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Virtual Best Practices Seminar: Factory Acceptance Testing *IVPD* Power and Distribution Transformers

Presenter: Charles Nybeck, PhD
Applications Engineer
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Auditor: Daniel Hering
Product-Manager ICM*system*
Power Diagnostix

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Moderator

- Michael Fleischer
  - Digital Marketing Specialist

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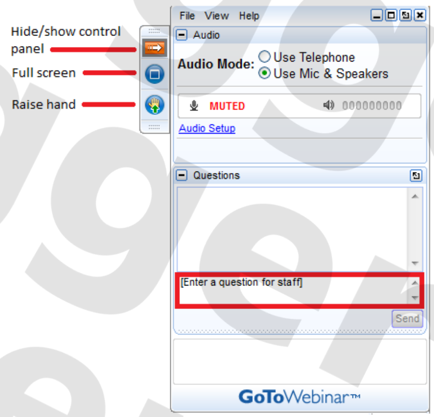
Q&A

- Send us your questions and comments during the presentation



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Today's Presenter and Panelists

Presenter

- Charles Nybeck
  - Applications Engineer

Panelists

- Jeroen Goedertier
  - Senior Service Engineer

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Presentation Outline

- Partial Discharge Fundamentals
- Normative References
- Factory Acceptance Testing (FAT)
- The ICMsystem
- Factory Acceptance Testing with the ICMsystem
- Summary

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Partial Discharge Fundamentals

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What is Partial Discharge (PD)?

- "A localized electrical discharge that only partially bridges the insulation between conductors and which can or cannot occur adjacent to a conductor" – IEC 60270
- Present when voltage stress across the void or surface exceeds the dielectric strength of the insulating material
- Physical and chemical changes may happen, which produce emissions that we can detect
- PD can manifest in multiple ways
  - Void discharge
  - Surface discharge
  - Corona discharge

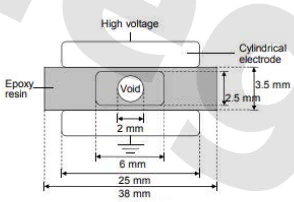

Figure 1. Test object for void discharge measurement

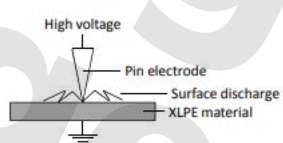

Figure 2. Test object for surface discharge experiment

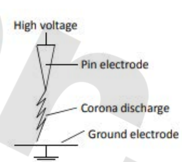

Figure 3. Test object for corona discharge experiment

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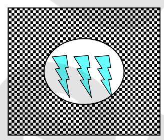
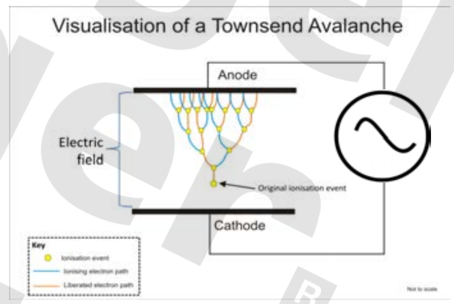
Occurrence of PD

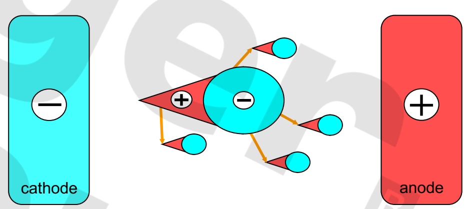
- For the occurrence of partial discharge two conditions must be met:
  - The local electric field must have reached the critical inception field ($E > E_{crit}$)
  - A free electron must be available to start the discharge avalanche
- Two main processes to derive this initial electron:
  - Ionization by photons
  - Field emission
- The statistical properties of these processes control the appearance of the PD pattern





Main Discharge Types – Ionization Processes

- *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



Provision of Starting Electrons

- In all cases free electrons are required to start partial discharge
- 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 – cast-resin transformers 3 minutes

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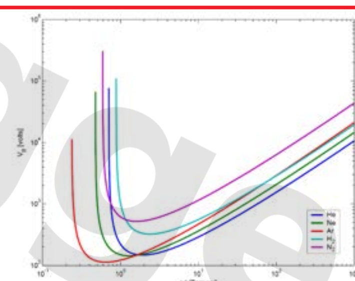
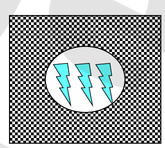
Properties of Insulation Materials



