SCIENCE
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TECHNOLOGY

PD Diagnostics under DC Voltage

Prof. Dr.-Ing. Uwe Schichler
Institute of High Voltage Engineering and System Performance
Graz University of Technology
Graz, Austria

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ISH2023
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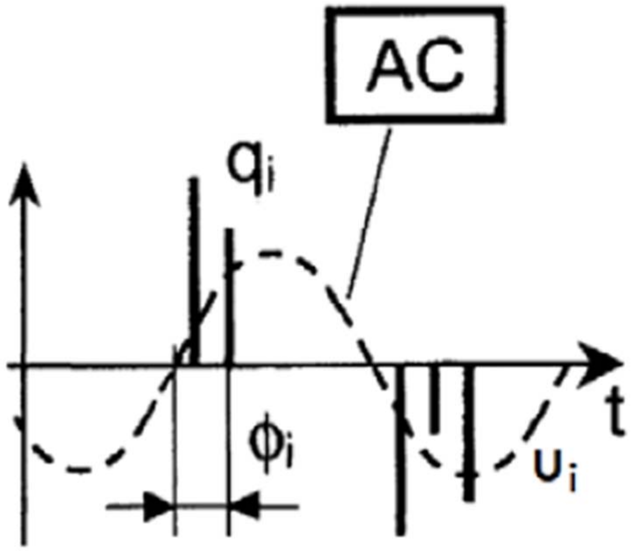
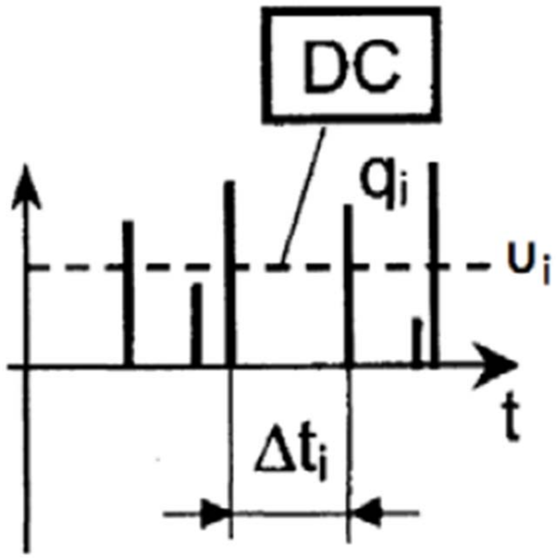
University of Strathclyde Technology
& Innovation Centre, Glasgow, UK

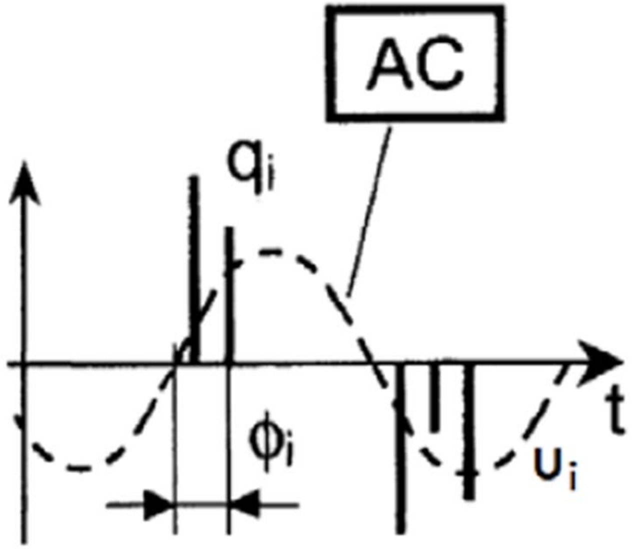
PD Diagnostics: AC versus DC

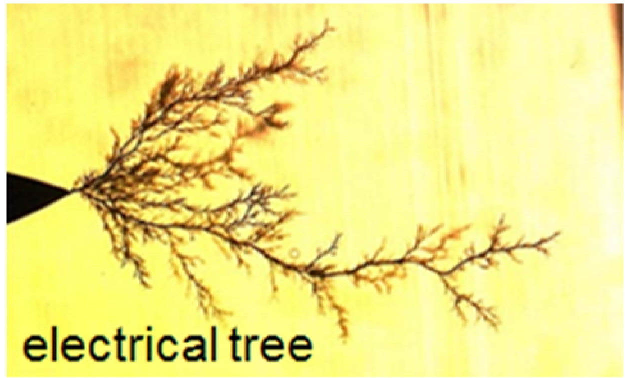


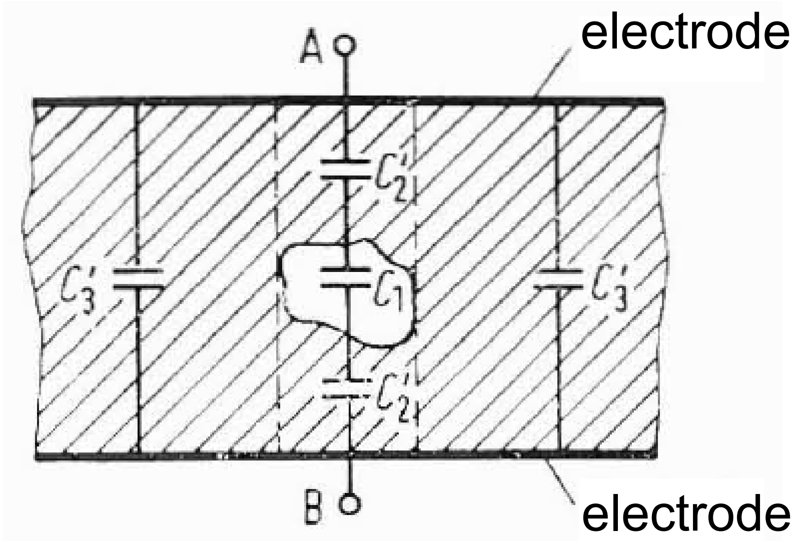


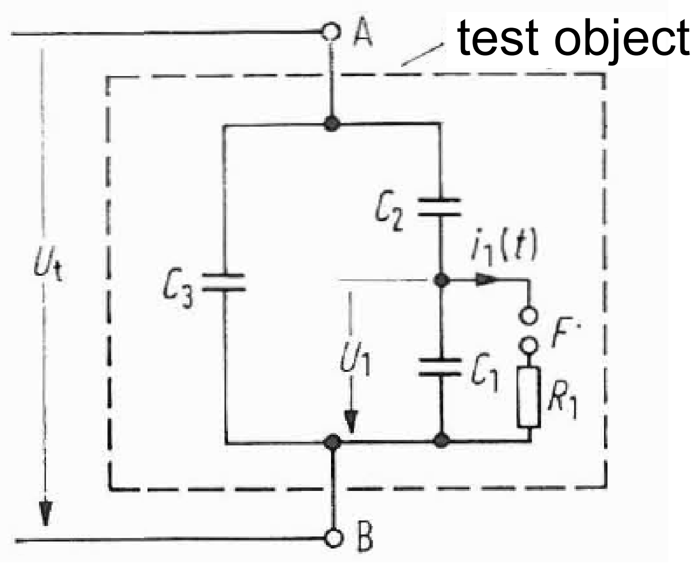
Fromm, PhD Thesis, 1995

PD Diagnostics under AC Voltage









PD detection methods:

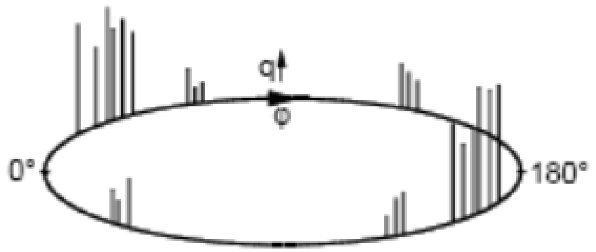
IEC 60270

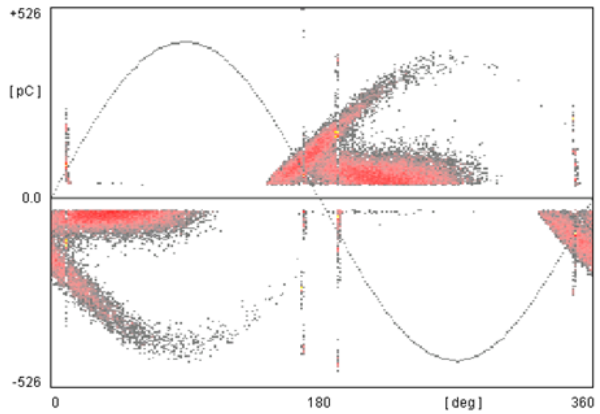
VHF/UHF

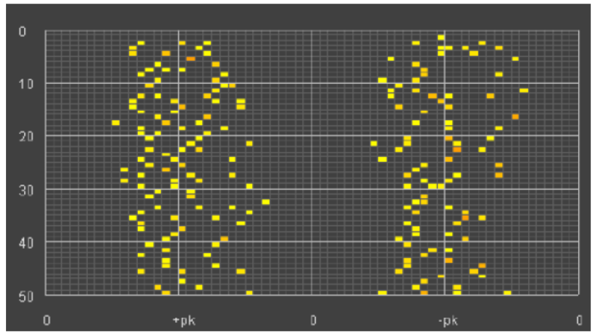
Acoustic

Optical

Chemical

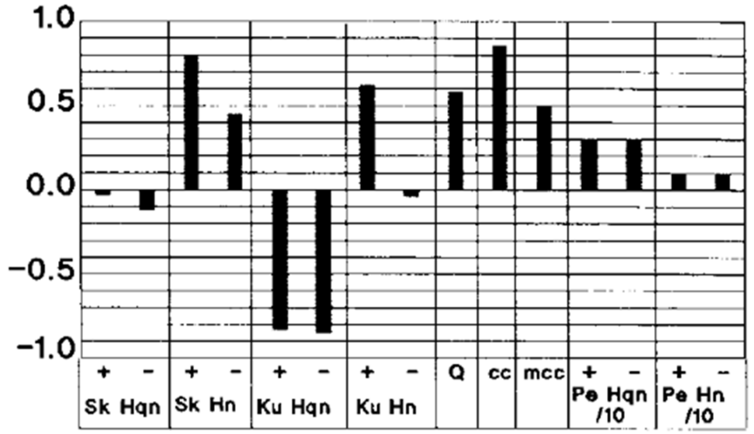


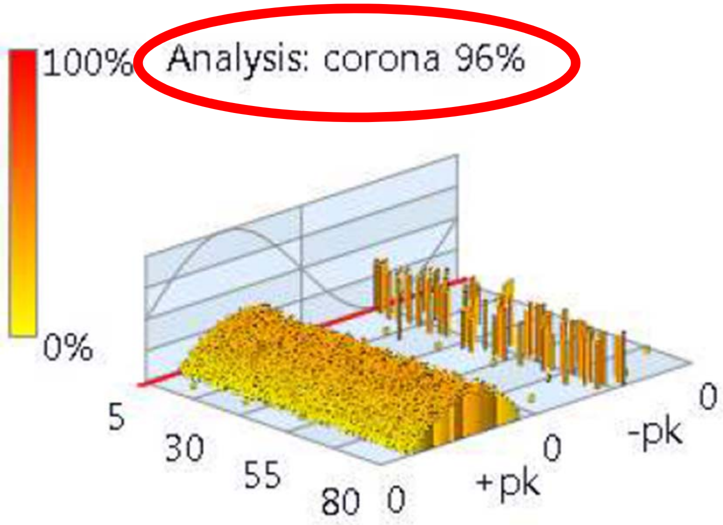


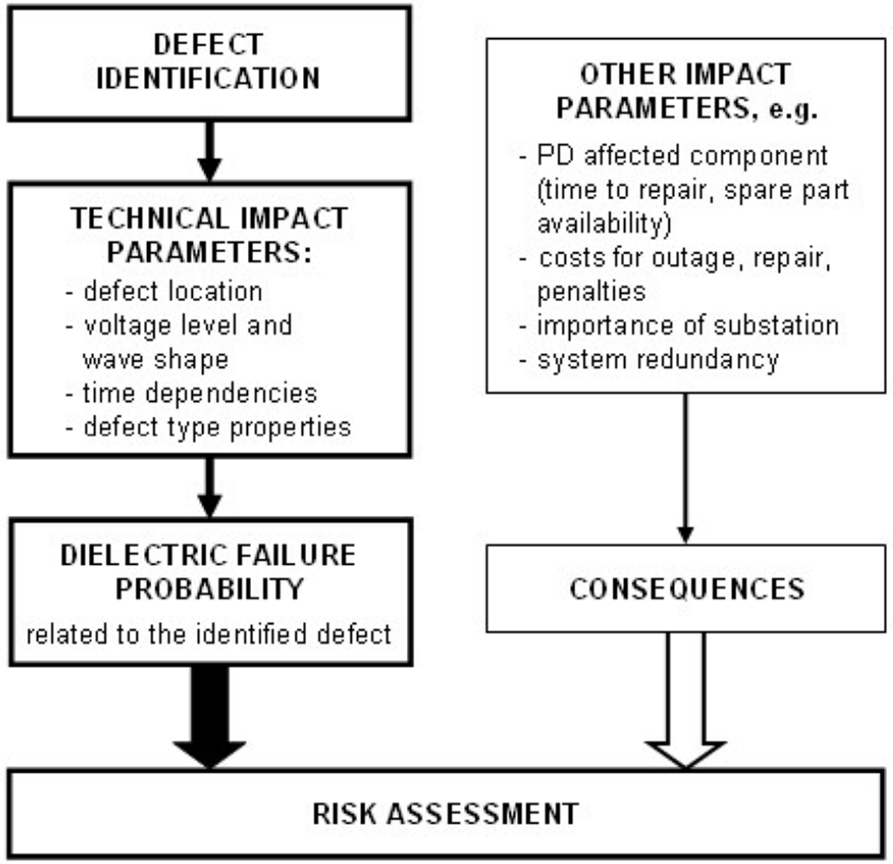


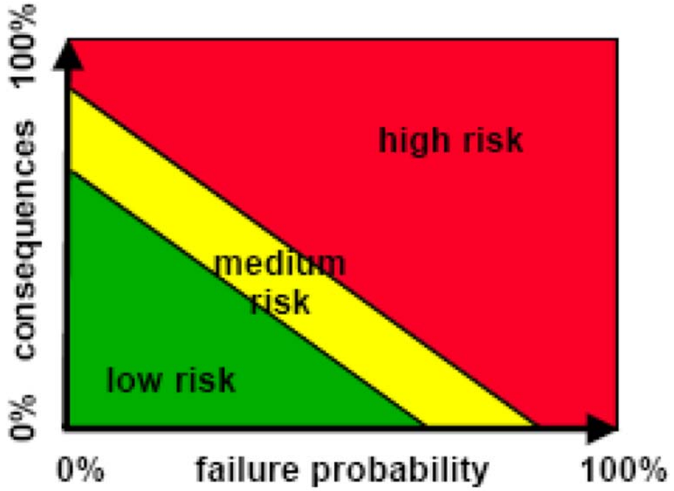
PD Diagnostics under AC Voltage

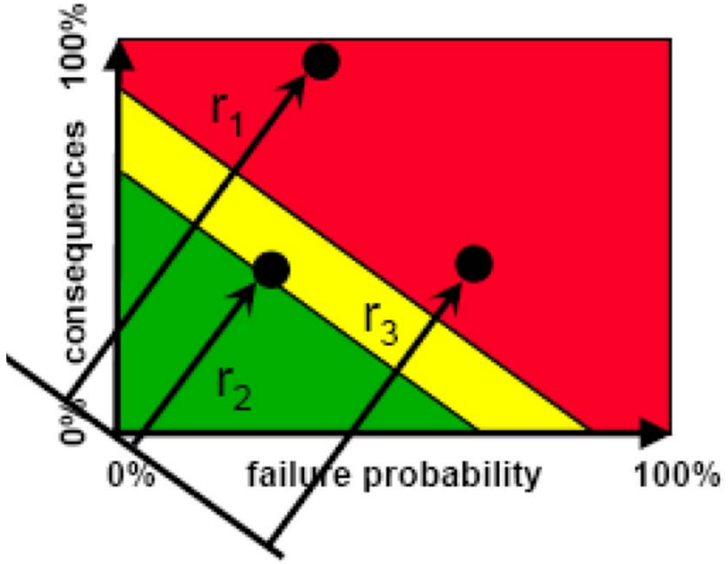
- Acceptance criteria (e.g. IEC 62271-203: 5 pC for GIS)
- Type of defect, critical defects and risk assessment



