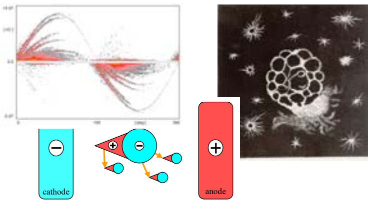
Partial Discharge – Context, History, Physics, and Examples



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Structure of this presentation

- Normative context – status and history
- Examples for signal transmission and processing
- Few points of gas discharge physics and their influence on the appearance of partial discharge
- Material and product related defect mechanism
- Typical partial discharge pattern

Revision PC57.113-2010 – Context

- Horizontal standard IEC 60270:2015 {3.1}
- Numerous vertical (product) standards covering rotating machines, transformers, cables, switchgear, and other equipment
- Various guides on IEC and IEEE product committee level covering methods and procedures
- Several Cigré documents mostly focusing on product level
- Synchronize with IEC 60270 and PC57.124

Revision IEC60270 – Context

- Horizontal standard: IEC 60270
  - First edition as IEC 270 in 1968
  - Second edition IEC 270 in 1981
  - Third edition IEC 60270:2000
  - Amendment IEC 60270:2015 {Ed 3.1}
  - New revision just started TC42/MT23
- Cigré documents:
  - TB662, D1.37: Guidelines for PD detection using conventional and unconventional methods
  - TB366, D1.33: Guide for PD measurements…
- IEC 62478: Meas. of PD by el. and acoustic methods

IEC 270:1968 – First Edition

- Main points introduced
  - Apparent charge as a reaction of the internal charge transfer (displacement current)
  - Derived quantities such as discharge energy, dis-charge current, quadratic rate, discharge power
  - Calibration based on $q_0 = U_0 \times C_0$
  - No superposition error for $\Delta t \geq 100\mu s$
  - Approximation $1\mu V \cong 1pC$ @ 100pulse/s & 150Ω
- Not yet covered
  - No bandwidth limits given
  - No weighting curve (pulse train response)

IEC 270:1981 – Second Edition

- Main points introduced
  - Separating wide band and narrow band instruments
  - Risetime of $U_0 \leq 100ns$, decay time > 100µs
  - Circuit for measuring discharge power
- Main points dropped
  - Partial discharge energy
  - Approximation $1\mu V \cong 1pC$ @ 100pulse/s & 150Ω
- Not yet covered
  - No bandwidth limits given
  - No weighting curve (pulse train response)

IEC 60270:2000 – Third Edition

- Main points introduced
  - Transfer impedance *Z(f)* - input current / output voltage (which implies that the input is a current)
  - Weighting curve - pulse train response
  - Recommended bandwidth and corner frequencies
    - Wide: 30kHz ≤ f_1 ≤ 100kHz, f_2 ≤ 500kHz
      100kHz ≤ Δf ≤ 400kHz
    - Narrow: 9kHz ≤ Δf ≤ 30kHz, 50kHz ≤ f_m ≤ 1MHz
  - Detailed calibration procedure
  - Type and routine test for calibrators and instruments
  - “Alternative calibration method”, Annex A.3

IEC 60270:2000 – Amd1:2015

- Main points introduced
  - Recommended bandwidth expanded
    - Wide-band: 30kHz ≤ f_1 ≤ 100kHz, f_2 ≤ 1MHz
      100kHz ≤ Δf ≤ 900kHz
  - Further calibration method “step voltage response”, Annex A.4
  - Tightened step voltage requirements
    $\Delta U \leq 0.03\ U_0$ during $t_d \geq$ 5µs (steady state)
  - Test circuits for performance test of calibrators
  - Annex E showing block diagrams of PD measuring instrument principles
  - Annex H - Test result evaluation with direct voltage

Revision PC57.113

- Technical points of PC57.113-2010
  What shall be kept/modified?
  - Recommended bandwidth
    f_1: ~100kHz f_2: ~300kHz BW: not specified
  - Pulse response: According to IEC60270
  - Calibrator specification
    C_0: <200pF t_{rise}: <100ns t_{fall}: >200µs (90/10%)
    f_{rep}: 100-1000Hz
  - Just two test circuits
    Applied and induced using bushing tap
    In-depth calculation for coupling capacitor