- 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



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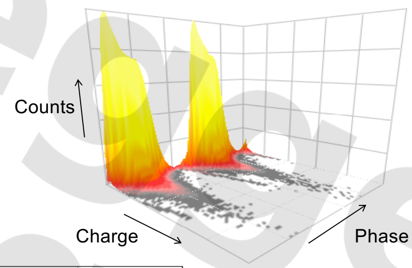
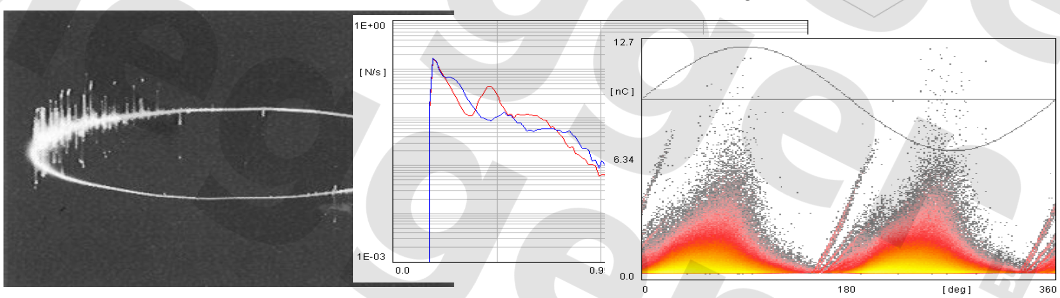
Visualization of Partial Discharge Activity

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





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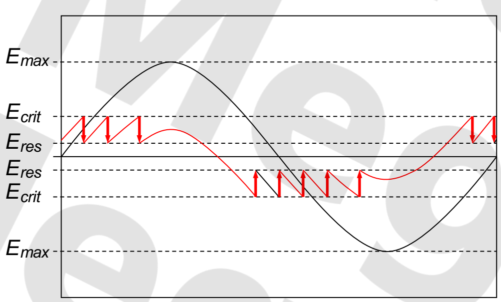
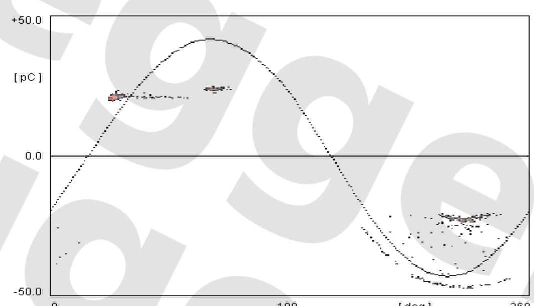
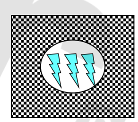
Discharges in a Spherical Gas Inclusion





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



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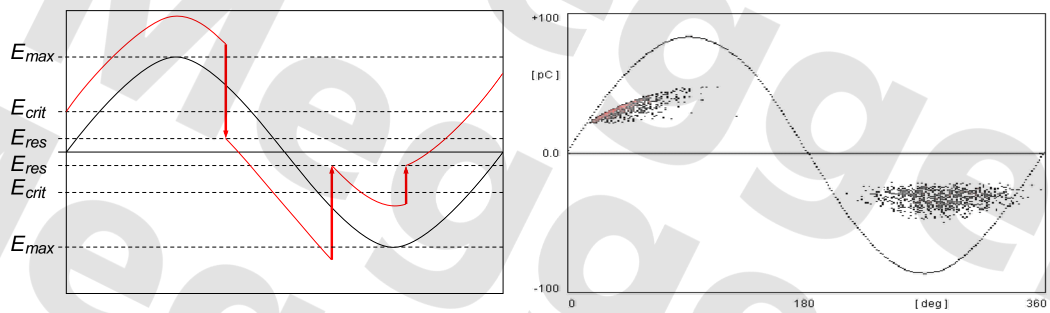
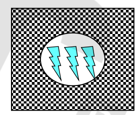
Discharges in a Spherical Gas Inclusion



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



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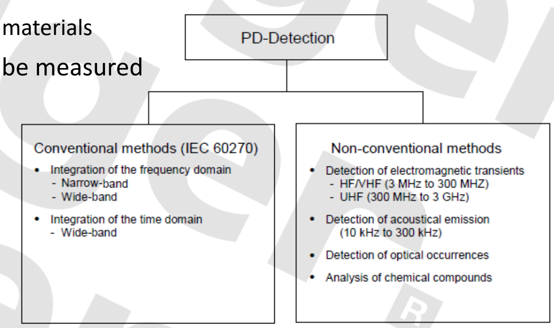
PD Causes and Measurement Techniques