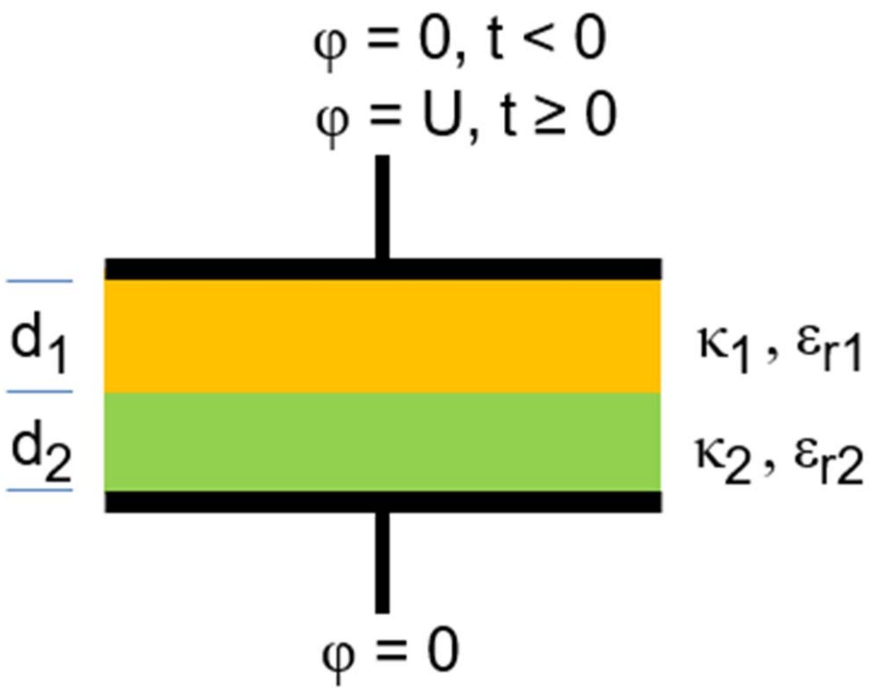


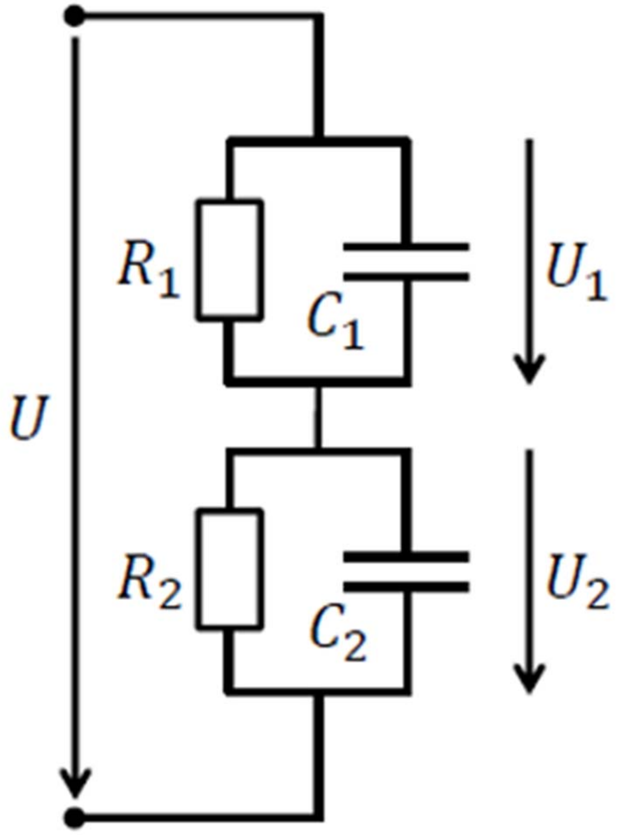




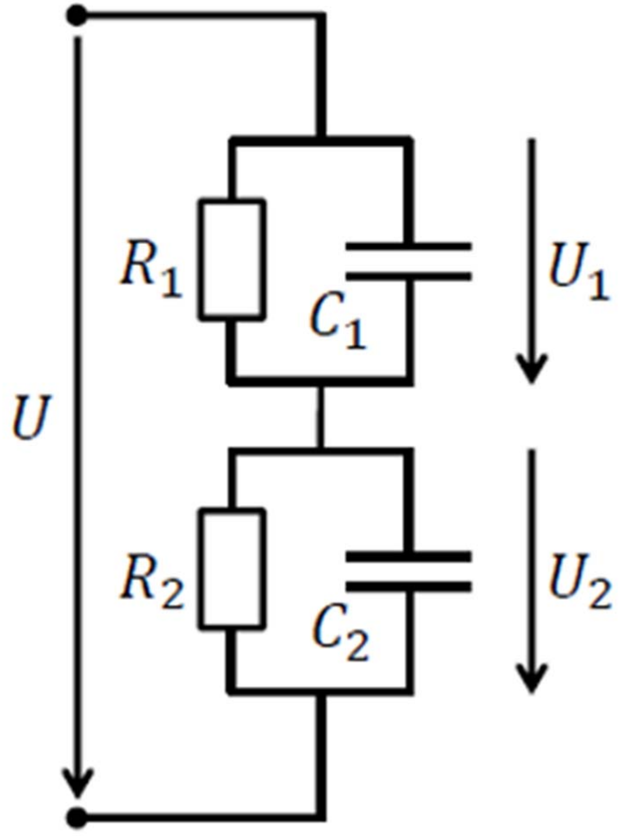


Electric Field under DC Voltage: Equivalent Circuit





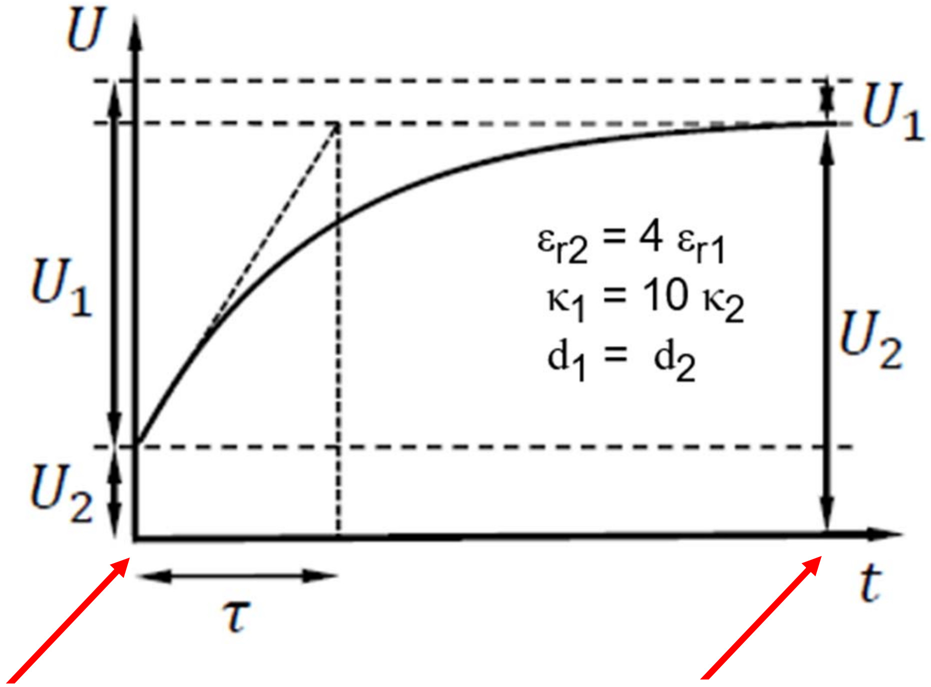
Electric Field: Transition from Capacitive to Resistive Field



$$U_1 = U\frac{R_1}{R_1+R_2}\left[1-\left(1-\frac{C_2R_2}{\tau}\right)\cdot e^{-\frac{t}{\tau}}\right]$$

$$U_2 = U\frac{R_2}{R_1+R_2}\left[1-\left(1-\frac{C_1R_1}{\tau}\right)\cdot e^{-\frac{t}{\tau}}\right]$$

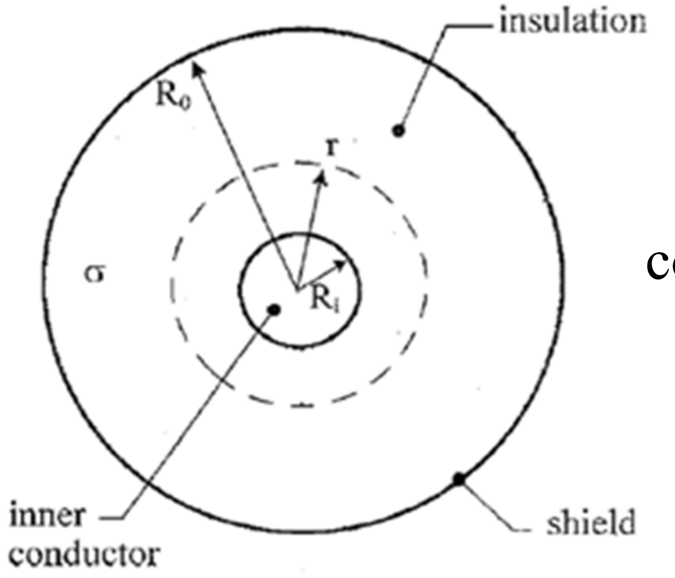
$$\tau = \frac{R_1R_2(C_1+C_2)}{R_1+R_2} = \frac{\varepsilon_1 d_2+\varepsilon_2 d_1}{\kappa_1 d_2+\kappa_2 d_1}$$



capacitive field
$t = 0$

resistive field
$t \to \infty\ (10\cdot\tau)$

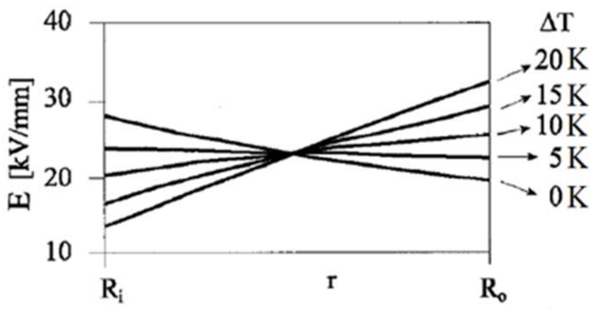
HVDC Cable: Electric Field Inversion



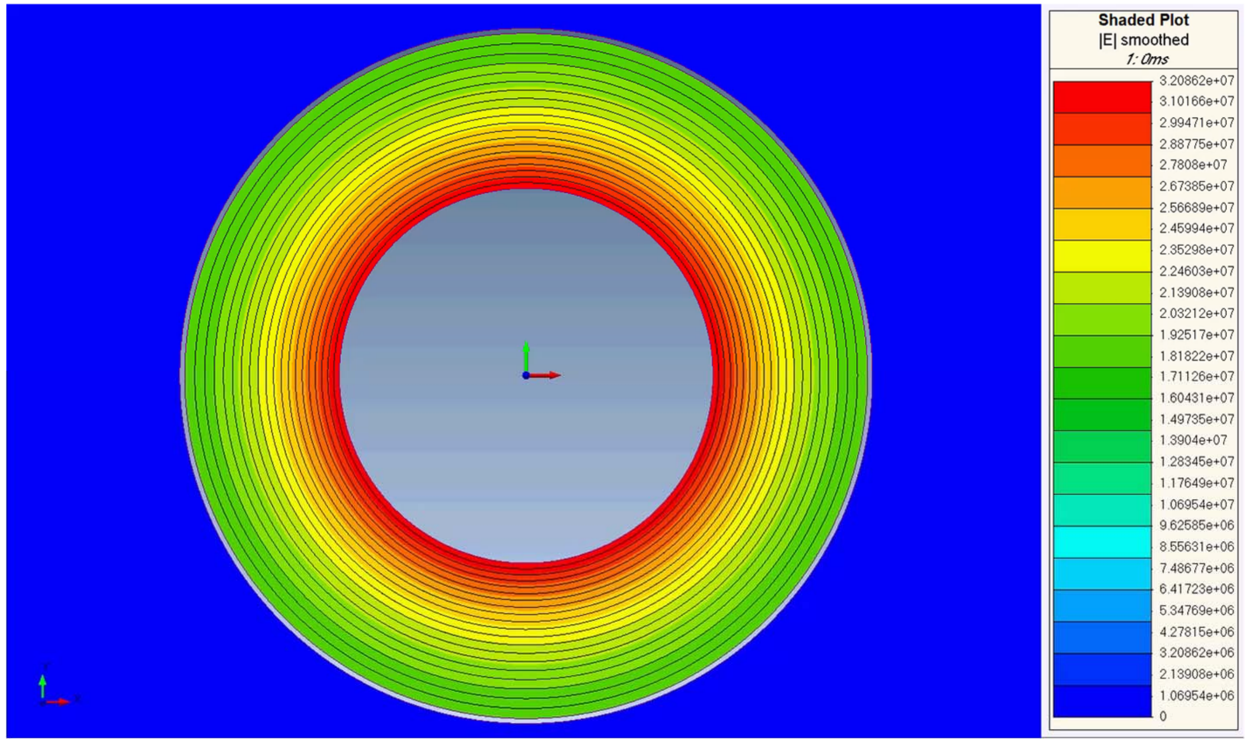
conductivity
$= f\,(T, E)$

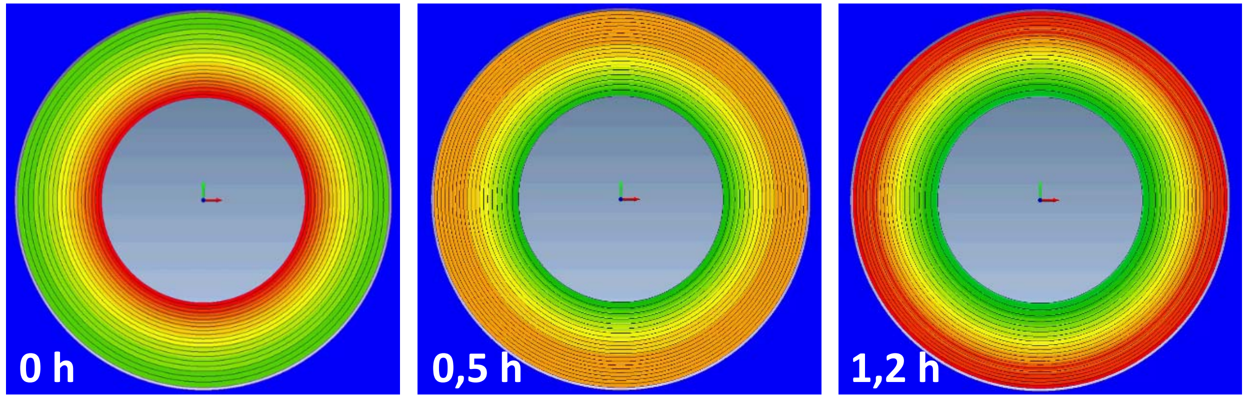
$$R_i = 19.2\text{ mm} \qquad \sigma = \sigma_0 \exp(\alpha T)\exp(\gamma E)$$
$$R_o = 42.4\text{ mm} \qquad \sigma_0 = 1\times10^{-16}\ \Omega^{-1}\text{m}^{-1}$$
$$\gamma \sim 0.03\text{ mm/kV} \qquad \alpha \sim 0.1\text{ K}^{-1}$$

