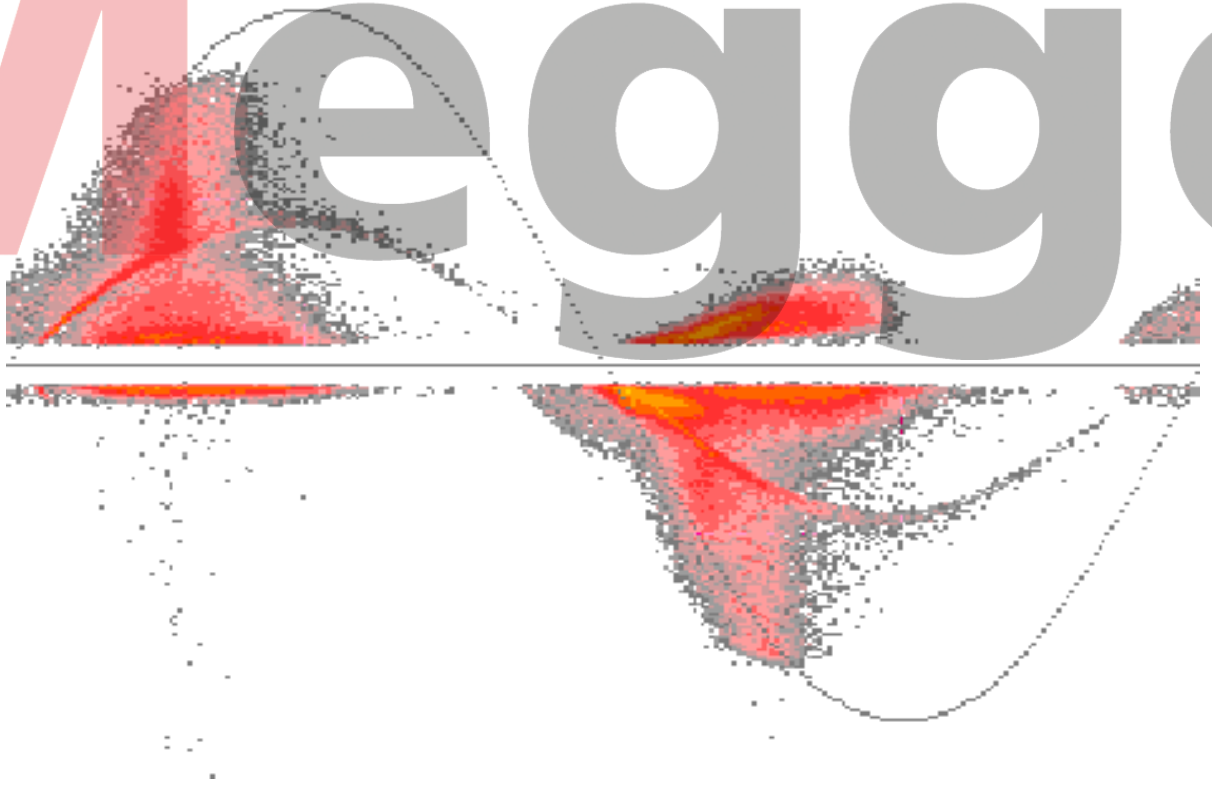
Partial Discharge Testing for Rotating Machines

Hussain Al-Juffairi
Abdulla Jawher

March 2025



Our History

1889: Sydney Evershed
Invents the insulation tester

1936: Biddle
James G Biddle Co. incorporated in USA

1951: Multi-Amp
Multi-Amp is founded

1923: First multi-meter tester
AVO Meter, world's first multi-meter developed

2002: Megger
Avo International renamed to Megger

1968: AVO
AVO acquires Evershed and Vignoles (Megger)

2012: SebaKMT Group
Global leader in cable testing join Megger group

2008: Pax
Innovators of advanced transformer diagnostics joins the Megger group

2007: Programma
Experts in transformers and circuit breakers, joins Megger group

2015: Radeburg
HV Cable research center opened in Germany

2018: Megger acquires Baker Instruments
Entering into the field of motor and generator testing

2019: Megger acquires Power Diagnostix
Enhancing our partial discharge portfolio

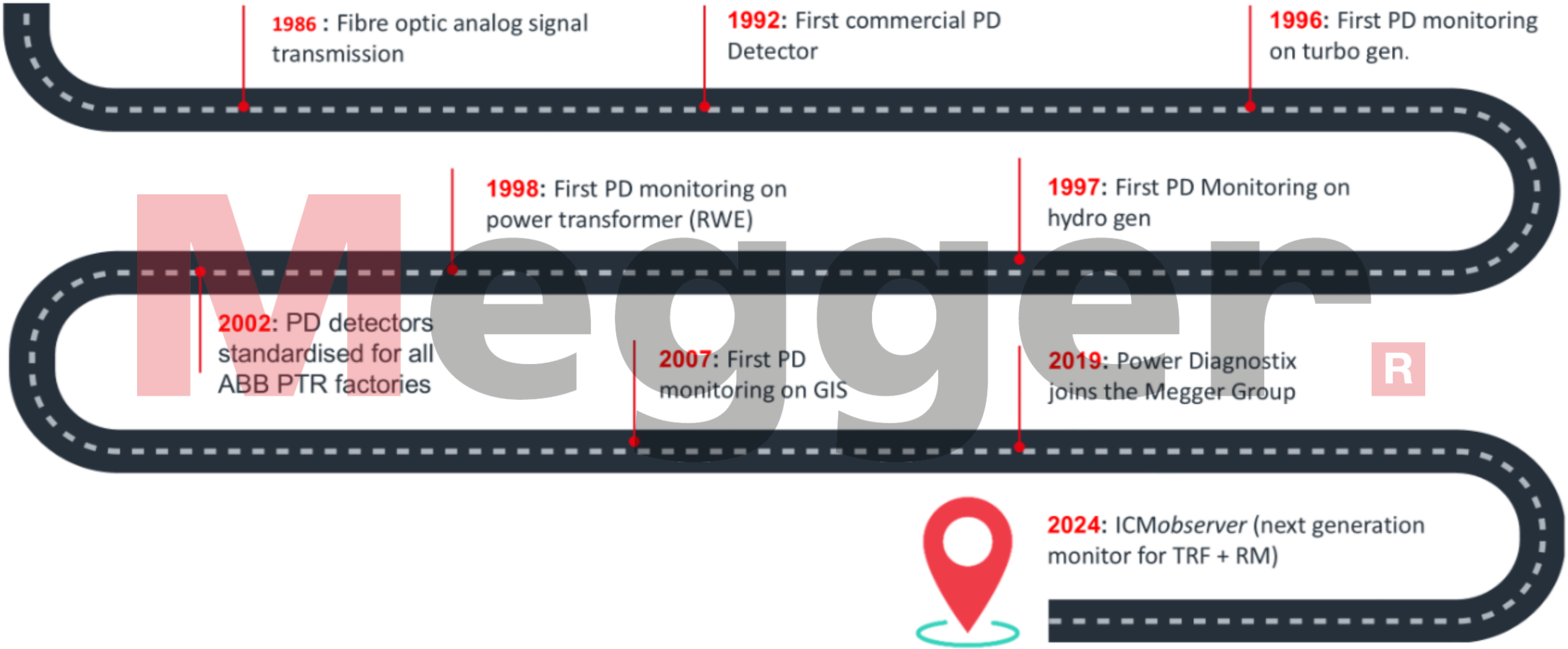
2023: Weidmann
Introducing Insulogix and AVO Diagnostic Services.

2021: Introducing Megger Grid Analytics

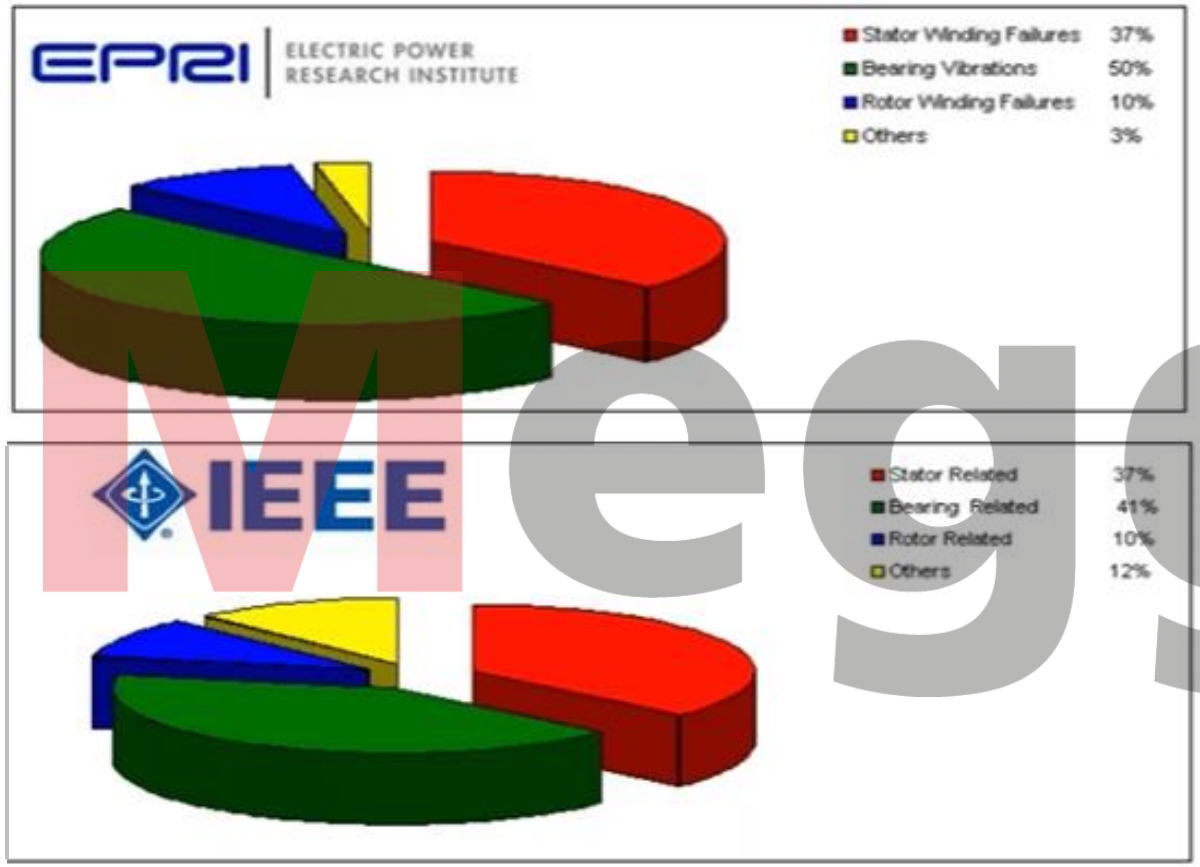
2021: Partnership with IPS
Megger enters into Asset Performance Management with strategic partnership

Megger

Our Journey



EPRI & IEEE Failure Studies



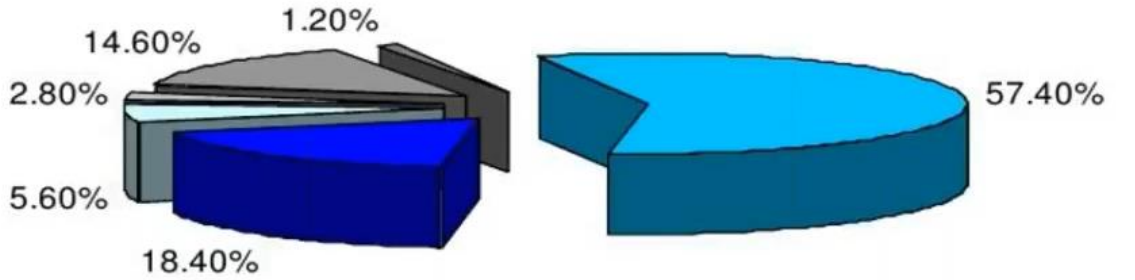
- Analysis of 7500 machines (1983)

37% Stator Winding Related

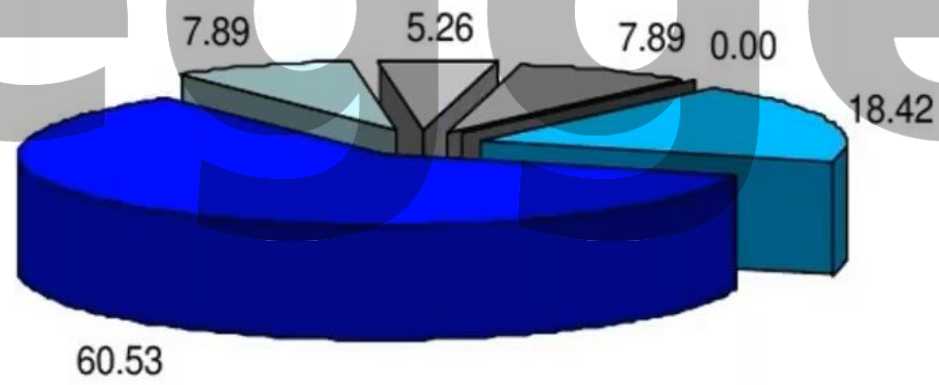
- Analysis of 3000 machines (1995)