- Partial discharge is caused by dielectric stress
  - Non-homogeneous distribution of the electric field
  - Presence of bubbles in solid and liquid insulation
  - Punctual effects that localize dielectric stress on insulation
  - Presence of moisture, cracks or water pockets
  - Presence of contaminants in the insulation surface
  - Voltage exceeding the dielectric strength of insulating materials
- PD current pulses occurring in HV apparatus cannot be measured directly because the PD source is not accessible.
  - Conventional (IEC 60270)
    - **Apparent charge**
  - Unconventional
    - **Electromagnetic**
    - **Acoustic detection**
    - Optical method
    - Chemical detection



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On-line vs Off-line Testing

- On-line testing (e.g. IEEE 400-3, C57.113)
  - Typical for commissioning / testing on-site
  - Demanding to manage corona noise with transformers above 110kV
  - Ability to detect load induced PD problems
  - Allows for more frequent testing or monitoring of PD activity
  - Major strength in trending ability
  - Permits examination of device condition throughout all factors of influence
    - Power loading
    - Temperature
    - Humidity

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Normative References

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Introduction – Normative References

- Power and distribution transformers are vital part of every distribution network
- Transformers are complex structures of mixed materials and components
- Extensive **F**actory-**A**cceptance **T**est (**FAT**) requirements
- Numerous standards address Factory-Acceptance Testing of power and distribution transformers
- Standards distinguish via ratings and dry-type/oil-immersed transformers

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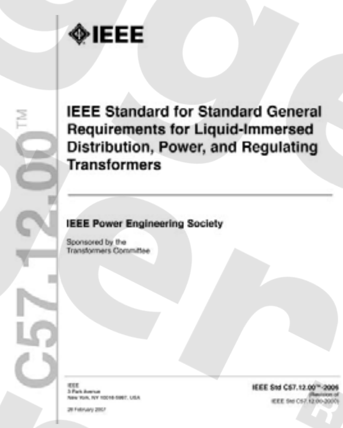
Introduction – Normative References

- Standards for FATs on power & distribution transformers
  - IEC-60060 (Horizontal standard for HV measurements)
  - **IEC-60076-3** (Power transformer)
  - **IEC-60076-11** (Dry-type)
  - IEC-61378 (HVDC transformer)
  - **IEEE C57.12.01** (Dry-type)
  - **IEEE C57.12.00** (Oil-immersed)
  - IEEE C57.12.90 (Oil-immersed)
  - IEEE C57.12.80 (All types)
  - …



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Introduction – Normative References

- Historic: **R**adio **I**nfluence **V**oltage (**RIV**) testing
  - Focused on radio disturbances radiated by the transformer during operation, mostly due to corona
  - Not intended to be a diagnostic tool

- Modern: **P**artial **D**ischarge (**PD**) testing supersedes RIV testing
  - PD measurements also give detailed information about the type of imperfection
  - Not only simply pass or fail criteria. PD testing used for in-depth analysis of the quality of the complete insulation system of the transformer

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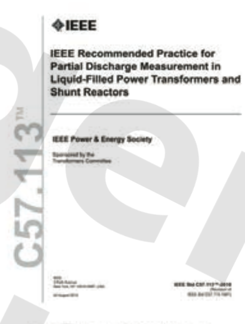
Introduction – Normative References

- Standards focused on **PD** measurements (for transformers):
  - **IEC-60270** (horizontal baseline standard)
  - IEC-62478
  - IEEE C57.113



- Standards focused on **RIV** measurements:
  - NEMA 107-2016
  - CISPR 18-2
  - ANSI C63.2
- Numerous additional standards for PD measurements like IEEE 454-1973 exist

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Introduction – Normative References

- IEC 60270-2015:
  - Frequency bands:

    - Wide-band (100kHz ≤ Δf ≤ 900kHz)
      Lower limit: 30kHz ≤ f_1 ≤ 100kHz
      Upper limit: f_2 ≤ 1MHz

    - Narrow-band (9kHz ≤ Δf ≤ 30kHz)
      Center frequency: 50kHz ≤ Cf ≤ 1MHz

- Factory-acceptance testing of transformers has to be done in the frequency range below 1 MHz (IEC 60270)

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PD Tests During Transformer Factory-Acceptance Tests

- PD testing part of the dielectric tests (IEC):
  - IEC 60076-3 – **I**nduced **V**oltage **PD** (**IVPD**) test:
    - Mandatory for power transformer with U_m ≥ 72.5kV
    - For transformers with U_m < 72.5kV after agreement with customer

- IEC 60076-11:
  - Mandatory for dry-type transformers covered by IEC 60076-11 with U_m ≥ 3.6kV
  - Rating >1kVA (single phase), 5kVA (three-phase)