conductor: 55 °C
screen: 35 °C
$U_{DC} = 450$ kV



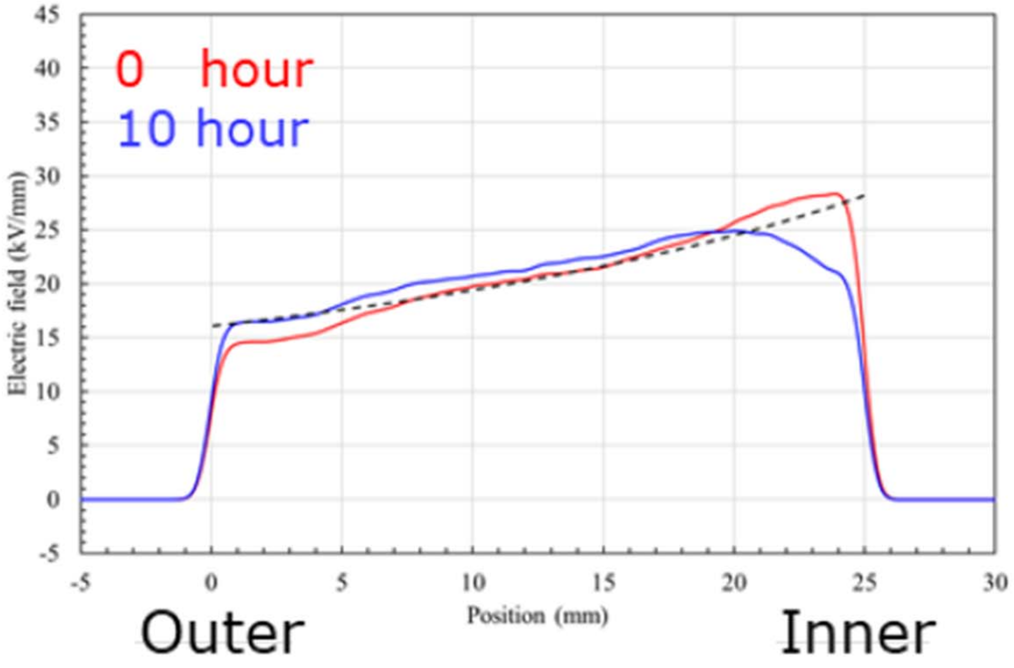
Jeroense, PhD Thesis, 1997

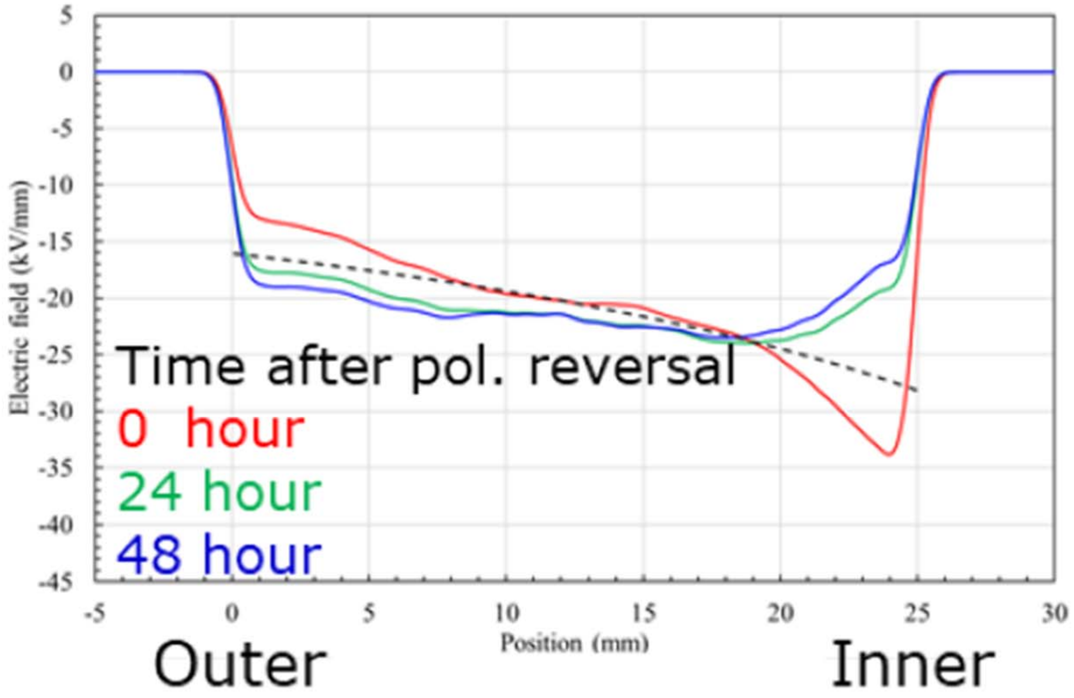




Ratheiser, 2020

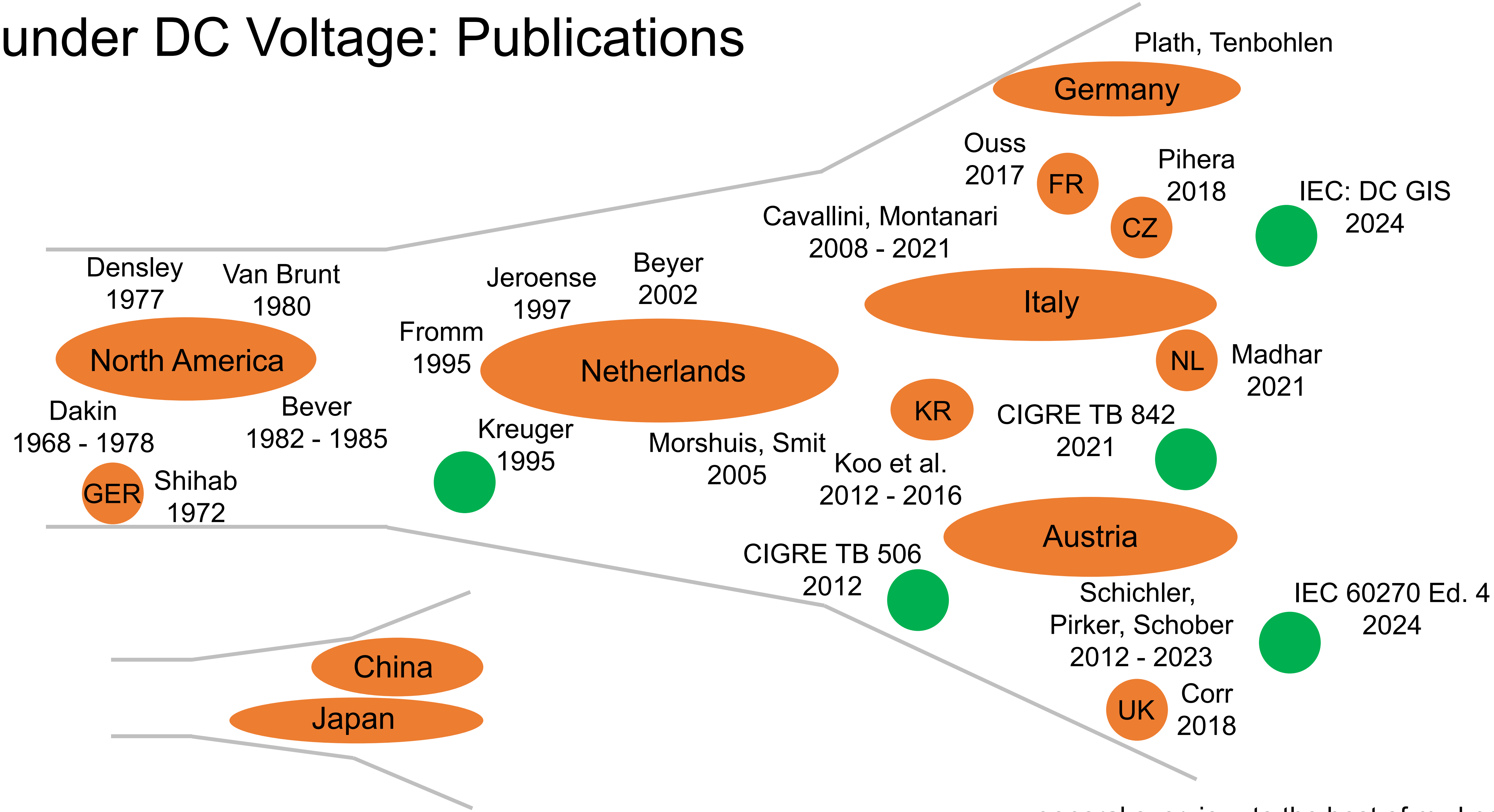
Electric Field influenced by Space Charge Accumulation





Mashio et al.
Jicable 2023
Report A10-3

PD under DC Voltage: Publications



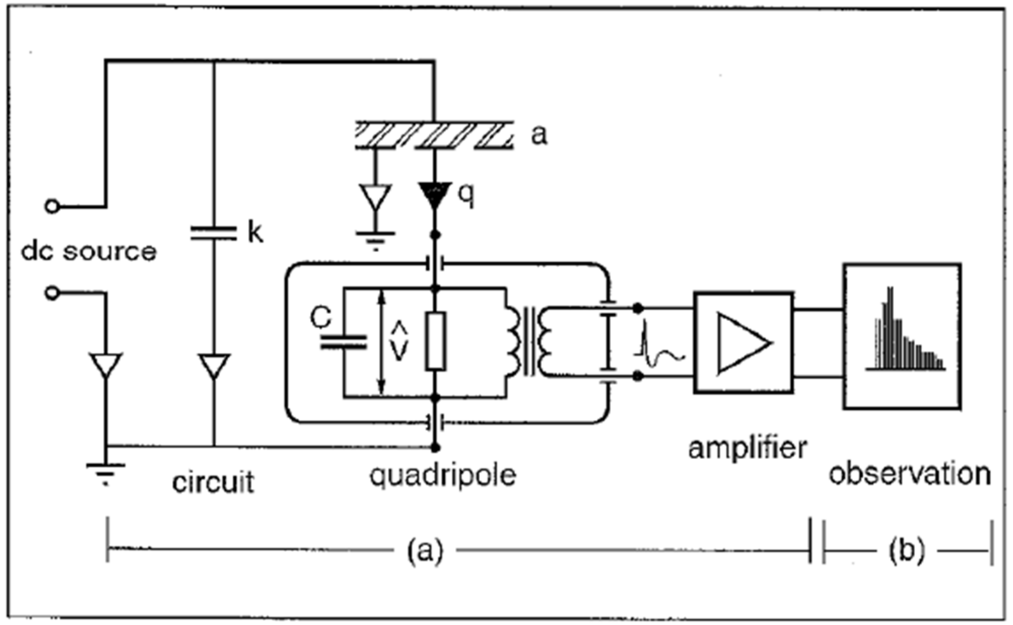
general overview, to the best of my knowledge

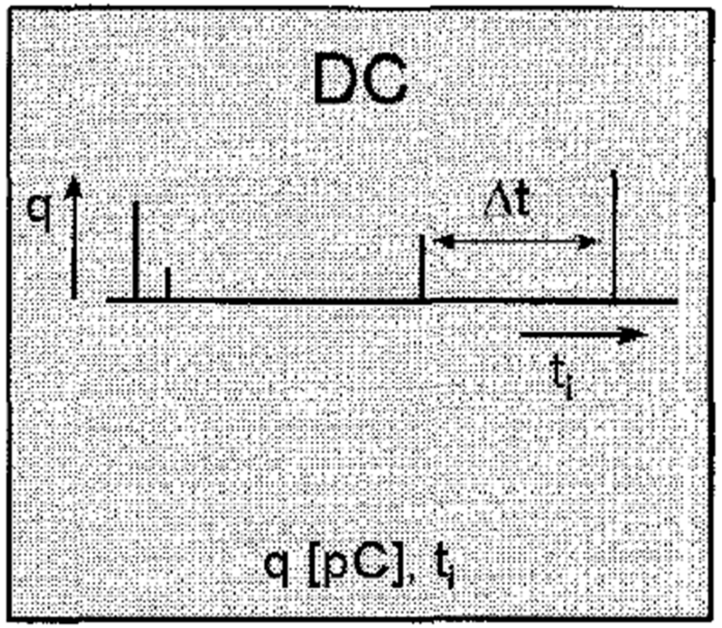
IEEE Electrical Insulation Magazine, 1997

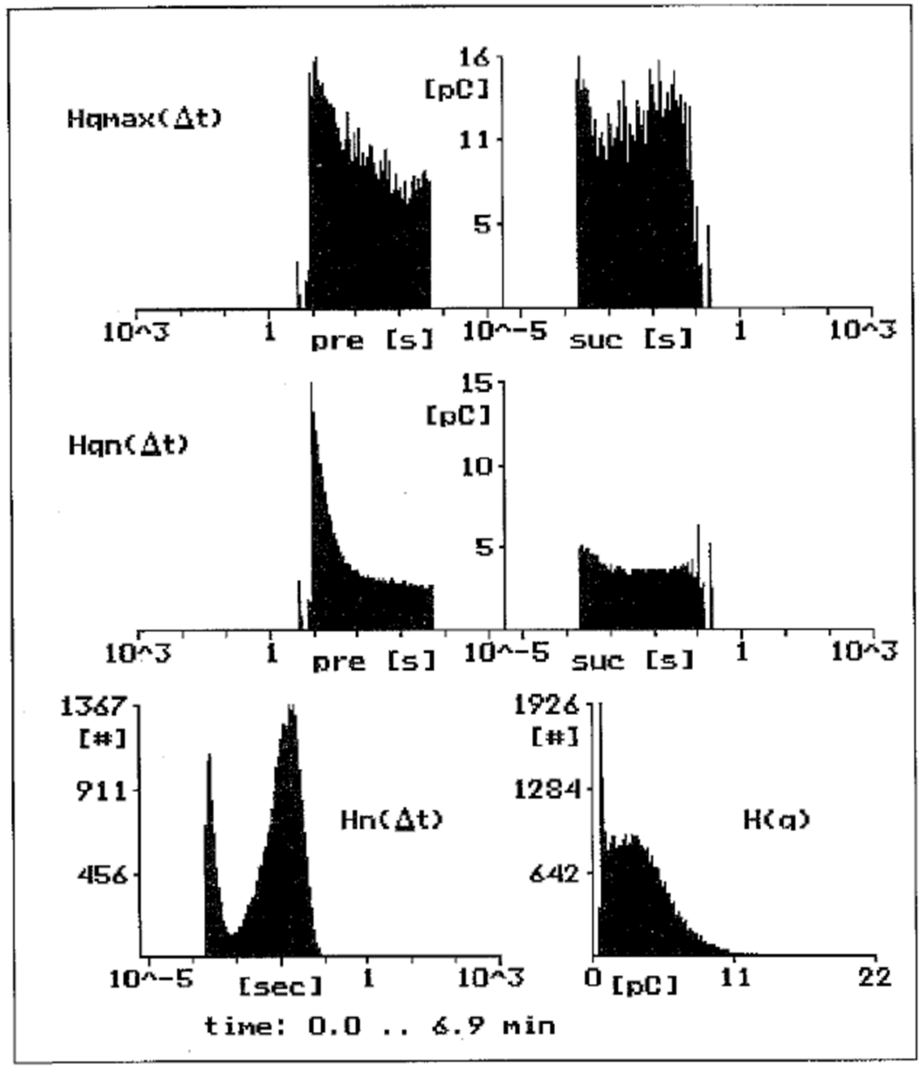
Partial Discharge Part XXIV: The Analysis Of PD In HVDC Equipment