Failure Study : HV motors in the Petrochemical Industry (1999)

HV-Motors < 2MW



HV-Motors > 2MW

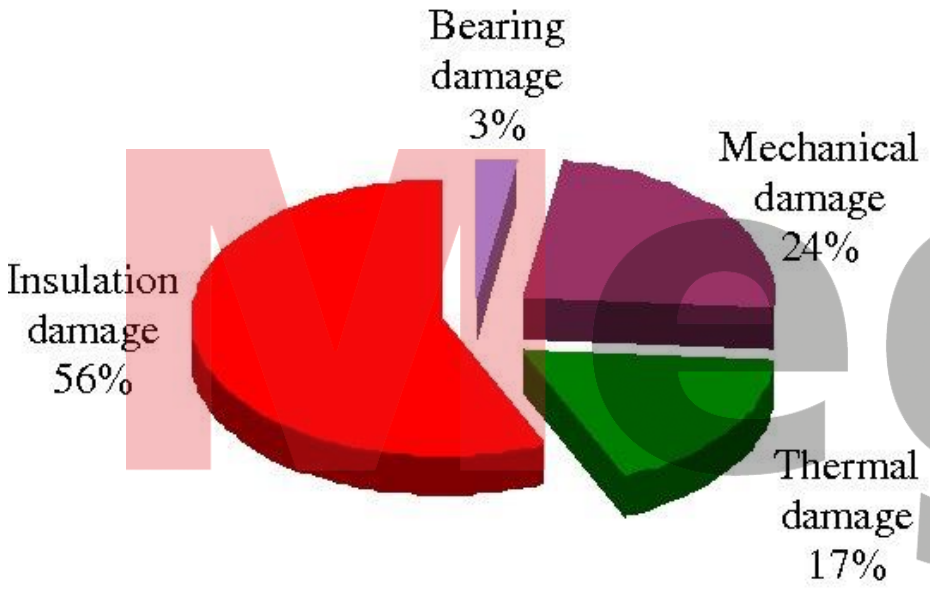


- Bearing
- Stator Windings
- Rotor- Bars/rings
- Shaft or coupling
- External device
- Not Specified

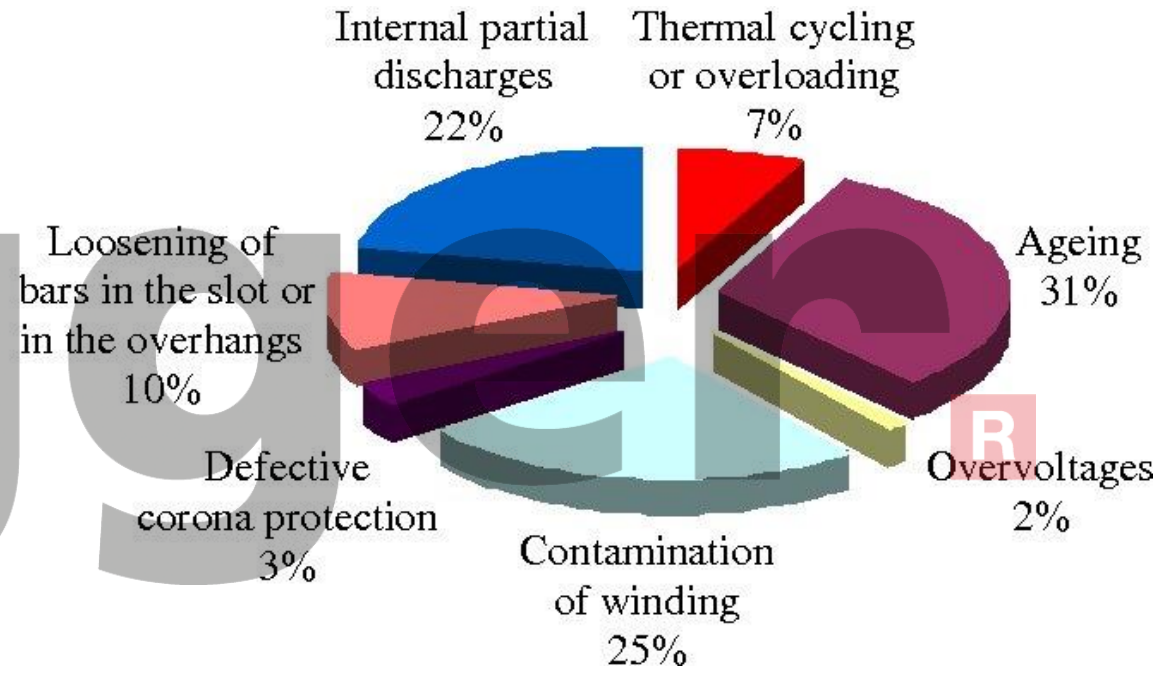
Reference: IEEE transactions on industry applications vol.35 N°3

Why testing/ monitoring the stator winding insulation status of critical motors and generators?

Source: CIGRE Study Committee SC11, EG11.02, “Hydrogenerator Failures – Results of the Survey“, (2003)



Damages leading to failure



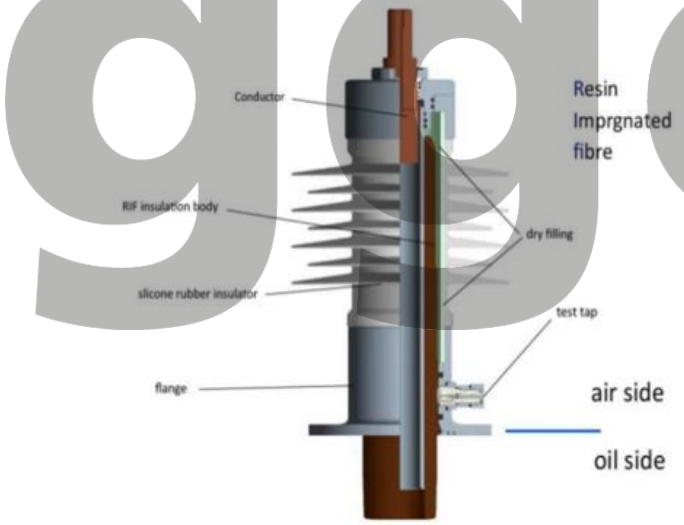
Root causes of insulation damage

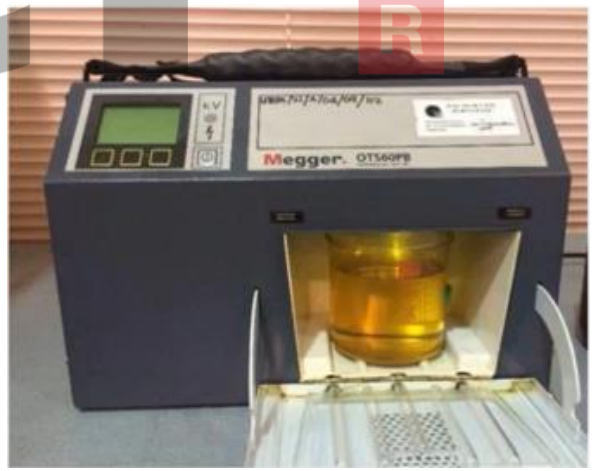
- Electrical diagnosis (static testing + Partial Discharge/ tan delta) of the stator winding is the most important predictive maintenance measure

Insulation Materials

- **There are number of different high voltage (HV) insulating materials that are used for certain applications**

- **Common HV insulating materials**
  - Gasses
    - Air (78% Nitrogen)
    - SF6
  - Liquids
    - Mineral oil
    - Silicon oil
  - Solids
    - Ceramic
    - Glass
    - Mica
    - Resin





Partial Discharge Basics

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 exceeds the dielectric strength of the insulating material
- Physical and chemical changes may happen to the insulator which produce emissions that we can detect
- PD can manifest in different in different ways:

a) Internal
b) Surface
c) External / Corona

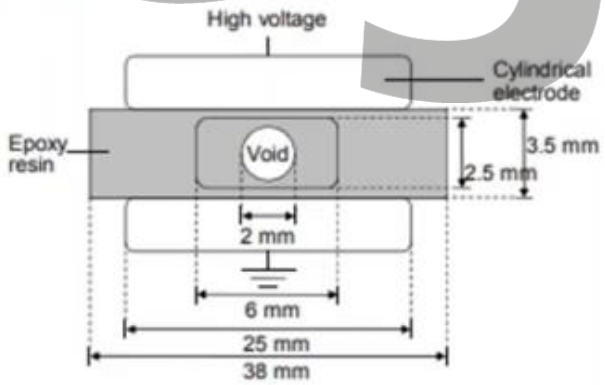


Figure 1. Test object for void discharge measurement

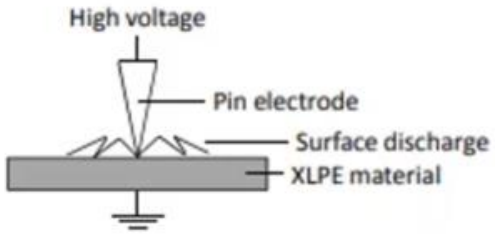


Figure 2. Test object for surface discharge experiment

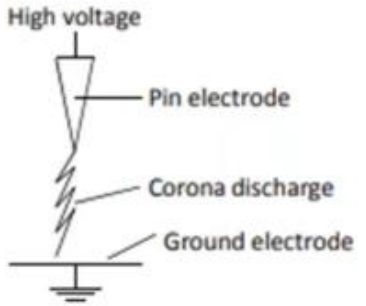
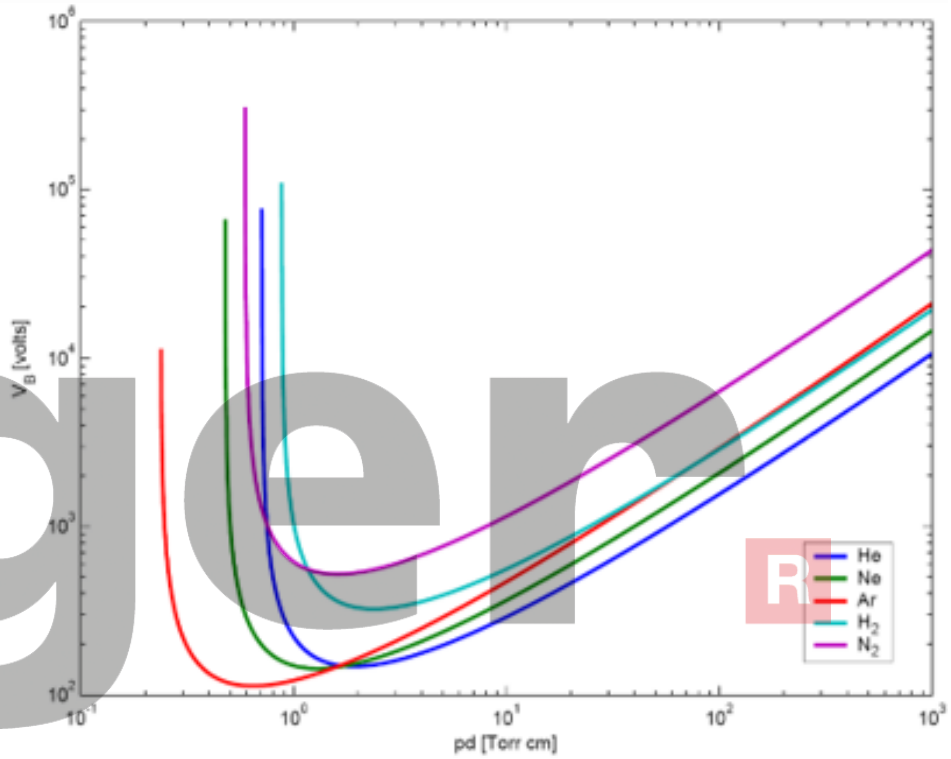


Figure 3. Test object for corona discharge experiment

Properties of Insulating 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)

