Introduction to Partial Discharge (Causes, Effects, and Detection)

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EA Technology History & Values

• Originally established as R&D center for the UK Electricity Industry (essentially EA Technology was the EPRI of the UK) in the late 1960’s. Privatized in the late 1990s.

• Provides research, strategic engineering consultancy, HV asset condition assessment services, specialized instrumentation, and Asset Management Software and Consulting.

• Instrumental in the development of PAS-55 and ISO-55000

• 100% employee owned and have provided products and service in 92 countries around the world
Partial Discharge – What is it and why do we care?
Is Partial Discharge Real?
What is Partial Discharge?

PD failure process

• Multiple causes
• Starts small
• ALWAYS gets worse
• Leads to FLASHOVER

PD is the inability of a portion of the insulation to withstand the electric field applied to it
Partial Discharge (PD)

The key to OUTAGE PREVENTION

Where can it occur?

• 3.3kV to 769kV
• Indoor Metal clad switchgear cubicles
• Indoor and Outdoor Insulators
• Transformer Cable Boxes
• MV & HV Cables, Terminations & Underground Vaults
• Transformers
• SF6 GIS / Oil Filled / Air Insulated
What is Partial Discharge (PD)?

Partial Discharge - A flashover of part of the insulation system due to a localized electric field greater than the dielectric withstand capability of that part where the overall insulation system remains capable of withstanding the applied electrical field.

One effect of this flashover is a high frequency current pulse that travels through the capacitance of the insulation (C1 & C3)
Equipotential Lines

Section through a homogenous insulator showing uniform electrical stress (equipotential) lines. A line indicates where the voltage potential is constant.

The same insulator with a void. The lower dielectric of the void causes a concentration of the electrical field through the void high enough to cause breakdown at working voltages.
Partial discharge breakdown of insulation produces:
- Light
- Heat
- Smell
- Sound
- Electromagnetic Waves
- an HF Electric Current
Products of Partial Discharge

How does PD damage insulation?

Partial discharge breakdown of insulation produces:
Light, Heat, Smell, Sound, Electromagnetic Waves, and an HF Electric Current

Nitric Acid

+ Water

Nitrous Oxides
CABLE TESTING Field Example

UK utility undertook a two year evaluation of RFCT based on-line testing that performed a PD condition based assessment of 191 33KV cables on their network over a two year period.

- 84% rated GREEN (no problems) >2% of those failed within 2 years
- 7% rated Amber (no problems) <21% of those failed within 2 years
- 7% rated RED (no problems) <40% of those failed within 2 years

84% rated GREEN (no problems)
>2% of those failed within 2 years

<21% of those failed within 2 years
7% rated Amber (no problems)
<40% of those failed within 2 years
7% rated RED (no problems)

Percentage of cable faults in each category within 2 years
Types of PD

- **Internal discharges** occurring in defects, voids or cavities within solid insulation

- **Surface discharges** occurring across the insulation surface

- **Contact discharge** occurs on floating metal in high field conditions

- **Corona discharge** occurring in gaseous dielectrics in the presence of inhomogeneous fields
• **Internal Discharge** occurs in all types of insulation as a result of defects, voids or cavities within solid insulation, also including oil and gas

• Practical Non-Invasive method to detect Internal Partial Discharge Activity is to use **Transient Earth Voltage (TEV)** detection instruments.
Partial Discharge (PD)

Surface PD

- **Surface discharges** occurring across the insulation surface Causes treeing and tracking

- Practical Non-Invasive method to detect **Surface Partial Discharge Activity** is to use Ultrasonic Emission detection instruments.
Causes of PD

- Surface contamination (lack of cleaning)
- Workmanship (poor installation)
- Material defects (manufacturing defects)
- Improper application (wrong parts for the job)
- Salt spray or Salt fog
- Mechanical damage (during install or in service)
- Age (electrical stress wears out insulation)
Standards associated with PD
IEEE 400 Series

IEEE 400 Guide to field testing shielded power cable
  • Cables only

IEEE 400.1 Guide to testing shielded power cable with DC
  • Not for Aged XLP cable
  • Fine for PILC
  • i.e.