Key Words: DC, partial discharge, PD testing

by
Peter Morshuis, Marc Jeroense, and
Jens Beyer
Delft University of Technology







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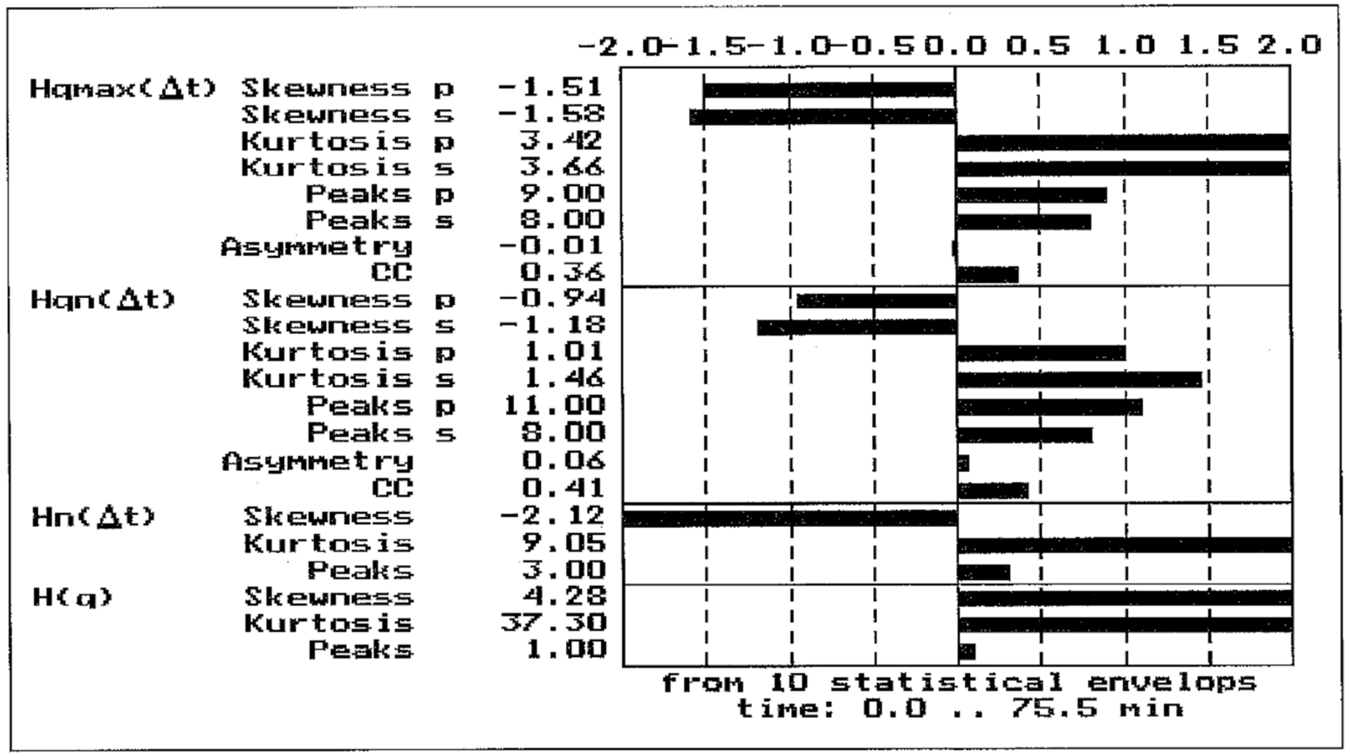
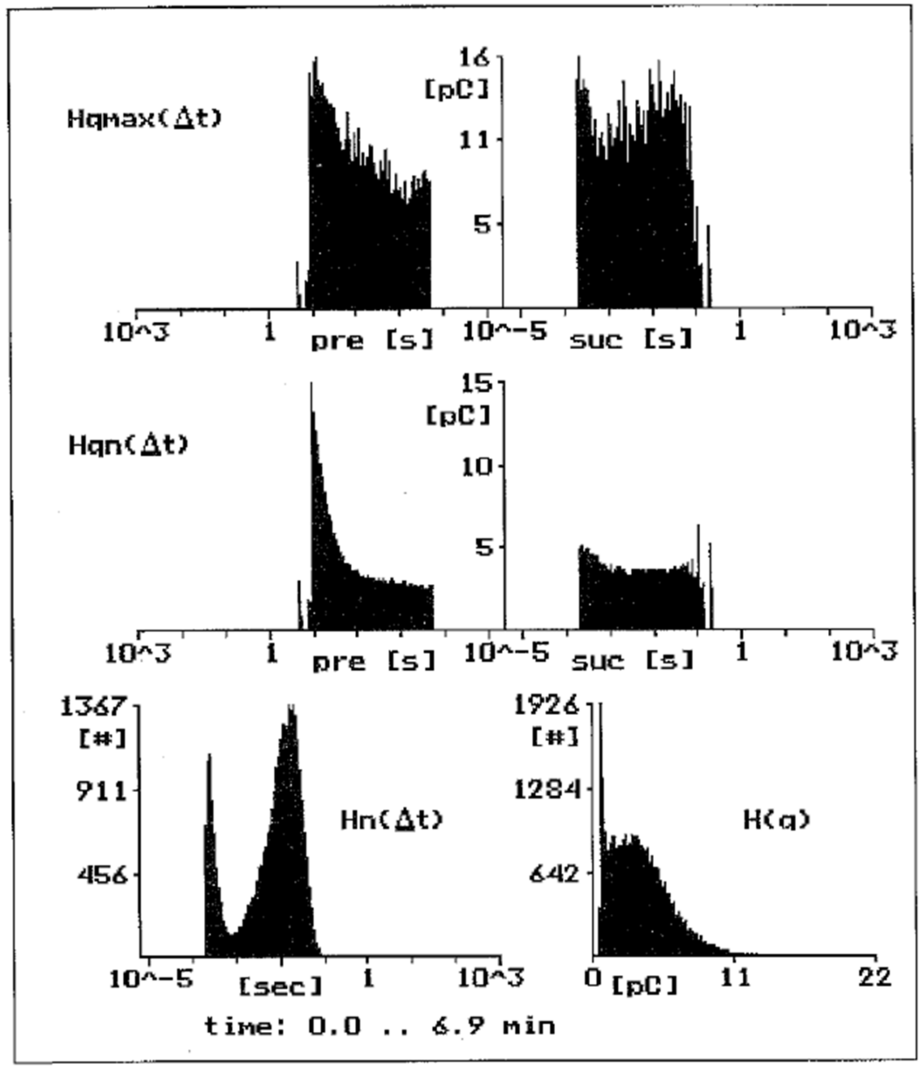
Fingerprint by 22 features





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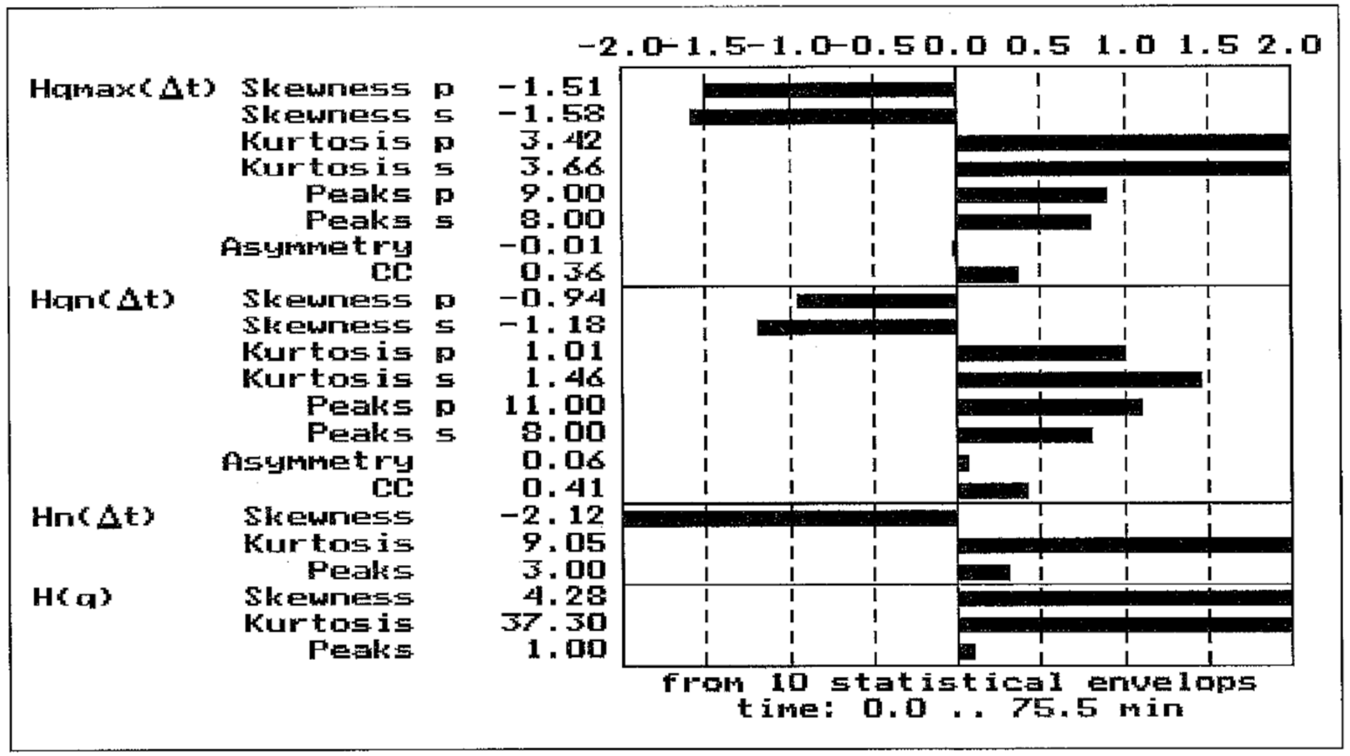
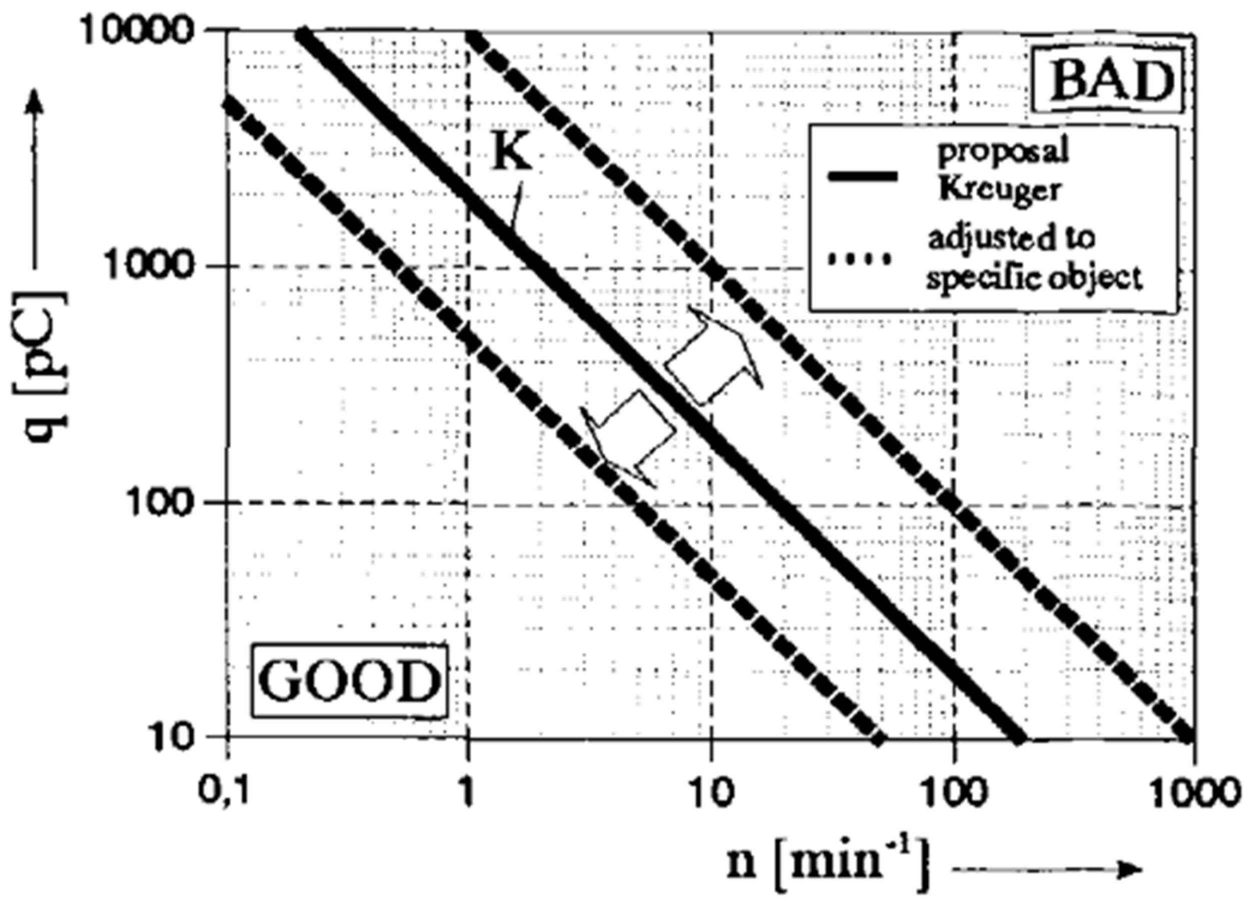
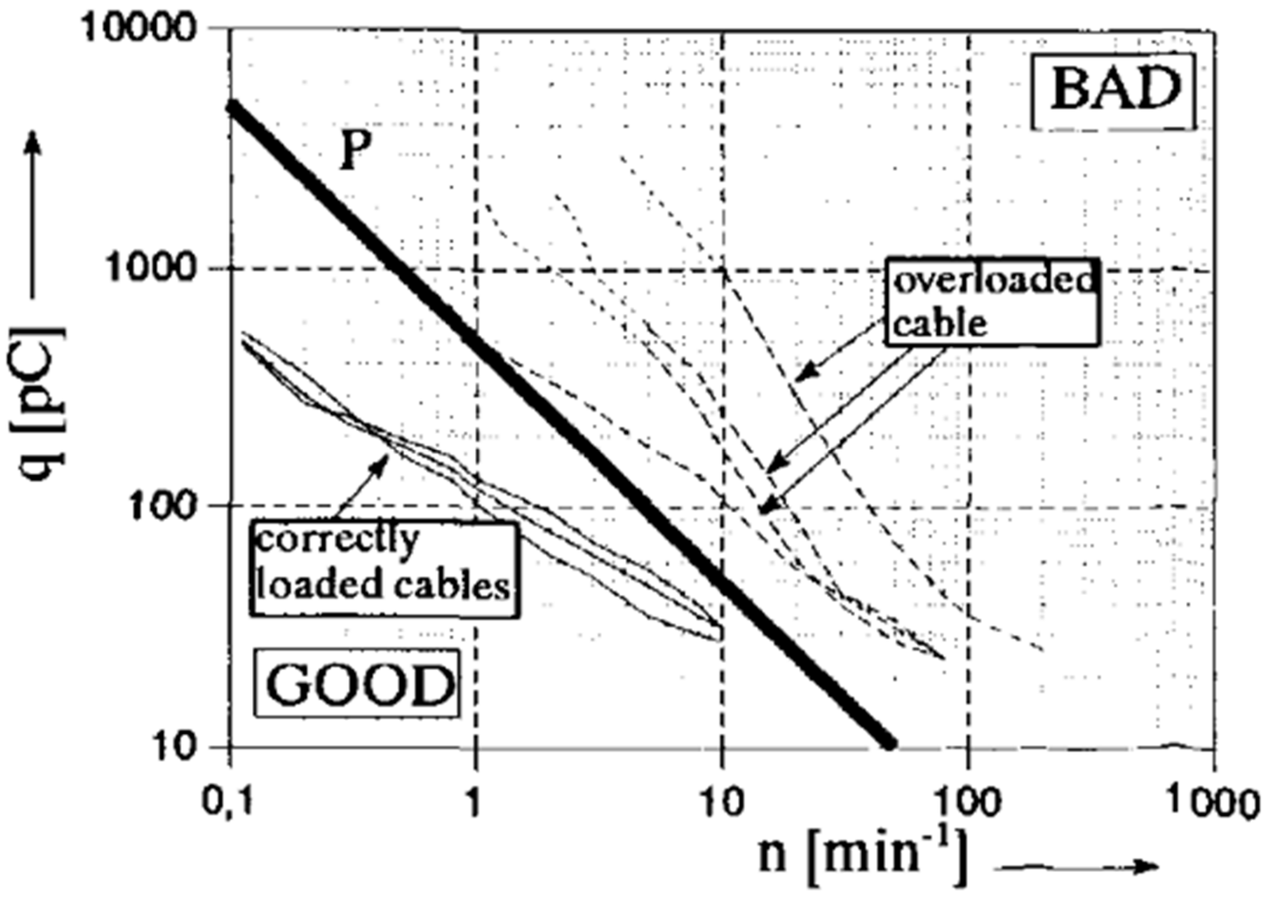