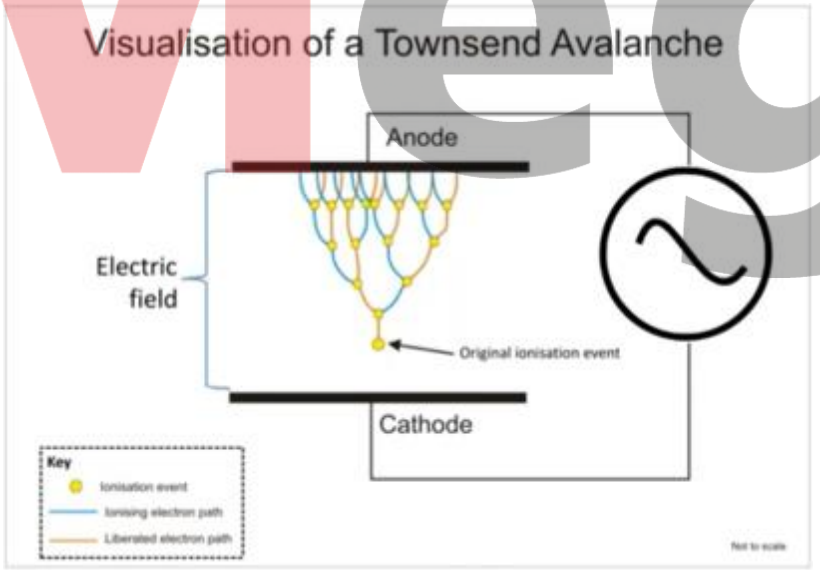


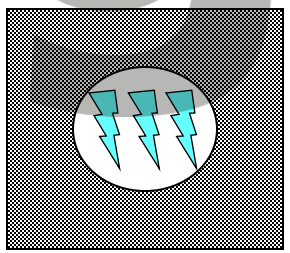
- Paschen's law: $E_{Breakdown} \sim pd$ (p > 1bar)
- Hydrogen cooled generators: 3-7 bar
- SF_6 insulated switchgear: 3-4 bar

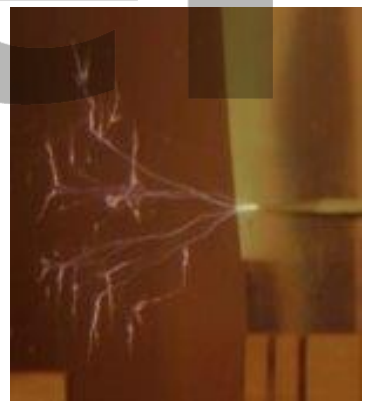
Partial Discharge Basics

Occurrence of PD

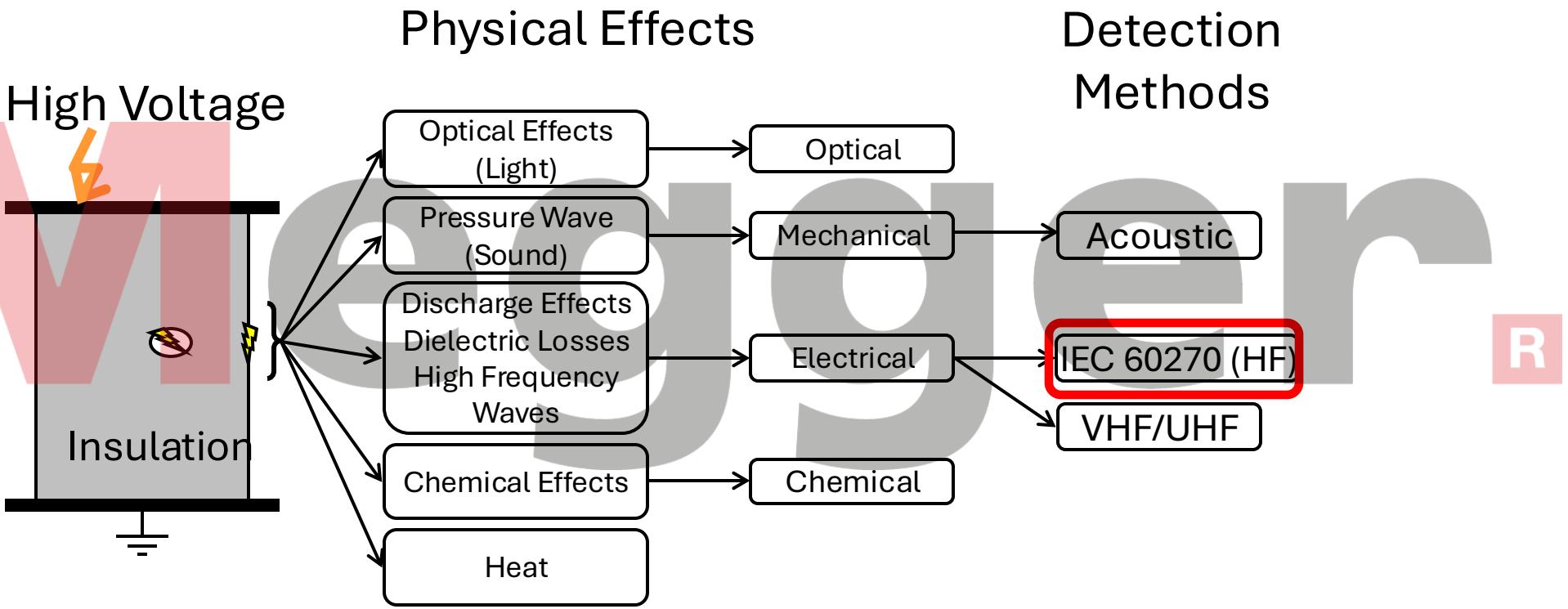
- For the occurrence of PD two conditions must be met:
  - The local electric field must have reached the critical inception field (E > E_{crit})
  - A free electron must be available to start the discharge avalanche







Partial Discharge Basics



Partial Discharge Basics

Why do we measure PD?

- Partial discharge is one root cause of insulation degradation
- PD detection is an early-stage test that can reveal any insulation weakness within the asset which prevents full breakdown and costly damages
- PD Location can help to find failure positions.
- PD measurements are non-intrusive and can be done online and offline with conventional or unconventional testing methods
- PD analysis helps to improve the design of insulation systems

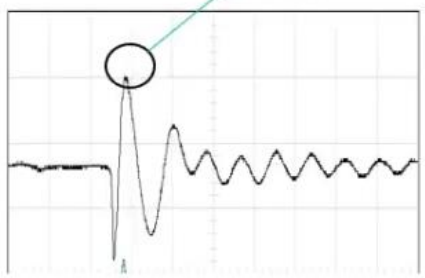
Figure: Flashover in transformer tank wall

Phase Resolved Pattern (PRPD)

PRPD Patterns

Y-axis: Amplitude
[pC], [mV], [dBm]

Z-axis: Number of PD Pulses
Translates into a color



Discharge impulse

X-axis:
Phase Angle
0..360°

AC Voltage

Color Table

Norm	Log
0	0
1 - 1	1 - 2
2 - 2	3 - 4
3 - 2	5 - 8
3 - 3	9 - 16
4 - 4	17 - 32
5 - 4	33 - 64
5 - 5	65 - 128
6 - 6	129 - 256
7 - 7	257 - 512
8 - 8	513 - 1024
9 - 8	1025 - 2048
9 - 9	2049 - 4096
10 - 10	4097 - 8192
11 - 10	8193 - 16384
11 - 11	16385 - 32768
12 - 12	32769 - 65536

Color of
accumulated pulses
in different modes

Normative References

- There are currently no standards defining acceptance criteria for Partial Discharge testing on rotating machinery
- The lack of such criteria often causes endless discussions between owner and manufacturer after submission of test reports, even during factory tests
- An important difference between rotating machines and other applications is property to be PD-resistant versus other PD-free insulation systems
- Frequently asked questions on this subject are:
  - How much PD is now too much PD?
  - Defining acceptance criteria for a PD-resistant insulation systems?

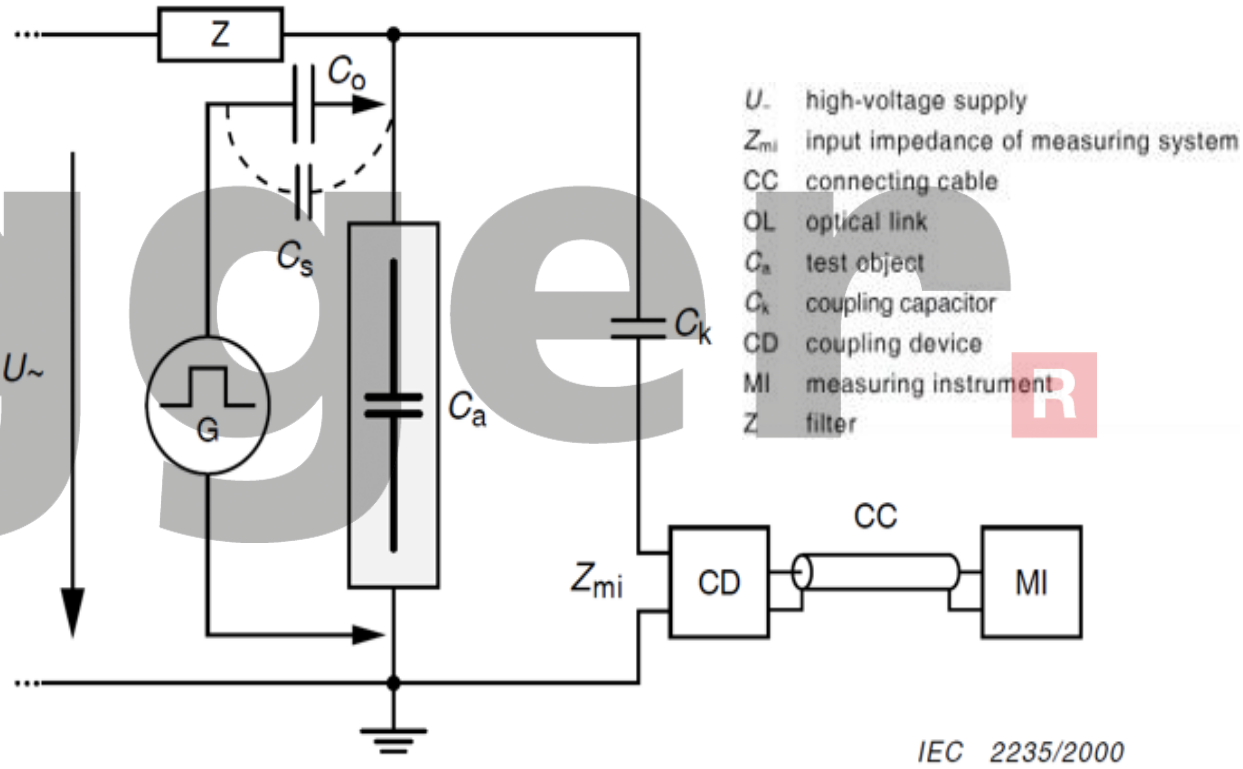
Normative References

- Main “horizontal” standard, i.e. the IEC 60270
- Technical specifications and guides from IEC, IEEE, Cigré, EASA and EPRI
  - Test circuits and procedures
  - Voltage application sequences
  - Test durations
  - PD-detection bandwidths
  - Calibration circuits
  - Typical PD-phenomena

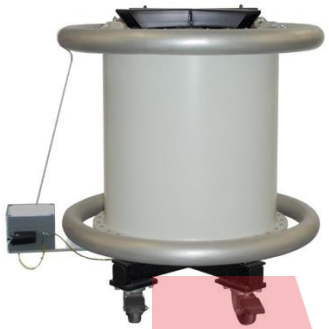
- IEC600034-27, IEEE 1434-2014, Cigré ref.258 and ref.558, etc.

