Aalto-yliopisto
Sähkötekniikan
korkeakoulu

High Voltage Engineering

Lecture 10: Condition Monitoring of Power Cable

Mahdi Pourakbari Kasmaei, 2020

ON-SITE DC MEASUREMENTS

Measurements – quick and simple, several kV voltage, does not require expensive equipment

Insulation Resistance

- Detects moisture and serious insulation degradation
- Cannot detect partial discharge
- Measured resistivity after a specific time duration (i.e. 60 s)

Polarization Index (PI)

- Ratio between measured insulation resistance at 10 min and 1 min after applying voltage

Diagnostics – rotating machines, transformers, cables

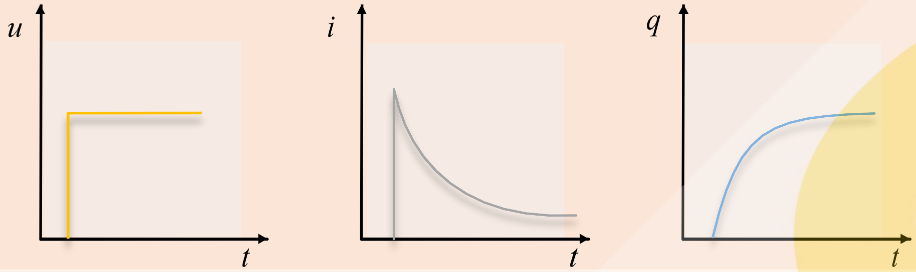
✓ Oil-paper diagnostics

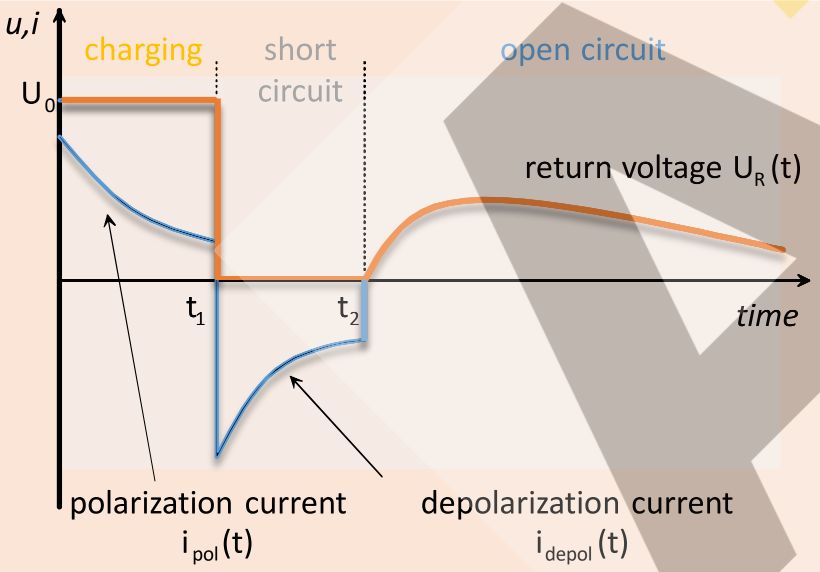
✓ XLPE diagnostics

✗ XLPE testing (high voltage)

Megger S1-5010

ON-SITE DC MEASUREMENTS





Dielectric Response (DR) in time domain

- DC-voltage is applied and polarization begins (**polarization current**)

  [when the test voltage is disconnected, the inserted charges begin to discharge (self-discharge) and voltage decreases]

- Insulator is short-circuited and polarization begins to dissipate (**inverse polarization current** = relaxation)

- When the short-circuit is removed, depending on the residual charge the insulator returns to a certain state of polarization and voltage (**return voltage**).

The magnitude of the occurrences depends on the relative duration of each phase.

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ON-SITE DC MEASUREMENTS

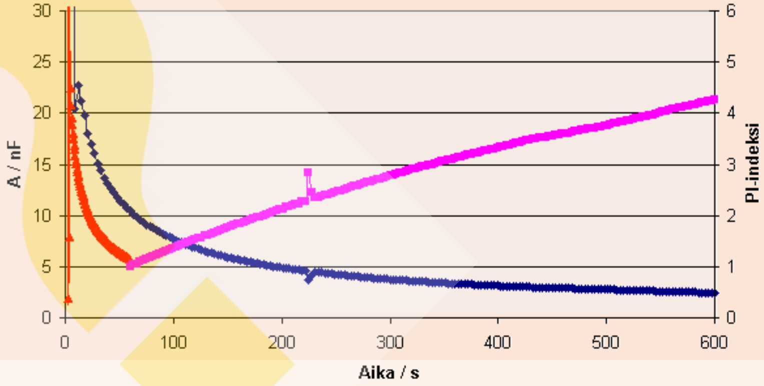
Condition diagnostics is based on polarization phenomenon variations and nonlinearity.

- Results give insight into **overall insulation state:** presence of moisture and water trees but location of problem not attainable

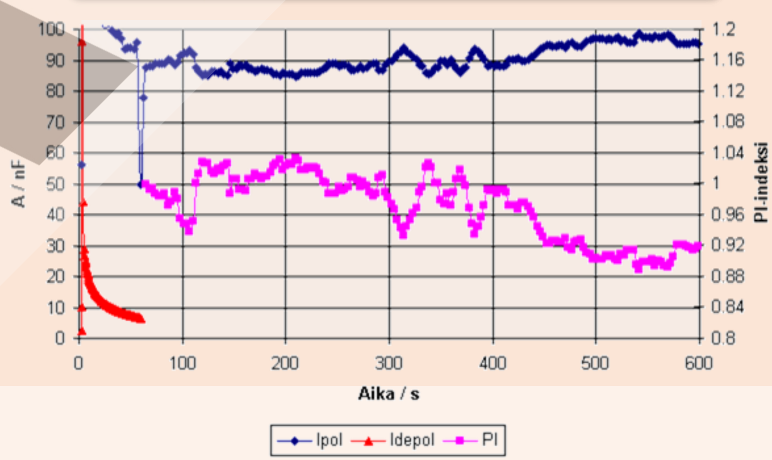
Return (Recovery) Voltage:

- Non-linearity of peak value as a function of charging voltage depicts changes in the insulator
- Highly dependant on duration of charging and short circuit phase
  - charging duration: **which polarization mechanisms have enough time to activate**
  - short circuit duration needs to be significantly shorter than charging phase
    - if all polarization mechanisms have time to relax, return voltage is zero and no information is attained

good cable



bad cable



ON-SITE VLF MEASUREMENTS

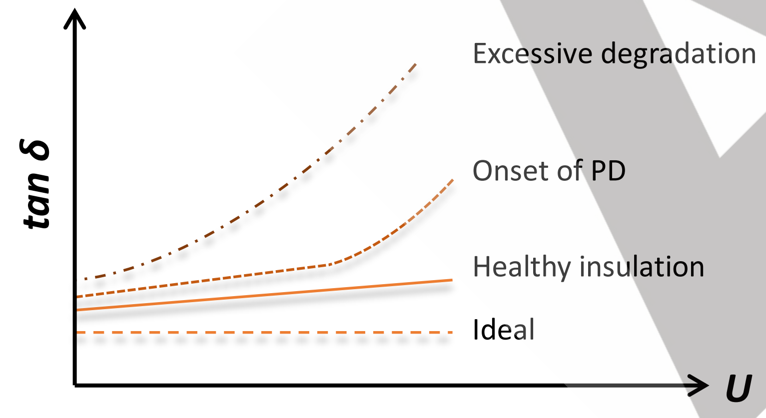
Very Low Frequency (VLF)

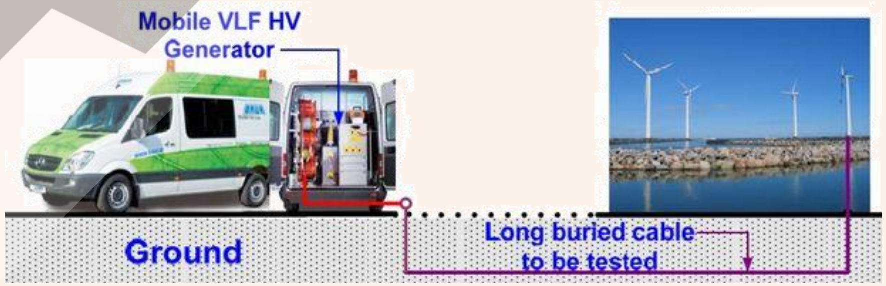
Combined **PD** and **dissipation factor** (tan δ) measurements as a function of voltage

- Current in a capacitor is proportional to frequency and magnitude of applied voltage

$$I = 2\pi f C U$$

- Low frequency (0.1 or 0.01 Hz) reduces current requirements for test objects with high capacitance (e.g. long cables)



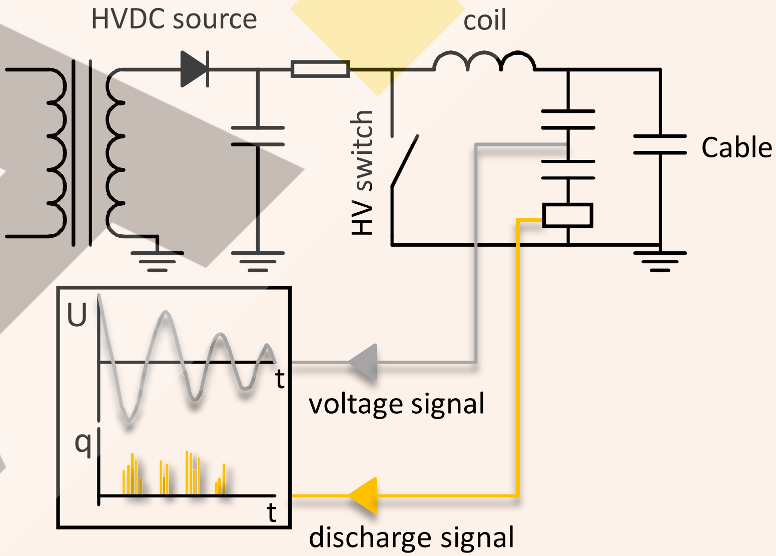


ON-SITE DAC MEASUREMENTS

Damped AC (DAC) – damped oscillating pulse

- Test object (e.g. cable) is charged using DC for a few seconds
- A choke (inductor) is connected in parallel to the test object
- Circuit **oscillates** based on the coil's inductance and the capacitance of the test object (typically 100 – 200 Hz)
- Oscillation slowly **attenuate**

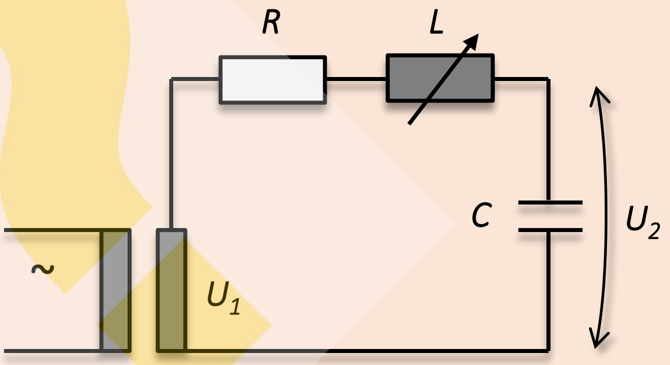
OWTS, 36 kV



ON-SITE AC MEASUREMENTS

Series resonance – voltage multiplication over test object under resonant conditions

Transformer secondary winding connected across HV reactor **inductance L** and **capacitive load C**. **Resistance R** is the total series resistance of the circuit

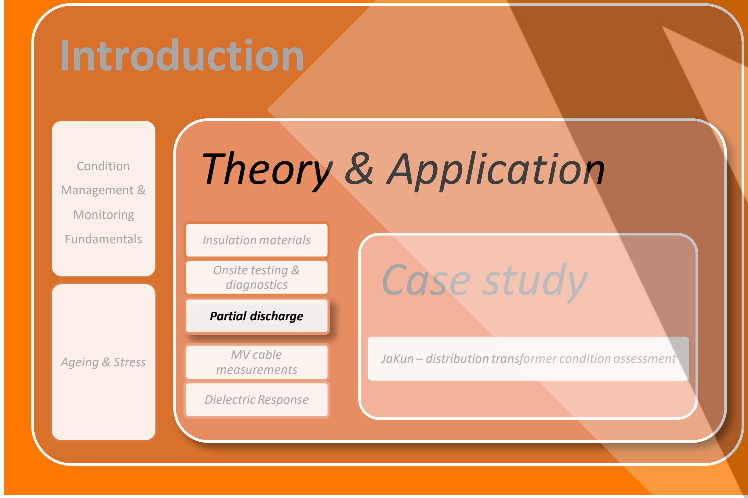


Resonance:

- ⇨ **Inductance** of reactor L is varied ($X_L = -X_C$)
- ⇨ On-site testing may have fixed L (compact and lighter)
  - – Resonance frequency depends on test object capacitance
  - – **Frequency** must be adjustable $f = 1 / 2\pi \sqrt{(LC)}$