IEC 60270:202? – Fourth Edition

- Current progress
  - First meeting of TC42/MT23 Oct 2017 (Canada)
  - Intended meeting Jun 2018 cancelled
  - Questionnaire sent to national committees
  - Upcoming meeting Nov 2018 (Poland)
- Different views of future direction
  - Focus on charge-based low frequency
  - Adding non-conventional techniques (IEC 62478)
- Stability date
  - Currently 2020 (decision by TC42)
  - Meaning: stays unchanged at least up to 2020

Properties and transmission of el. PD signals

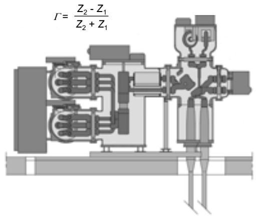
- The rise time of the electron avalanche is determined by the gaseous dielectric:
  - Under Nitrogen atmosphere, the rise time is about 1ns and, hence, causing a bandwidth of ~350MHz
  - Under SF_6, an electro-negative gas, the rise time is below 200ps and the bandwidth is up to 2000MHz
- Various effects reduce the signal bandwidth:
  - Dispersion, radiation, and attenuation
  - Reflection and band-pass effects
- Thus, for distributed power engineering equipment, only a reduced frequency band reaches the detector

Electrical transmission of PD signals in GIS

- The basic construction of cables, GIL, and GIS is coaxial
- The impedance is a function of ln *D*/*d*
- Impedance steps cause reflections (pos. & neg.)
- Complex higher modes
- Hard to predict for three phase design
- Internal coatings cause dispersion

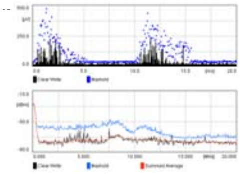
$$Z = \frac{1}{2\pi}\sqrt{\frac{\mu_0}{\varepsilon_0\,\varepsilon_r}}\,\ln\left(\frac{D}{d}\right)$$

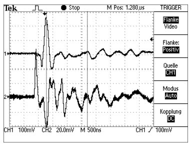
$$\Gamma = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$



Electrical signal transmission in transformers

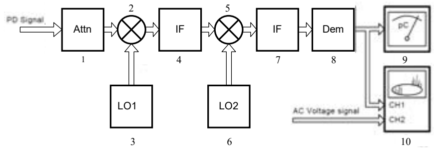
- Signals travelling the conductors
- Capacitive cross-coupling
- Radiation and reception
- Behavior in freq. domain
- Behavior in time domain





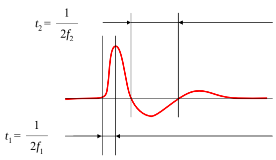
Common detector principles

- Instrument with "quasi-integration" at a low pass filter and subsequent A/D conversion
- Instr. with early A/D conv. and digital post processing
- Instrument with active integration
- Instrument with "traditional" analog super heterodyne principle to allow both narrow and wideband detection



Influence of acquisition bandwidth

- Pulse response for "wide band" IEC60270 processing
- Upper corner frequency f_1 determines the rise time of the pulse response
- Lower corner frequency f_2 determines the decay time of the pulse response
- Consequences:
  - Superposition errors (pulse pile-up)
  - Noise modulation
  - Dead-time issues
  - Max. repetition rate

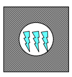


Early research on discharge phenomena

- Electrical discharge, such as lightning or St. Elmo's fire frightened and fascinated mankind
- The triboelectric effect was described by W. Gilbert 1600 - "vis electrica" as the power of amber
- G. C. Lichtenberg conducted 1777 the first systematic research on electrostatic discharge

Occurrence of partial discharge

- For the occurrence of partial discharge two conditions must be met:
  - The local electric field must have reached the critical inception field ($E > E_{crit}$)
  - 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 these processes control the appearance of the PD pattern