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PD Tests During Transformer Factory-Acceptance Tests

- PD testing part of the dielectric tests (IEEE):
  - C57.12.00 (oil-immersed):
    - Mandatory for class II power transformer (115kV ≤U_n ≤765kV)
    - Not mandatory for oil-filled class I power & distribution transformers
- C57.12.01 (dry-type):
    - Mandatory for dry-type transformers above 1.2kV with solid-cast and/or cast-resin encapsulated windings

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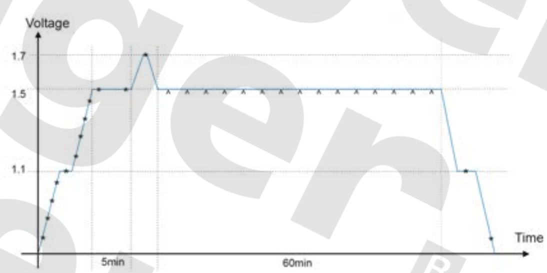
PD Tests During Transformer Factory-Acceptance Tests

- Test-sequence for oil-immersed transformers
  - Voltage applied with elevated frequency to avoid core saturation at the elevated voltages and to shorten test
  - Enhanced voltage level duration according to IEEE C57.113:

7200 cycles.



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PD Tests During Transformer Factory-Acceptance Tests

- Test-sequence for oil-immersed transformers
  - PD Measurement required on all bushings with $U_m \geq 72.5kV$, up to six bushings maximum, usually done using test-tap
  - Acceptance limit depending on standard and agreements in a range of 250pC* (IEC 60076-3)
  - Noise floor < 50pC (IEC 60076-3)*
  - PD level shall not increase by more than 50pC and sudden increase in the last 20 minutes shall occur, otherwise measurement has to be extended by 1 hour (IEC 60076-3)
  - Additional available decoupling points, e.g. neutral or tertiary-windings, may give valuable information in case of failure

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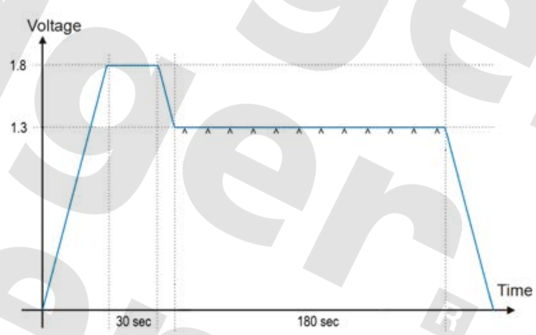
PD Tests During Transformer Factory-Acceptance Tests

- Test-sequence for dry-type transformers
  - Only three HV windings measured via coupling capacitor or test-taps.
  - Test sequence much shorter compared to oil-immersed transformers.
  - Acceptance limit stricter: 10pC

  - Only 180sec. Testing time!



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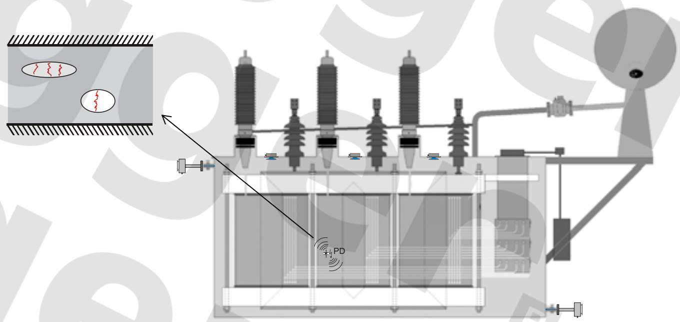
Partial Discharges in Transformers

- Partial Discharge is a breakdown of a small area of the overall insulation
- Each PD pulse generates different measurable electrical signals:
  - Local displacement current pulse
  - Electromagnetic pulses
  - Acoustic signals



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Partial Discharges in Transformers

- Local displacement current pulse rise time ~1ns for Nitrogen at the origin
  - Bandwidth of 350MHz maximum
- Current pulse → voltage pulse at the measurement terminals due to transformer RLC network
- RLC network causes attenuation, dispersion, reflections, and filtering
  - Reduced frequency band reaches the detector
- High frequency signal components are more susceptible these effects
- This signal stays up to some limits in correlation with the real discharge value Qp
  - Calibration according to IEC60270 with known imprecision for failures within the winding – up to 50% - resulting in apparent charge measurement

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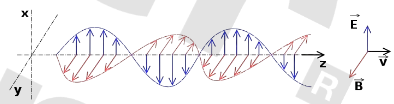
Partial Discharges in Transformers