Table I
Average Recognition in Percent for Five Types of Measurements

References	Corona (+ or -)	PD in oil	Electrode bounded cavity	Surface discharges	Dielectric bounded cavity
Measurement					
Corona	89	0	0	0	0
PD in oil	0	93	0	0	0
Electrode bounded cavity	0	0	83	0	0
Surface discharges	0	0	0	41	0
Dielectric bounded cavity	0	0	0	0	89

Acceptance Criteria – Mass-impregnated HVDC Cables

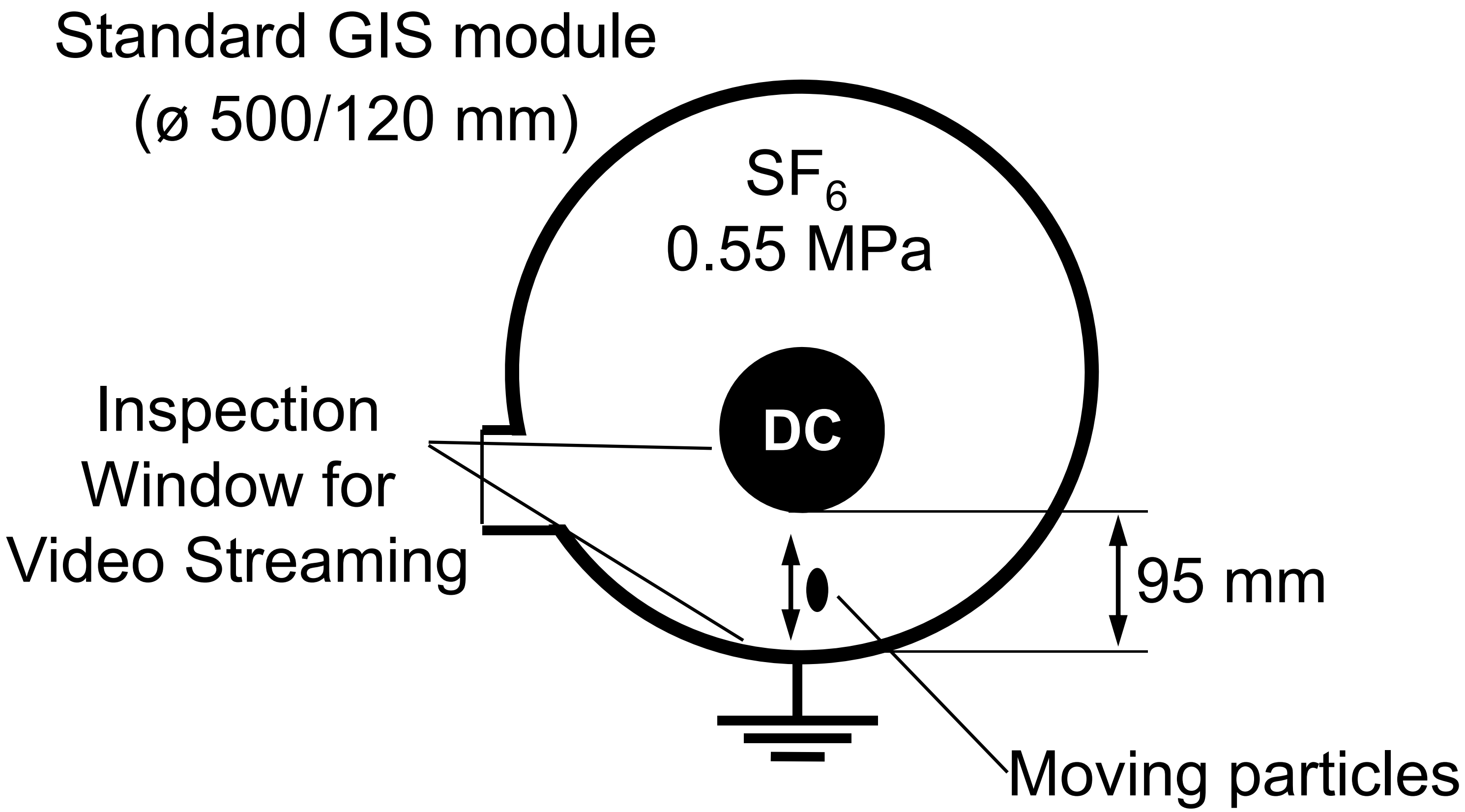


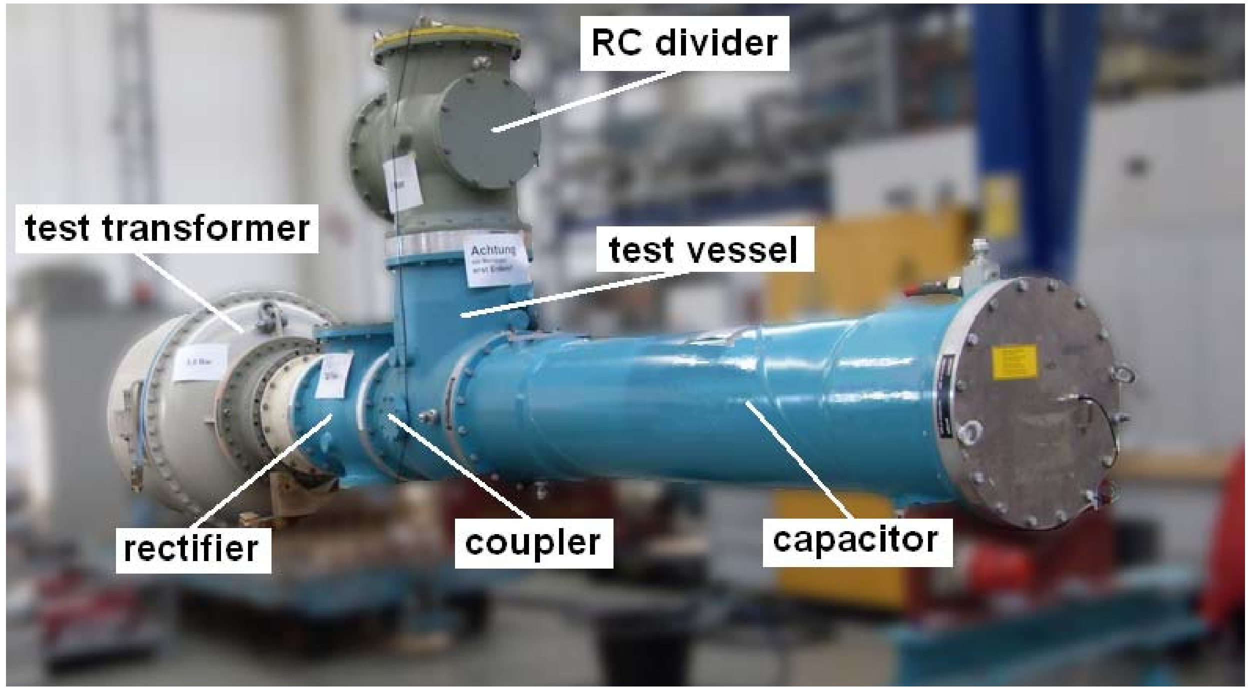


Proposal by Kreuger: $n \cdot q \leq 2\ nC \cdot min^{-1}$

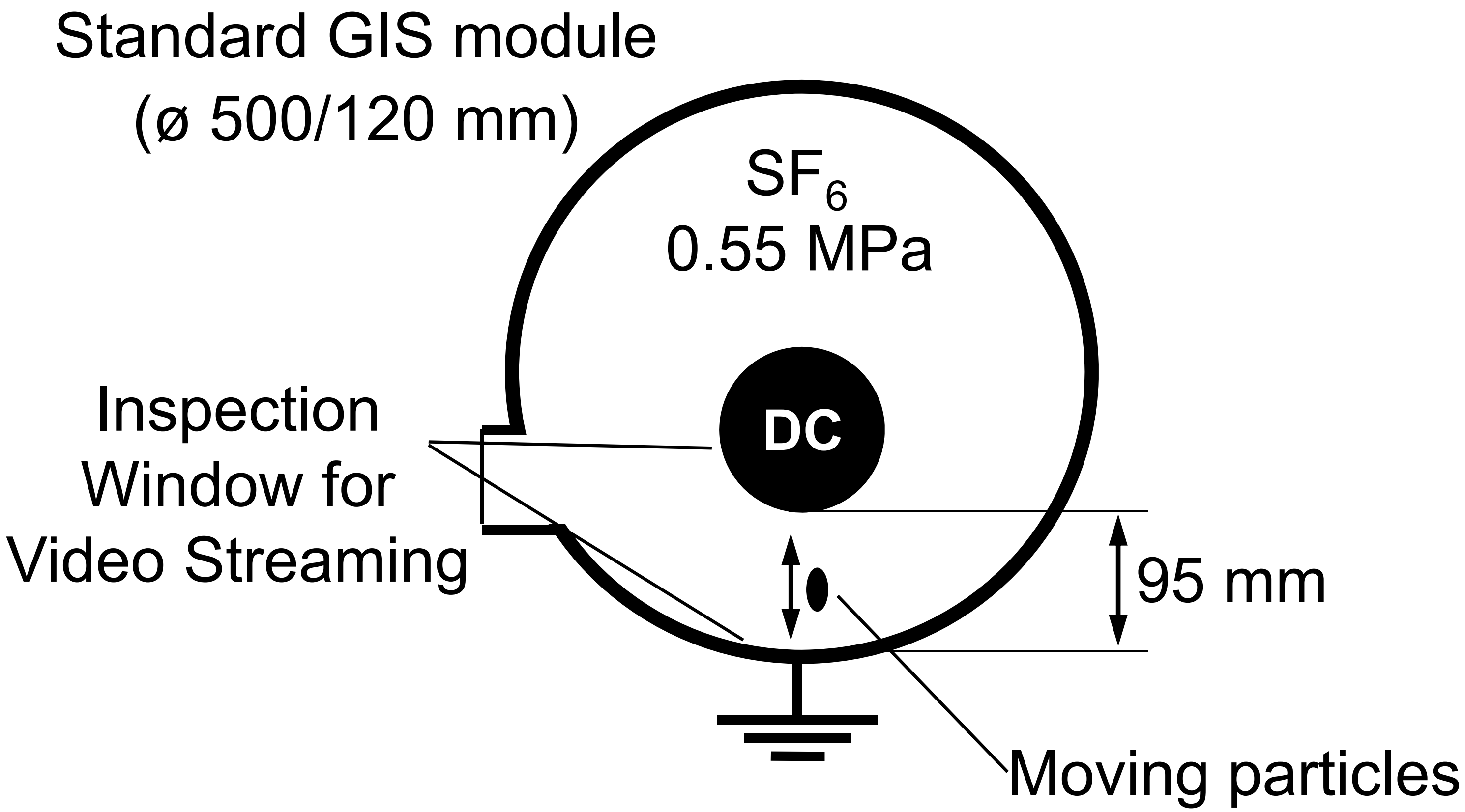
Jeroense, PhD Thesis, 1997

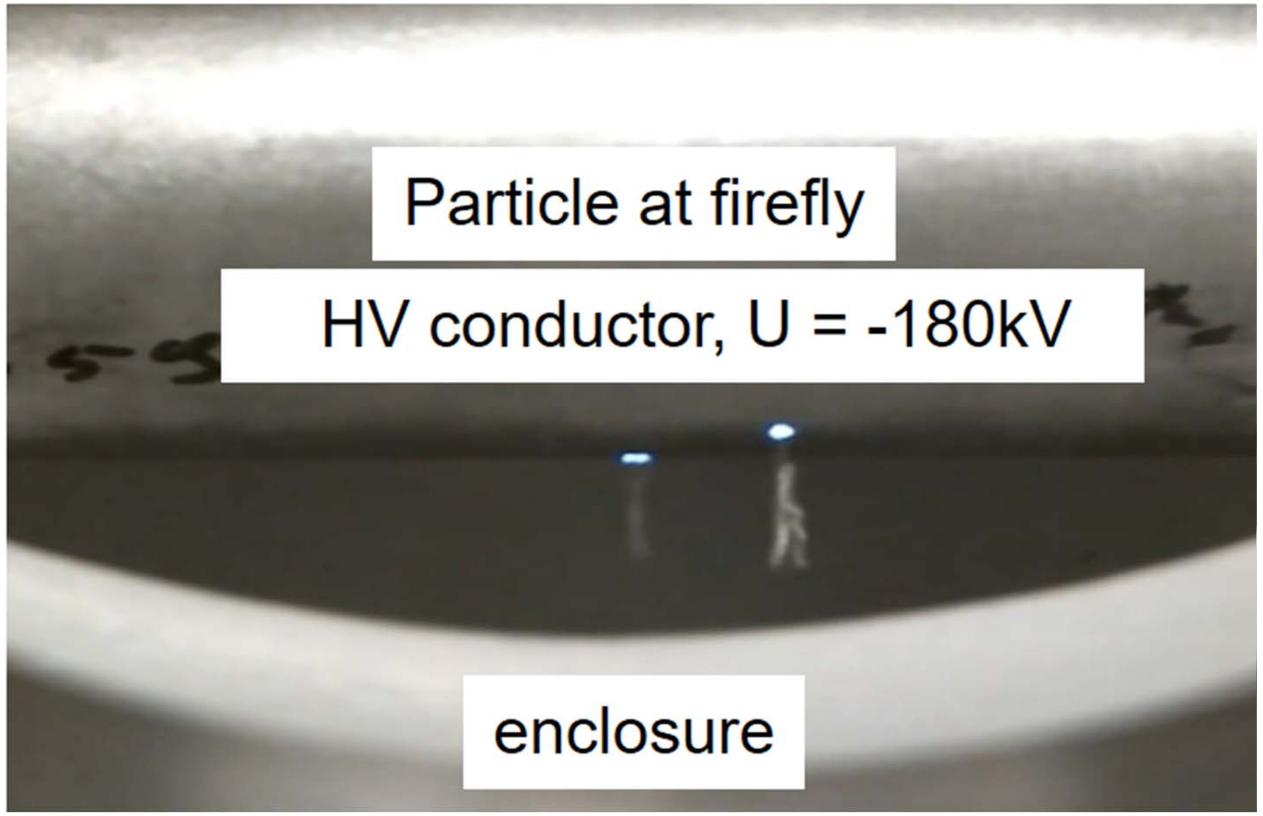
HVDC GIS: Moving particles





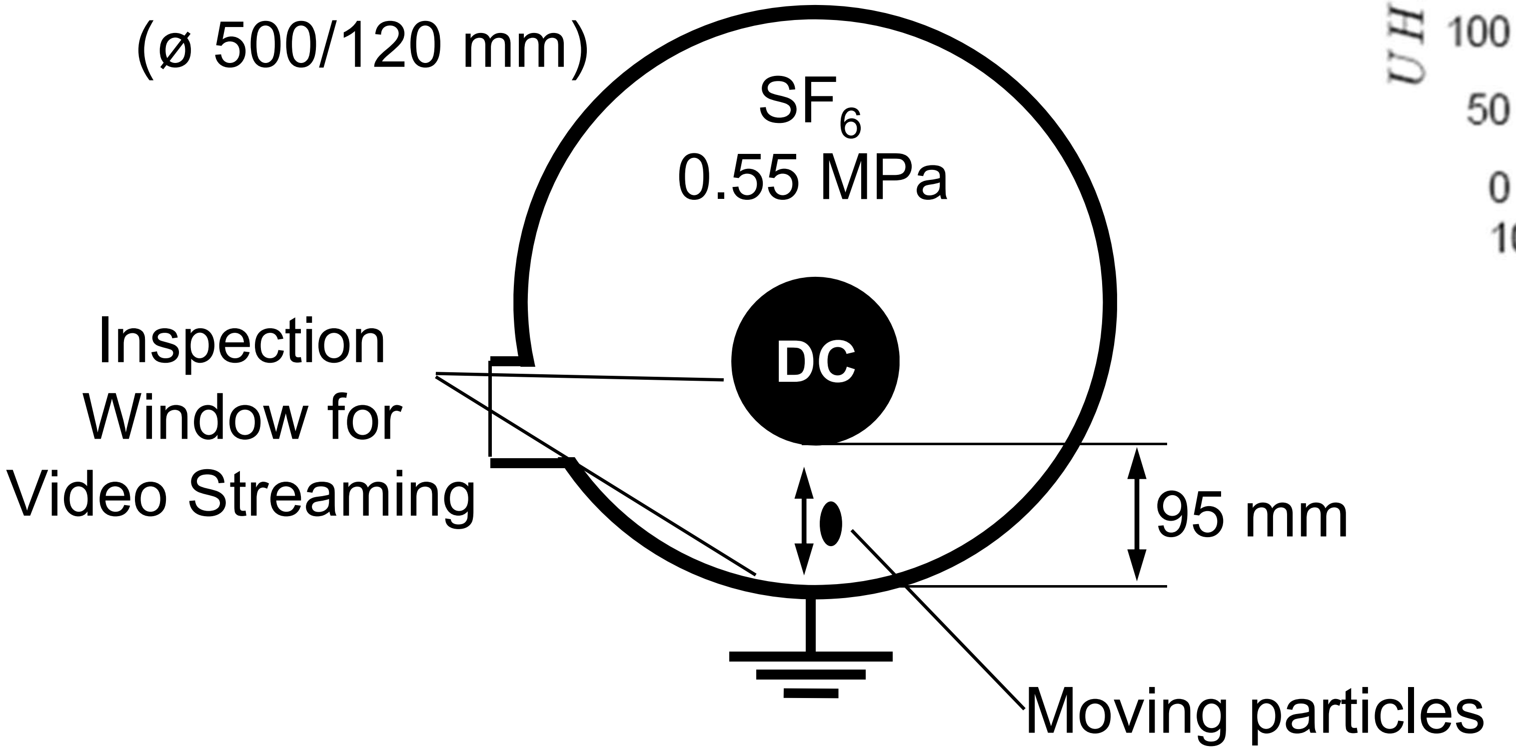
HVDC GIS: Moving particles



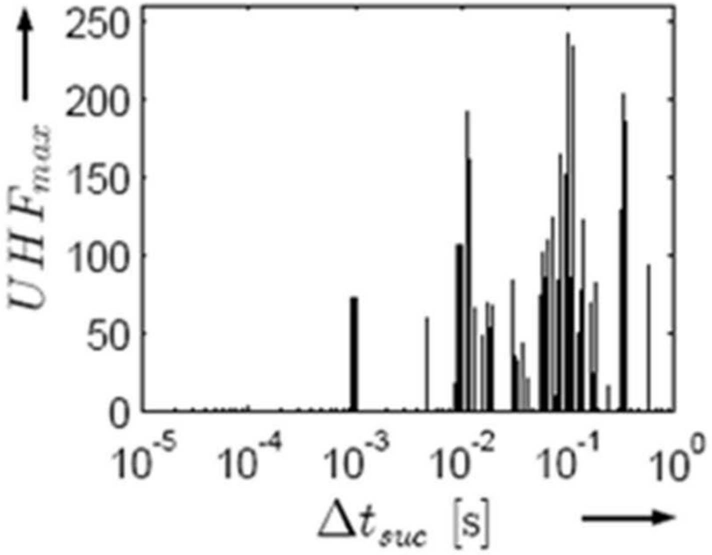


HVDC GIS: Moving particles

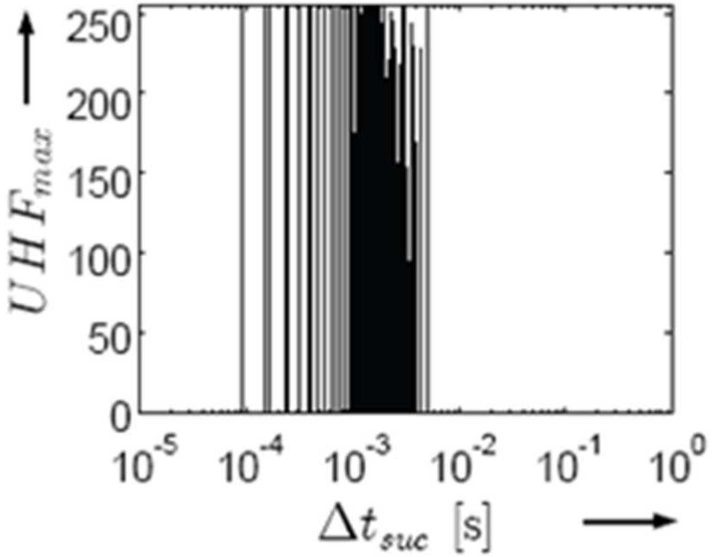
