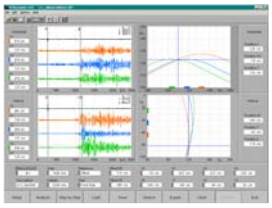
Acoustic Transformer PD Location aided by electrical PD Measurements and Pattern Analysis



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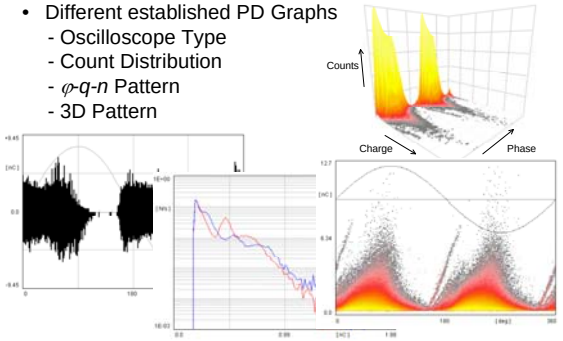
Partial Discharges in Insulation Systems

- Partial Discharge is the electrical Breakdown of a Part of the overall Insulation
- PD Activity is a Symptom of electrical Degradation as well as a cause of Insulation Degradation
- Technical Insulation Systems offer different Stability against Partial Discharge Activity
  - Polyethylene
  - EPR, EPDM
  - Oil-Paper
  - Epoxy-Mica
- Material correlated Defect Mechanism

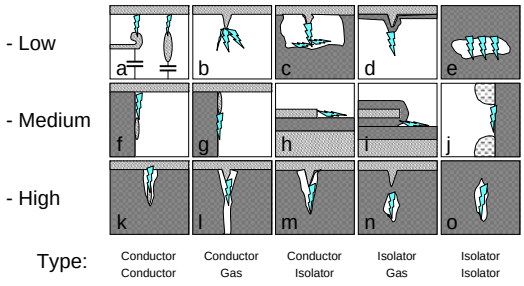
Visualization of Partial Discharge Activity

- Different established PD Graphs
  - Oscilloscope Type
  - Count Distribution
  - φ-q-n Pattern
  - 3D Pattern



Partial Discharge Electrode Configurations

Surface dominance:



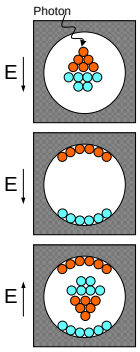
Properties of Insulation Materials

- Typical Breakdown Strength:
  - Air: 24 kV/cm bar
  - Hydrogen H_2: 16 kV/cm bar
  - SF_6: 88 kV/cm bar
  - Transformer Oil: ~150 kV/cm (20°C)
  - Epoxy Resin: ~300 kV/cm
  - Polyethylene: >500 kV/cm (Foils up to 8000kV/cm)
- Paschen's Law: $E_{Breakdown}$ ~ pd (p > 1bar)
  - Hydrogen cooled Generators: 3-7 bar
  - SF_6 insulated Switchgear: 3-4 bar
  - Temperature-modulated internal Pressure of embedded Voids

Occurrence of Partial Discharges

- For the Occurrence of Partial Discharge two Conditions must be met:
  - The local electrical Field must have reached the Streamer Inception Field ($E > E_{Str}$)
  - A free Electron must be available to start the Discharge Avalanche
- Two main Processes to derive this initial Electron:
  - Ionization by Photons
  - Field Emission
- The statistical Properties of this Processes control the Appearance of the PD Pattern

Discharges in a spherical Gas Inclusion

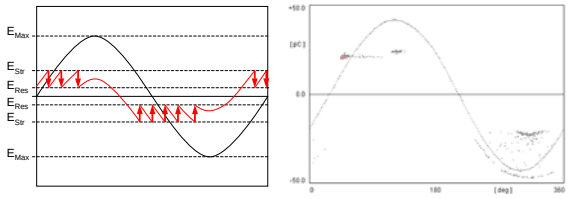


No Discharge although E > E_{Str}
- Photon provides initial free Electron
- E Field accelerates the Electron
- Discharge Avalanche occurs