- Electron avalanche causes an Electromagnetic pulse which is radiated in all directions from its origin
- Discharges in oil or solid materials can show frequency components above 350MHz
- Such UHF pulse signals can be decoupled by UHF antennas
- UHF signals cannot be correlated with the amount of discharge at its origin (No calibration in terms of pC (IEC) applicable) - (measurement in dB/µV)
- UHF signal strength strongly depends on location of antenna and travel path of the electromagnetic pulse



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Partial Discharges in Transformers

- Acoustic Signal is caused by the electron avalanche causing a pressure increase with impact to the surrounding materials
- Signal Spectra in a range of some MHz at its origin
- Signal strength measured with piezo sensors on the transformer tank strongly dependent on the travel path and materials involved
- Strength of acoustic signals can’t be correlated with the amount of discharge
- Acoustic signals typically only used for location of PD sources

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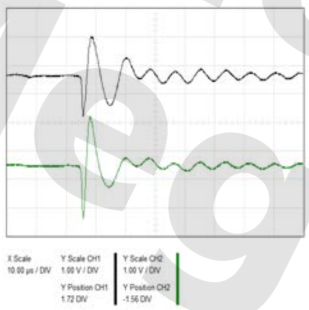
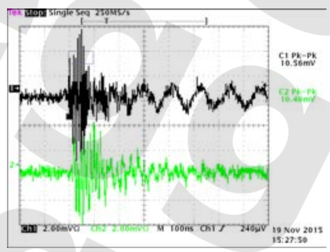
Partial Discharges in Transformers

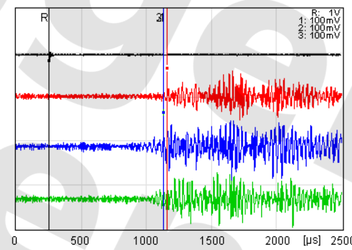
Electric PD Pulse taken from the test tap of a bushing



UHF PD Pulse taken from UHF antenna on an oil valve



Acoustic Signal measured on the tank wall



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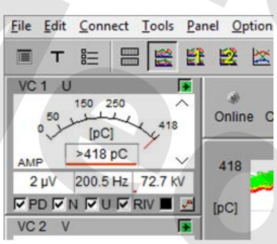
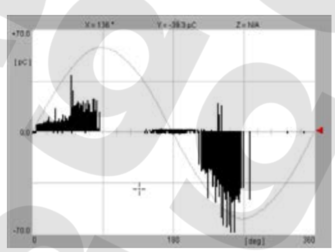
Partial Discharges in Transformers

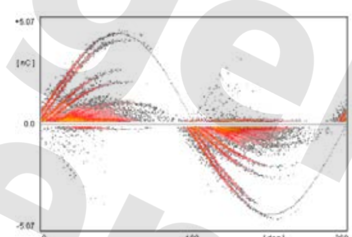
Simple meter display giving apparent charge in pC



Scope view offers additionally limited research capabilities



Phase-**r**esolved **PD** pattern (**PRPD**) for in-depth interpretation



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The ICMsystem

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The ICM*system*

- Advanced PD-detection system and analysis tool
- Simultaneous real time acquisition on up to 10ch
- Integrated spectrum analysis up to 10MHz (BW: 9kHz/300kHz)
- Time domain analysis
- Measurements with AC and DC voltages
- Integrated acoustic PD location functions

Technical details

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The ICM*system*

- Advanced (SC/MC/ACT) control software
- High Resolution PRPD-Pattern (16-bit)
- Powerful Suppression Tools
- Input sensitivity <0.02pC
- IEC 60270 compliant
- Field and factory environment

Technical details

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The ICM*system*

Decoupling

- Test tap via quadrupole
- Coupling capacitor
- HF-Current Transformer

Pre Amplifier

- <1MHz (IEC-60270) RPA1
- RPA for different frequency ranges or Acoustics on request

Instrument

- ½ 19inch ICM*system*
- Full 19'' ICM*system*

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The ICM*system*

Minimum configuration:

- Full 19 inch acquisition unit
- Six acquisition channels
- Six preamplifier & quadrupoles
- PD calibrator

Full configuration:

- Spectrum & Smart-Trigger
- Ten channels & preamplifier
- 3 CC100B/V for tertiary windings
- Quadrupole and/or CT100 to decouple neutral as well

Configuration for power transformers

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The ICM*system*

Minimum configuration:

- ½ 19 inch acquisition unit
- Three acquisition channels
- Three preamplifier & Coupling Capacitors
- PD calibrator

Full configuration:

- Spectrum & Smart-Trigger
- Four channels & preamplifier
- CT100 for additional decoupling options or noise suppression

Configuration for distribution transformers

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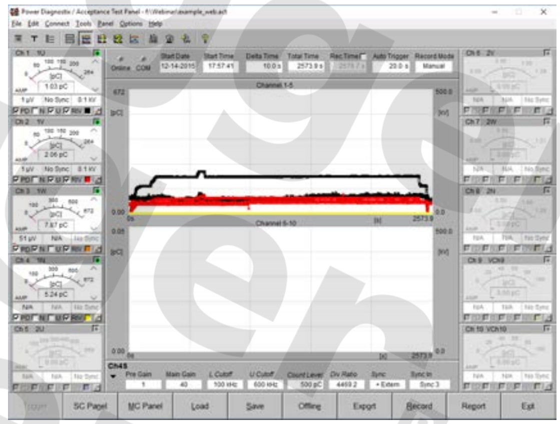
The ICM*system*

Overview:

- 3 Display Modes
- **Single Channel Panel**
  - Optimize Settings for HV-lab
  - In-depth research in case of failure
- Multi Channel Panel
  - Comparative view of the last PRPDs recorded on all channels
- **Acceptance Test Panel**
  - Dedicated mode for transformer Factory-Acceptance Testing

Software



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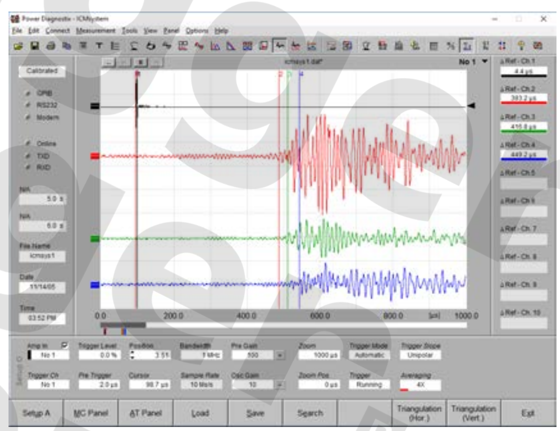
The ICM*system*

Single Channel Panel:

- 12 different Display views with sub-views
- Views used for in-depth research on transformers:
  - Scope view
  - **MAP view**
  - Spectrum view (optional)
  - **Oscilloscope view**

Software



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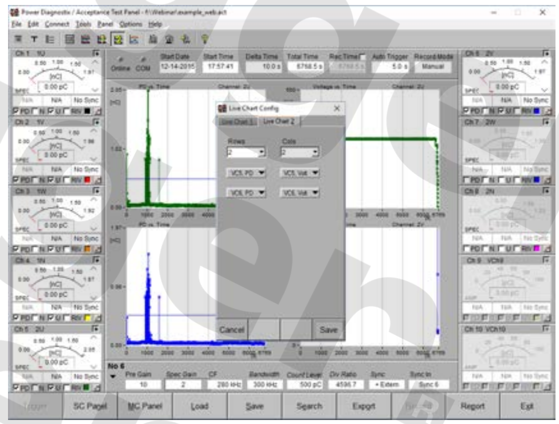
The ICM*system*

Acceptance Test Panel:

- Developed for fast and easy transformer acceptance testing
- Meters of all ten channels in parallel.
- Four display views:
  - Table view with recorded values
  - Stripchart view
  - Live Chart views

  can be configured independently

Software



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Factory Acceptance Testing with the ICMsystem

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Factory-Acceptance Testing using The ICM*system*

Optimize Settings for HV-lab

Common problem for factory-acceptance testing:

- PD signals are decoupled between test-object or coupling capacitor and common ground
- During construction of many transformer factories PD measurements were either not considered at all or not common
- Often no separated ground system for the HV laboratory
- High frequent disturbances created from machinery used for manufacturing affect sensitivity of PD measurements
- Evaluate filter settings to optimize sensitivity prior testing
- Use PD measurement device together with calibrator and typical test setup, incl. device under test