Testing Methods

- **Conventional Method (IEC 60270)**
  - Device under test must be taken out of service
  - Measurement can be accurately calibrated
  - Noise sources, other than radiated, can be eliminated
  - Requires coupling capacitor

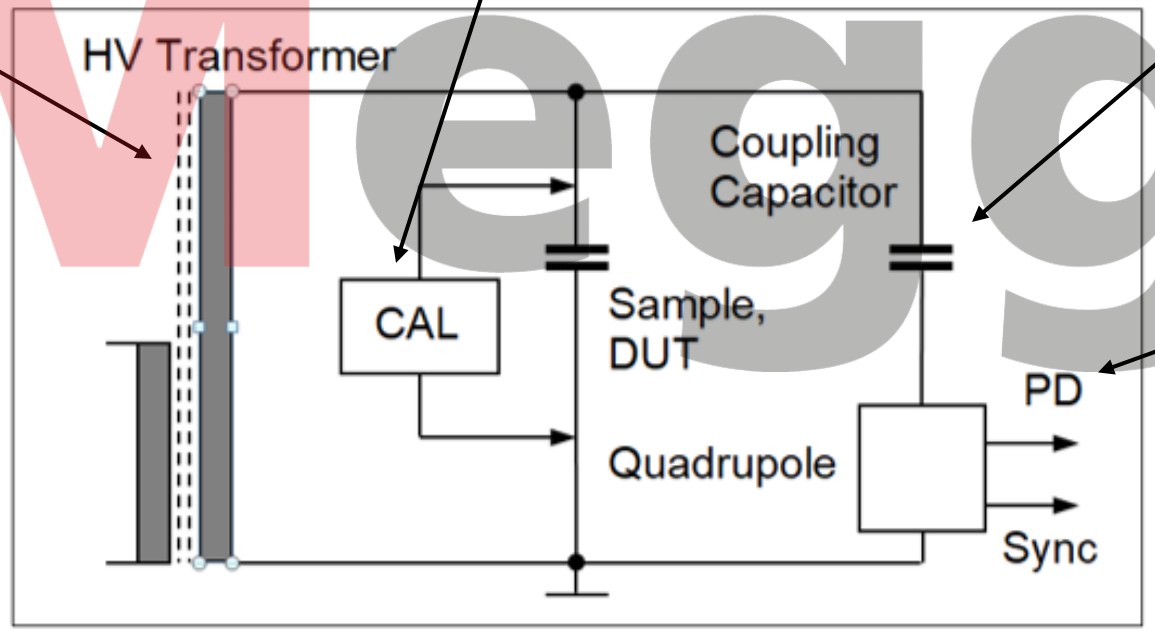


Laboratory Measurements



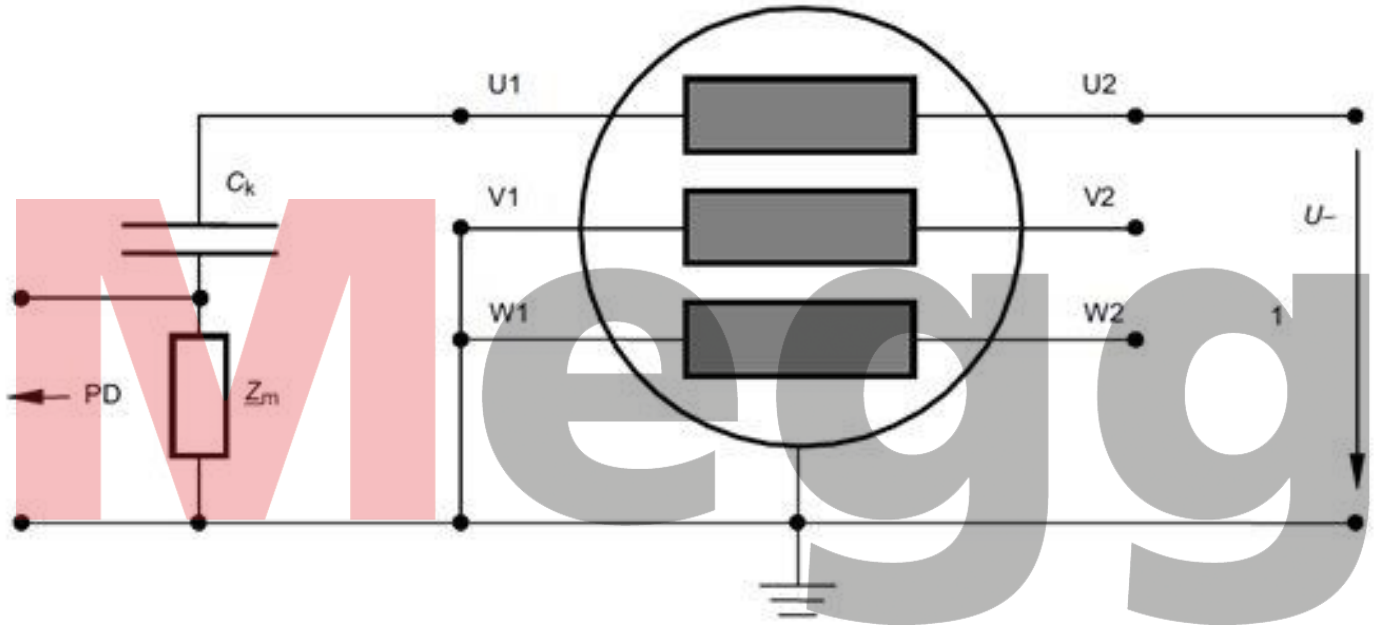
PD Calibrator
CAL1A

Coupling
Capacitor
CC200B/V



PD detector
ICM*compact*

Recommended Offline Test Circuits (1/2)

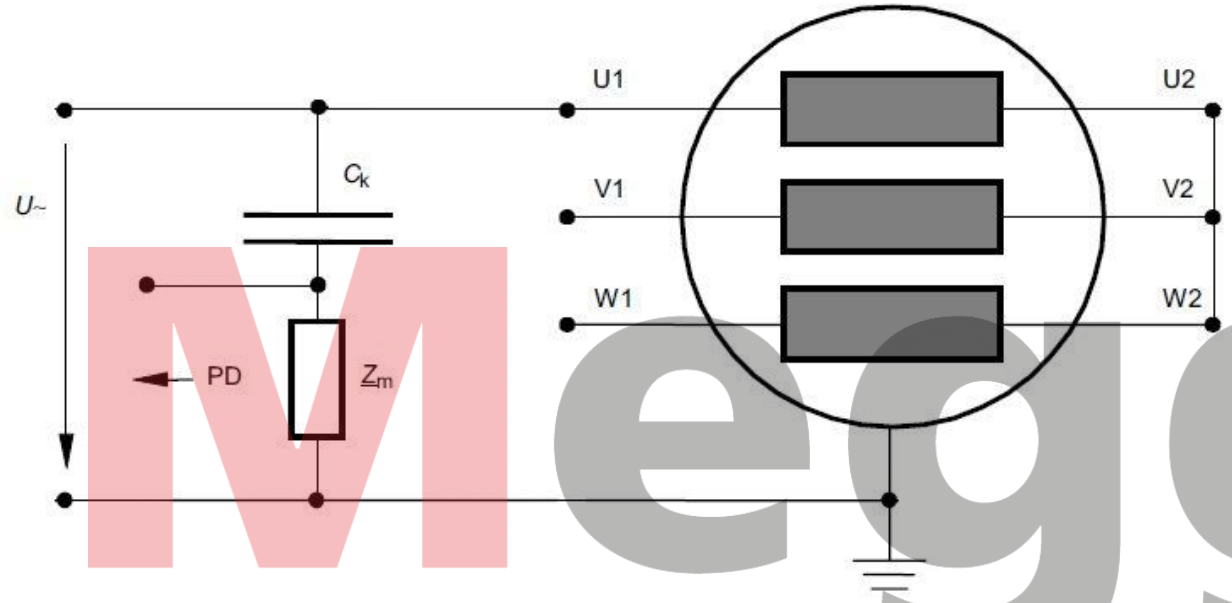


ID number	HV	Ground	C_K
E1.1	U1	V2W2	U2
E1.2	V1	U2W2	V2
E1.3	W1	U2V2	W2
E1.4	U1V1W1	-	U2V2W2

According to IEC TS 60034-27

- Motor or generator windings with accessible neutral connection allow energizing of complete winding to ground and the individual phases to ground

Recommended Offline Test Circuits (2/2)



ID number	HV	Ground	C_K
Accessible star point			
E2.1	U2V2W2	-	U1
E2.2	U2V2W2	-	V1
E2.3	U2V2W2	-	W1
E2.4	U1V1W1	-	U2V2W2
Inaccessible star point			
E2.5	V1	-	U1
E2.6	W1	-	V1
E2.7	U1	-	W1

According to IEC TS 60034-27

- Motor or generator windings with internal neutral connection allow energizing of complete winding only (phase to ground)

Motor/Generator Online Connection

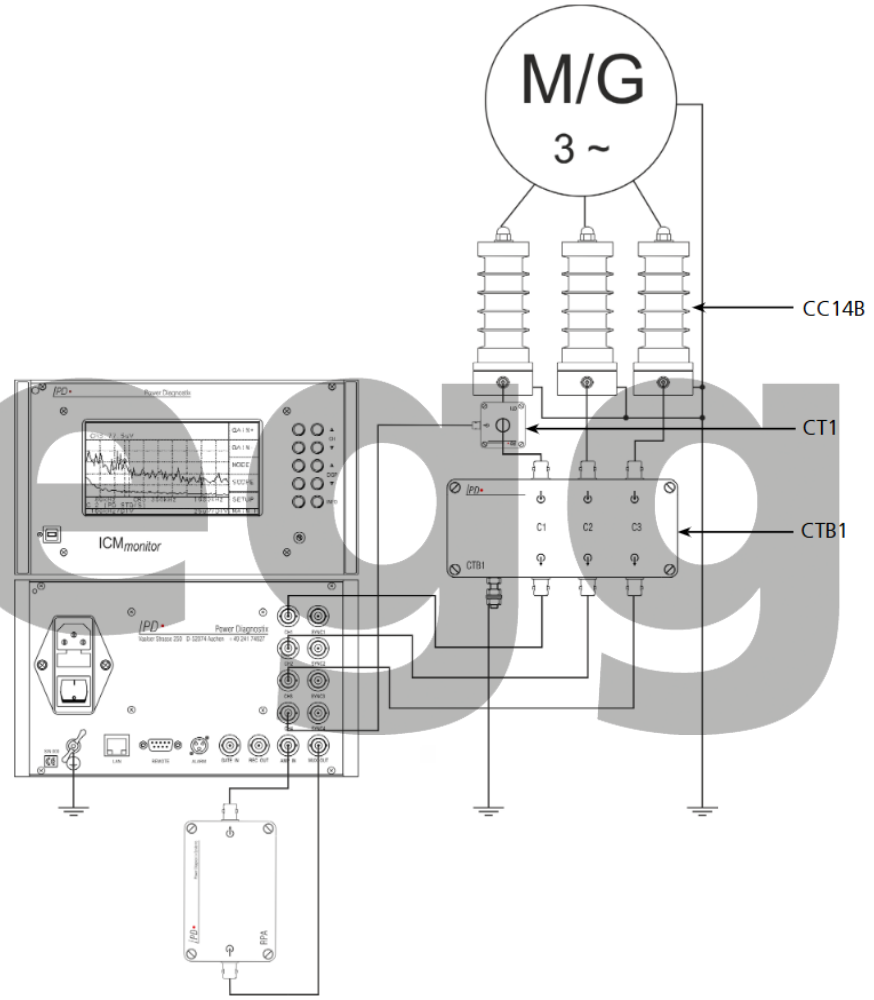
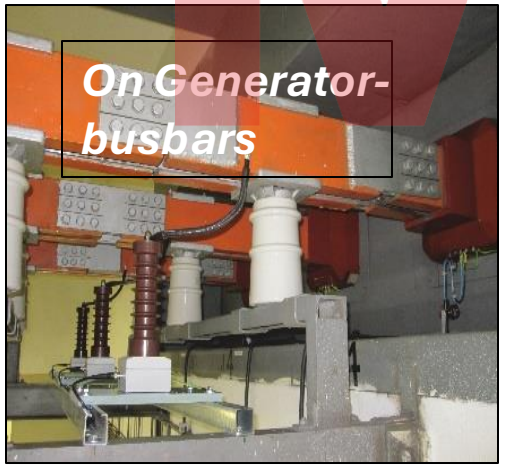