Typically used for ***cable and capacitor*** *testing*

Partial Discharge



Introduction

Condition Management & Monitoring Fundamentals

Ageing & Stress

Theory & Application

Insulation materials

Onsite testing & diagnostics

Partial discharge

MV cable measurements

Dielectric Response

Case study

JaKun – distribution transformer condition assessment

Types of PD

Onset of PD

Measurement Methods

Identification of PD

Example results

PARTIAL DISCHARGE (PD)

Locally occurring small electric discharge inside or on the surface of an insulator which does **not** bridge the electrodes

Partial discharge does not cause immediate failure of equipment as a consequence of the insulator's deterioration

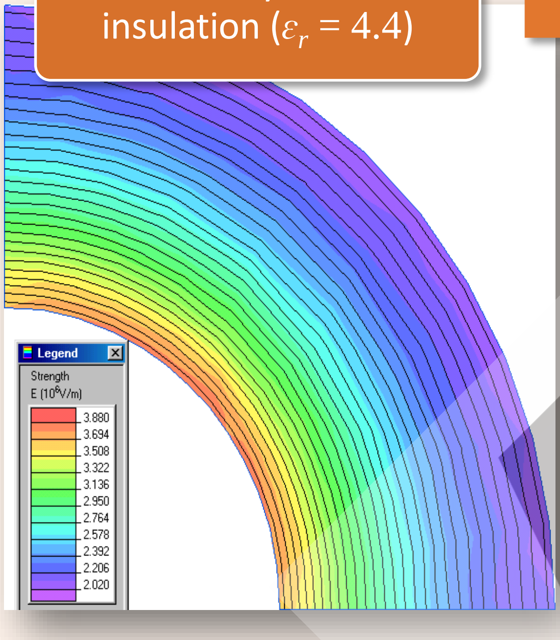
Long-term partial discharge can have serious effects on the insulator performance

Complete dissolution of insulating properties can take up to **several years**

*Occurs with **AC**, **DC**, and **impulse voltage** in gas, liquid and solid insulation and interfaces*

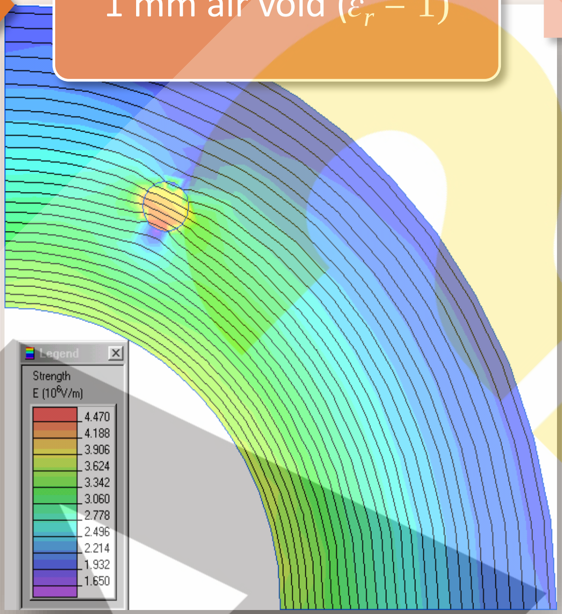
ONSET OF PARTIAL DISCHARGE

6 mm healthy XLPE cable insulation ($\varepsilon_r = 4.4$)



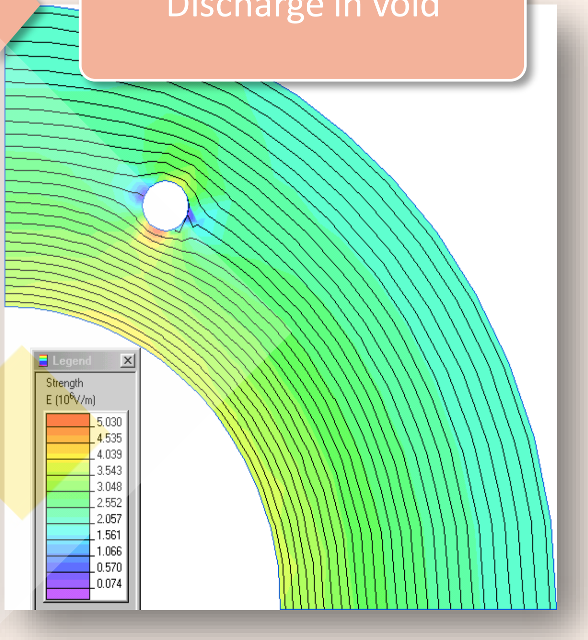
- Conductor surface 16.4 kV
- Outer surface 0V
- Uniform potential distribution
- Highest electric field along conductor surface
- XLPE can withstand ~ 60 kV/mm

1 mm air void ($\varepsilon_r = 1$)



- Highest electric field inside void
- Electric field strength exceeds the dielectric strength of air (3 kV/mm)
- Rapid ionization begins
- Free charge carriers are created

Discharge in void



- A discharge channel is formed and the void becomes conductive
- Charges propagate and the electric field inside void collapses (voltage collapse)
- A local space charge is formed
- Ionization ceases (no electric field inside void, no potential difference) and discharge is extinguished

ONSET OF PARTIAL DISCHARGE

Generation of a new discharge

- **Constant DC-voltage stress:**

  Space charge caused by the previous discharge dissipate gradually under constant DC stress and eventually an electric field within the void is reinstated.

  - Free charges diffuse and recombine

  - Slow process
  - Small repetition frequency

- **Increasing voltage stress:**

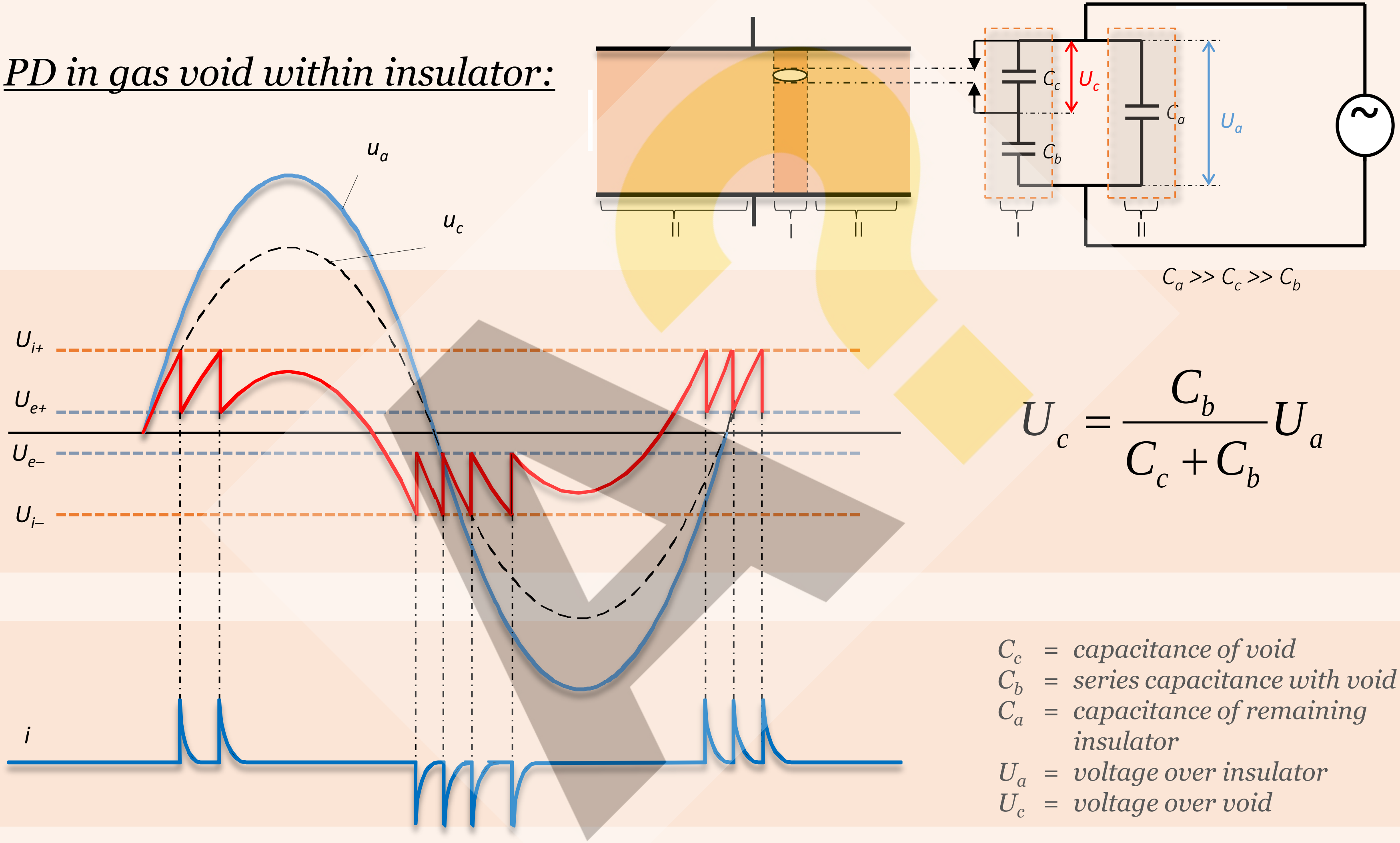
  AC and transient voltages

  - Increase compensates space charge
  - Electric field inside void increases
  - Critical level is achieved
  - Onset of new discharge

  - Polarity change also compensates space charge

ONSET OF PARTIAL DISCHARGE

PD in gas void within insulator:



$$U_c = \frac{C_b}{C_c + C_b} U_a$$

C_c = *capacitance of void*
C_b = *series capacitance with void*
C_a = *capacitance of remaining insulator*
U_a = *voltage over insulator*
U_c = *voltage over void*

ONSET OF PARTIAL DISCHARGE

Inception (ignition) voltage U_i

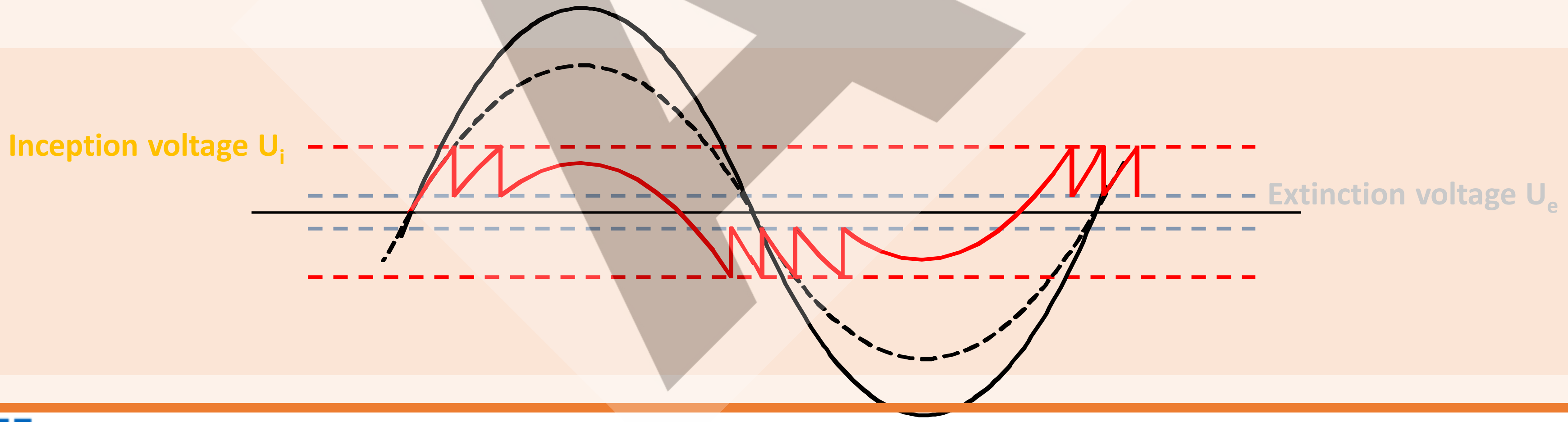
Voltage level at which repetitive discharge of similar amplitude is observed when the test voltage is increased from a level where no discharge is present.