Standard GIS module
(ø 500/120 mm)



Moving particle



Particle at firefly

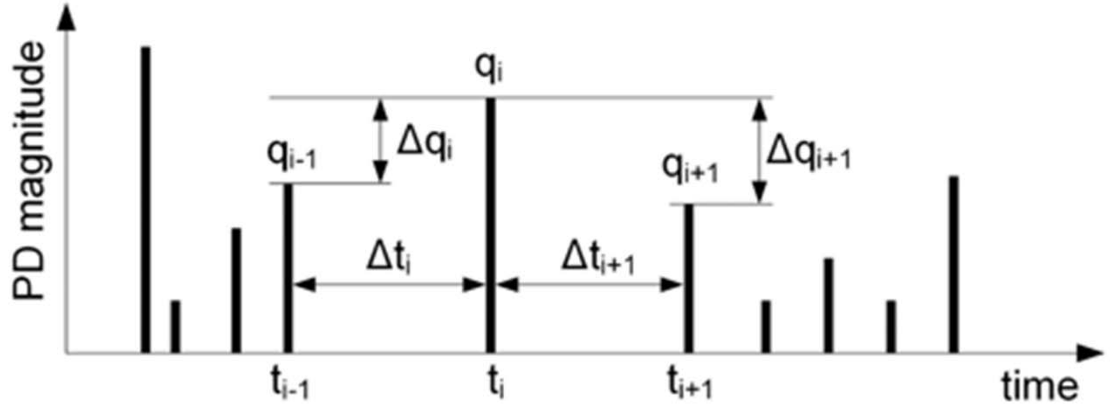


Defect	Δt_{min}	Δt_{max}	Δt_{avg}
Protrusion	5µs	10s	50ms
Floating electrode	1µs	5s	500ms
Moving particle	2µs	50ms	20ms
Particle in Firefly	200ns	100ms	150µs
Void	1µs	10min	5s
Particle on Insulation	1µs	10min	10ms

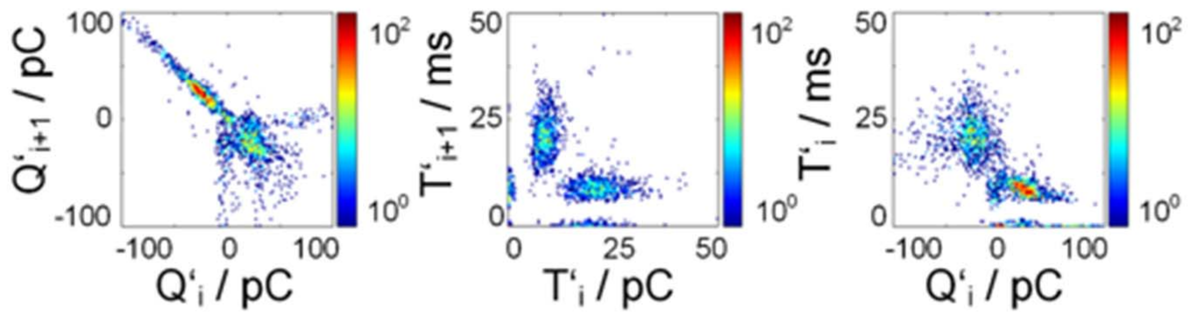
Partial Discharge Pattern at DC Voltage

- Fundamental quantities of a partial discharge pulse at DC voltage
  - PD magnitude q_i
  - Occurrence time t_i
  - Voltage level v_i

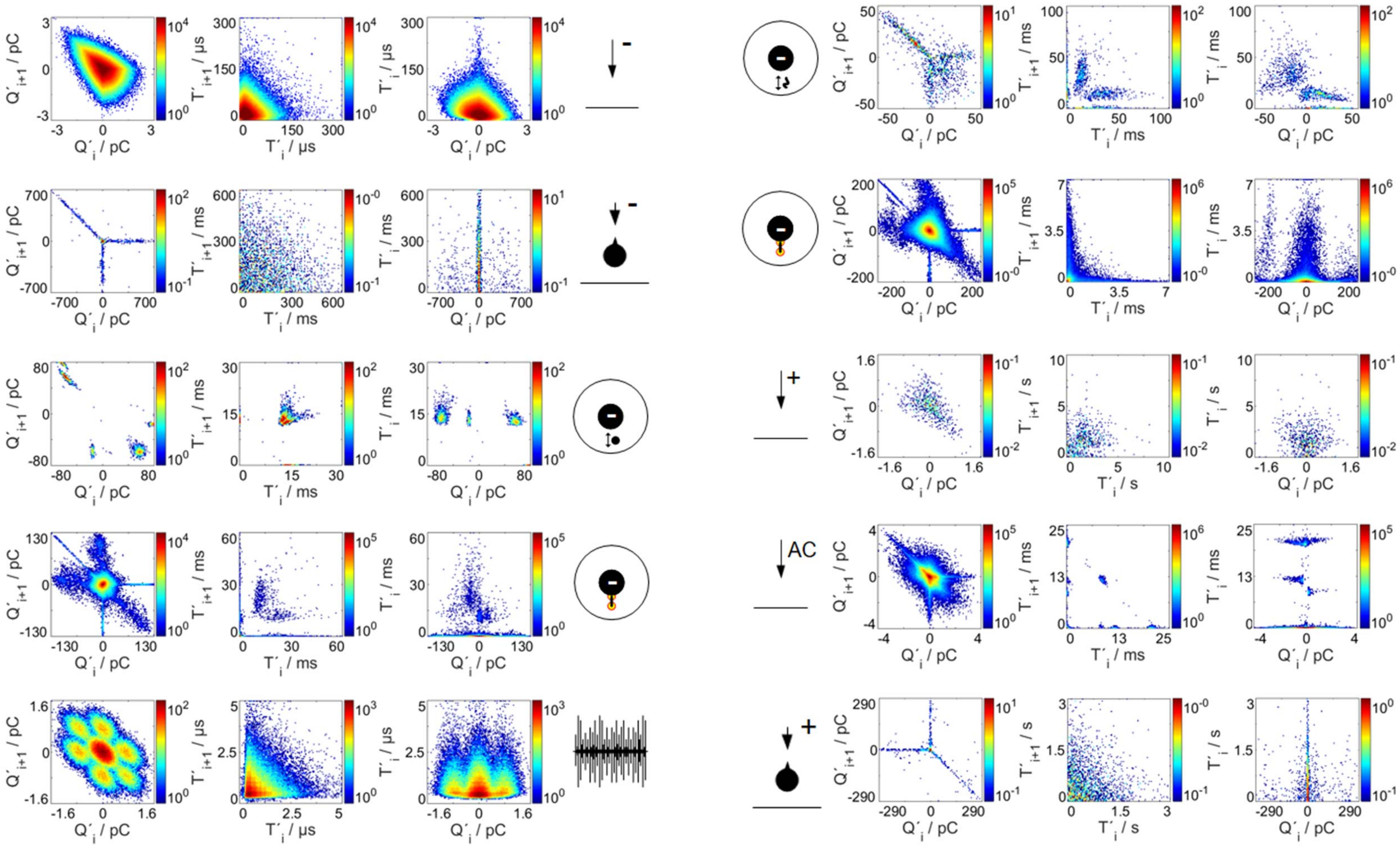
  } Pulse sequence



- Interpretation of the pulse sequence using the NoDi* pattern
  - Differential values of q_i and t_i
  - $\Delta q_i = q_i - q_{i-1}$
  - $\Delta t_i = t_i - t_{i-1}$
  - Identification of PD defects is possible by a human expert