Figure Example connections of a standard ICMmonitor to a rotating machine

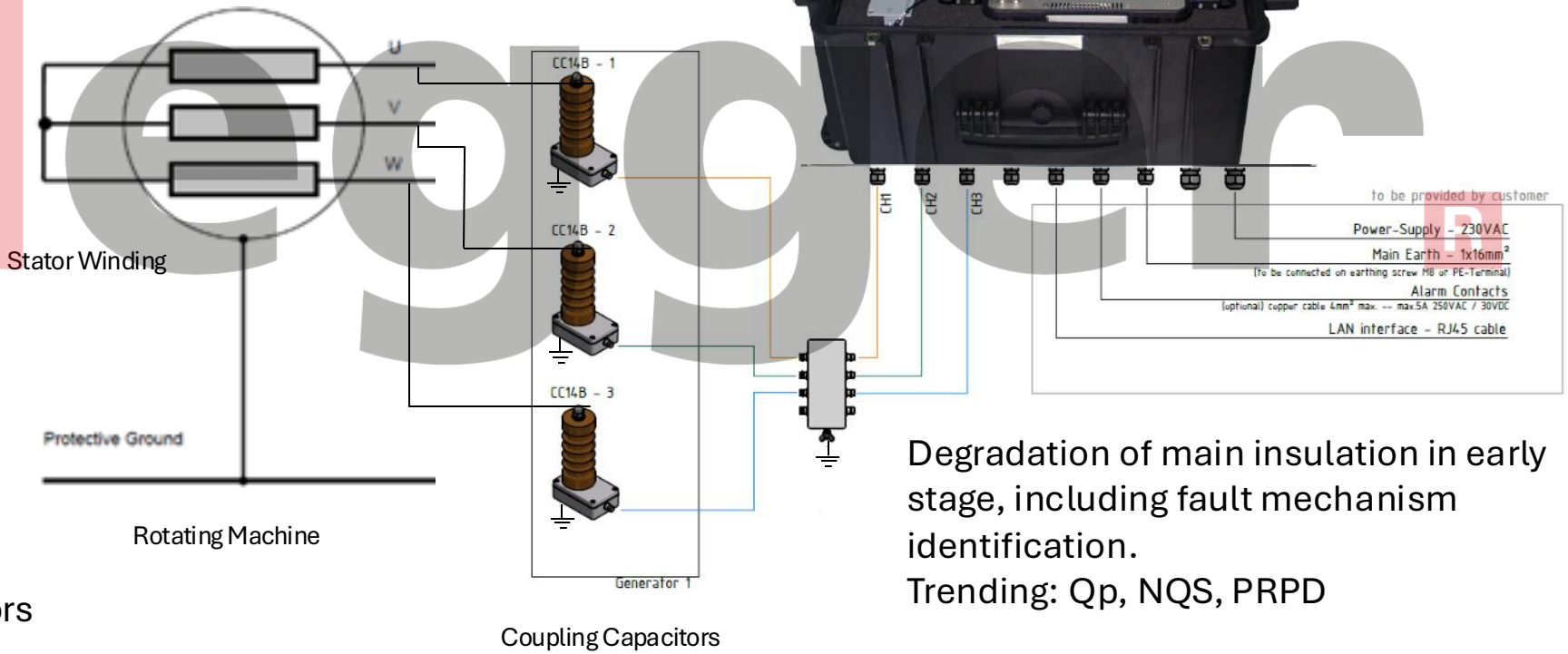
Monitoring of Rotating Machines

On Motor terminals



Examples of coupling capacitors installations

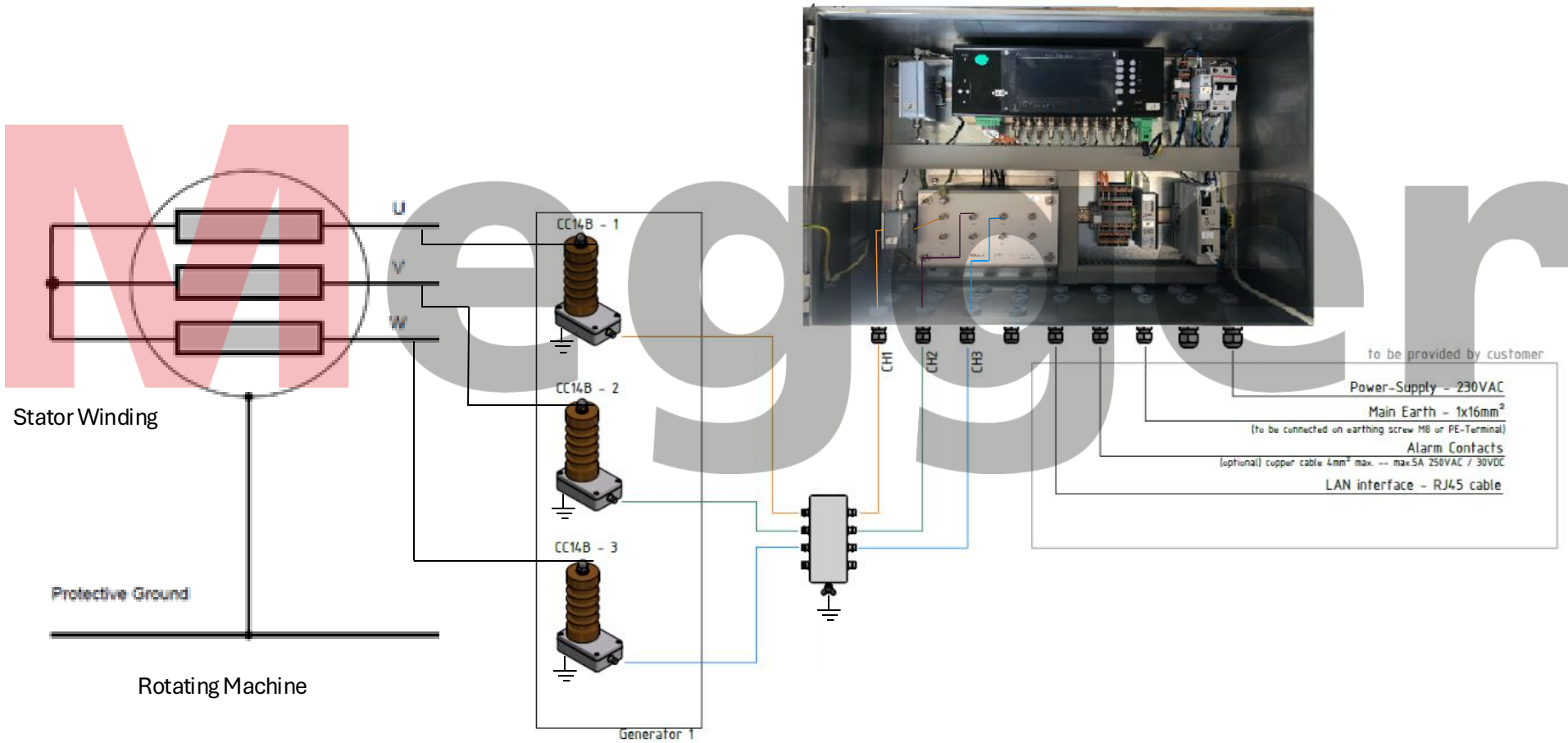
Portable Online PD-Monitoring System



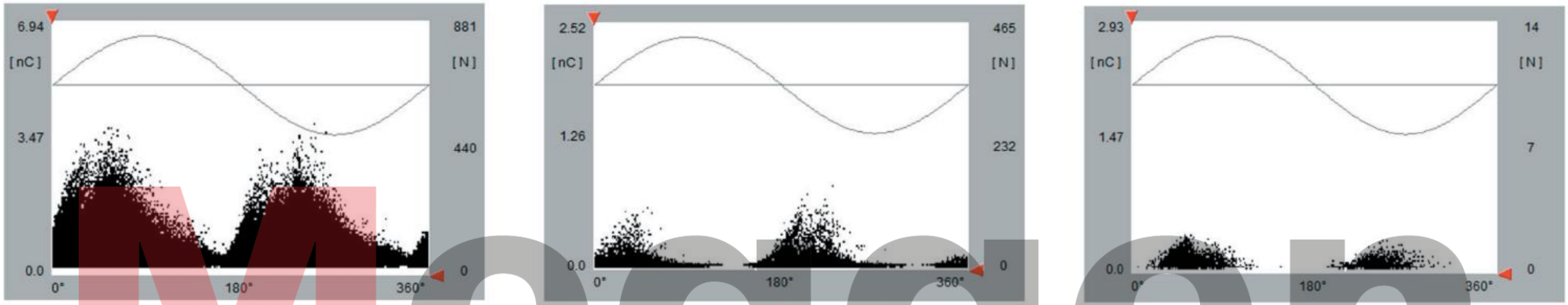
Degradation of main insulation in early stage, including fault mechanism identification.
Trending: Qp, NQS, PRPD

Monitoring of Rotating Machines

Permanently installed PD monitoring
system with remote access, automatic trending and alarming.



Effect of Frequency Bandwidth



40 – 800 kHz (IEC60270)
1215697 Counts

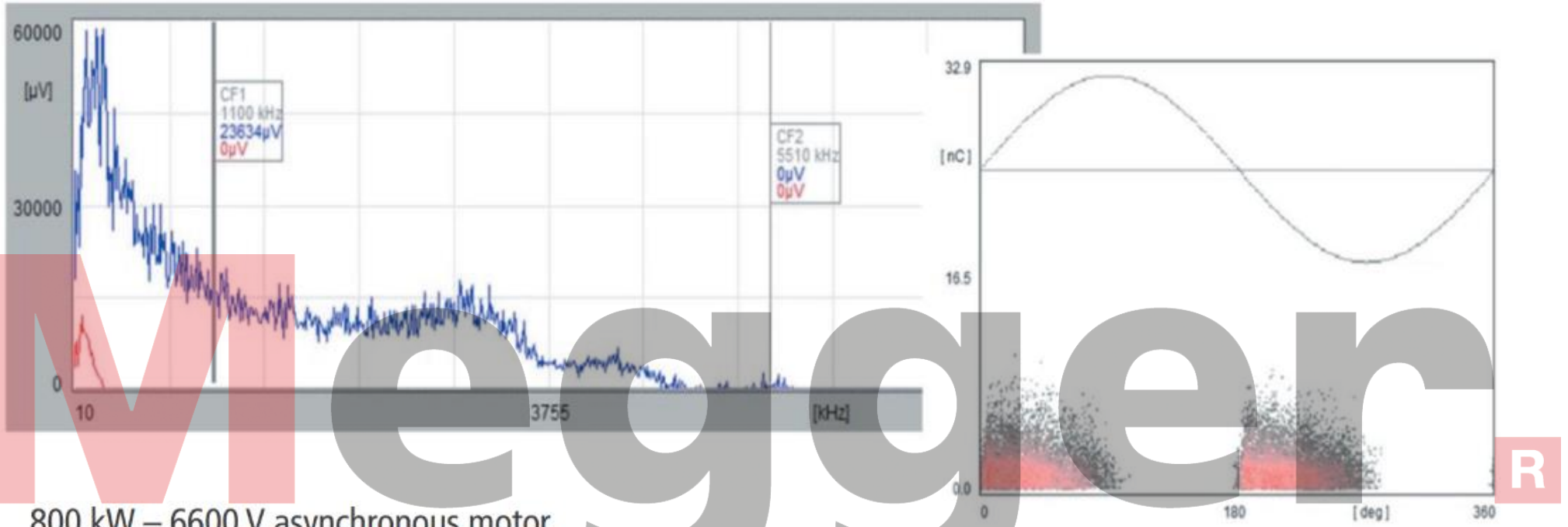
2 – 20 MHz
110843 Counts

20 – 200 MHz
2270 Counts

- 1200 kW – 6600 V asynchronous motor with internal neutral connection
- New VPI impregnated stator winding
- Off-line PD measurement, 60 s PD pattern acquisition (coupling capacitor)
- Same test object and test voltage, different band pass filters

Figure 1: Three tests on the same motor

Frequency Spectrum



- 800 kW – 6600 V asynchronous motor with internal neutral connection
- Internal PD activity in the main insulation (ground wall)
- Off-line PD measurement (conventional circuit acc. IEC 60270)
- Available signal up to 5.5 MHz

Figure 2: Frequency spectrum for PD test

Useful frequencies for electrical PD measurements

- Low Frequency Range (IEC 60270, < 1 MHz)

  - Best Coverage of the entire device under test
  - Partly hampered by Noise Interference
  - Best Choice for conventional Off-Line Tests

- Medium Frequency Range (2-20MHz)

  - Reasonable coverage (Signal Transmission)
  - Moderate Noise Situation
  - Best compromise for on-line monitoring (Survey Type)

- High Frequency Range (20-500MHz)

  - Limited coverage
  - Excellent near-field detection

- Ultra High Frequency range (300-3000MHz)

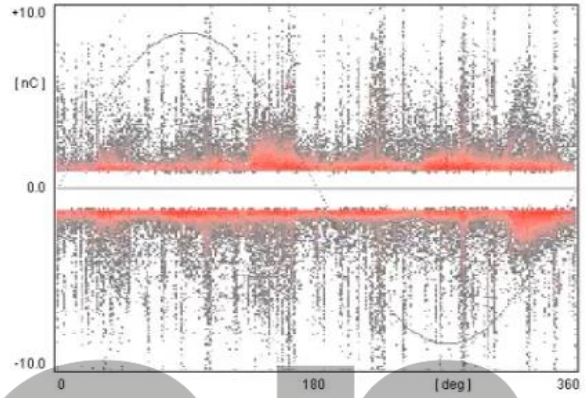
  - Reasonable Coverage, acceptable number of sensors
  - Comparably low Noise Interference

Noise Gating

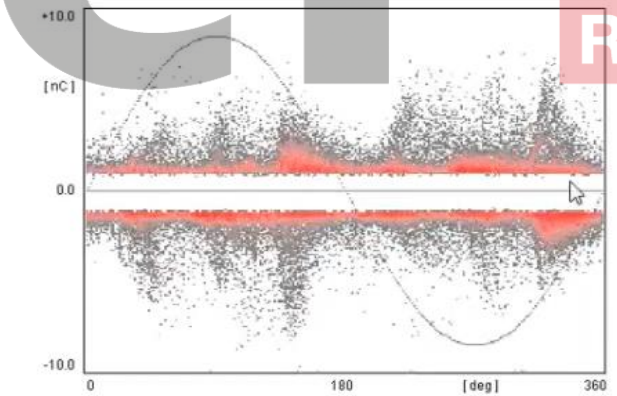
- CT1 or CT100 can pick up disturbance pulses from shields of signal cables or from ground connections
- Instrument interrupts PD measurement for the duration (in microseconds) of disturbance pulses.