- Situations where discharges ignite below the normal operation voltage are dangerous. In these cases, discharges are continuously stressing the insulation

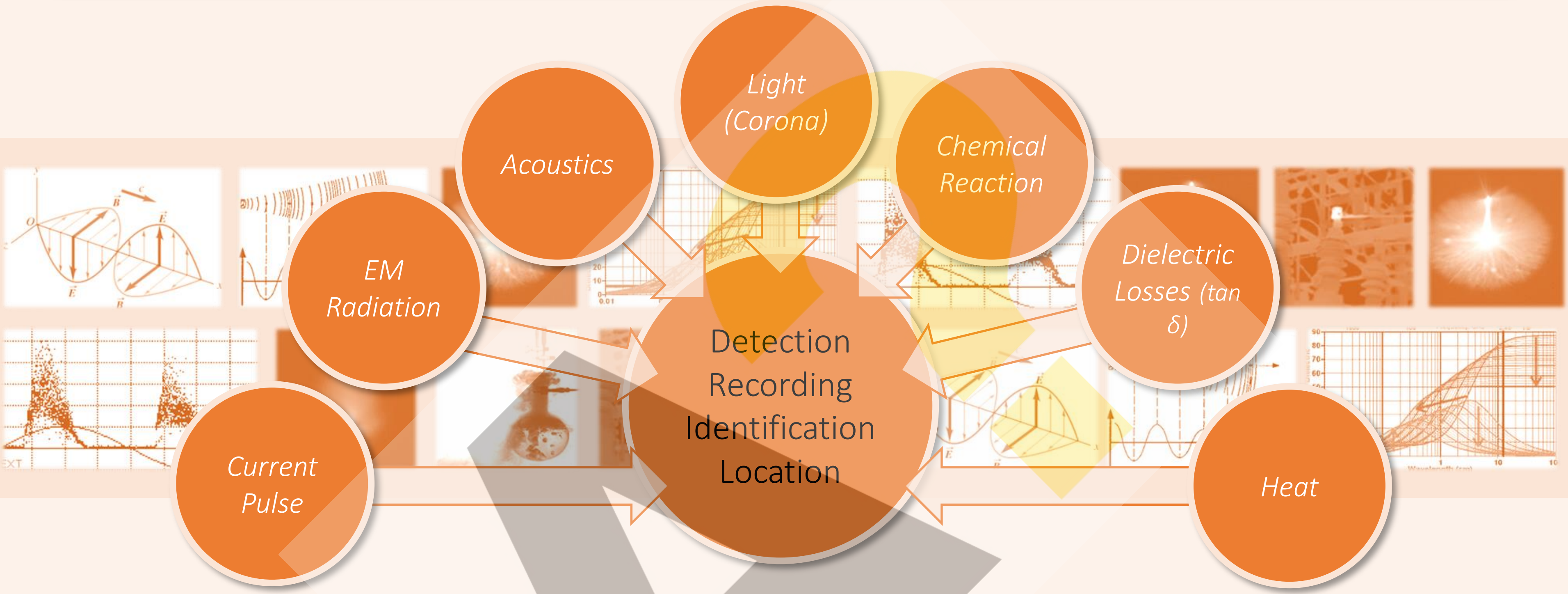
Extinction voltage U_e

Voltage level at which repetitive discharges depreciate below a certain value when the test voltage is decreased from a level where discharge is present.

- For good insulators, discharges should extinguish at a value greater than the normal operation voltage. If this is not the case, discharges are continuously stressing the insulation



MEASURING PARTIAL DISCHARGE



Light (Corona)

Acoustics

Chemical Reaction

EM Radiation

Dielectric Losses (tan δ)

Current Pulse

Heat

Detection
Recording
Identification
Location

Commissioning and quality related testing

- Insulation fulfills standards so that PD does not exceed allowed levels
- Equipment operation is maintained during service

Condition monitoring and insulation life expectancy assessment

- Acquired correlation between measured parameters and life expectancy

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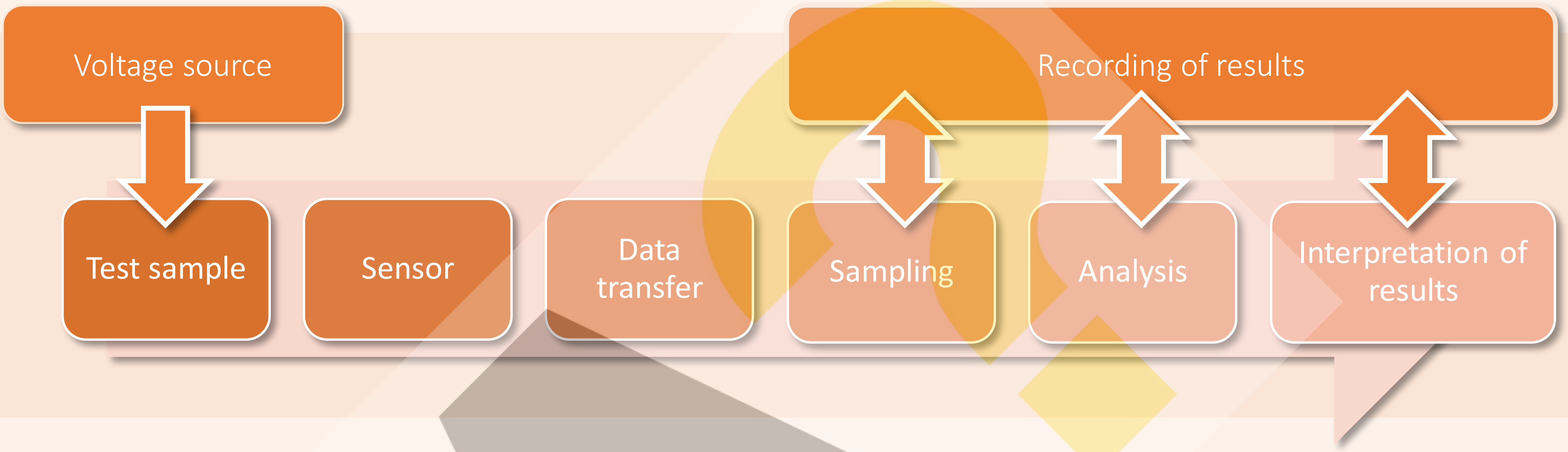
MEASURING PARTIAL DISCHARGE



Voltage source

Recording of results

Test sample

Sensor

Data transfer

Sampling

Analysis

Interpretation of results

Electrical methods

Acoustic methods

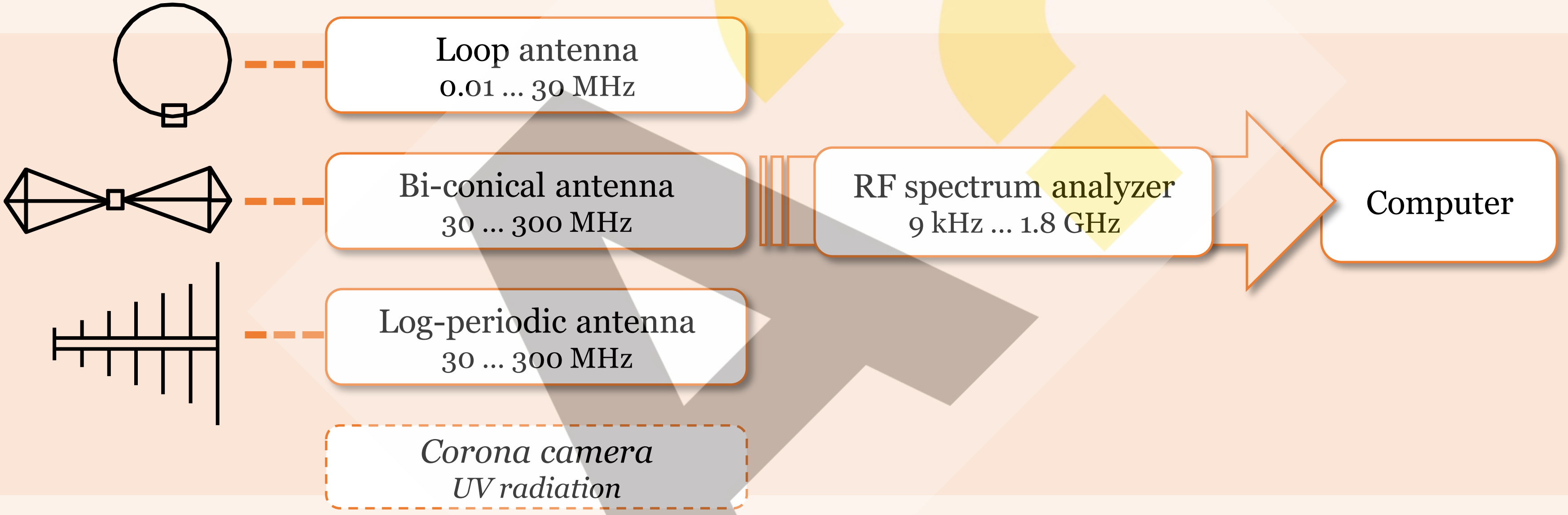
Electromagnetic methods

Chemical methods

ELECTROMAGNETIC RADIATION METHOD

EMR and RF techniques – measure waves emitted by PD

- Service interruptions and electrical contact are **not required**
  - specific frequency band to avoid interference with communication links (radio, TV, cellular)
  - hindered by onsite EMI (most suitable for OHL surveying)



Loop antenna
0.01 … 30 MHz

Bi-conical antenna
30 … 300 MHz

Log-periodic antenna
30 … 300 MHz

Corona camera
UV radiation

RF spectrum analyzer
9 kHz … 1.8 GHz

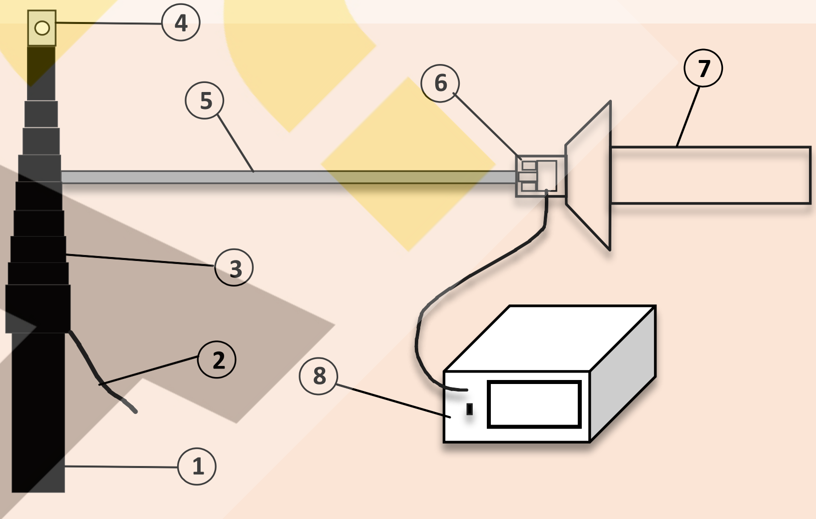
Computer

Detection, Identification, (Location) – onsite, online

ACOUSTIC METHOD

Piezoelectric acoustic sensor – measure sound emitted by discharge

- *Piezoelectricity* = electricity resulting from pressure
- GIS (5 – 100 kHz), transformers (100 – 400 kHz), bushings, cable joints and terminations
  - Also applicable to high interference industrial environments
  - Accuracy is in the order of centimeters (attenuation and reflections from multiple insulation layers can be a problem)



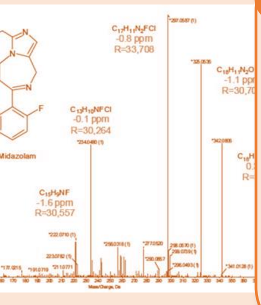
1 – 4.) cable, 5. Contact rod, 6. Piezoelectric sensor, 7. Handle, 8. Recording device

Detection, Identification, Location – onsite, online

CHEMICAL METHOD

Discharge produces **chemical reactions** that are characteristic of specific material and fault types

Gas analysis – *gas chromatography* or *mass spectrometry*



Transformer oil dissolved gas analysis (DGA)

Determine concentration ratios of various compounds – hydrogen H_2, methane CH_4, acetylene C_2H_2, ethylene C_2H_4, ethane C_2H_6

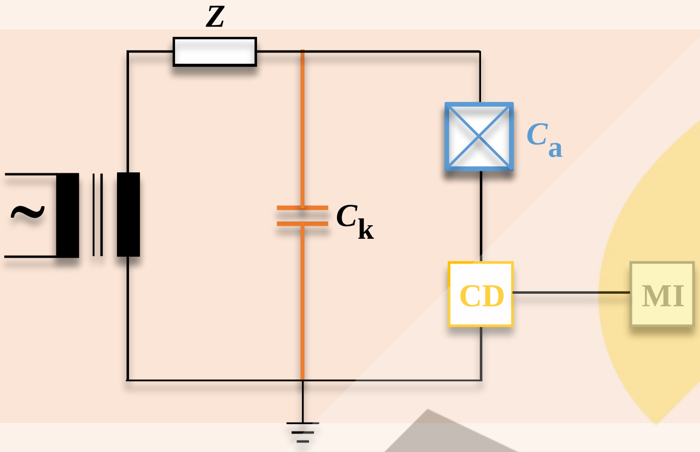
IEC recommended limits for PD (values vary for different equipment type):

Methane / hydrogen < 0.1
Acetylene / ethane < 0.2

GIS gas analysis

- Breakdown by-products of SF_6 (SOF_2, SO_2F_2, SO_2, SOF_4, SF_4, HF)
- Composition and volume depends on location and nature of fault

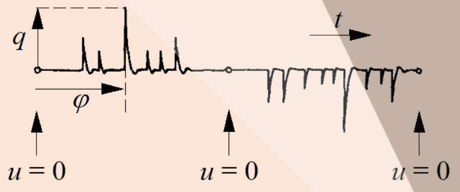
ELECTRICAL METHOD

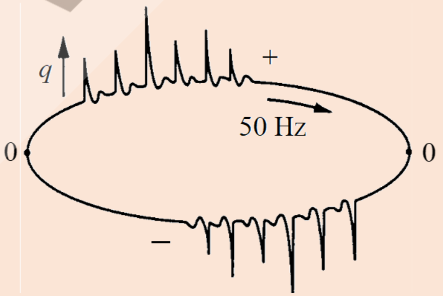


C_a	*test object*
Z	*filter circuit to remove disturbances*
C_k	*small impedance and PD free coupling (blocking) capacitor*
CD	*measurement probe converting current pulse into voltage pulse*
MI	*measurement instrument*