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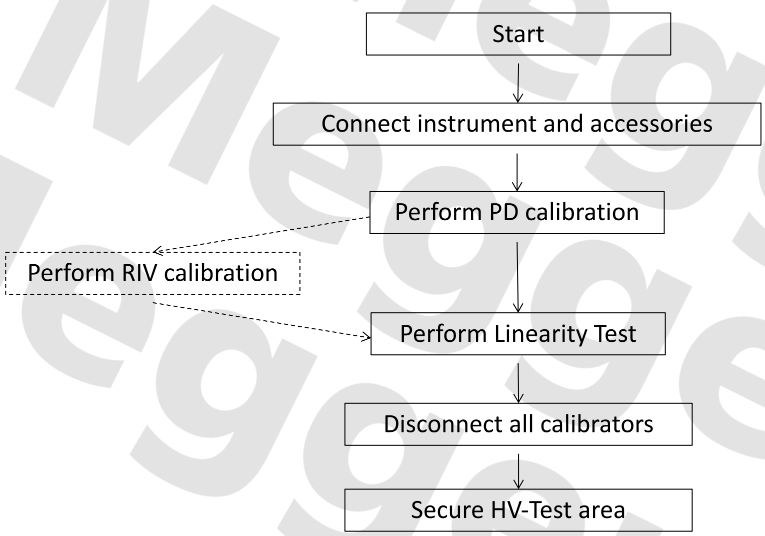
Factory-Acceptance Testing using The ICM*system*

IVPD preparation



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Factory-acceptance testing using the ICM*system*

IVPD test

Start recording
↓
Apply voltage & trigger values for PD and voltage at predefined levels
↓
For 1h (180 sec) set auto-trigger
↓
Wait until voltage curve specified for DUT is complete
↓
Create FAT-report

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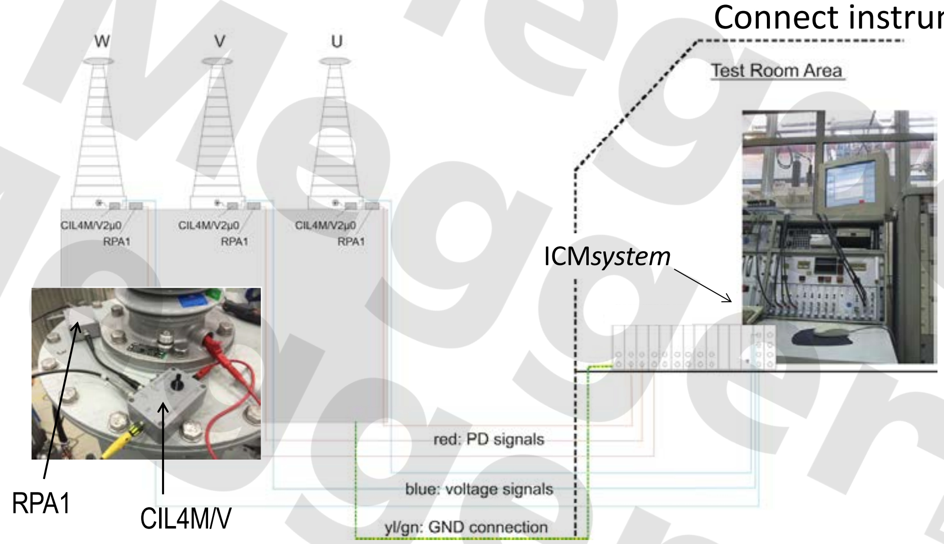
Factory-Acceptance Testing using The ICM*system*

Connect instrument (PT)



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Factory-Acceptance Testing using The ICM*system*

Connect instrument (DT)

ICM*system*
with 4 parallel
input channels

Remote control computer
with ICM*system* software

Coupling capacitor
CC100B/V

Preamplifier
RPA1

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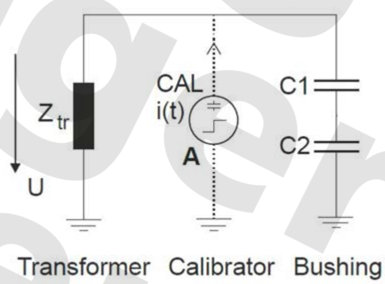
Factory-Acceptance Testing using The ICM*system*

- PD measurements are relative measurements and require a calibration (IEC60270)
- Compensation of the test circuit´s overall attenuation
- Injection of a calibration pulse with defined magnitude & magnitude adjustment of the signal response
- Valid for the test setup in final arrangement, at a specific detection bandwidth and calibration magnitude
- ICMsystem ACT software offers calibration matrix



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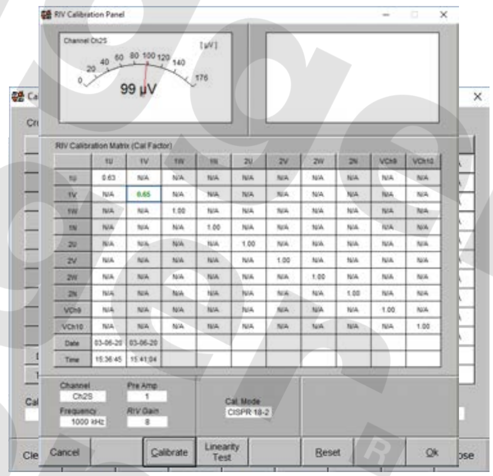
Factory-Acceptance Testing using The ICM*system*

- Connect calibrator
- Inject specified calibration value
- Open Calibration Panel
- Calibrate with specified charge
- Open Linearity Test Panel to perform linearity test
- Repeat with next phase
- Additional RIV calibration if required

In some cases a dedicated PRPD calibration is necessary.