CT100

CT1



PD Pattern & Brush Noise



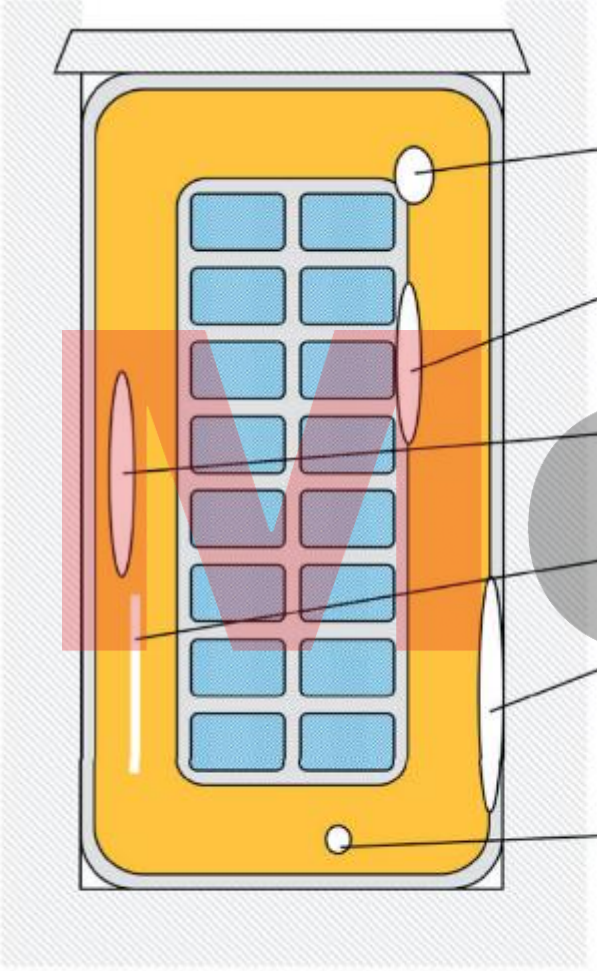
Brush Noise effectively gated

Stator Condition Assessment

- Failure root-cause investigations emphasize the importance of electrical and dielectric measurements

- A global recommendation for stator winding condition assessment:
  - Factory acceptance test (FAT) include offline PD and Tan Delta measurements as baseline reference
  - A first offline inspection 6-12 months after the commissioning
  - Further offline measurements every two years
  - Alternatively, Permanent installation of coupling capacitors for 6 months online measurements combined with offline every 4-5 years

Stator Bars Defects



A: Strongest electrical field

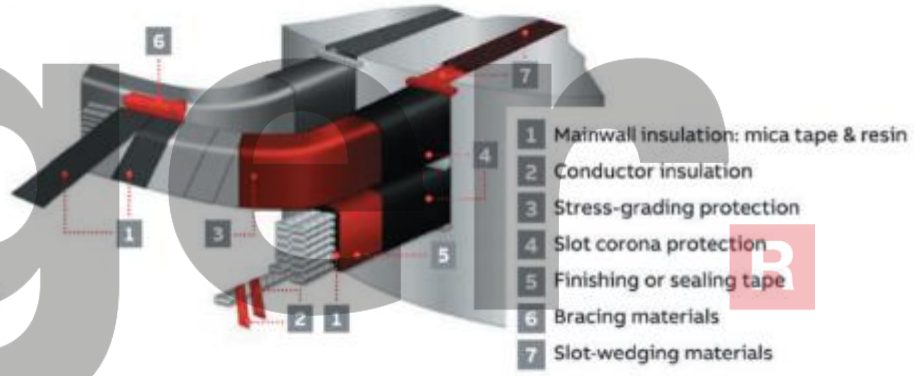
B: Delamination of the main insulation from the winding

C: Tape layer delamination

D: Treeing in layers

E: Ground wall delamination, so-called slot discharge

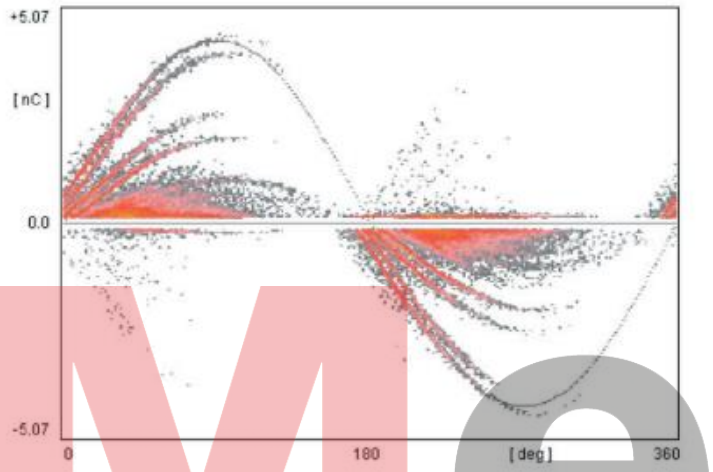
F: Internal voids

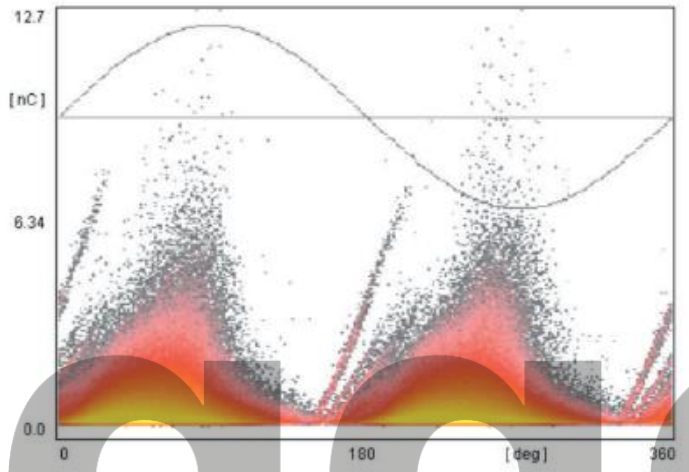


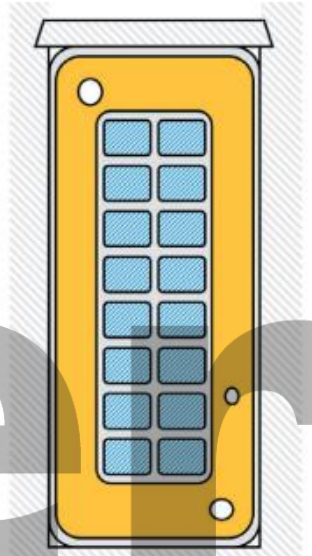
© ABB (white paper)

Figure 3: Defect locations in stator bars

Voids

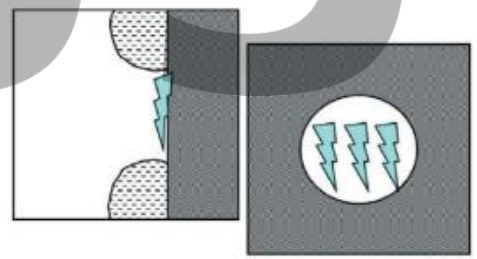






Symmetrical electrode configuration

- Multiple voids of different sizes
- Increased test voltage
- Voltage shaped clusters (line type pattern)
- Void and surface discharge



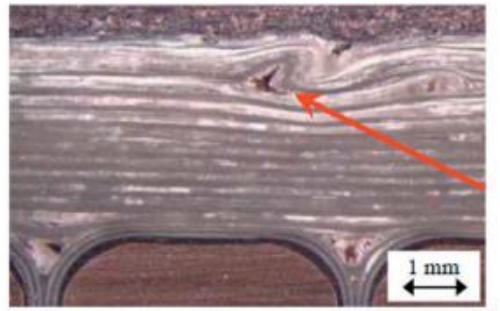
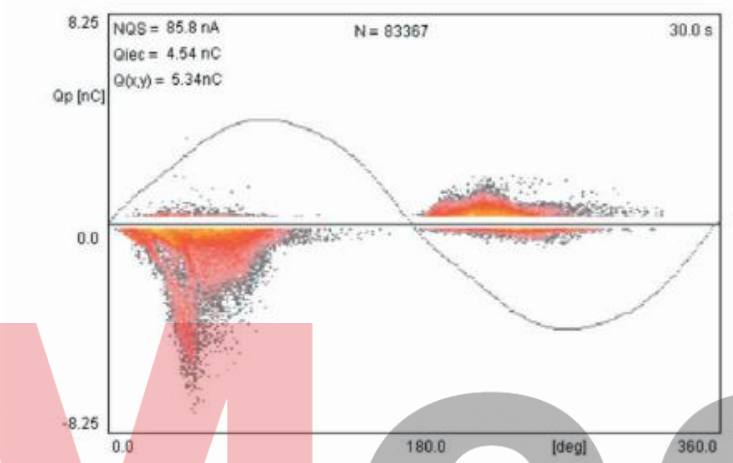
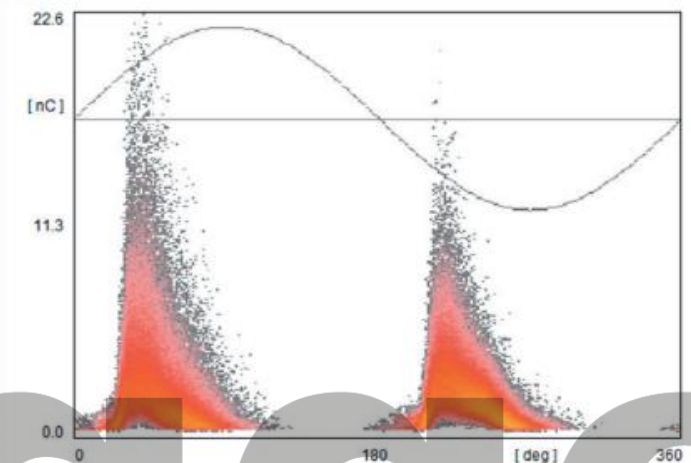
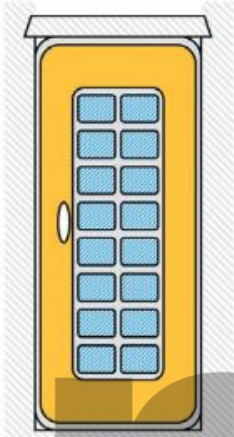


Figure 4: Void discharges

Delamination (Positive)







- Main pattern properties:
- Asymmetrical pulse distribution for both cycles
- Dominant positive cycle
- Delamination at inner conductor circuit
- Normal ageing: frequent load cycling (e.g. pump storage stations)

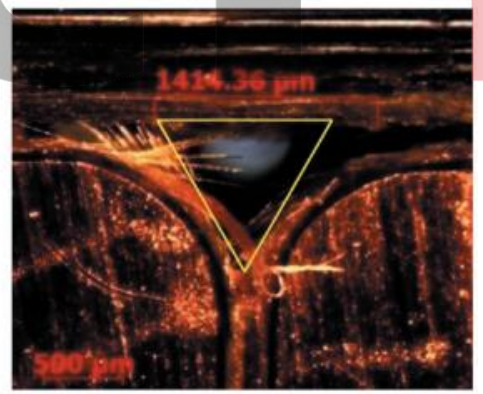
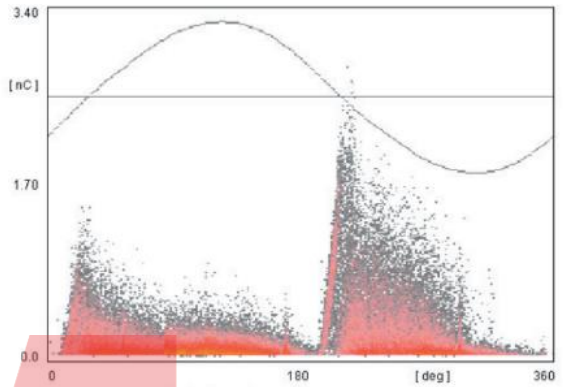
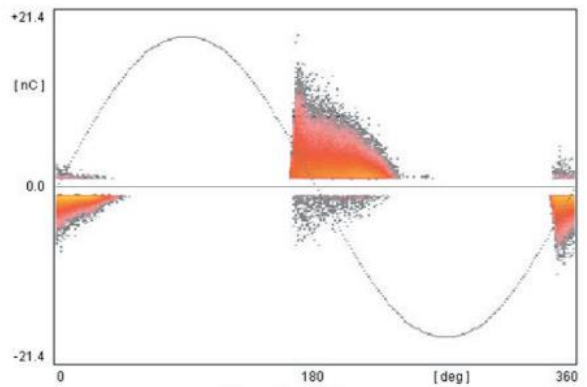


Figure 5: Conductor binding delamination

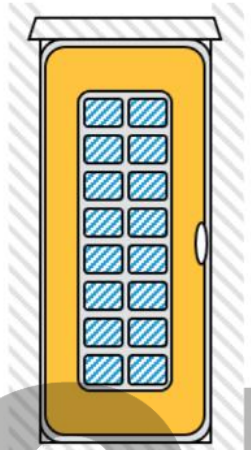
Delamination (Negative)



Unipolar Pattern



Bipolar Pattern



Asymmetrical electrode configuration

- Predominantly in the negative half cycle
- Often typical triangular pattern
- Strongly load dependent due to magnetic forces
- Delamination at the slot corona prevention layer
- Consequent high Ozone (O3) generation causing 'collateral damage'