IEEE 400.2 Guide to field testing shielded power cable with VLF
  • Offline
  • Time consuming
  • Excellent data quality
  • PD, Withstand, Tan Delta

IEEE 400.3 Guide to field PD testing of shielded power cable
  • It’s a guide, not a standard!
  • It does not conflict with or support IEC 60270
  • It discusses online and offline testing
IEC 60270 Edition 3.0, 2000
- Direct connection only
- Defines measurement circuit
- Defines measurement technique
- Defines calibration pulse generator
- Measures PD in picoColoumbs
  \[(1 \text{ picoColoumb} = 1 \text{ uA for } 1 \text{ uS})\]

Annex D – Use of RF meters for PD detection

Annex F – Non-Electrical methods of PD detection
  (Acoustic, Visual, Chemical)
IEC 60270 & IEEE 4000 test equipment
Invasive versus Non-invasive detection techniques
Invasive – Offline

Invasive methods require taking an outage to effect the test. Effectively this includes all direct connected test gear

- All forms of offline testing are by definition invasive
- VLF PD cable testing requires the cable to removed from service for 3-4 hours to test
- Tan-Delta and other cable test methods require removing the cable from service
- System Frequency PD cable testing requires getting truck mounted equipment on site and removing the cable from service
- Permanently installed systems & sensors need to be de-energized to install
Electrical Tests Commonly Done - Offline

• **High Pot (potential)** Tests for ability to withstand voltage for brief periods

• **Insulation Resistance (megger)** Tests for resistance to ground that might cause leakage

• **Tan – Delta** Tests for overall insulation health by comparing resistive and capacitive currents

• **IEEE-400 and IEC 60270 PD** Tests for partial discharge offline (VLF, etc.)
Non-invasive – Online

Also known as No-Outage testing, this type of testing requires no de-energizing of equipment and is safe to do around live voltages.

- **Ultrasonic/Acoustic testing** – through louvers, vents, contact sensors, and parabolic dishes
- **TEV testing** – Makes use of the Transient Earth Voltage phenomenon to safely detect internal discharge from outside cabinets
- **RFCT testing** - By attaching RFCT to cable ground straps, the PD current can be safely measured on live cables
- **RF Testing** – Specifically designed directional and non-directional radio receivers can pickup the EMI generated by PD

* installing RFCT on live cables requires opening the HV compartment and appropriate safety measures need to be followed
Practical Online PD Detection Methods

Surface Discharge Activity

• Ultrasonic Emission
• TEV Detection - when high amplitude surface discharge
• RFCT Detection of Current Pulse
• RF Detection of EMI
Practical Online PD Detection Methods

Internal Discharge Activity

• Transient Earth Voltage (TEV) Detection
• RFCT Detection of Current Pulse
• RF Detection of EMI
Practical Online PD Detection Methods

Cable Discharge Activity

- RFCT Detection of Current Pulse
- RF Detection of EMI – near terminations
- TEV Detection – on outside of sheath
- Ultrasonic Emission – only when very near surface
Direct Connected – Offline Testing
Very Low Frequency – VLF
VLF (for PD)

Offline, Very Low Frequency  IEC 60270 / IEEE 400.3 compliant test.
Requires an outage and cable to be disconnected on both ends.
Offline PD Testing

VLF, .01-1 Hz, Resonant AC

(VLF is by far the most prevalent at medium voltage)
Offline PD Testing

HF Current flow due to defect flashover

Pure AC Voltage Source → Source Impedance → Filter → Coupling Capacitor → Measuring Impedance → Cable under test → Defect → Voltage pulses at A

Current pulse

Cable Shield

Measuring Instrument
Direct Connect – PDIV / PDEV

PDIV – PD Inception voltage
PDEV – PD Extinguish voltage

PDIV 16KV
PDEV 13KV
LINE 11KV

PD might start with a transient but won’t stop

PDIV 16KV
LINE 11KV
PDEV 10KV

PD might start with a transient but won’t continue
Offline Test Equipment - Test Van

- Transformer
- VLF generator
- Test bushings
- Detector filter (allows LV detection lead to be connected to HV Supply and filters Hz)
Portable Unit - Approximately 500lbs
Direct Connected Offline Testing – Tan Delta
Tan Delta

Tan Delta is a measurement of the loss angle or dissipation factor. Effectively, it is measuring the ratio of the capacitance and resistance in a cable.

In a perfect cable there would be no $I_R$ and the arrow $A$ would be straight up.

