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)

Electrical Representation of Partial Discharge (stator winding example)



- Potential difference (voltage) builds across an air-filled void due to capacitive voltage divider
- PD occurs if E = V/d > 3kV/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



09:24:56

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



Off-line PD Test Set



PD Display: Phase Resolved PD (PRPD) Plot



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, LPOFlow 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



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



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





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

Internal Voids

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 online 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 online testing
- Transformers, cables, switchgear should have no PD. Stator windings will always have PD – look for trend or high levels of PD

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