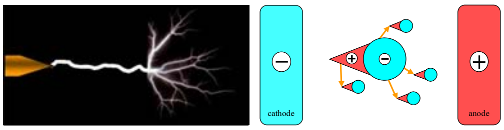


Provision of starting electrons

- Plenty free electrons on metallic surface – immediate inception of partial discharge if $E > E_{crit}$
- Polymeric low energy surfaces (PE, PP, PTFE, etc.) offer literally no free electrons – ionization needed
- The sources of ambient radioactivity (cosmic photons, ^{222}Rn, soil, fallout) cause ~$2 \cdot 10^6$ free electrons per second and cubic meter – delayed inception
- Hence, it takes in average 15 minutes until a spherical void of 1mm diameter is hit and discharge starts
- Common testing times of epoxy molded equipment often too short – dry-type transformers 3 minutes

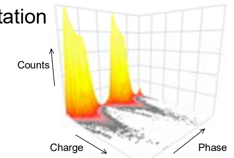
Main discharge types

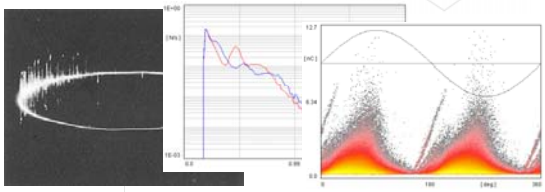
- *Trichel* discharge (trichel, glow, and "corona")
  Ionization process: Collision ionization
- *Streamer* discharge (filament and bunch streamer)
  Ionization process: Collision and photo ionization
- *Leader* discharge (stem bunch and spark)
  Ionization process: Collision, photo, & thermal ionization



Visualization of partial discharge activity

- Historic evolution of representation
  - Early meter style
  - Oscilloscope, Lissajous
  - Count distribution
  - φ-*q*-*n* pattern
  - 3D pattern

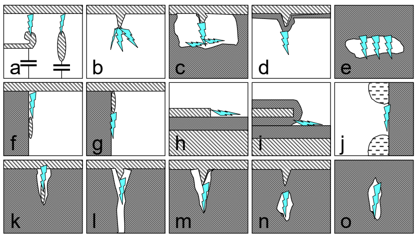




Partial discharge electrode configurations

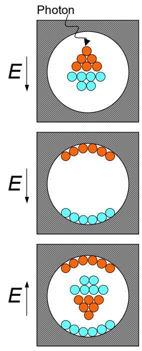
Surface dominance:

- Low
- Medium
- High



Type:	Conductor Conductor	Conductor Gas	Conductor Isolator	Isolator Gas	Isolator Isolator

Discharges in a spherical gas inclusion

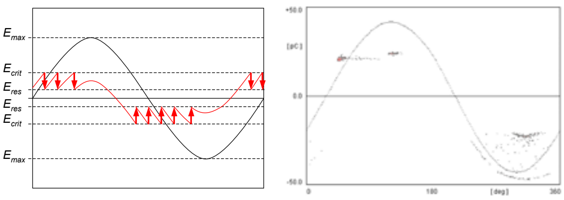


No discharge although $E > E_{crit}$
- Photon provides initial free electron
- Electric field accelerates the electron
- Discharge avalanche occurs

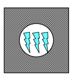
Charge separation after discharge
- Positive gas ions and electrons
- Space charges on the surfaces
- Residual field $E = E_{res}$

Reversed polarity during next half cycle
- De-trapping of electrons, $E > E_{crit}$
- Electric field accelerates the electron
- Discharge avalanche occurs

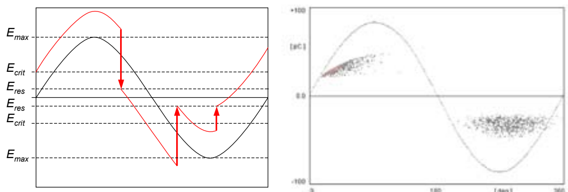
Discharges in a spherical gas inclusion



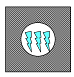
High availability of starting electron
- Regular discharge for $E > E_{crit}$
- Stable (low) discharge amplitude
- Regular PD pattern