Detection, Measurement, Identification, Location

Measure current pulses which compensate the expelled energy from the insulator during discharge so that the energy balance is maintained



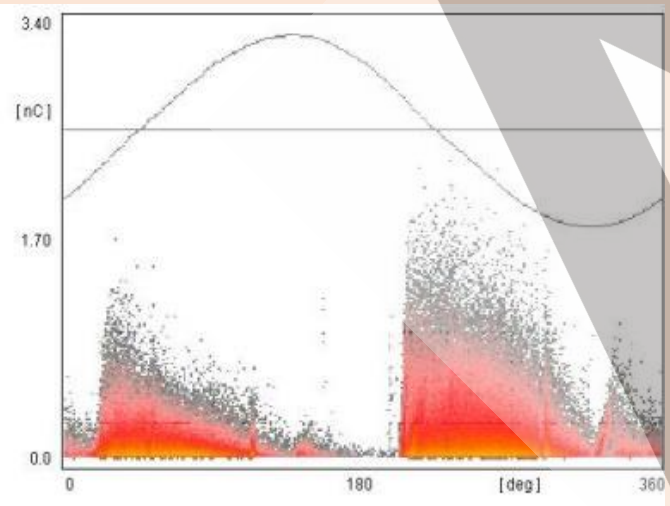


ELECTRICAL METHOD

Charge of partial discharge cannot be measured

change in charge at insulator connectors = *apparent charge of partial discharge*

Apparent charge q_o, when applied to the insulator, causes a measured (voltage) change equivalent to partial discharge in the insulator



⇨ can be measured outside of insulator

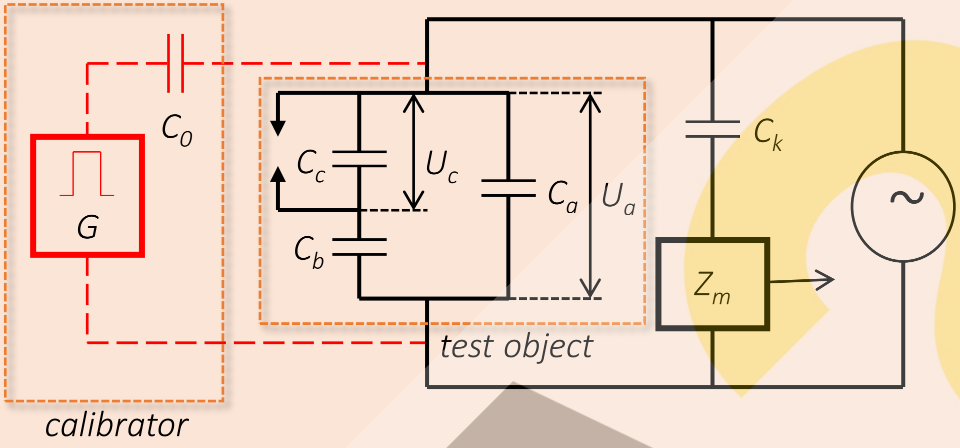
⇨ **proportional** to:

- discharge power and energy
- magnitude of **damage**

Note: apparent charge is **not** the same magnitude as the actual partial discharge.

- The observed apparent charge at the insulator terminals is much smaller than the displaced charges during discharge

ELECTRICAL METHOD



CALIBRATION

A known charge is inserted from a calibrator via a small capacitance C_o to the test object

- When the voltage changes by a value of U_o, the calibrator's charge changes by a value of $q_o = C_oU_o$

PD measurement must be re-calibrated for each test object and test connection

- Small changes in the test circuit changes the **scaling factor** (magnitude of PD seen by the measurement instrument)

$$\Delta u = \frac{q_0}{C_m + (C_s + C_h)\left(1 + \frac{C_m}{C_k}\right)}$$

C_s = test device capacitance (C_a, C_b, C_c)
C_m = measurement probe capacitance
C_k = coupling capacitor capacitance
C_h = stray capacitance of the circuit

- C_o may be external or integrated into the calibrator
- Calibrator range is selected according to the 50% and 200% threshold values defined in standards
  e.g. if acceptable level of PD is 100 pC, the range can be between 50 – 200 pC.

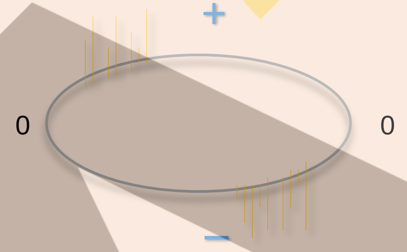
“TRADITIONAL” IDENTIFICATION

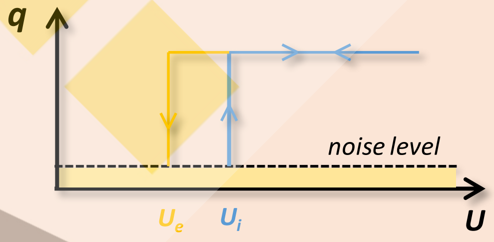
From the oscilloscope screen

Based on the position of observed discharge pulses with reference to the applied test voltage, inception voltage, and extinction voltage

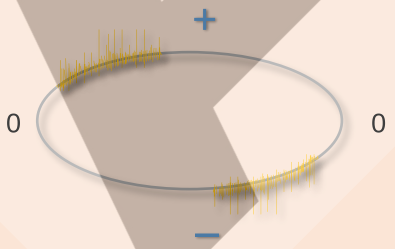
- Observed results are compared to model figures (requires proficiency and experience)

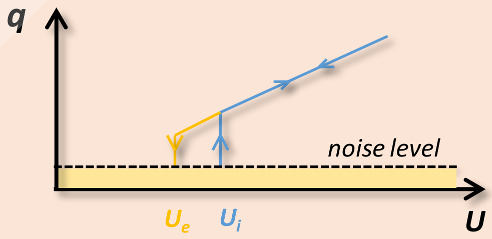
Void





Multiple voids





“TRADITIONAL” IDENTIFICATION

a) discharge in **insulation**: discharges are symmetrical

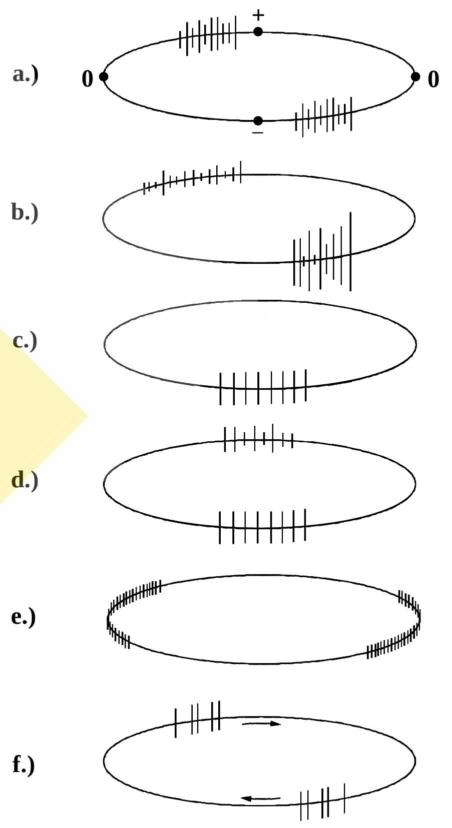
b) discharge on an **electrode**: discharges are not symmetrical

c) negative corona in **gas**: amplitude does not vary, on higher voltages on both polarities

d) corona in **oil**: like c, but non-stable discharges on positive polarity

e) **loose contact**: discharges at zero voltage, when the capacitive current is highest

f) **floating object**: position of the discharges is moving



IDENTIFICATION TECHNIQUES

TIME-DIVISION IDENTIFICATION

Examine **individual** discharge pulse waveforms and approximate physical phenomena occurring in discharge area (type of discharge)

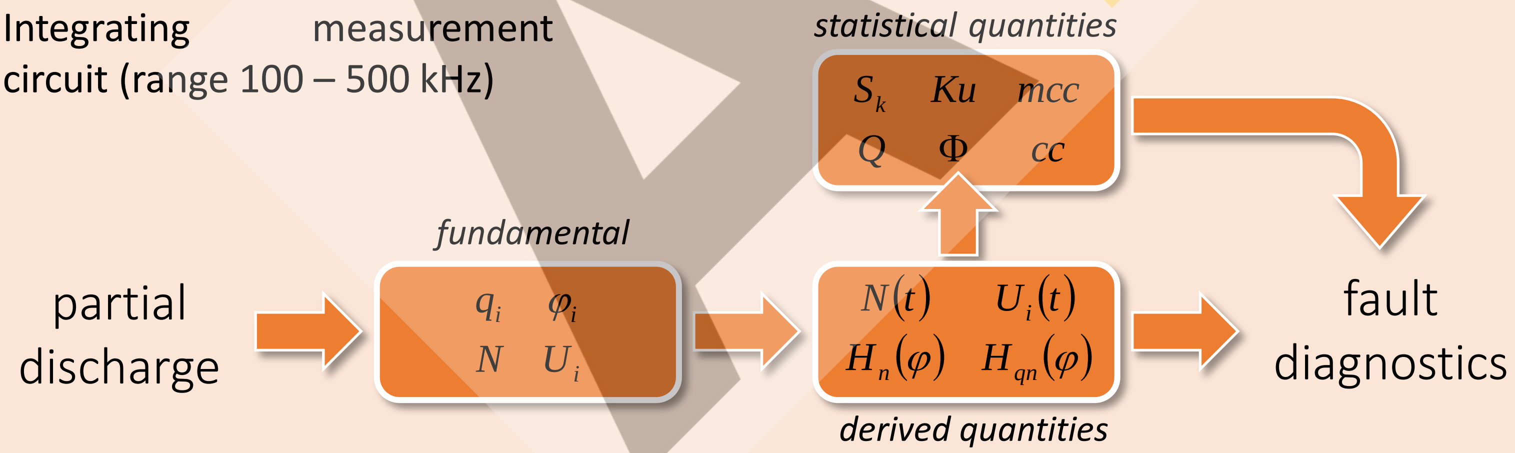
- Front time of discharge pulse is ns-range → measurement system bandwidth 500 – 1000 MHz

+ *Impact of external interference on measured data is reduced*

– *Implementation of measurement circuit and equipment (how to accurately record a ns pulse)*

PHASE-BASED IDENTIFICATION

Integrating measurement circuit (range 100 – 500 kHz)



statistical quantities

S_k Ku mcc

Q Φ cc

fundamental

q_i φ_i

N U_i

partial discharge

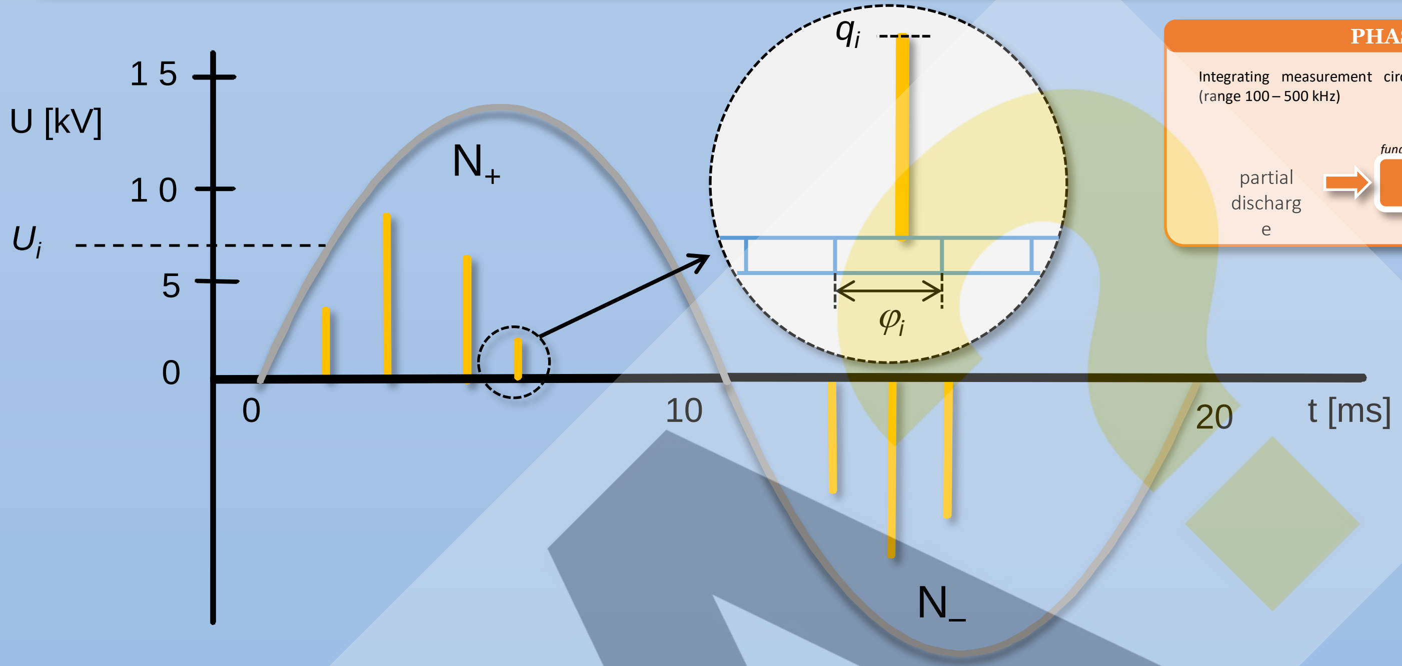
$N(t)$ $U_i(t)$

$H_n(\varphi)$ $H_{qn}(\varphi)$

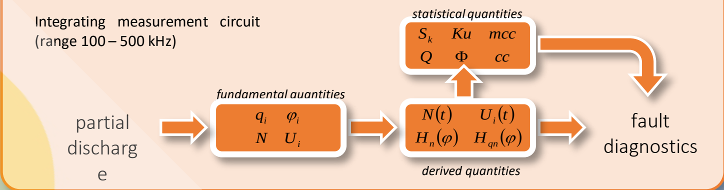
derived quantities

fault diagnostics

FUNDAMENTAL QUANTITIES



PHASE-BASED IDENTIFICATION



Basic values of PD

- **number of discharges N** (pulse count)
- **discharge voltage U_i** (in this context *i* is an index. Not to be confused with *inception voltage* U_i)
- **apparent charge q_i** (amplitude)
- **phase angle φ_i**