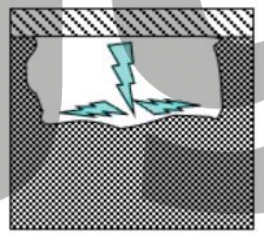
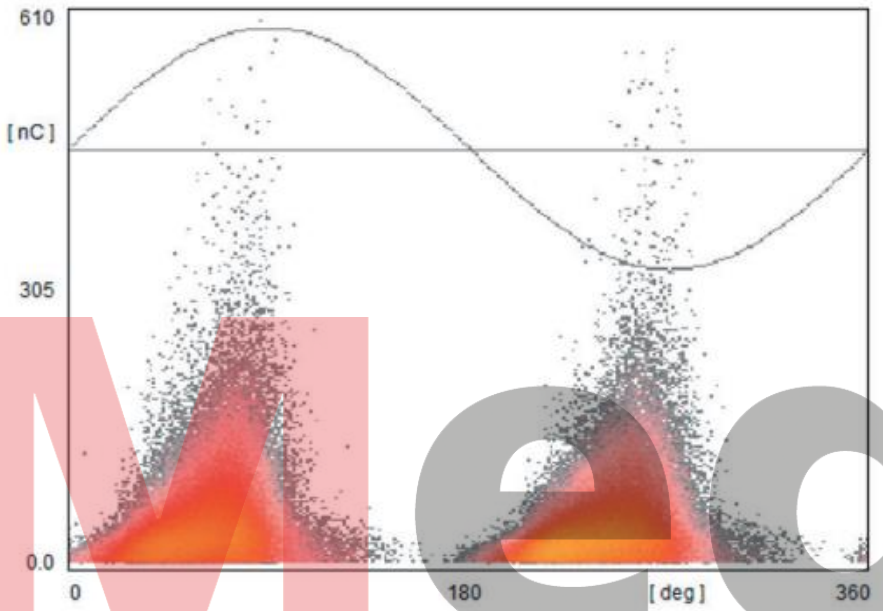
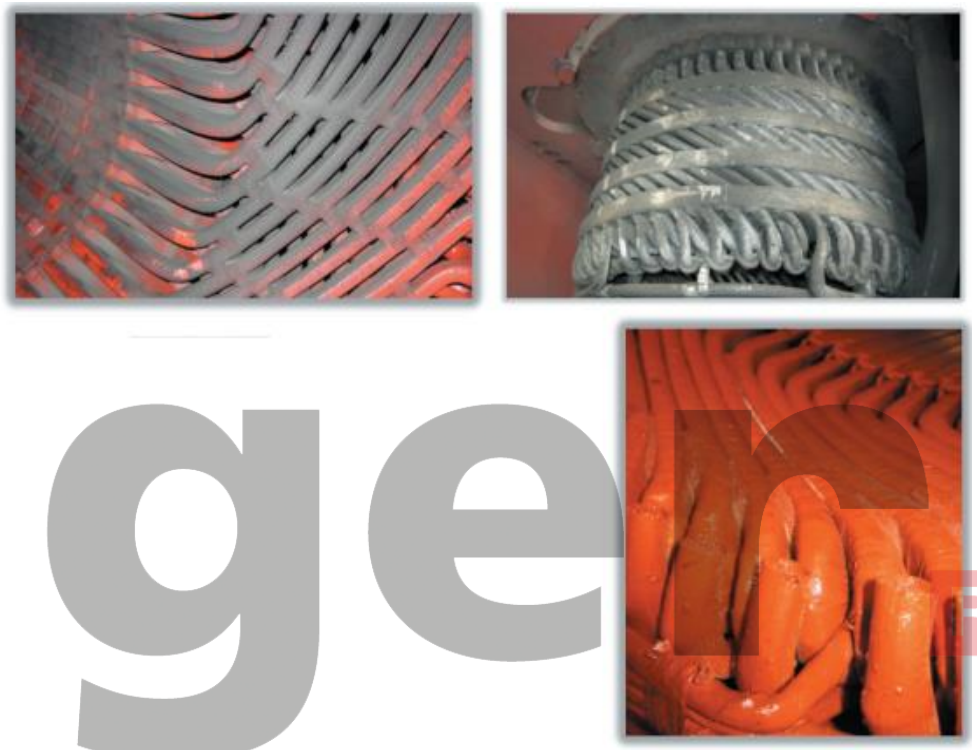


Figure 6: Slot discharge at machine bars

Surface Discharge



Contaminated overhang

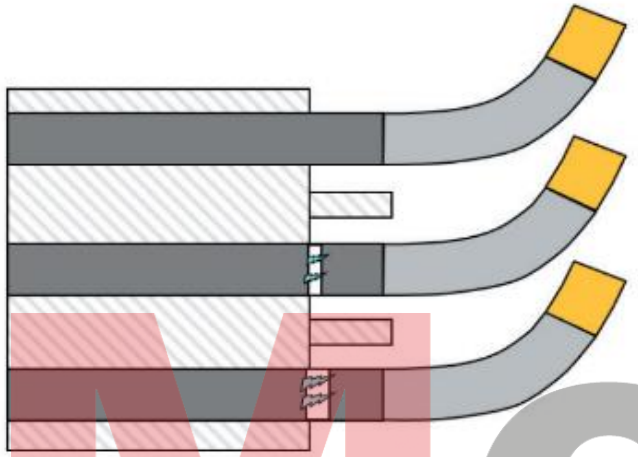


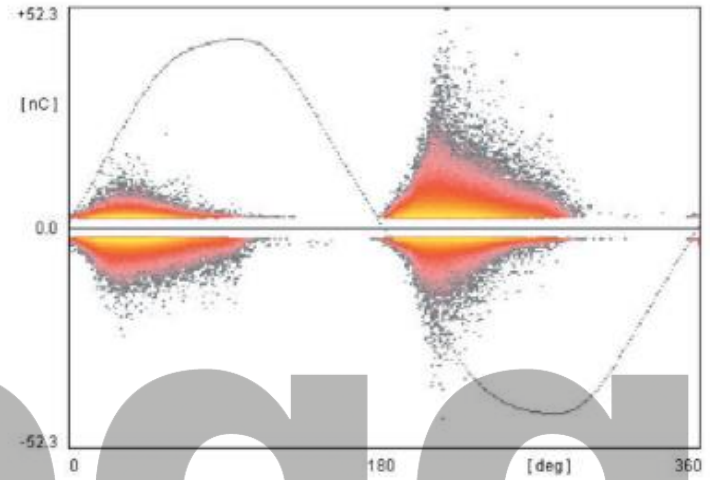
- Similar, often triangular, PD pattern for both half cycles (90°/270°)
- Strongly voltage dependent discharge magnitude

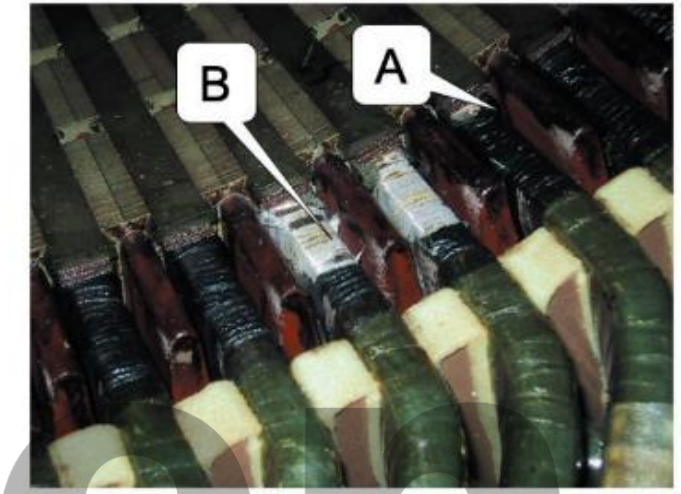
- Contaminated or moist insulation surface
- Insufficient spacing between windings
- Insufficient grading by the semi-conductive layer

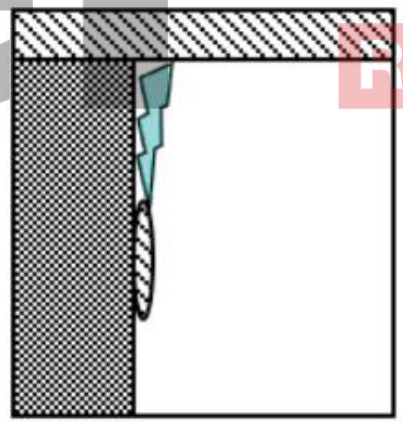
Figure 8: End winding surface discharge

Slot-Exit PD activity









Defect mechanism with vacuum impregnation systems

- Thermal stress causes surface cracks
- Initial state: surface discharge
- Discharge level: 10 – 50 nC
- Gap grows due to the PD 'consuming' insulation

Figure 9: Slot-exit PD activity – initial stage

Off-line vs On-line

- Off-line Testing (IEC 60270)
  - Most important for laboratory and workshop setups
  - Requires separate power supply to induce PD activity
  - Device under test has to be taken out of service
  - Gas type, pressure, and humidity may differ from the operating condition
  - Noise sources, other than possibly radiated noise, can be eliminated
  - Measurement can be accurately calibrated
  - Voltage level can be adjusted.
  - PDIV and PDEV can be measured.
- On-line testing
  - Typical for commissioning / testing on-site
  - 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

Summary

- PD monitoring helps to assess the insulation health of Hydro generators, Turbo generators, motors, or other RMs
- PD Trending and changing PD patterns indicate incipient failure
- PD pattern analysis assists with failure Investigations (root cause analysis
- Added value id PD monitoring is combined with load, temperatures, and other values.

We are providing PD solutions for a wide customer base

Original equipment manufacturer (OEMs)

Power Utilities

Heavy industry

Repair shops

Service Providers

Test laboratories

Providing partial discharge solutions based on your purpose and need

Applications

- Quality assurance & quality control (e.g. Factory acceptance test)
- On-site offline testing
- On-site online testing
- Permanent monitoring
- Temporary monitoring

Assets

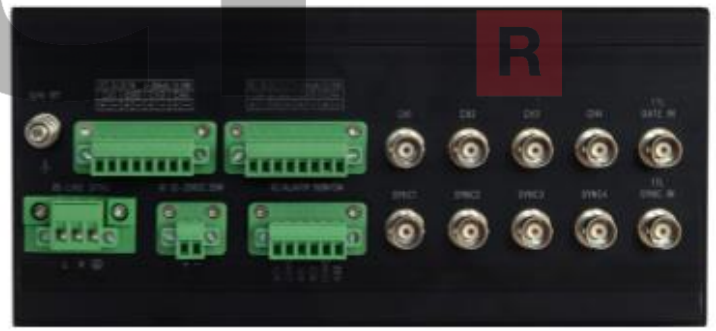
- Transformer
- Rotating Machine
- Cable
- GIS
- AIS

ICMobserver

- Versatile partial discharge (PD) monitoring system for all types of medium and high voltage assets
- Fully parallel voltage and PD measurement on all channels
- Remote access and analysis options
- State-of-the-art digital signal processing for an immediate data display and in-depth analysis without the need for further equipment
- Partial discharge measurements according to IEC 60270

