
- Since about 1960, all distribution class cables made with PE (polyethylene), XLPE (cross linked polyethylene) or EPR (rubber)
- Since about 1990, most transmission class cables up to 230 kV made with EPR or XLPE
- Cables have splices along its length and terminations at each end
Cable Construction

• Center conductor at high voltage, insulation, then concentric shield which is grounded
• Semicon layer over HV conductor, and under shield to prevent PD at the conductor and on the surface
Crossection of XLPE Cable

- Conductor
- XLPE Insulation
- Aluminum Sheath

Conductor Size: 2500mm²
Diameter: 170mm
Weight: 43kg/m
Power Cable Termination
Cable System Failure Processes

Oil paper cables:

• Dig-ins
• Cuts in sheath leading to ‘oil starvation’
• Overheating due to dry soil (makes transmission of heat away from the cable harder), circulating sheath currents, overloading – leads to oil migration, paper embrittlement
• Splice or termination failure caused by poor workmanship, thermal cycling, pollution (electrical tracking)
• All but the dig-ins may cause PD at least a few weeks to months before failure.
Cable System Failure Processes

PE, XLPE and EPR:
• By far the most likely failure process is ‘water treeing’, where diffusion of moisture through the plastic (after 10-20 years) becomes ‘organized’ into tree shaped channels by electric stress – occurs in underground or underwater cables – does NOT produce PD
• Overheating due to overloading, poor heat transmission or being too close to hot objects (pipes, etc.)
• Splice or termination failure caused by thermal cycling (creating a void and thus PD) or pollution (leading to tracking by PD)
• PD likely only with splice or termination problems
• All such cables have a factory PD to ensure no void at about 4 times working voltage
Electric Tree in XLPE Cable Due to PD at Conductor Shield
PD Testing of Power Cables

• For oil-paper transmission class, primarily use on-line PD
• All XLPE and EPR cables: all factory PD tested
• In-situ off-line PD testing: use 50/60 Hz or VLF (0.1 Hz) to energize the power cable capacitance
• On-line PD testing of cables sometimes also performed – but high risk of false indications due to electrical noise
On-Line PD Testing of Power Cable

Power Cable  Splice  Termination

RFCT  RFCT
Basic Interpretation

• No cable should ever have any PD (even at 2-3X overvoltage)
• Thus any detected PD is bad.
• Terminations and splices may produce PD months before failure
• Experience with on-line PD is that false positives and false negative diagnosis likely to occur
Limitations of On-Line PD for XLPE or EPR cables

• Can not detect PD far from sensor – not too bad since bulk of cable will never produce significant PD anyway
• Little experience
• Need to calibrate mV into pC in off-line set-up
• If measuring PD at a termination, then could confuse switchgear/transformer PD with cable PD
• As with all PD methods, will not detect water trees, by far the most common cause of distribution cable failure
Air-Insulated (Metalclad) Switchgear
Metalclad Switchgear Components

- Circuit breakers on infeeds
- Circuit breakers for each output cable circuit
- Bus tie circuit breakers
- Power cable outputs
- Power cable or bus infeed
- 3 phase HV busses supported by insulating boards
- Potential transformers (PTs) and current transformers (CTs) to measure V and I
- Switchgear composed of cells (cubicles), usually each with a circuit breaker (infeed or output). The HV bus connects all the cells together
Typical Switchgear Layout

Infeed transformer
Metalclad Switchgear Insulation Failure Processes

- Electrical tracking due to contamination
- Air gaps at bus supports, CT windows
- Electric treeing of PTs, CTs

All cause partial discharge (PD), usually for months (treeing) or years (tracking and gap PD) before failure

In addition, failures may be due to defective circuit breaker operation, poor or overheated electrical contacts, animals; which may not cause PD
Examples of Surface Tracking due to contamination/humidity
Examples of Air Gap Discharge
Examples of Air Gap Discharge
MetalClad Switchgear PD Testing

• In some countries (e.g. Canada), all switchgear is factory PD tested to ensure no PD at < 1.2 rated phase to ground voltage

• In-situ of-line testing using conventional PD detectors also sometimes performed

• On-line PD testing also can be performed in susceptible switchgear (in humid, polluted environments) – sensors are capacitors, RFCTs (on grounds) and TEV antenna installed between the enclosure and doors
Incoming Bus Bars PD Sensors
Power Transformers

Several types:
- Oil-filled transmission class (>69 kV)
- SF6 filled transmission class (>69 kV)
- Oil filled distribution class (<35 kV)
- Dry type transformer (<69 kV)

Now virtually all oil-filled transformers are used outdoors due to fire hazard from exploding oil if there is a fault.
Oil-Filled Transmission Class Power Transformer
Oil-Filled Transformer Failure Processes

- Long term overheating degrades oil and paper – creating gas bubbles
- High current faults from system moving windings
- Oil contamination (usually by water- water vapour)
- ‘on-load tap changer’ mechanical problems
- Any sustained PD will quickly degrade organic paper or oil

None of these normally produce PD, until the final few weeks or months of the failure process
Oil Filled Transformer Testing

• All transformers are factory PD tested to ensure no PD
• Measuring the evolution of gas (mainly CO2 and hydrogen) is by far the most common monitor
• Can also measure type of gas (called gas in oil analysis) – periodic or continuous testing – **this is most sensitive test**
• Most popular off-line test is the Power Factor test – detects when oil gets contaminated by carbon (from PD in oil or paper) or water.
Oil Filled Transformer PD Testing

• On-line PD (usually measured by acoustic sensors, by RFCTs on HV bushing tap or UHF antenna within the transformer) rarely used so far – false indications are common, thus credibility is low
• PD can only occur in gas bubbles. Once PD occurs bubble usually disintegrates preventing further PD
• PD in operation is very erratic
• Any PD eventually leads to failure.
Motor and Generator Stator Windings
Crossection of a stator slot
PD a Symptom or Cause of Many Failure Processes

- Poor impregnation of coils: (voids)
- Overheating of coils: (delamination)
- Looseness of windings in slot: (slot discharge)
- Deterioration of semiconductive or grading coatings: (slot or endwinding discharge)
- Thermal Cycling: (voids next to copper)
- Contaminated windings: (electrical tracking)
- PD will not find stator endwinding looseness, metallic debris or water leaks due to crevice corrosion
Tape wrinkling and poor impregnation of groundwall during epoxy VPI
Loose coils in the slot
Inadequate spacing between coils
PD Testing of Stator Windings

- Factory PD testing rarely done – there is no IEEE or IEC requirement (unlike all other apparatus)
- Some endusers do in-situ off-line PD tests
- On-line PD testing is more common
- Usually detect PD with capacitors
- As with other apparatus, the difficulty with on-line testing is separating stator PD from noise
- Note that almost all stator windings >3.3 kV have PD in normal service
Capacitive PD Sensors on Machine Terminals
PD Interpretation in Stators

• Trend PD magnitude over time
• Compare PD magnitude with other similar machines
• Unlike other apparatus – some level of PD will not cause failure
Conclusion

- PD is an important cause of failure in equipment with pure organic insulation
- In machines PD normally a symptom of poor manufacturing or insulation aging
- PD can be detected in the factory, or in-situ (either off-line or on-line)
- Electrical noise can cause false indications in on-line testing
- Transformers, cables, switchgear should have no PD. Stator windings will always have PD – look for trend or high levels of PD
References

3. IEC 60270
4. IEC 62478