DERIVED QUANTITIES

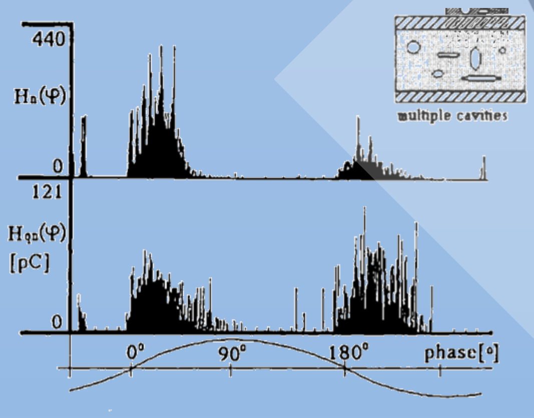
Formed distributions based on fundamental quantities – typically a function of time or phase angle

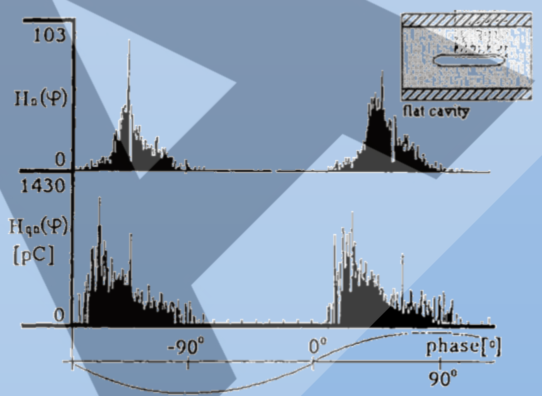
$H_n(\varphi)$ = pulse count-phase distribution

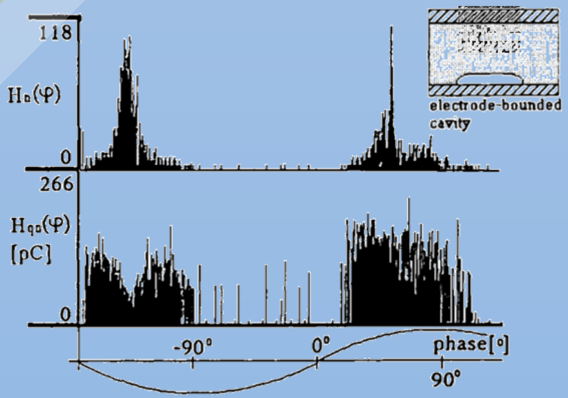
- number of observed discharges in each phase window as a function of the phase angle
- recognition of discharge sources and their behavior in time

$H_{qn}(\varphi)$ = mean pulse height-phase distribution

- average amplitude in each phase window as a function of the phase angle
- noise reduction (difference between statistical characteristics of discharge and noise)







STATISTICAL QUANTITIES

- Comparison of formed distributions with normal distribution
- Amplitude asymmetry [Q]
- Phase asymmetry [Φ]
- Cross correlation [cc]
- Modified cross correlation [mcc]
- Skewness [Sk] (FI = vinous)
- Kurtosis [Ku] (tapering, FI = suippous)
- Number of discharges (pulse count) [N]

STATISTICAL QUANTITIES

Amplitude asymmetry *Q*

Average half-cycle amplitude or pulse number ratio

$$Q = \frac{Q_s^- \,/\, N^-}{Q_s^+ \,/\, N^+}$$

$Q_s^{\pm}$ *sum of discharge amplitudes*

$N^{\pm}$ *number of discharge occurrences*

Phase asymmetry *Φ*

Difference of inception voltages in the positive and negative half-cycle

$$\Phi = \frac{\varphi_{inception}^-}{\varphi_{inception}^+}$$

$\varphi_{inception}^{\pm}$ *inception phase in the positive or negative half cycle*

STATISTICAL QUANTITIES

Cross correlation, *cc* – evaluates difference in shape of distributions $H_{qn}(\varphi)^{+}$ and $H_{qn}(\varphi)^{-}$

$$cc = \frac{\sum x_i y_i - \sum x_i \sum y_i / n}{\sqrt{\left[\left(\sum x_i^2 - \left(\sum x_i\right)^2 / n\right)\left(\sum y_i^2 - \left(\sum y_i\right)^2 / n\right)\right]}}$$

x_i	magnitude of discharge pulse in the phase window *i* of the positive half cycle
y_i	magnitude of discharge in the corresponding phase window *i* of the negative half cycle
n	number of phase windows in a half cycle

cc = 1 ⇨ *100 % shape symmetry*
cc = 0 ⇨ *total asymmetry*

Modified cross correlation, *mcc* – modified to include distribution height information

Product of phase asymmetry, discharge asymmetry, and the cross correlation factor

$$mcc = Q \cdot \Phi \cdot cc$$

STATISTICAL QUANTITIES

Skewness Sk and Kurtosis Ku – asymmetry and deviation of distribution shape with respect to normal distribution

$$Sk = \frac{\sum (x_i - \mu)^3 P_i}{\sigma^3} \qquad Ku = \frac{\sum (x_i - \mu)^4 P_i}{\sigma^4} \boxed{-3}$$

x_i	individual unit in a pulse sequence or distribution
P_i	probability of x_i
μ	mean value (average) of units in a pulse sequence or distribution
σ	standard deviation of units in a pulse sequence or distribution

“Excess kurtosis”

The kurtosis for a standard normal distribution is three. This definition is used so that the standard normal distribution has a kurtosis of zero.

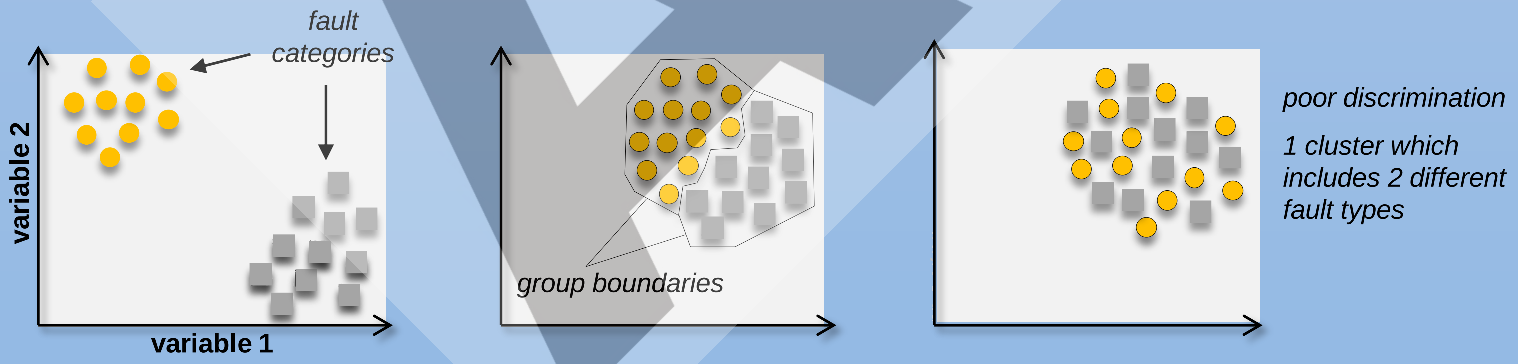
FINGER PRINT

The previously presented quantities are used to form a **finger print**

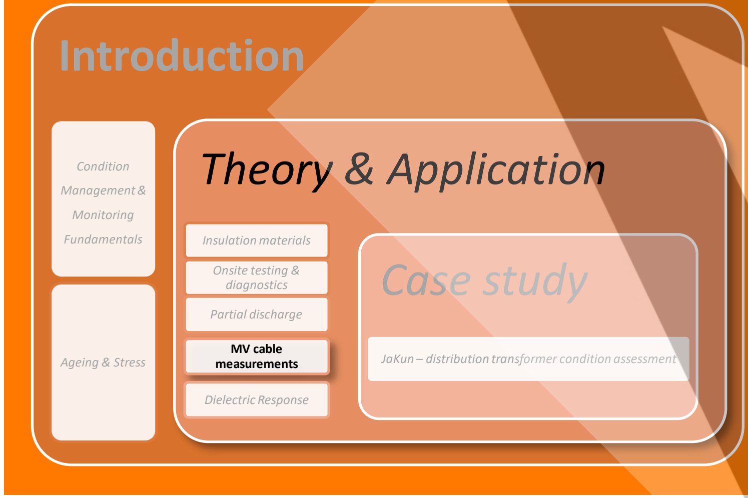
Finger prints can be used to distinguish different fault types

- **Finger print library** (database) consisting of general model finger prints and more detailed product-specific finger prints
- Recorded discharge finger print is compared to library finger prints
- Mapping method, **cluster analysis**, neuro-network

Example of cluster analysis:



Medium voltage cable diagnostic measurements



Introduction

Theory & Application

Condition Management & Monitoring Fundamentals

Ageing & Stress

Insulation materials

Onsite testing & diagnostics

Partial discharge

MV cable measurements

Dielectric Response

Case study

JaKun – distribution transformer condition assessment

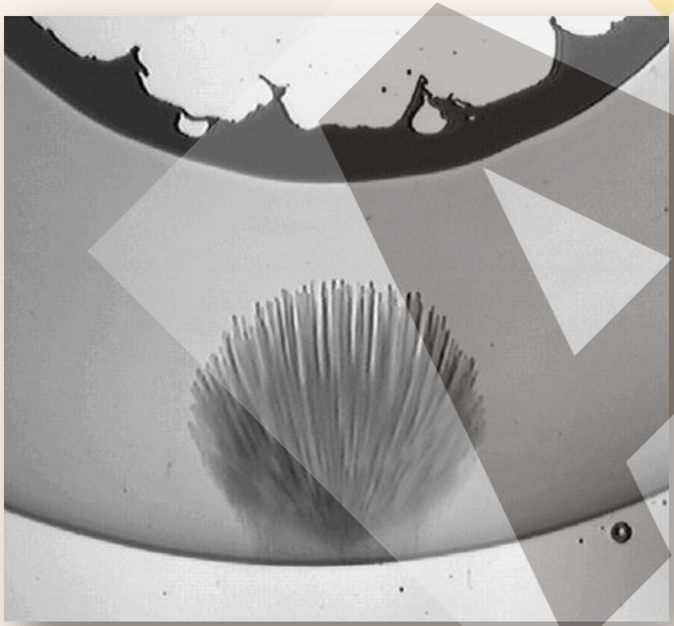
Dielectric response

Partial discharge

OFFLINE CABLE MEASUREMENTS

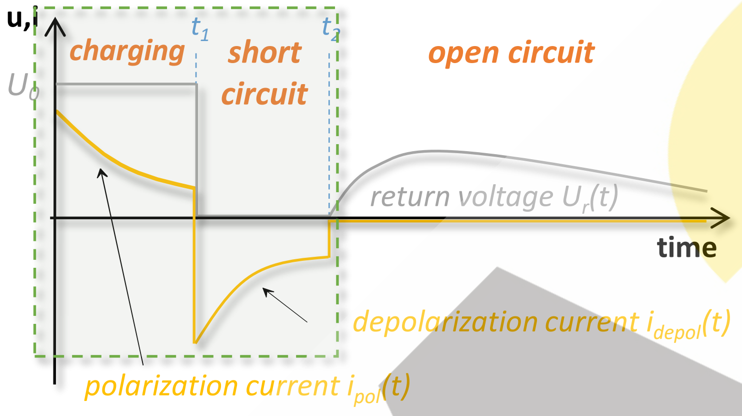
Dielectric response DR – general overview of cable condition