As the cable ages and gets water trees and electrical trees, resistance through the insulation creeps in. This causes $I_R$ and the angle increases.
Tan Delta

Typical set up

- Bluetooth
- To cable under test
- To shield of cable
Online systems
Surface Discharge - Ultrasonic Emission
**Ultrasonic Survey**
(Practical Considerations)

- Influenced by environment (e.g. temperature, humidity, pollution).
- When monitoring ultrasonically the environmental conditions (%RH and Temperature) should also be monitored.
- Discharge has a distinctive crackling noise.
- Often intermittent, particularly during early stages.
- Severity of discharge is not necessarily related to noise amplitude.
Environmental Factors

- Moisture in air will play a significant role in whether discharge is active.
- When monitoring ultrasonically the environmental conditions (%RH and Temperature) should also be monitored.
## Ultrasonic Interpretation

<table>
<thead>
<tr>
<th>Ultra dB</th>
<th>Category</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 6</td>
<td>Good background</td>
<td>No observable/measurable deterioration</td>
</tr>
<tr>
<td>7 - 10</td>
<td>Fair</td>
<td>Minor Deterioration which requires no specific action</td>
</tr>
<tr>
<td></td>
<td>Very slight fizzing only just above the background</td>
<td></td>
</tr>
<tr>
<td>11 - 20</td>
<td>Poor</td>
<td>Moderate Deterioration Item can be returned to service. Reinspect in 30 days.</td>
</tr>
<tr>
<td></td>
<td>Heavy fizzing or crackling</td>
<td></td>
</tr>
<tr>
<td>&gt; 20</td>
<td>Action Required</td>
<td>Serious Deterioration Item cannot be returned to service without shut down or engineering advise</td>
</tr>
<tr>
<td></td>
<td>Spitting or sparking or heard with the naked ear</td>
<td></td>
</tr>
</tbody>
</table>
Ultrasonic Sensors

- Four different sensors are available for ultrasonic measurements
  - Built in Sensor – for general purpose airborne ultrasonic measurements
  - Flexible Sensor – for general purpose measurements that are harder to reach
  - UltraDish – Focuses sound energy for making measurements from a greater distance
  - Contact Sensor – for making measurements when there isn’t an air path from the source to the sensor
Discharge noise can be picked up
Outside gear via louvers in cabinet

• Measurement relies on an air path
  out of the switchgear

• Types of air paths
  – Vents / Louvers
  – CB Bushings / HV spouts
  – Gaps around panel joints
  – Bolt holes

Ultrasonic Detection
Ultrasonic Detection

- Measurement relies on an air path out of the switchgear

- When there’s no air path?
  - Contact sensor turns panel into sensor
  - Designed to work through cabinet metalwork, no direct air path needed

Contact probe

Designed to work through cabinet metalwork, no direct air path needed
Ultrasonic Detection

- Technician takes a minute or two at each cubicle
- Listens to audio via headphones
- Watches display for patterns
- Moves the probes along each air gap
Internal Discharge – TEV Detection
Transient Earth Voltage (TEV) Identification

- Identified over 30 years ago
- Measurement bandwidth 2 – 80 MHz
- TEV pulse rise time was found to be circa 5ns
- 3dB Bandwidth = \( \frac{0.35}{\text{rise time}} \).
- Therefore for 5ns, bandwidth = \( \frac{0.35}{5} \) GHz, i.e. 70 MHz
At HF, PD currents are constrained to flow in a thin layer on the surface of conductor. Skin depth in mild steel at 100MHz 0.5um
Internal Partial Discharge Effect 2 (EM Wave)

This effect is usually less than the current pulse unless the PD is phase to phase!
Phase to Phase Partial Discharge (Current pulse – NO TEV)

No TEV reading

NO CURRENT PULSE ON METALWORK

HIGH FREQUENCY PULSE FROM PHASE TO ANOTHER.