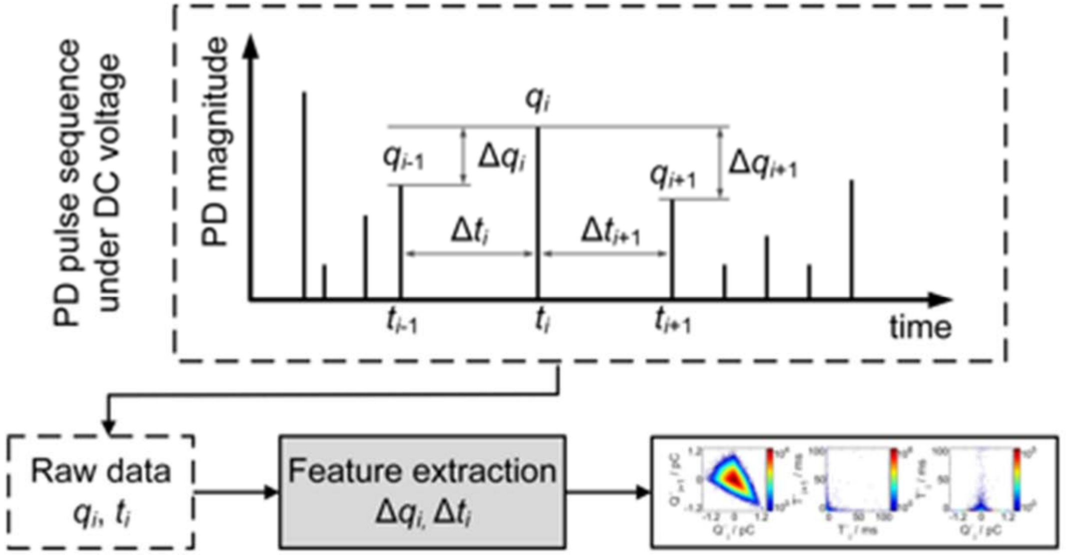
NoDi* Pattern



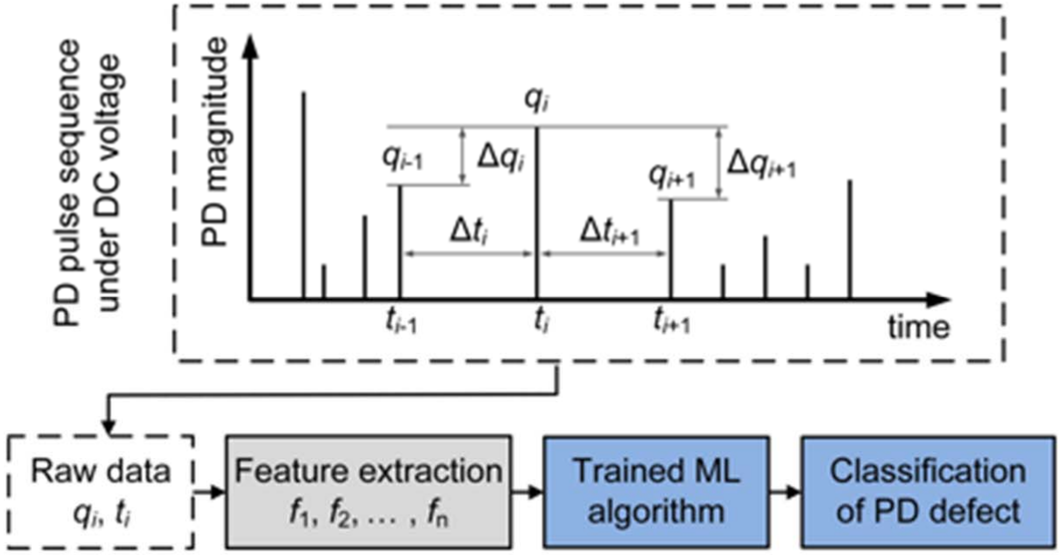
Pirker, PhD Thesis, 2020

PD Classification under DC Voltage by Pulse Sequence Analysis

- PD classification with NoDi* pattern
  - Fundamental quantities q_i and t_i
  - Investigation of Δq and Δt
    - $\Delta q_i = q_i - q_{i-1}$
    - $\Delta t_i = t_i - t_{i-1}$
  - Human expert



- PD classification with machine learning
  - Fundamental quantities q_i and t_i
  - Investigation of characteristic parameters
    - Features → feature extraction
    - Significant and sufficient
  - Automatic classification algorithms



Features and Feature Extraction

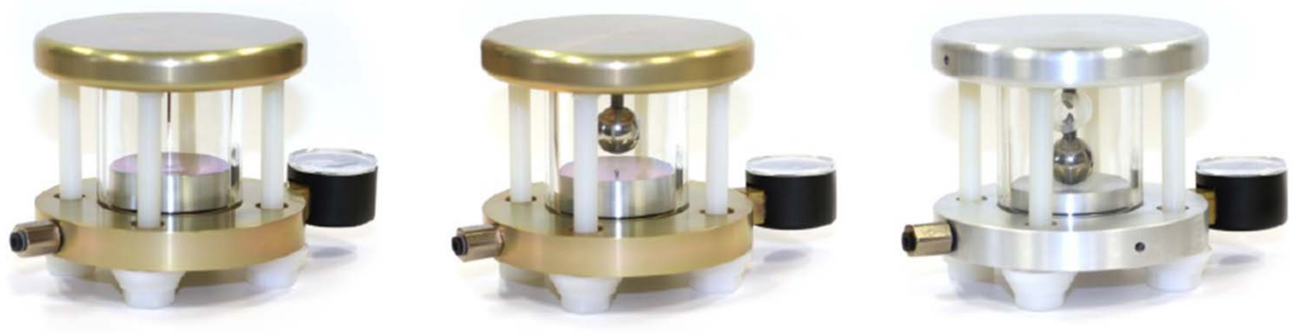
- Fundamental quantities
  - PD magnitude q and occurrence time t
  - Derived parameters: Δq, Δt, $\Delta q/\Delta t$
- Correlation coefficient
  - $r = \frac{\sum_{i=0}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=0}^{n}(x_i - \bar{x})^2 (y_i - \bar{y})^2}}$
- Weibull parameters
  - $F(x) = 1 - e^{-(x/\alpha)^{\beta}}$
- Pulses per second
  - $PPS = N / \Delta t$
- Frequency parameters

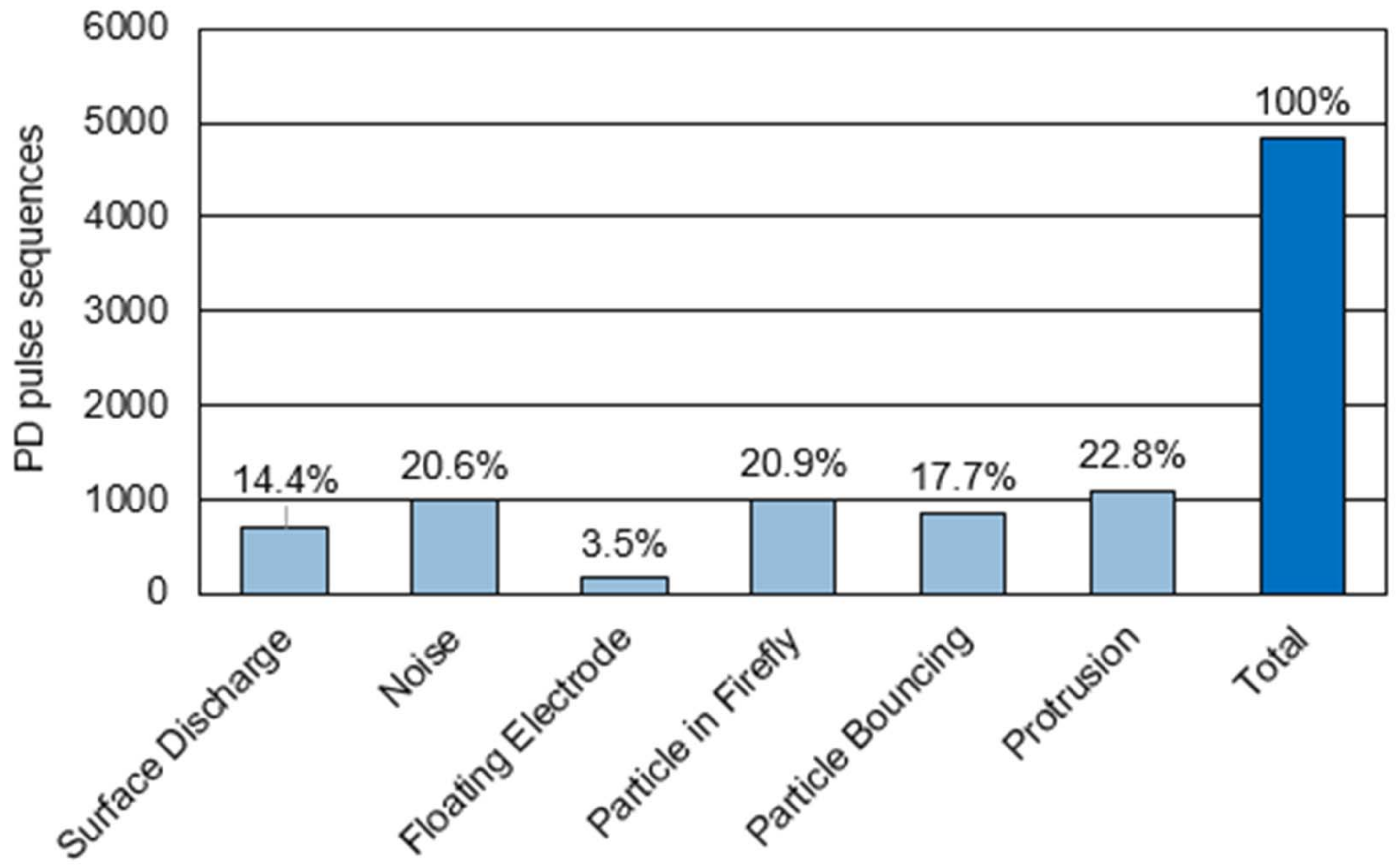
- Statistical parameters
  - Minimum: $x_{\min} = \min(\boldsymbol{x})$
  - Maximum: $x_{\max} = \max(\boldsymbol{x})$
  - Mean: $\bar{x} = \frac{1}{N}\sum_{n=0}^{N-1} x_n$
  - Sample variance: $s^2 = \frac{1}{N-1}\sum_{n=0}^{N-1}(x_n - \bar{x})^2$
  - Sample skewness: $g_1 = \frac{1}{N}\sum_{n=0}^{N-1}\left(\frac{x_n - \bar{x}}{s}\right)^3$
  - Sample kurtosis: $g_2 = \frac{1}{N}\sum_{n=0}^{N-1}\left(\frac{x_n - \bar{x}}{s}\right)^4$
  - Coefficient of variation: $CV(\boldsymbol{x}) = \frac{\sqrt{s^2}}{\bar{x}}$

35 features used for classification

Database for HVDC GIS/GIL

- Different measurement setups
  - Test cells
  - 420 kV GIS busbar
- Typical partial discharge defects
  - Busbar corona
  - Chamber corona
  - Floating electrode
  - Moving particles
  - Surface discharge
- Typical Noise
- Variation of gas pressure
  - 0.05 – 0.5 MPa SF_6
- 5.000 pulse sequences





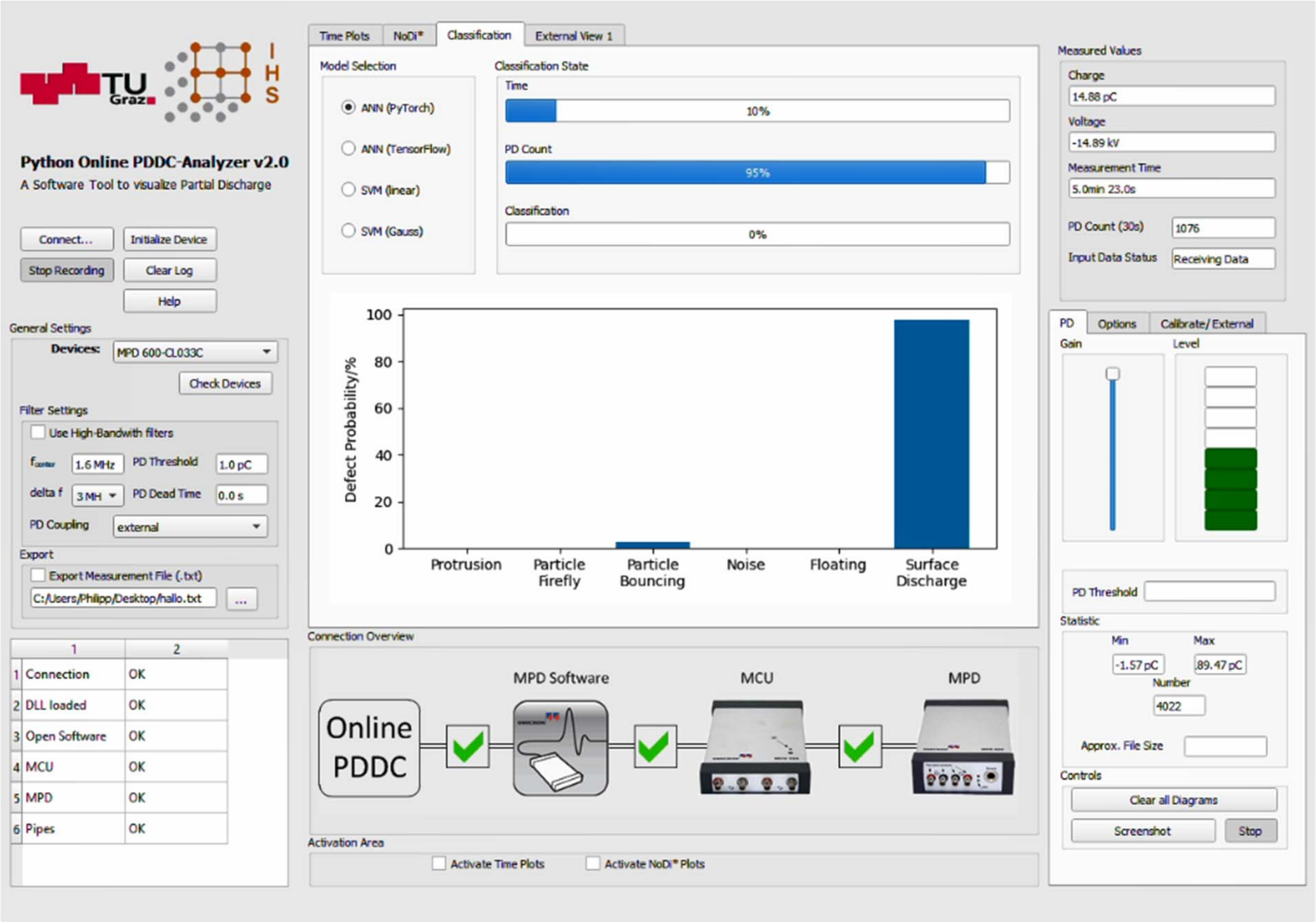
Classification

- Four different classification algorithms
  - Linear SVM (scikit-learn)
  - RBF kernel SVM (scikit-learn)
  - ANN (PyTorch)
  - ANN (Tensorflow)

Machine learning algorithm	Classification accuracies	
	Validation	Testing
Linear SVM (scikit-learn)	97.3 %	98.1 %
RBF kernel SVM (scikit-learn)	96.9 %	97.3 %
ANN (PyTorch)	98.0 %	97.8 %
ANN (Tensorflow)	97.2 %	97.3 %