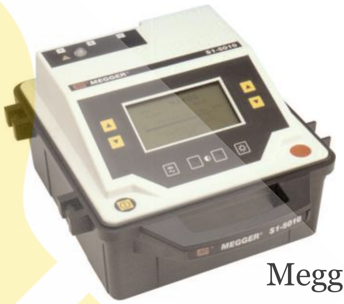
- Detection of water content (water treeing in XLPE, moisture in oil-paper)
- DR measurements:
  - – time domain (**PDC – Polarization and Depolarization Currents**)
  - – frequency domain (**FDS – Frequency Domain Spectroscopy**)



OFFLINE CABLE MEASUREMENTS

Polarization and depolarization currents, PDC (time domain)



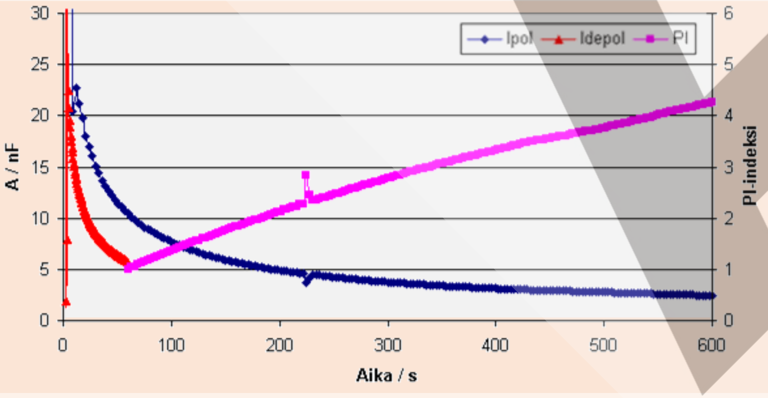


Megger S1-5010

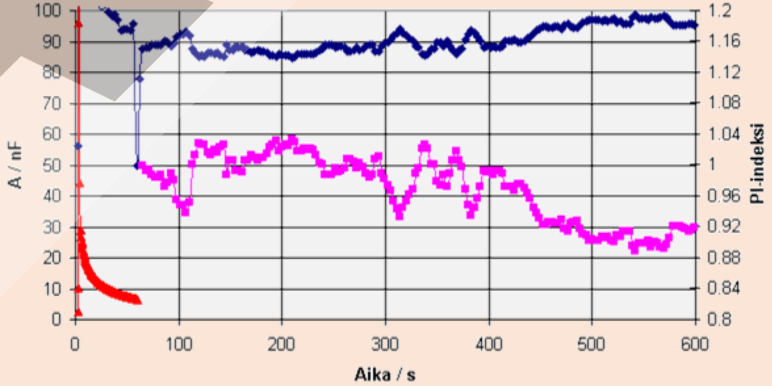
I_{pol} and I_{depol} should exhibit similar trends

PI > 4 indicates good condition

Good cable



Bad cable



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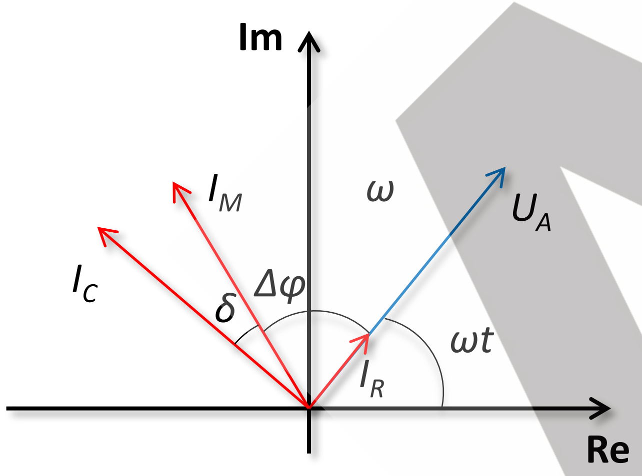
OFFLINE CABLE MEASUREMENTS

Dielectric response, FDS (frequency domain)

Dissipation factor *tan δ* as a function of frequency

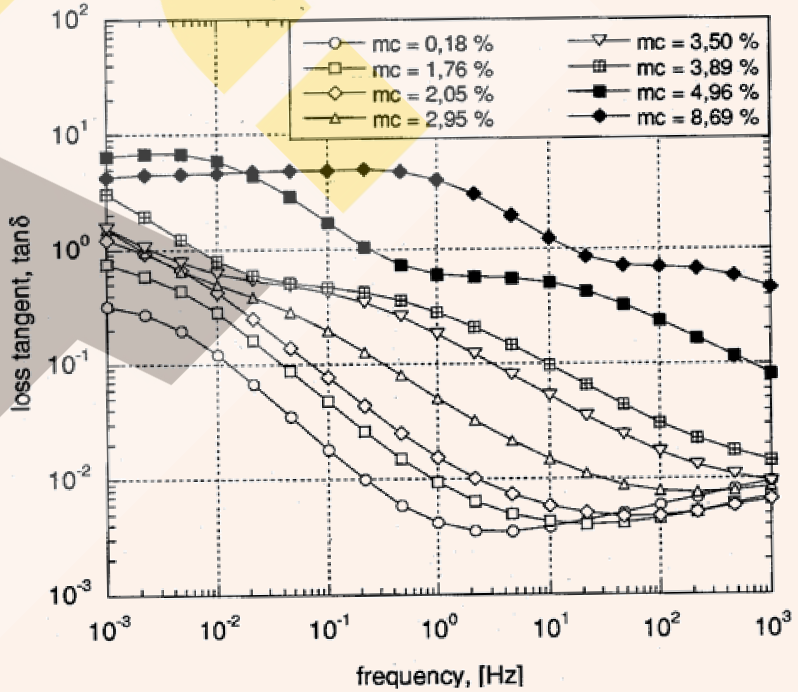
- **Minimum** *tan δ* correlates to moisture content (high *tan δ* = high m.c.)



Accurately measures voltage and current from which **complex impedance** is calculated

⇨ capacitance, loss, resistance, etc.

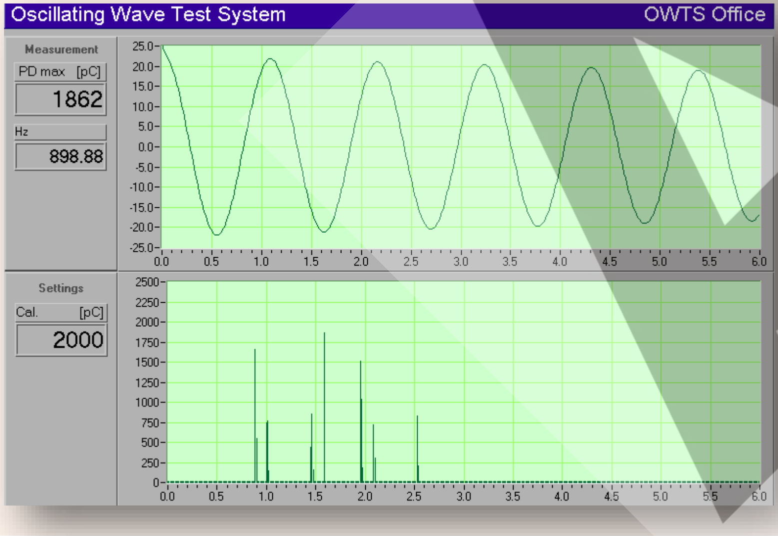
IDA 200



OFFLINE CABLE MEASUREMENTS

PD measurements using DAC

- Detection of harmful local faults
  - Detection
  - Identification
  - **Location**
- New and existing cable systems
  - $1.5U_0$, $1.7\ U_0$, $2U_0$
  - New connection $2U_0$



Oscillating Wave Test System

OWTS Office

Measurement

PD max [pC]

1862

Hz

898.88

Settings

Cal. [pC]

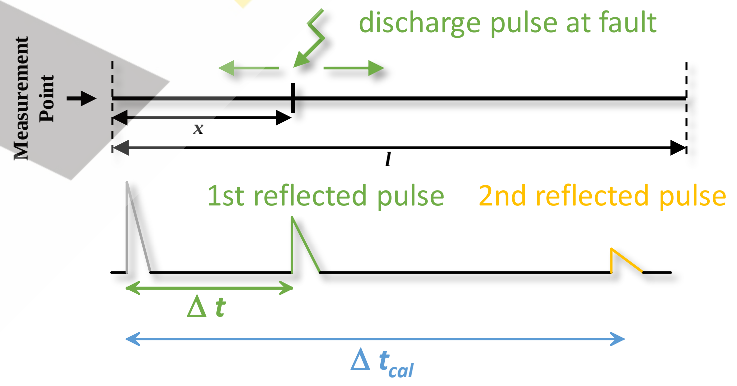
2000

DISCHARGE LOCATION IN A CABLE

1st pulse	$t_1 = \frac{x}{v}$
2nd pulse	$t_2 = \frac{2l - x}{v}$
Time difference	$\Delta t = t_2 - t_1 = \frac{2(l - x)}{v}$
Propagation velocity	$v = \frac{2l}{\Delta t_{\mathrm{kal}}}$
Discharge location	$x = l - \frac{1}{2} v \Delta t$

Calibration – pulse propagation velocity

Measurement– partial discharge location



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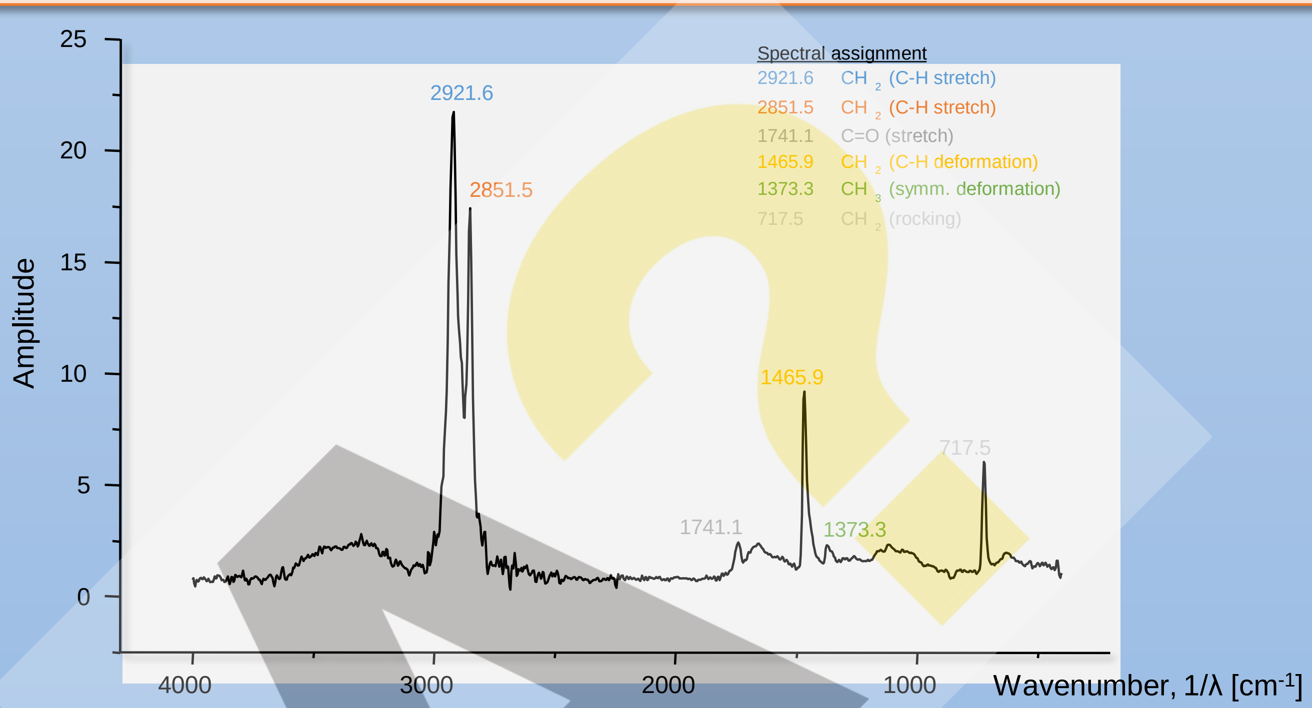
OFFLINE CABLE MEASUREMENTS



FTIR analysis – Fourier transform infrared spectrometry

- Chemical finger print – identify **composition** of sample
  - post-fault (for comparison), offline, requires test sample
- Technique to acquire an infrared spectrum of absorption, emission, or photoconductivity of a solid, liquid or gas (how well a sample **absorbs light** at each wavelength)

OFFLINE CABLE MEASUREMENTS

FTIR analysis

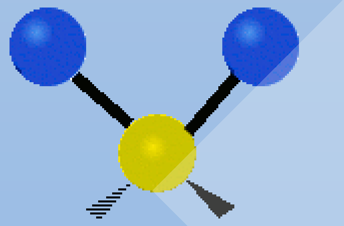
Molecules absorb specific frequencies (**resonant frequencies**) that are characteristic of their structure