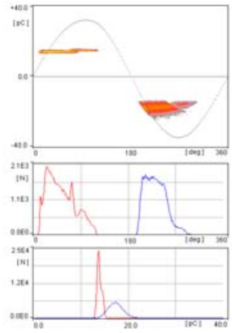
Discharges in a spherical gas inclusion



Low availability of starting electron
- Random discharge occurrence for $E > E_{crit}$
- Higher discharge amplitude
- Typical distributed PD pattern

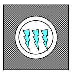


Discharges in a spherical gas inclusion

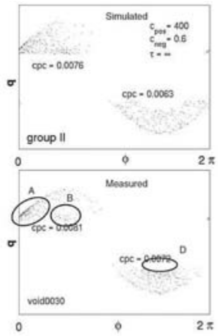


Stable applied voltage (4kV)

- Electrical field $E \sim 1.2\ E_{Str}$
- Standard (float?) glass sphere
- Clear epoxy molding
- 24h night and daylight
- UV of 300nm equals ~4eV
- Complex photo ionization processes with glasses
- UV-modulated PD pattern
- Day: ~85s^{-1}, 1.3nA
- Night: ~2s^{-1}, 40pA
- Be careful with transparent specimen



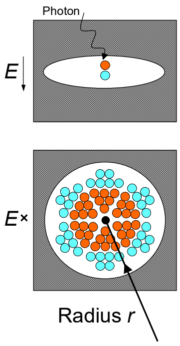
Discharges in a spherical gas inclusion



Impact of charge carrier generation

- High availability (day)
- Charge carrier generation rate:
  - $c_{pos} = 3 \cdot 10^4 s^{-1} \rightarrow 33\mu s$
  - $c_{neg} = 6 \cdot 10^3 s^{-1} \rightarrow 167\mu s$
- Low availability (night)
- Charge carrier generation rate:
  - $c_{pos} = 4 \cdot 10^2 s^{-1} \rightarrow 2{,}5ms$
  - $c_{neg} = 6 \cdot 10^{-1} s^{-1} \rightarrow 1{,}6s$
- Few seconds decay
- Little impact for 50Hz:
  - $\tau = \infty$

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

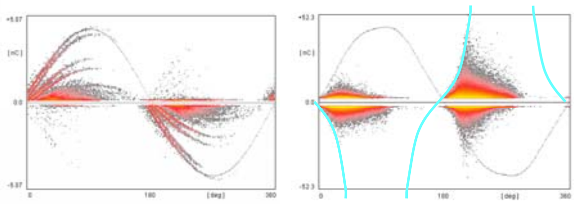
Transition into surface discharge

- Produces “Lichtenberg” figure
- Radius $r \sim E$
- “Ideal” delamination > $Q \sim E^3$

Influence of surface properties

- Different materials
- Surface conductivity
- Corrosion, aging

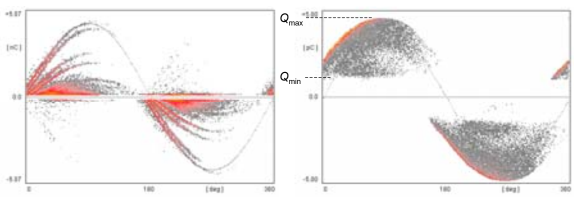
Discharges in a flat delamination



Envelope of pattern unveils discharge type

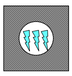
- Cavity with low electron availability $Q \sim E$
- Envelope of surface discharge type $Q \sim E^3$
- Usually, theoretical envelope only filled partly
- Aging and corrosion increases electron availability