HV BUSBAR – Phase A

HV BUSBAR – Phase B

HV BUSBAR – Phase C

JOINT/GASKET

PARTIAL DISCHARGE
Phase to Phase Partial Discharge
(Current pulse – NO TEV)

HV BUSBAR – Phase A

HV BUSBAR – Phase B

HV BUSBAR – Phase C

EM wave incident to inside surfaces
Partial Discharge TEV Interpretation

- **Probable Internal**
- **Probable Surface Discharging**
- **No Internal Significant Discharging**
- **Probable Background Interference**
- **Possible Floating Metal**
- **Bad Conn**

Diagram showing the TEV interpretation based on TEV readings and pulses per cycle.
TEV Detection

• Technician takes a minute or two at each cubicle
• Places TEV probe firmly against panel
• Watches display for patterns
PD in resin core CT

Channel cut through resin by discharge

Cause – Manufacturing Defect (Void in resin)
## Surface Discharge and Internal Discharge Differences

<table>
<thead>
<tr>
<th>Internal PD</th>
<th>External PD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not affected by Humidity</td>
<td>Affected by Humidity</td>
</tr>
<tr>
<td>0.5-6 Pulses per Cycle</td>
<td>6-30 Pulses per Cycle</td>
</tr>
<tr>
<td>Rarely Audible</td>
<td>Often Audible</td>
</tr>
<tr>
<td>Detected best by TEV</td>
<td>Detected best by Ultrasonic</td>
</tr>
<tr>
<td>Hold UltraTEV against Ground or Metalwork</td>
<td>Hold UltraTEV at airgaps of enclosures or point UltraDish at Elbows, T’s, or splices.</td>
</tr>
</tbody>
</table>
Cable Partial Discharge
Cable Partial Discharge

Cable partial discharge is a classic example of local concentration of electrical stress.

Cable terminations and splices have carefully designed components to distribute the electrical stresses equally.

These components include semiconducting layers and stress cones.

When these cones are not correct discharge occurs.

Discharge can also occur where insulation is defective (holes, voids, damage) in mid-cable.
Equipotential Lines

Section through a homogenous insulator showing uniform electrical stress (equipotential) lines. A line indicates where the voltage potential is constant.

The same insulator with a void. The lower dielectric of the void causes a concentration of the electrical field through the void high enough to cause breakdown at working voltages.
Cable PD Detection

- RFCT placed on ground straps of cables
- Test may do 1 or 3 phases at once
- Test may run automatically or require operator involvement
- Different filters and triggers are applied
- Typically less than 10 minutes to get results

Safety First
RFCT based testing of cables

Shielded MV Cable

Void (PD Site)
Initial PD Current Pulse

PD causes high current pulse to travel down shield to ground strap

Instrument measures current pulse on ground strap

Data Collection

Phase Reference

Earth Ground
Current through ground strap results from PD down cable. Entire length of cable can be tested from one end.
## Evaluation Scale

<table>
<thead>
<tr>
<th>Comments</th>
<th>Color Code</th>
<th>XLPE Cable</th>
<th>XLPE Accessories</th>
<th>PILC Cable</th>
<th>PILC Accessories</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discharge within “acceptable” limits.</td>
<td>Green</td>
<td>0-250pC</td>
<td>0-500pC</td>
<td>0-2500pC</td>
<td>0-4000pC</td>
</tr>
<tr>
<td>Some concern, more frequent monitoring</td>
<td>Yellow</td>
<td>250-500pC</td>
<td>500-2500pC</td>
<td>2500-7000pC</td>
<td>4000-10000pC</td>
</tr>
<tr>
<td>monitoring recommended.</td>
<td>Red</td>
<td>&gt;500pC</td>
<td>&gt;2500pC</td>
<td>&gt;7000pC</td>
<td>&gt;10000pC</td>
</tr>
<tr>
<td>Major concern, locate PD activity and repair</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Cable Partial Discharge Examples

Treeing

Voids / Carbonisation

Damage from flashover to screen

Erosion from PD
Cable Partial Discharge

Terrible cut line causes electrical stress

Stress causes partial discharge

Partial Discharge causes erosion of insulation
Direct connected online systems
On–Line systems

Direct connected online systems use permanently installed HV capacitors and current transformers to measure PD directly.

• Periodic or 24x7 monitoring with alarming
• Typically include remote communications
• Can include humidity and load monitoring
• Can be used for Rotating machines, Metal clad switchgear, MV/HV Cables, and Transformers
Direct connected monitoring systems
PD Couplers
Practical application of spot testing
Data Analysis – VLF, Ultrasonic, TEV, Cable
Analyzing Data – Two crucial pieces of data

Picking Milliamps of PD out of Kiloamps of current is not trivial. Two key pieces of information are vital.
One sign of recognizable PD Activity is clustering of points on the phase resolve plot at a distance of 180° apart.