- The frequency of the vibration can be associated with a particular bond type
- Vibrational mode = degrees of freedom (changes in the permanent dipole)

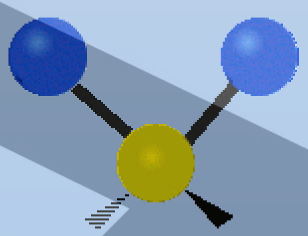
Spectral assignment

2921.6	CH$_2$ (C-H stretch)
2851.5	CH$_2$ (C-H stretch)
1741.1	C=O (stretch)
1465.9	CH$_2$
1373.3	CH$_3$
717.5	CH$_2$ (rocking)

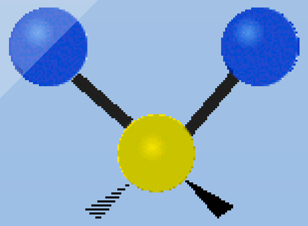
Symmetrical stretching



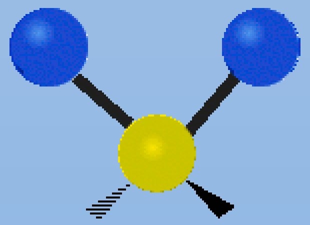
Asymmetrical stretching



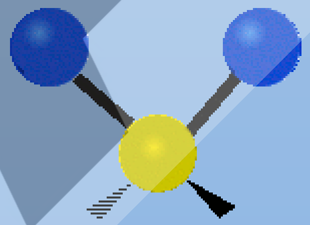
Scissoring



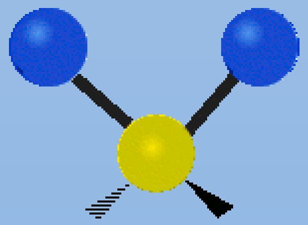
Rocking



Wagging



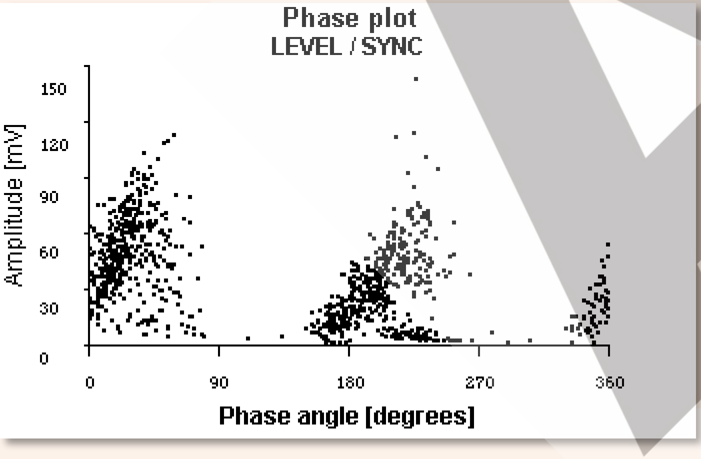
Twisting

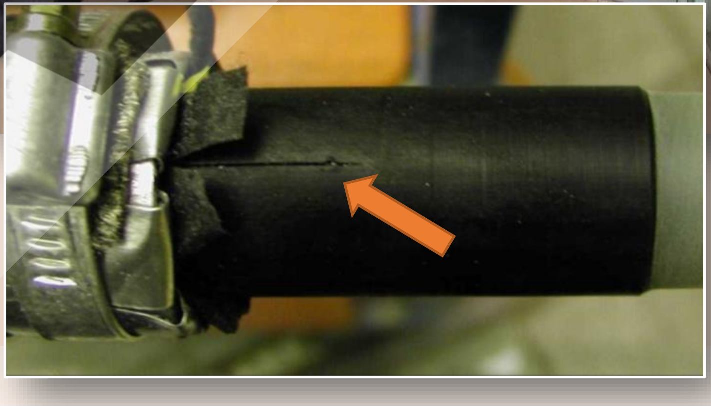


ONLINE CABLE MEASUREMENTS

Acoustic PD detection

- Enables detection of harmful faults in cable accessories
  - Joints, terminations, etc.
- Performed during **normal operating** conditions
- Can be adopted for GIS measurements also





XLPE CABLE FDR (frequency domain)

ASSESMENT:

VDP response
(Voltage Dependent Permittivity)

- Voltage dependent increase of losses (ε'') and capacitance (ε').

TLC response
(Transition to Leakage Current)

- The response changes characteristics at a higher voltage levels. Leakage currents are added.

LC response
(Leakage Current)

- Insulator becomes conductive. Leakage currents through water trees are present already at low voltage levels.

XLPE CABLE FDR (frequency domain)

RESULTS:

LC or TLC response

- The cable is diagnosed as **bad**.
- The voltage withstand level is usually under 2.5 times the nominal voltage.
- Depending on leakage current level, cable design and voltage level of the network, the cable can be used for some additional time or has to be **replaced immediately**.

VDP response

- The cable is **significantly aged**.
- The voltage withstand level is usually in the range 2.5 to 4 times nominal voltage.
- Depending on cable design and level of response, the cable can remain in service for several years or has to be scheduled for **early replacement**.

No ageing detected

- Voltage withstand level over 4 times nominal voltage
- Repeat measurement within 5 to 10 year period.

Capacitance part (ε')

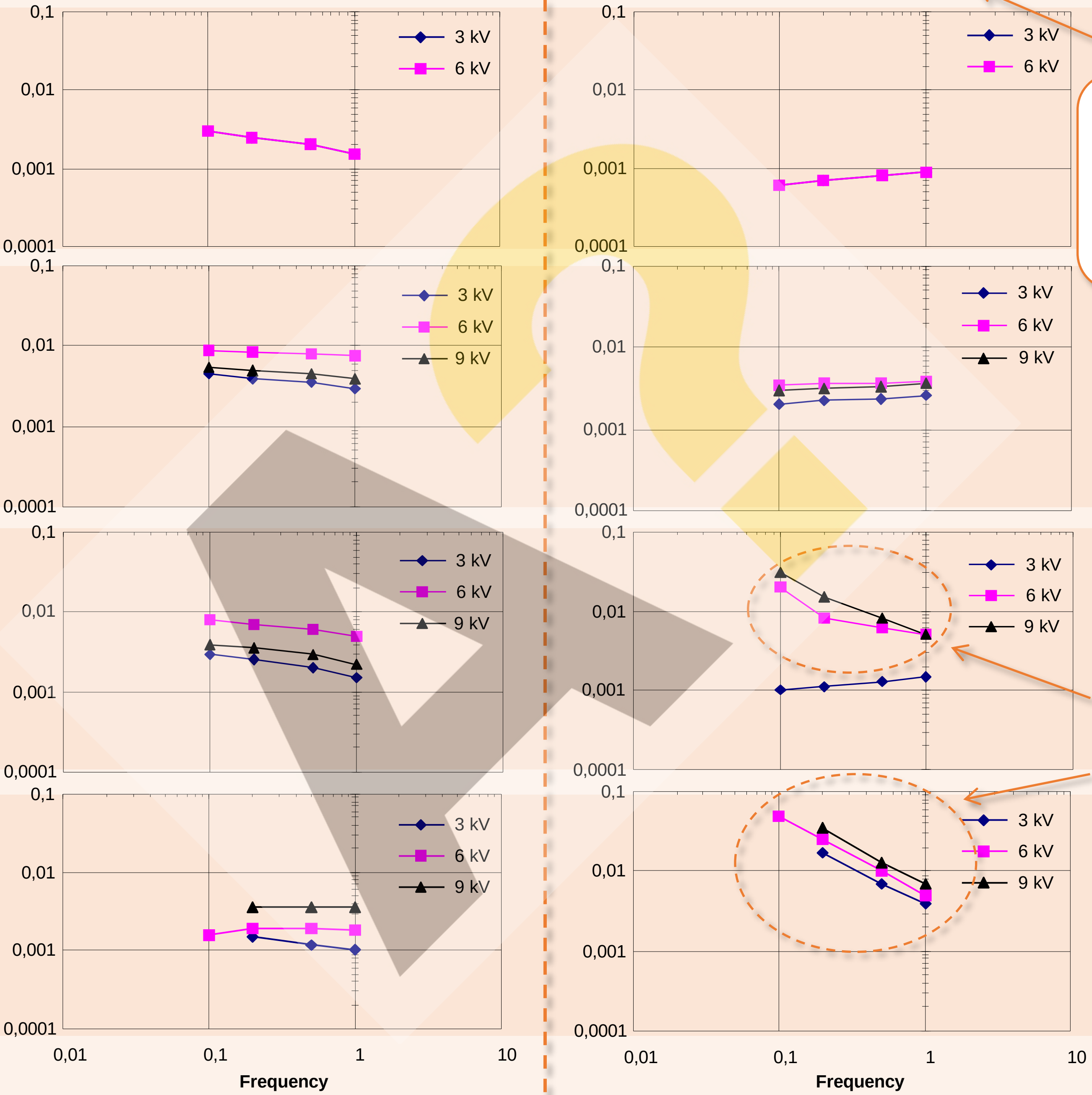
Loss part (ε'')

Healthy

VDP response

TLC response

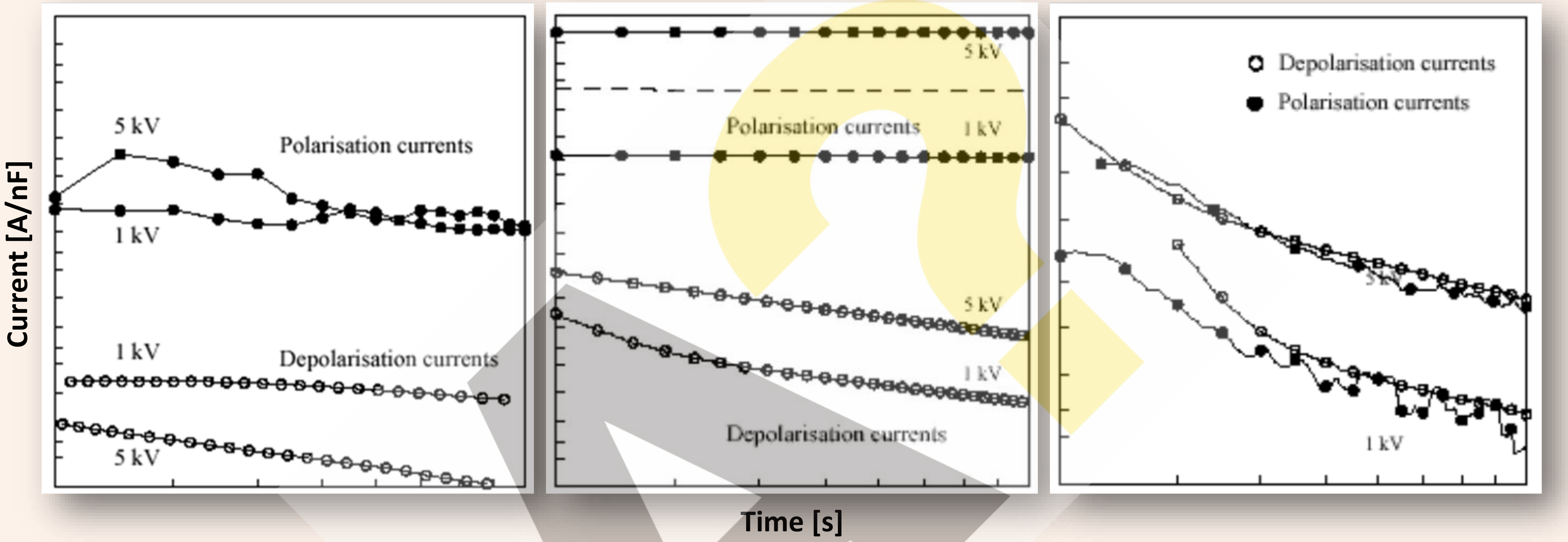
LC response



ε´´ is related to conductivity and resistive losses – conductivity should be small for insulators