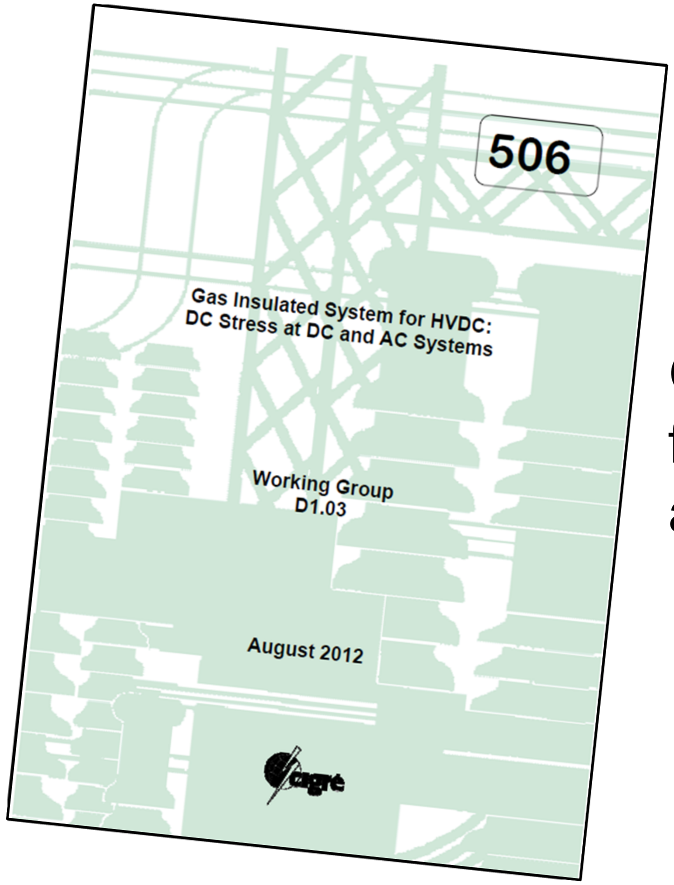
We started in 2016 with WEKA

Classification by Online PDDC-Analyzer

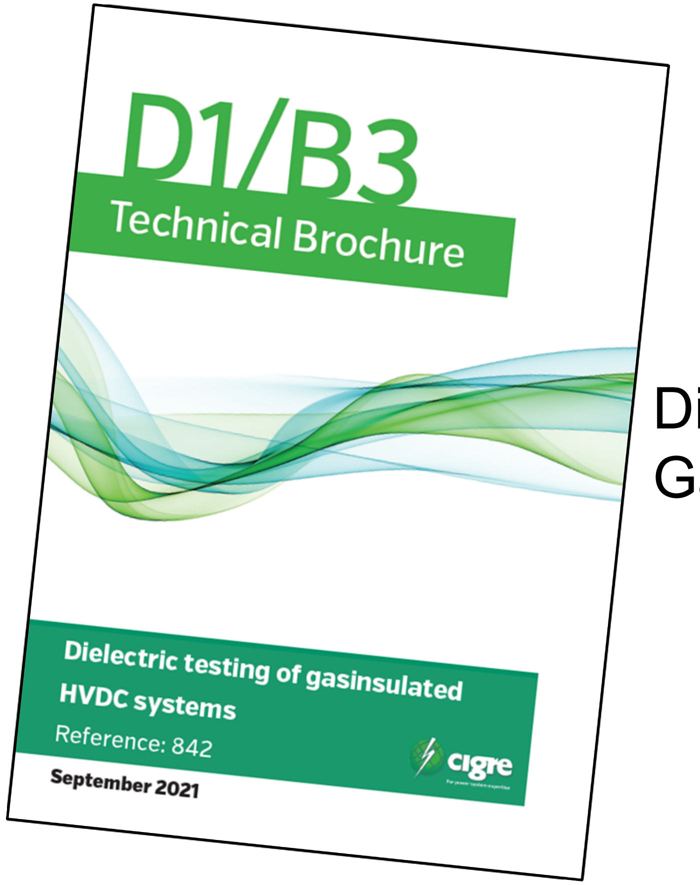


Schober, 2022

CIGRE Technical Brochures



Gas Insulated System for HVDC: DC Stress at DC and AC Systems

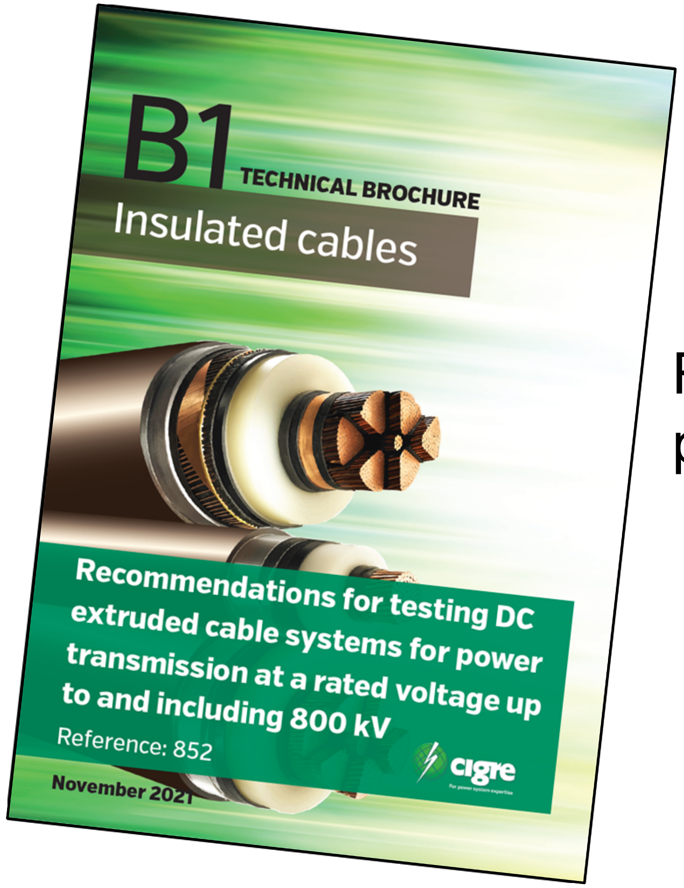


Dielectric testing of Gasinsulated HVDC systems

CIGRE TB 506, 2012
Chapter 8: Partial Discharges in HVDC applications
Summary of 22 references: years 1960 - 2002

CIGRE TB 842, 2021
Chapter 5: Typical defects and their PD characteristic
Appendix B: Pulse Sequence Analysis (PSA)
Summary of TB 506 + 21 references up to 2020

CIGRE Technical Brochures



Recommendations for testing DC extruded cable systems for power transmission at a rated voltage up to and including 800 kV

CIGRE TB 852, 2021
PD measurement under DC voltage: not mentioned

IEC 60270, Edition 4, CDV (2023)

No changes compared to Edition 3 from 2015

11 Partial discharge measurements during tests with direct voltage

11.1 General

Test objects with solid or liquid impregnated insulation show very different partial discharge characteristics when tested with direct voltage compared with those with alternating voltage. The differences may be minor in objects with gaseous insulation.

Some of these differences are summarized as follows:

– the discharge pulse repetition rate may be very low for direct voltage applied to solid insulation, because the time interval between discharges at each discharge site is determined by the relaxation time constants of the insulation;

– numerous discharges may occur when the applied voltage is changed. In particular, polarity reversal during test can cause numerous discharges at low voltage, but subsequently the pulse repetition rate will decrease to the steady-state condition;

– in liquid insulation, motion of the liquid tends to reduce the relaxation time constants so that discharges are more frequent;

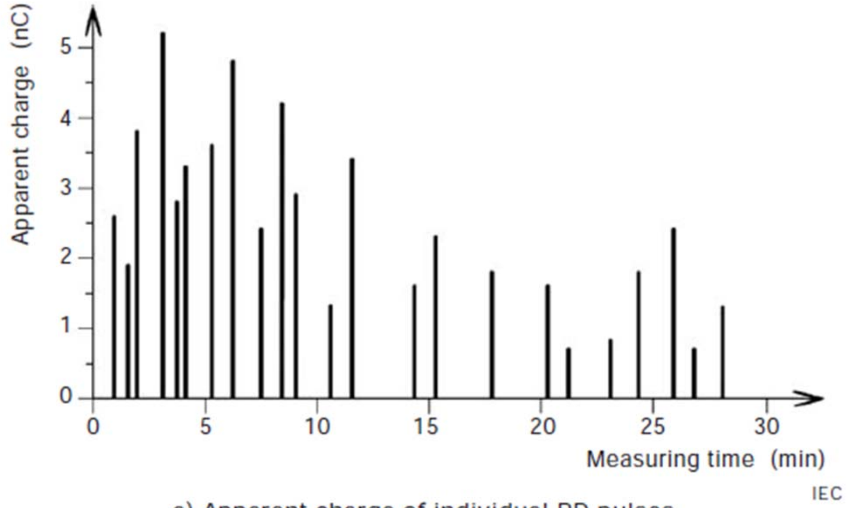
– the PD characteristics of test objects may be affected by ripple on the test voltage.

NOTE 1 With direct voltage, the effect of voltage changes on PD can be pronounced because the initial field stress distribution is primarily determined by volume or surface resistivities, as it would be under conditions of constant, steady-state DC voltage (or under conditions of constant AC voltage).

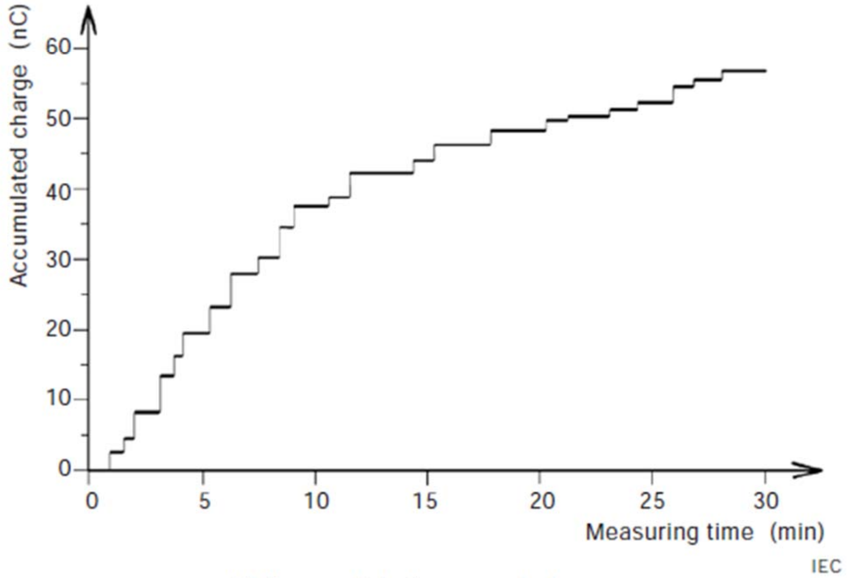
NOTE 2 Specific PD magnitudes, pulse count limits and the duration of voltage application should be determined by the relevant equipment committee(s).

IEC 60270, Edition 4, CDV (2023), Annex H

No changes compared to Edition 3 from 2015

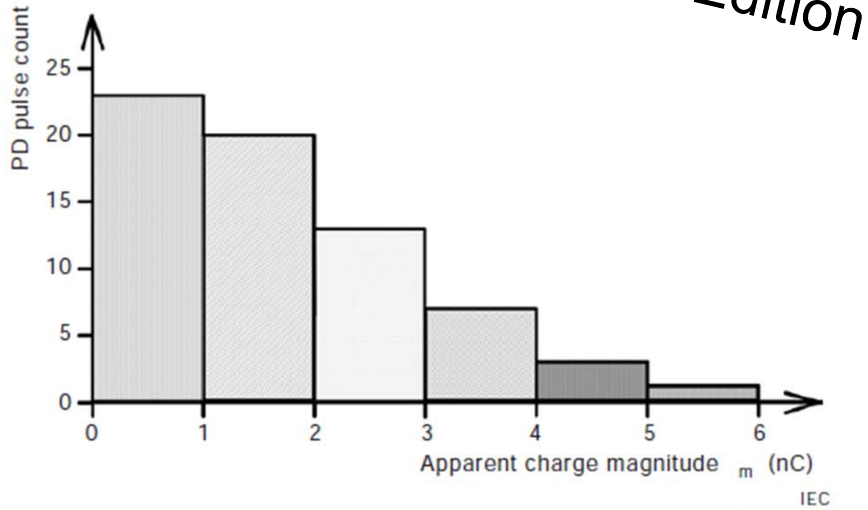


a) Apparent charge of individual PD pulses

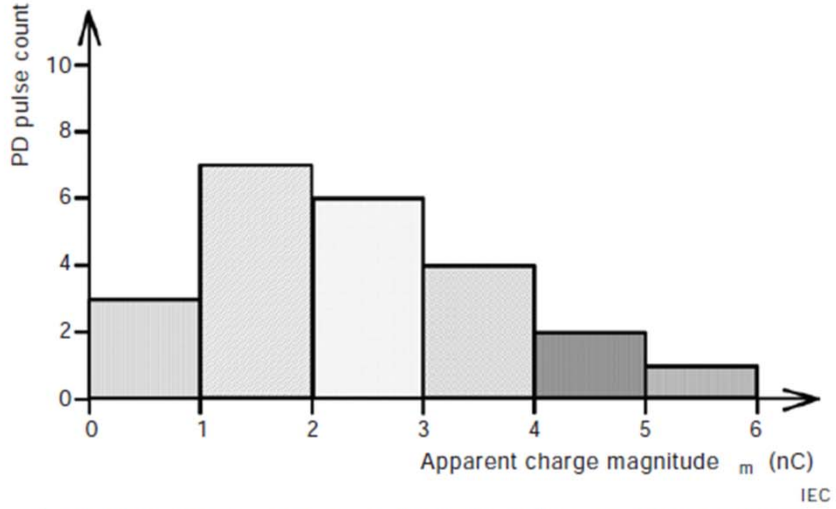


b) Accumulated apparent charge

Figure H.1 – Display modes of apparent pulses against measuring time



a) PD pulse count ***m*** exceeding the following limits for the apparent charge magnitude q_m: 0 nC, 1 nC, 2 nC, 3 nC, 4 nC, 5 nC.



b) PD pulse count ***m*** occurring within the following apparent charge intervals q_{mi}:(0-1) nC, (1-2) nC, (2-3) nC, (3-4) nC, (4-5) nC

Figure H.2 – Histograms of PD pulse count ***m*** against apparent charge intervals

IEC TS 62271-318, Edition 1, CD (2022)

IEC

17C/886/CD

COMMITTEE DRAFT (CD)

PROJECT NUMBER: IEC TS 62271-318 ED1	
DATE OF CIRCULATION: 2022-11-25	CLOSING DATE FOR COMMENTS: 2023-02-17
SUPERSEDES DOCUMENTS: 17C/735/NP, 17C/747A/RVN	

IEC SC 17C : ASSEMBLIES

SECRETARIAT: Germany	SECRETARY: Mr Mark Kuschel

OF INTEREST TO THE FOLLOWING COMMITTEES: TC 8,TC 17,SC 17A,TC 99,TC 115

FUNCTIONS CONCERNED:
☐ EMC ☒ ENVIRONMENT ☒ QUALITY ASSURANCE ☒ SAFETY

This document is still under study and subject to change. It should not be used for reference purposes.

Recipients of this document are invited to submit, with their comments, notification of any relevant patent rights of which they are aware and to provide supporting documentation.

TITLE:
High-voltage switchgear and control gear- Part 318- DC gas-insulated switchgear assemblies

High-voltage switchgear and control gear –
Part 318 – DC gas-insulated switchgear assemblies

Technical content for dielectric tests is mainly taken from CIGRE TB 842

PD measurement under DC voltage at type test and routine test (mentioned as alternative, acceptance criteria: 5 pC) and after installation (recommendation, acceptance criteria: 10 pC), Reference is given to IEC 60270 and CIGRE TB 654 (UHF), PSA is mentioned

Conclusion

- Measurement of PD pulse sequence under DC voltage
  - Magnitude, time of occurence, voltage
  - Noise suppression
- DC PD pattern for typical defects, e.g. NoDi* pattern
- Identification of PD defects
  - Pulse Sequence Analysis
    - DC PD pattern
    - Machine learning tools
- Experience and knowledge rules
- Test procedures and acceptance criteria
- Standards for PD measurement under DC voltage
- Standards for reliable DC equipment, e.g. HVDC GIS

Race to Net Zero Emissions
…be a part of it!