Discharges in a spherical gas inclusion

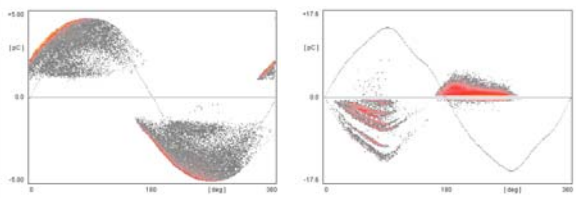


Low availability of starting electron

- Discharge pattern indicates U/U_{inc}
- $Q_{max}/Q_{min} = 2(E_{max} - E_{res}) / (E_{crit} - E_{res})$
- Line type pattern: $\Delta t_i >> 1/f$ (recombination)
- Filled pattern: $\Delta t_i \sim 1/f$ (space charges)

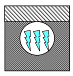


Discharges in a spherical gas inclusion

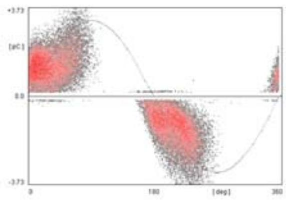


Asymmetrical availability of starting electron

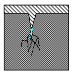
- Different discharge pattern per half cycle
- Positive half cycle: low availability
- Negative half cycle: higher availability



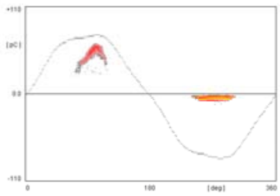
Treeing in polymeric material

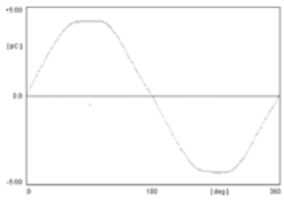


Asymmetrical electrode configuration
- Initial breakup of solid material (PE, PP)
- Continues as gas discharge
- Discharge increases with tree growth

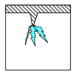


Discharges at a sharp point

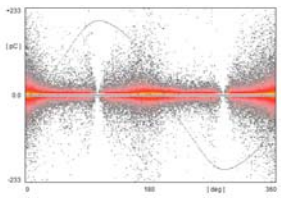


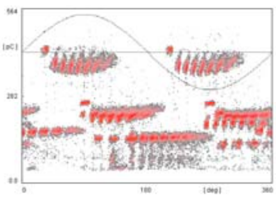


Asymmetrical electrode configuration
- Strongly non-symmetrical electrical field
- Low inception voltage for "Trichel" discharge
- Starts in the negative maximum
- Positive streamer: incipient break down

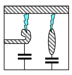


Discharges of floating potential



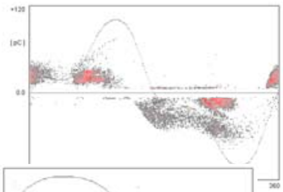


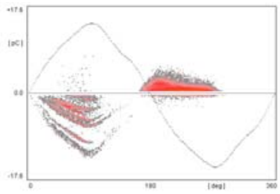
Symmetrical pattern centered with the zero crossing
- Floating shields with small metallic gap
- Complicated in three-phase GIS (right)
- Distributed pattern with insulated gap

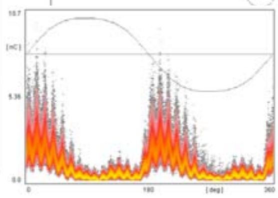


Influence of HV harmonics and distortion

- Off-line transformer test:
  Core saturation
- Power frequency harmonics
- Load current distortion

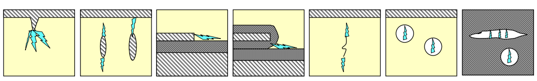






Partial discharge sources in transformers

- Sharp points and particles
- Surface and tracking discharge
- Fiber bridges in oil
- Gas inclusions
  - Voids (bubbles in oil and solid)
  - Delaminations (paper and solids)
- Humidity (indirect)



Revision PC57.113-2010

- Synchronize with current work on the IEC 60270
- Consider including a tutorial of basic discharge physics and material related defect mechanism
- Improve knowledge of generic *φ-q-n*-pattern and the related discharge types
- Consider moving away from “acceptance level” to a mandatory noise floor