-1 slope = insulation is becoming conductive

XLPE CABLE PDC (time domain)



bad cable

- Nonlinear polarization current

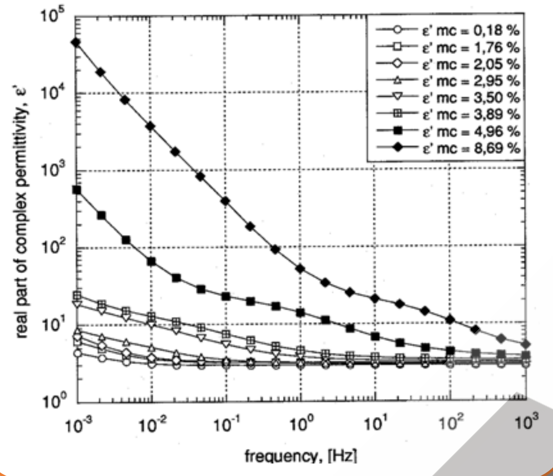
bad cable

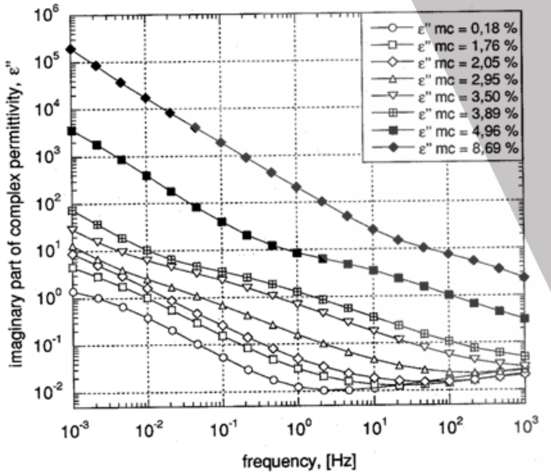
- I_p differs from I_{dp}

good cable

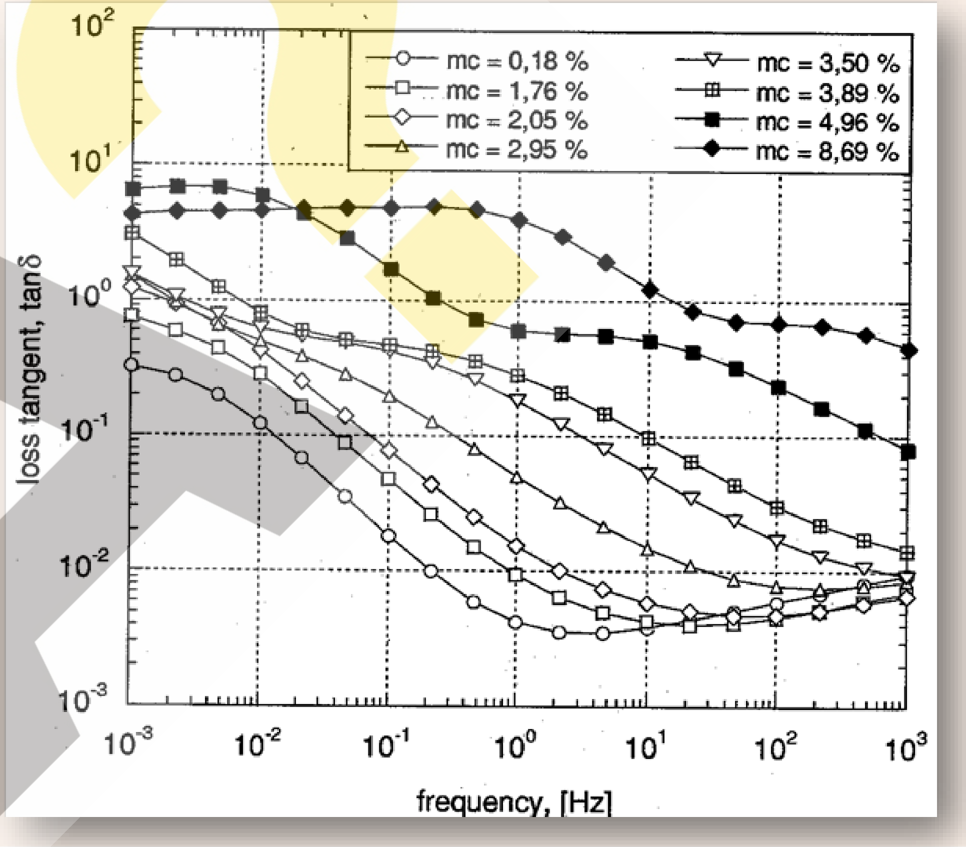
- Voltage linearity
- I_p equal to I_{dp}

OIL-PAPER CABLE FDR (frequency domain)





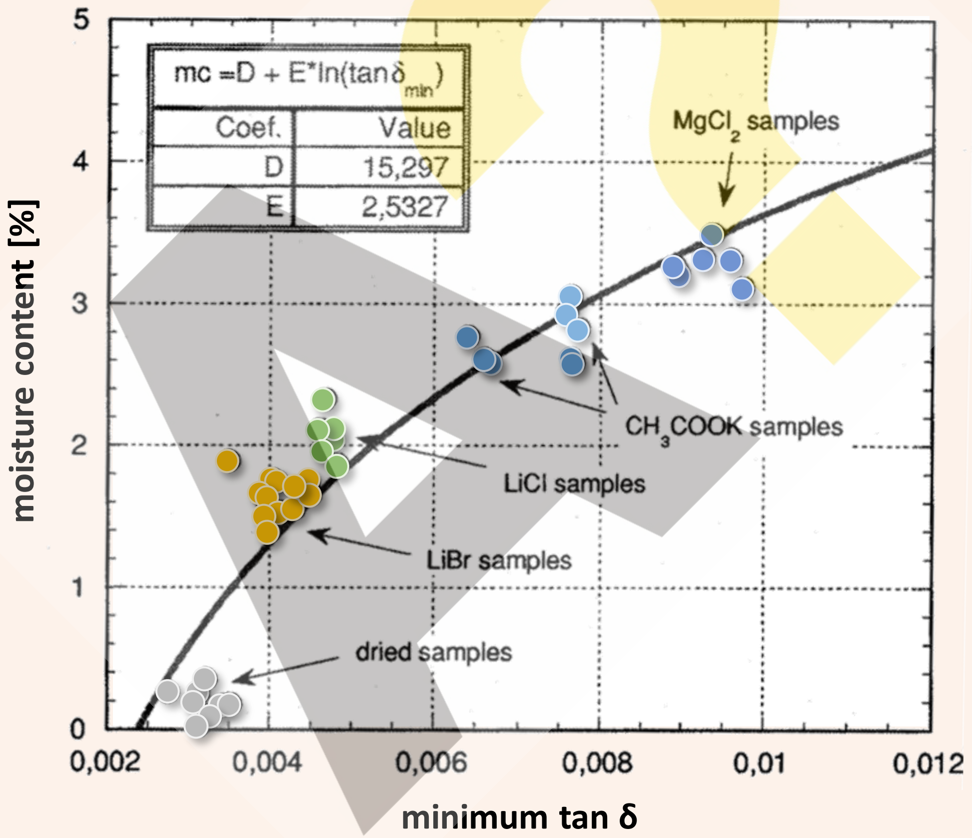
$$\tan\delta = \frac{\mathrm{Re}(Z)}{\mathrm{Im}(Z)}$$



OIL-PAPER CABLE FDR (frequency domain)

Correlation between **minimum tan δ** and **moisture content**

- known moisture content of specific samples



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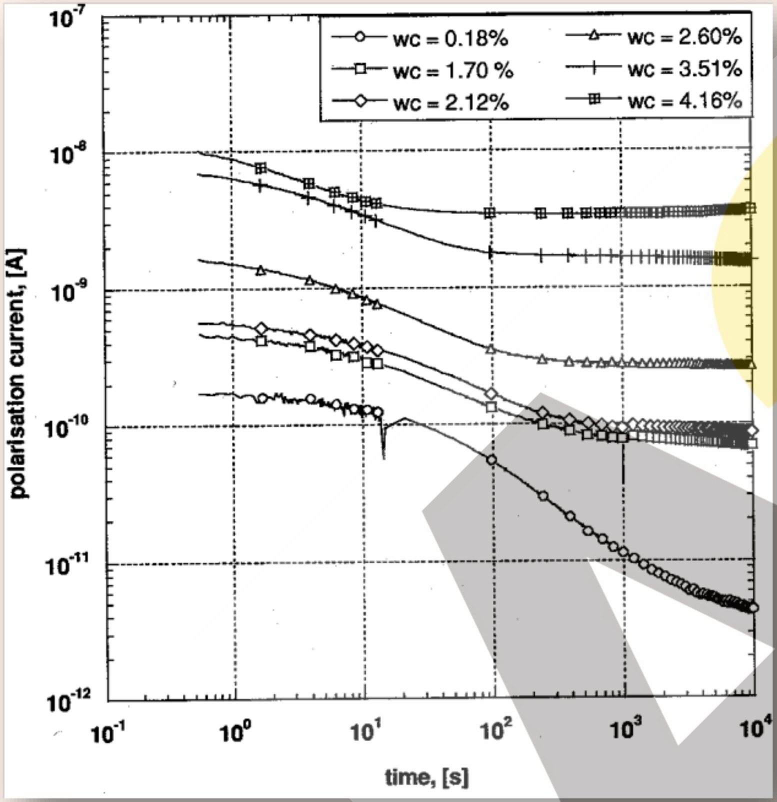
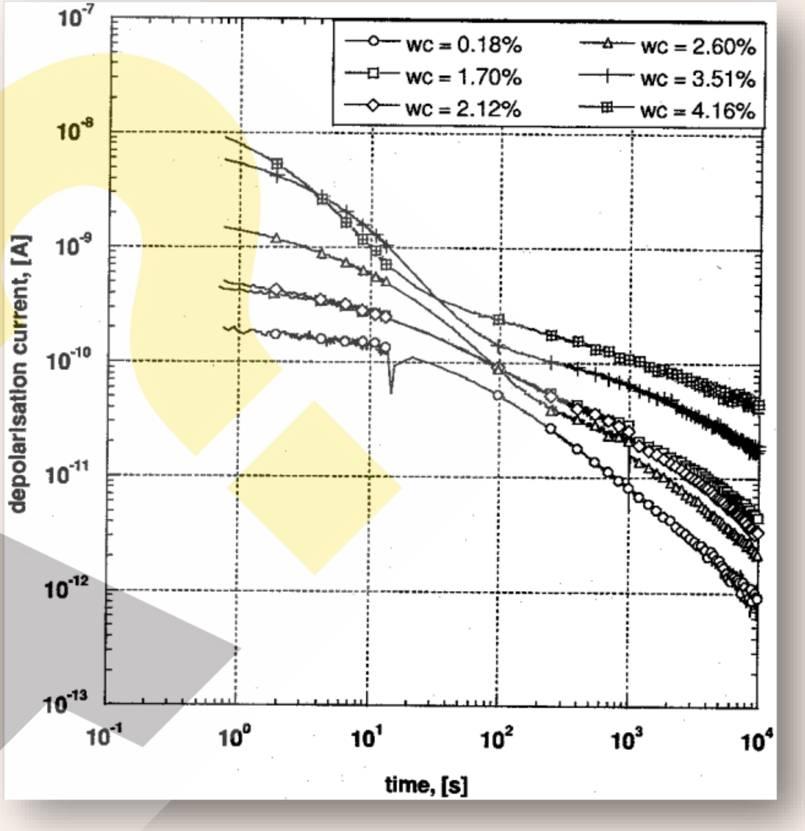
OIL-PAPER CABLE PDC (time domain)

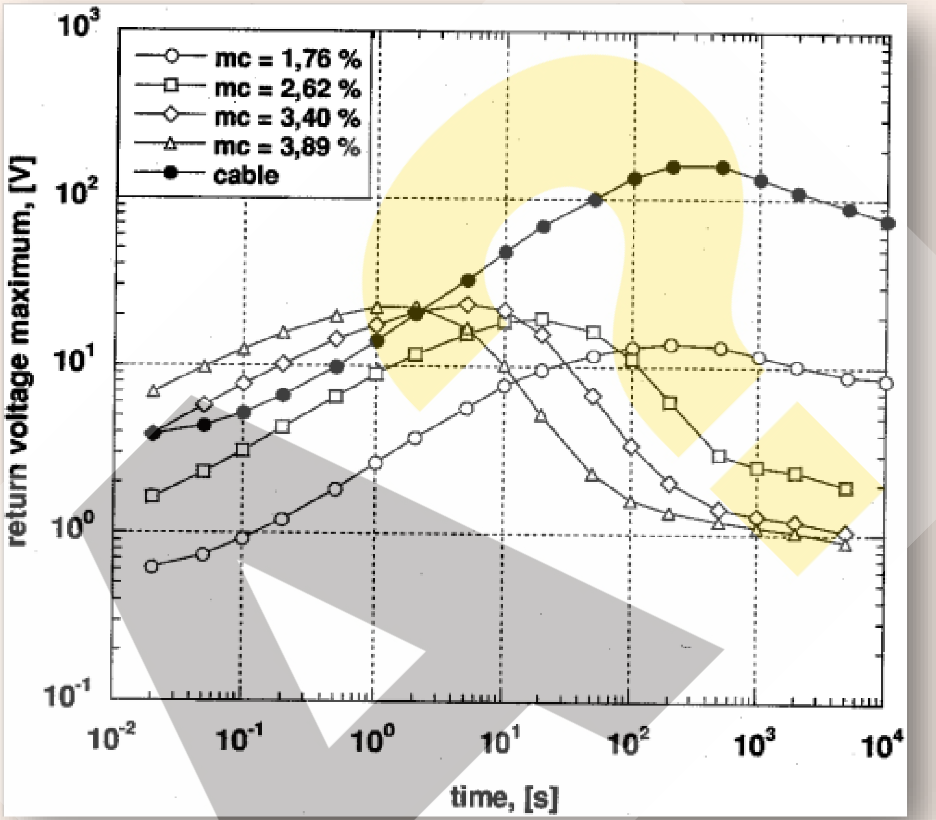




I_p and I_{dp} should be relatively similar

more moisture = more deviation

OIL-PAPER CABLE RVM (time domain)



Charging time resulting in largest return voltage describes insulator moisture content

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