Charge Separation after Discharge
- Positive Gas Ions and Electrons
- Space Charges on the Surfaces
- Residual Field E = E_{Res}

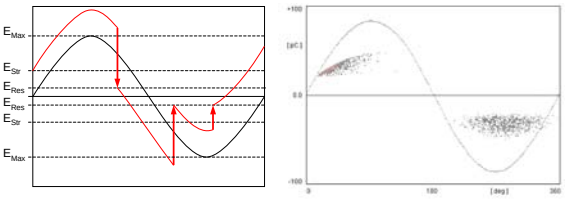
Reversed Polarity during next Half Cycle
- De-trapping of Space Charge E > E_{Str}
- E Field accelerates the Electron
- Discharge Avalanche occurs

Discharges in a spherical Gas Inclusion



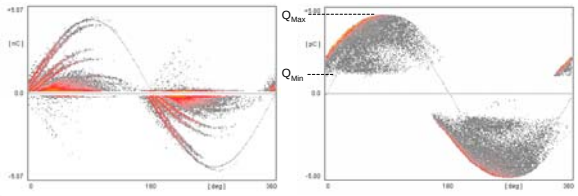
High Availability of Starting Electron
- Regular Discharge for E > E_{Str}
- Stable (low) Discharge Amplitude
- Regular PD Pattern

Discharges in a spherical Gas Inclusion



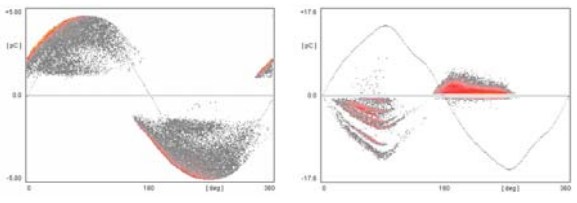
Low Availability of Starting Electron
- Random Discharge Occurrence for E > E_{Str}
- Higher Discharge Amplitude
- Distributed PD Pattern

Discharges in a spherical Gas Inclusion



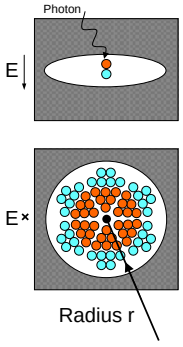
Low Availability of Starting Electron
- Discharge Pattern indicates U/U_{Inc}
- $Q_{Max}/Q_{min} = 2(E_{Max} - E_{Res}) / (E_{Str} - E_{Res})$
- Line Type Pattern: n << 1/f (recombination)
- Filled Pattern: n ~ 1/f (space charges)

Discharges in a spherical Gas Inclusion



Asymmetrical Availability of Starting Electron
- Different Discharge Pattern per Half Cycle
- Pos. Half Cycle: Low Availability
- Neg. Half Cycle: Higher Availability

Discharges in a flat Delamination

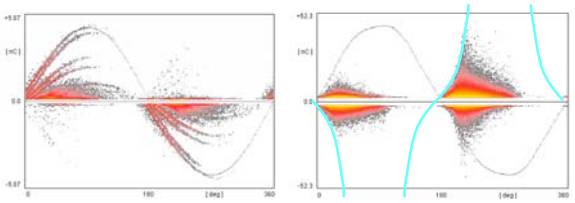


Initial Process as with spherical Void
- Photon provides initial free Electron
- E Field accelerates the Electron
- Avalanche bridges the Gap

Transition into Surface Discharge
- Produces “Lichtenberg” Figure
- Radius r ~ E
- “Ideal” Delamination > Q ~ E^3

Influence of Surface Properties
- Different Materials
- Surface Conductivity
- Corrosion, Aging

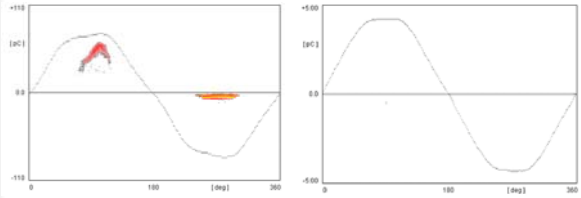
Discharges in a flat Delamination



Envelope of Pattern unveils discharge type

- Cavity with low electron availability Q ~ E
- Envelope of surface discharge type Q ~ E^3
- Usually, theoretical envelope only filled partly
- Aging and corrosion increases electron availability