Amplitude
In pC
Around 0

1 Cycle wide (16.66 ms)
Partial Discharge tends to occur on the rising edge of the voltage sine wave. As such, PD impulses tend to be synchronized to the AC waveform and 180 degrees apart.

Phase Resolved plots show PD impulses on a power system cycle so groupings 180 degrees apart can be seen.

Phase resolved plots are available for TEV, Ultrasonic, and Cable PD modes.
Analyzing Data – Waveforms

A typical waveform from online Cable PD testing should have a large unipolar pulse indicating the discharge.

Very fast time base (40 uS)

Amplitude
In mA
Around 0
Activity – Actual PD Phase Plot
Non-PD Patterns – Random Noise

Background Noise

• Below is an example of background interference, which is characterized by random activity along the Phase Resolve plot.

• Background interference may be caused by a number of sources including radio masts and DC light fittings.
Non-PD Patterns – VFD Noise

**Machine Noise**
- Data captured on circuits which have rotating machines operating on them will contain some machine noise
- Machine noise is characterized by vertical lines spread across the phase resolved plot
Partial Discharge – Examples
PD in unshielded cables

A very large office building had full time partial discharge monitoring installed due to the critical nature of its operations. The monitor had ultrasonic sensing into each compartment from outside as shown below.

The cables to the 33VK PTs were unshielded. They were installed in a way that passed Highpot testing. However, electrical field stress was ignored.

The monitor started recording ultrasonic energy when the humidity increased. This was monitored for several months before corrective action was taken. Every cable was damaged!
Ultrasonic Trends over Time

Ultrasonic reading from top of cabinet with PD

Ultrasonic reading from bottom of cabinet with PD

Ultrasonic reading from other 10 cabinets without PD

Note large increase in 3 months and difference from other cabinets.
PD in unshielded cables

Cause – Lack of stress control due to poor installation
Termination – Poor workmanship

The same office building had numerous 33KV terminations. The monitor started indicating TEV in one compartment. After several months, Ultrasonic became apparent as well.

The yellow phase termination suffered poor workmanship. It started as internal discharge (TEV) but progressed to surface discharge as the termination was eaten away. The final picture shows the fixed assembly.
PD in Shielded Cable Terminations

Cause – Lack of stress control due to installation errors
Surface Discharge Activity Detected by Ultrasonics
PD in Switchgear

Cause – Environment (Salt & Humidity)
PD in resin core CT

Channel cut through resin by discharge

Cause – Manufacturing Defect (Void in resin)
Surface Discharge Activity Detected by Ultrasonics
Cable failures – Case Studies
Cable failure example 1

Cable Type – PILC / XLPE
Voltage – 11 KV
Age – 1 Hour
Failure Location – PICAS to XLPE Branch Adapter
Cable failure example 1

Proximate Cause – Incorrect positioning of adapter tubes
Ultimate Cause – Workmanship

Takeaways
- Horrific workmanship
- Numerous future failure points present

30 mm gap in insulation
Only 1 shear bolt touching
No putty in shear bolts
Cable failure example 2

Cable Type – XLPE
Voltage – 33KV
Age – 18 months
Failure Location – Joint
Cable failure example 2

Proximate Cause – Not deburring connector
Ultimate Cause – Workmanship

Takeaways
- Poor understanding of instructions
- Lack of attention to detail
- Lack of training

Furrowing not removed
Sand in joint
Sharp edge of shear bolt
Cable failure example 3

Cable Type – XLPE
Voltage – 11KV
Age – 28 years
Failure Location – Mid cable
Cable failure example 3

Proximate Cause – Moisture
Ultimate Cause – **Mechanical damage to sheath**

**Takeaways**
- Mechanical damage to otherwise good cable
- Replace waterlogged section
- Better installation practices
Cable failure example 4

Cable Type – PILC
Voltage – 11KV
Age – 47 Years
Failure Location – Mid cable
Cable failure example 4

Proximate Cause – Partial Discharge
Ultimate Cause – Age

Takeaways
- Not a bad lifespan
- Partial discharge testing would have prevented unplanned failure
- Replace Cable
Thank you

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