PD Calibration



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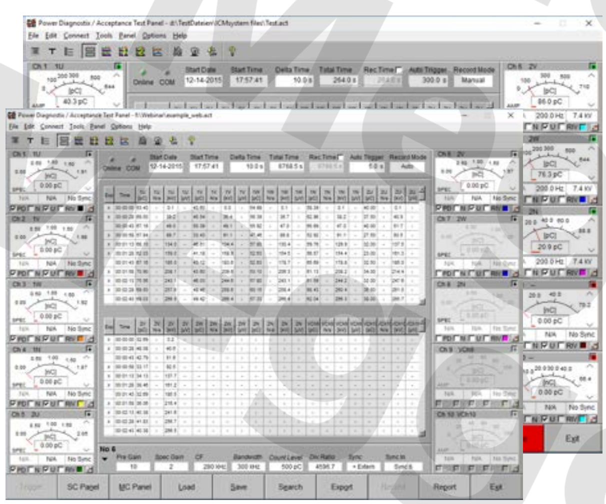
Factory-Acceptance Testing using The ICM*system*



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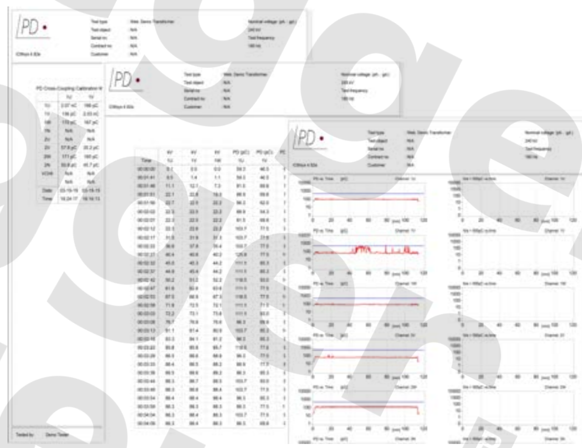
Factory-Acceptance Testing using The ICM*system*

FAT report

- Various report formats available
- Data Export into Word, HTML or Text-file for own reporting
- Alternative: Configurable direct print-out
  - Configuration:
  - Report:



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Summary

- Partial Discharge is a breakdown of a small area of the overall insulation where each avalanche generates three different measurable signals
  - Local displacement current pulse
  - Electromagnetic pulses
  - Acoustic signals
- Numerous standards address Factory-Acceptance Testing of power and distribution transformers, distinguishing via ratings and dry-type/oil-immersed transformers
  - Strict test circuits
  - Acceptance criteria
  - Voltage sequence
- ICM*system* available in multiple configurations to fit Factory-Acceptance Testing of distribution and power transformers
  - ACT software to aid in FAT

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Survey and Contact Information

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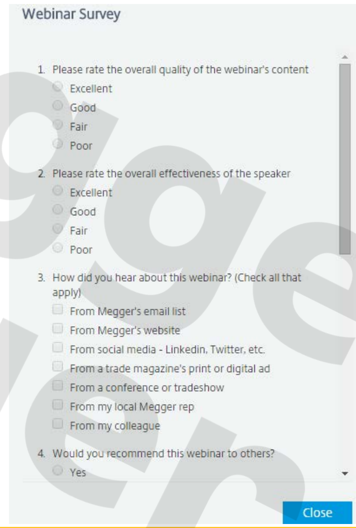

Please help us improve by filling out the survey after the webinar ends

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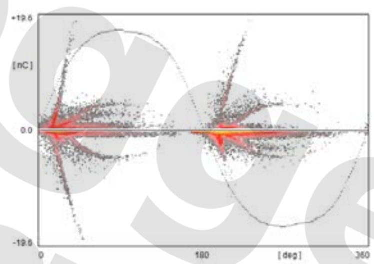
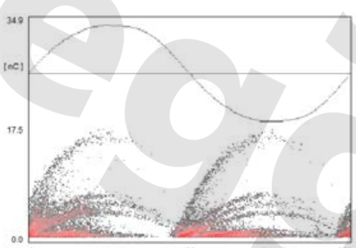
Questions?





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