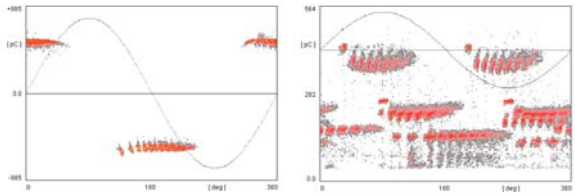
Discharges at a sharp Point



Asymmetrical Electrode Configuration

- Strongly non-symmetrical electrical field
- Low Inception Voltage for Trichel Discharge
- Starts in the negative Maximum
- Positive Streamer: Incipient Break Down

Discharges of floating Potential

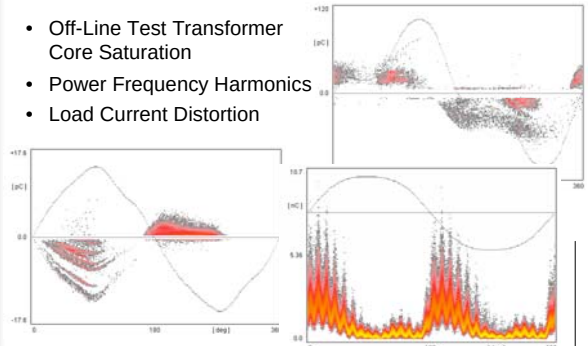


Symmetrical Pattern centered with the Zero Crossing

- Floating Shields of built-in CT
- Unconnected embedded shields
- Complicated in three-phase Configuration

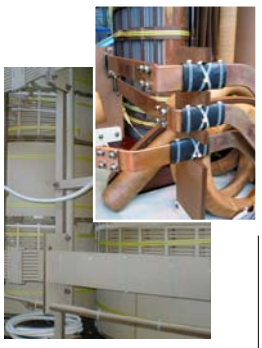
Influence of HV Harmonics and Distortion

- Off-Line Test Transformer Core Saturation
- Power Frequency Harmonics
- Load Current Distortion

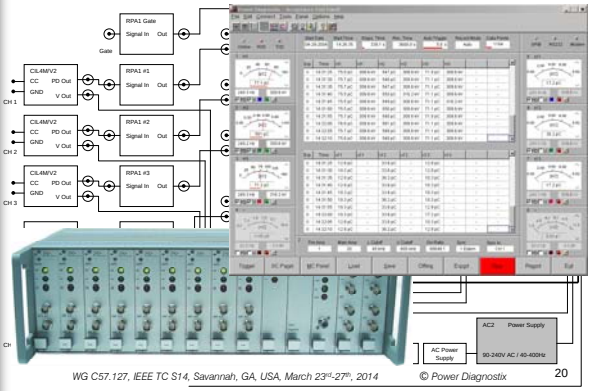


Properties of Transformer Windings

- Highly complex Network
  - Cross-Coupling
  - Attenuation
  - Impedance Changes
- Complex Insulation System
  - Oil-Paper
  - Pressboard
  - Porcelain
  - Composite Bushing



Acceptance Testing of Power Transformers

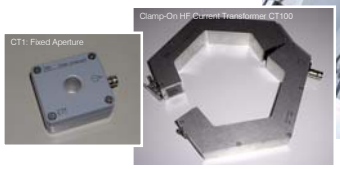


Locating Transformer PD Problems

- Evaluation of the High Frequency Properties
- Measurements in Frequency and Time Domain
- Pattern Acquisition
- Acoustic Location

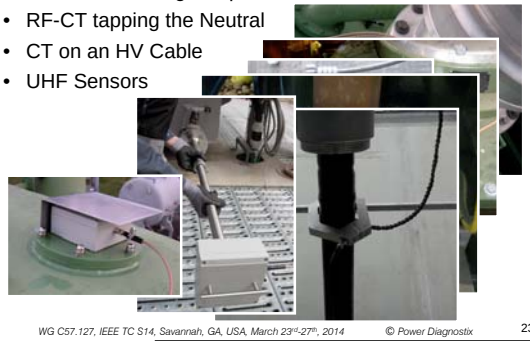

Additional Coupling Methods

- RF Current Transformer tapping the Ground Leads of the Core and Frame Connection
- Clamp-On CTs tapping the Neutral Bushing
- Acoustic Sensors
- UHF Antennas



On-site Coupling Methods

- Installed 'Bushing Couplers'
- RF-CT tapping the Neutral
- CT on an HV Cable
- UHF Sensors

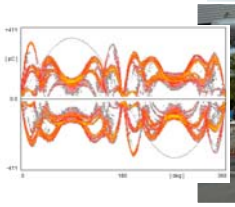


Off-Line On-Site Testing

- Three-phase 1.3MVA Source for induced Voltage
- Three 450kVA Inverter Sets
- 2MVA matching Transformer
- 400V Supply
- Instruments

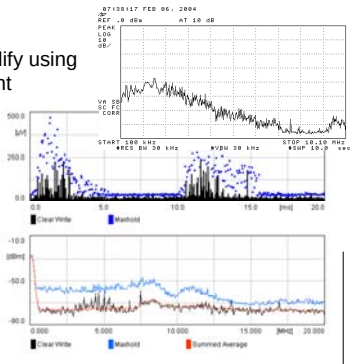

Off-Line On-Site Testing

- Testing a 660MVA Transformer
- Moving out the 500kV Reactor
- Switching Noise Pattern
- HV Filters and step-up Transformer

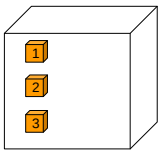

Using Spectrum Analyzers for PD Testing

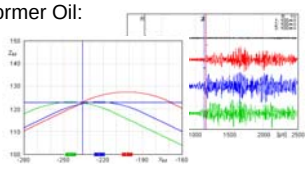
- Input Protection
- Control S/W to simplify using a complex Instrument
- Data, Screen Shots

Acoustic Triangulation - ideal vs. real

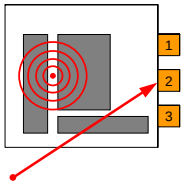
- "Textbook" Triangulation
- Real-life Transformer:
  - Interior not homogeneous
  - No uniform transmission Speed
  - Tank not a thin Membrane
- Multiple Transmission Paths
- Sound Speed in Transformer Oil:
  - 1400ms^{-1} @ 20°C
  - 1200ms^{-1} @ 80°C
- Solving "flat" Problems
  - horizontal
  - vertical

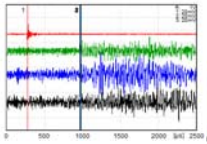




Transmission Paths in Transformers

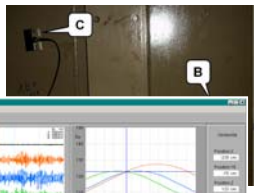
- Clear View, Angle < 30°
- Clear View, Angle > 30°:
  - Wall Signal arrives first
  - Location impossible, if all > 30°
  - Reposition sensors
- Higher Speed in Structure
  - Indicates closer Location
  - Moves with sensor position
- Source hidden deeply in Winding:
  - High attenuation
  - No straight sound path
  - False Location > Experience





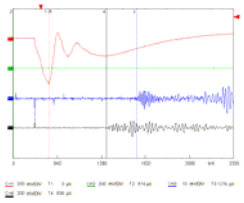
Transmission Paths in Transformers

- Charge Injection (Sensor A)
- Received Signals (B & C)
- Triggering on el. PD Signal
- Averaged acoustic
- Triangulation



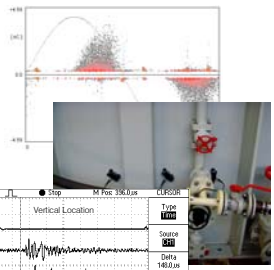
Acquiring Acoustic Signals

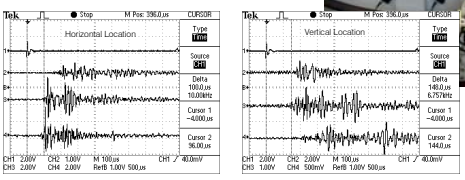
- Piezo-electric Sensor with Phantom Supply
- Remote controlled Battery operated Transmitter
- Fiber-optic Isolation
- Control Software



Case 1 - 30MVA DistributionTransformer

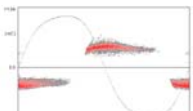
- 5nC at U_N on HV1
- Cross-coupling as with calibration coupling matrix
- Clear Oil Path
- Location just 14cm behind tank wall

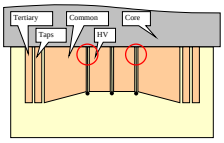


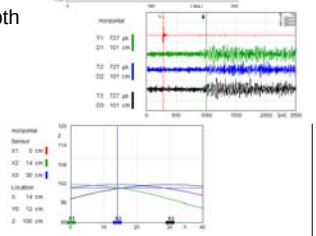


Case 2 - 300MVA Shell Type Autotransformer

- Up to 15nC on common
- Floating Potential
- Limited Access due to Shell Type Design
- Location in ~100cm depth

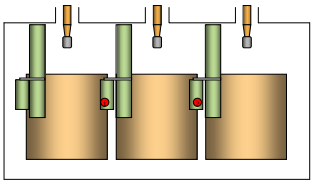


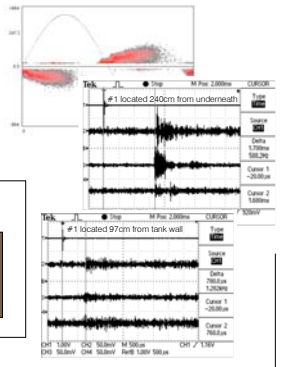




Case 3 - 700MVA Grid Autotransformer

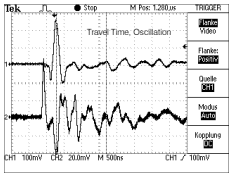
- About 1nC on common
- Paper Layer Delamination with Reverse Switch Wiring
- Poor Side Access due to Wall Shunts

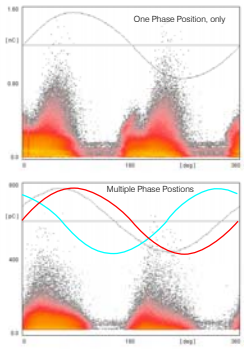




Case 4 - Grid Transformer

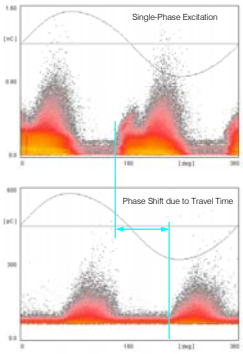
- Single-Phase Excitation
- Three-Phase Excitation
- Calculating the differential electrical Field
- Analyzing the Signal in Time-Domain





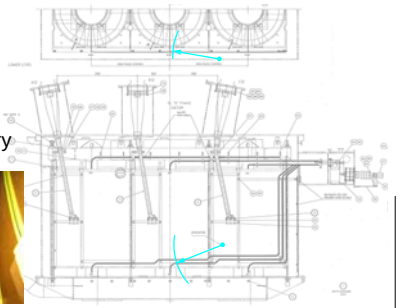
Case 4 - Grid Transformer

- Electrically acquired Pattern
- Acoustically acquired Pattern
- Comparing Intensity and Phase Shift versus Position



Case 4 - Grid Transformer

- Damped Wall Shunts hamper acoustic Emission
- Identifying the PD Source
- Bad Cleatbar Connection
- PD between HV and Tertiary



Acoustic Transformer PD Location aided by electrical PD Measurements and Pattern Analysis

Thank You for Your Attention!