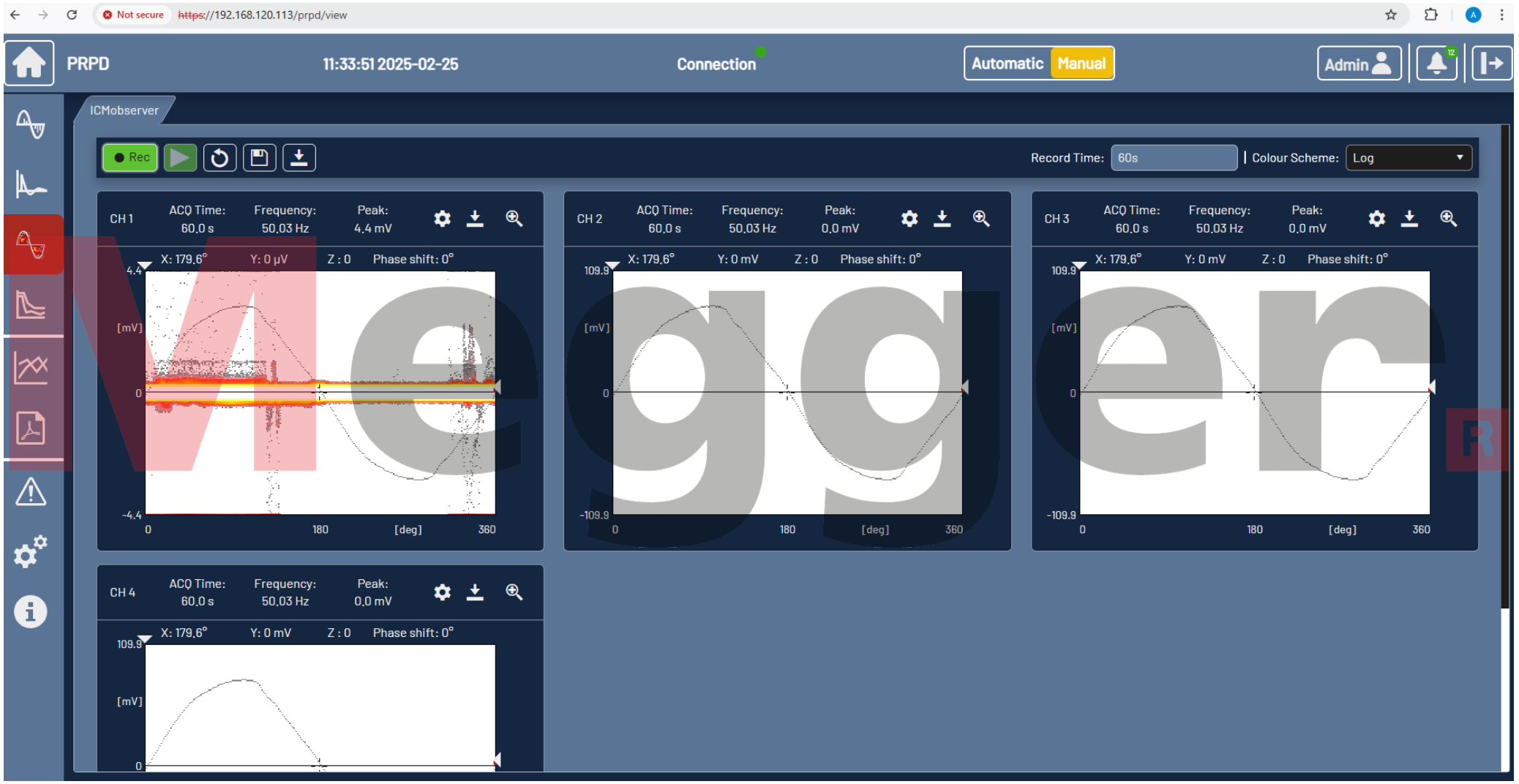
Standard Features

- PD spectrum analysis for the selection of frequency bands with less disturbances
- Adjustable bandwidth from a few kHz to 10 MHz
- Parallel phase-resolved partial discharge measurement for up to four channels
- Parallel digital oscilloscope for fault location on power transformers and cables
- Effective noise gating for blocking phase-stable or phase-independent noises
- Four analogue inputs for monitoring additional environmental conditions, such as temperature and drive
- For analogue outputs for external monitoring purposes
- Web server for automatic data acquisition and storing for trend analysis, PRPDs, alarming, and reporting
- Built-in web-interface for access via PC or tablet without additional software

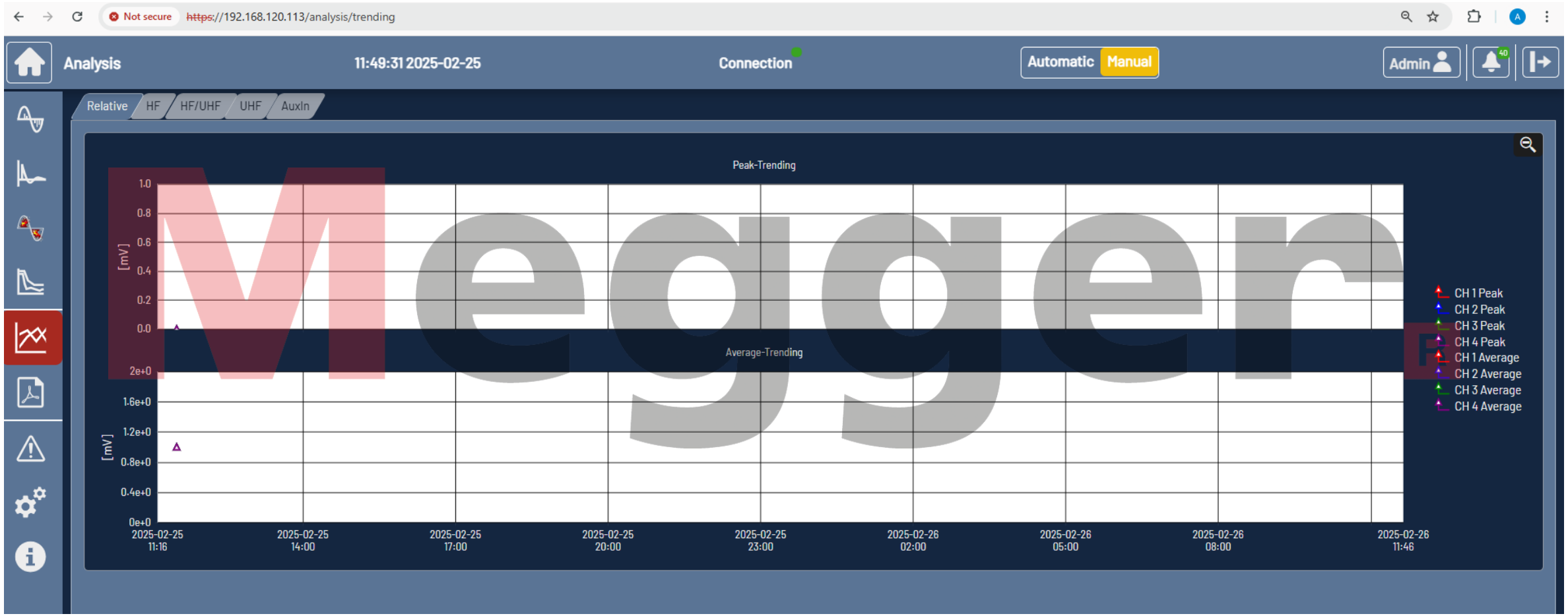


ICMobserver Software Dashboard

Phase Resolved Partial Discharge Pattern

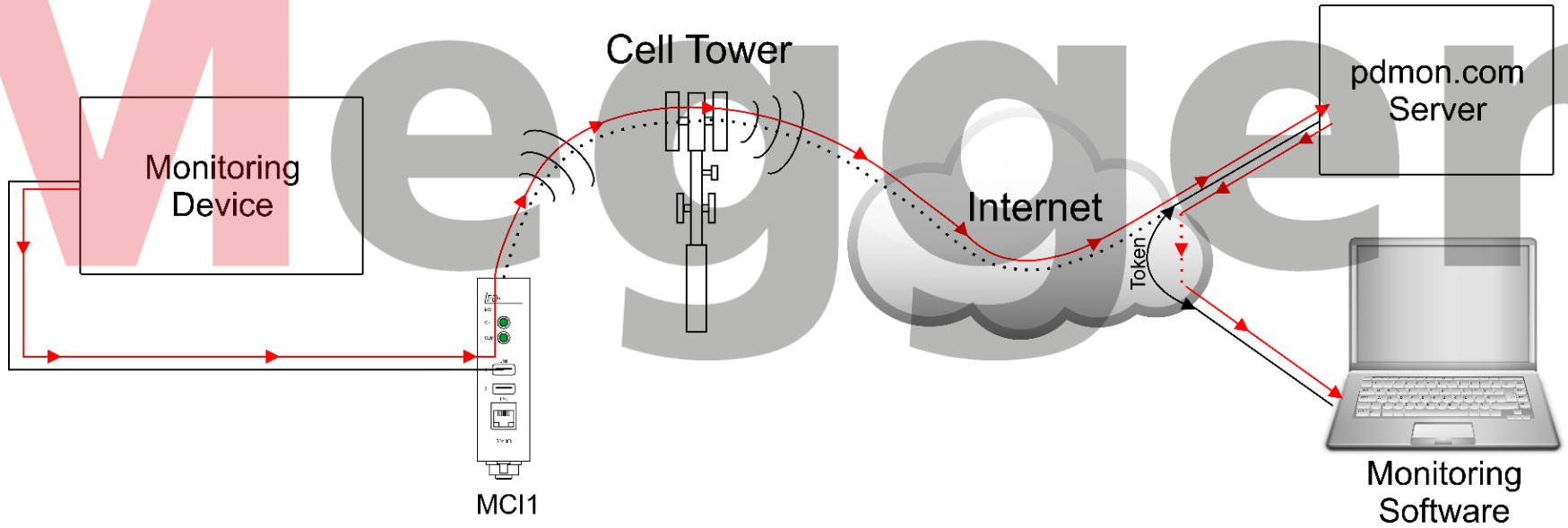


PD Trend



Monitoring Web Server

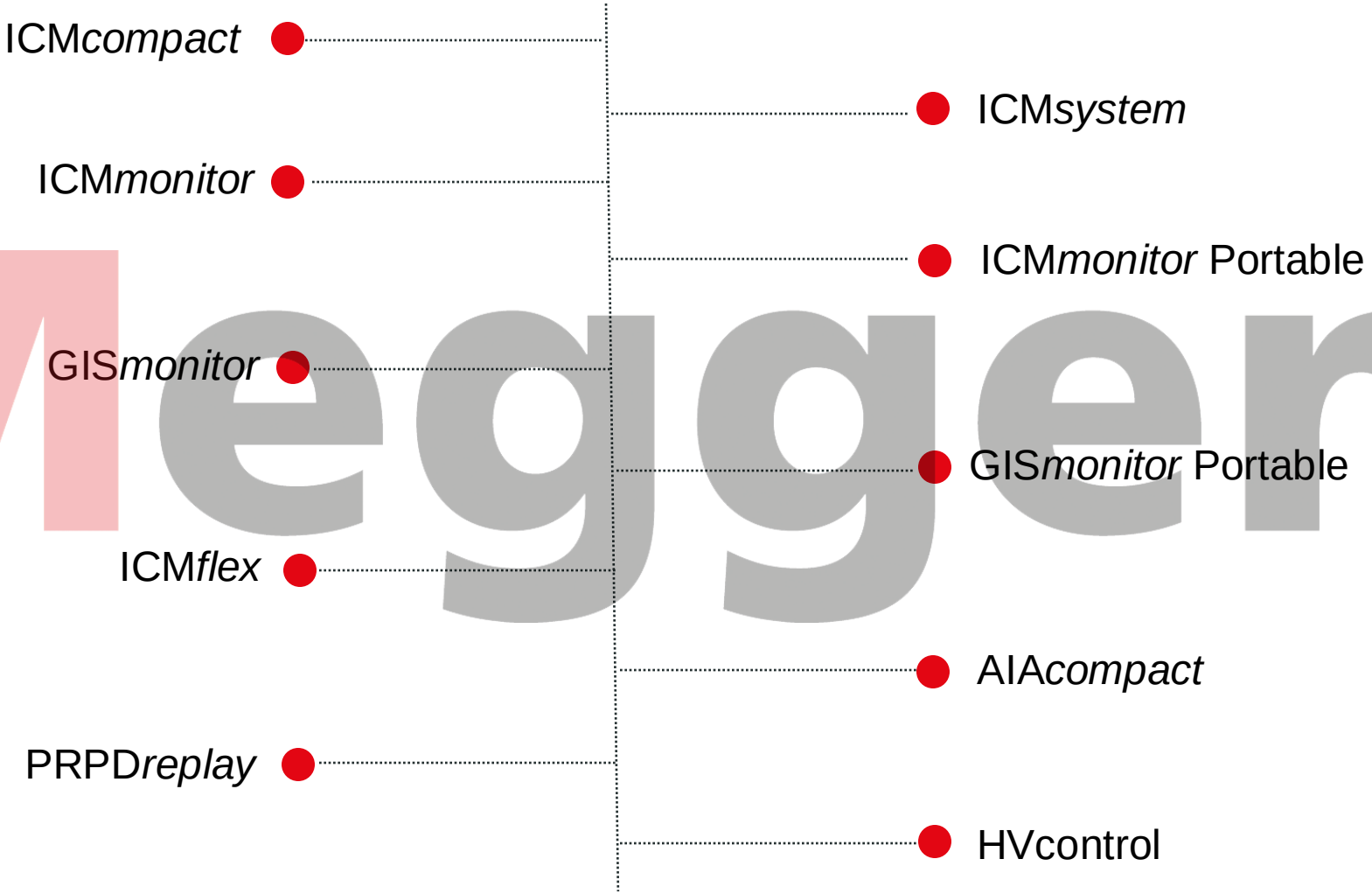
Mobile Communication Interface (MCI) allows remote access via 3G/4G/5G



Accessories for PD Measurements

- Coupling Capacitors
- HV PD Filters
- Quadrupoles
- Preamplifiers
- PD & RIV Calibrators

Our product portfolio covers various partial discharge needs



Our partial discharge measurement devices

ICM*compact*

What makes it special?

- Stand-alone partial discharge device
- Quality assurance and quality control (end-of-line, FAT)
- Available in various housing (Stand-alone, In-house device (test bench), portable version)

Customer groups

- Repair shops*
- OEMs*
- Power utilities
- Heavy industry
- Service providers
- Test laboratories

Applications

- Factory acceptance test
- On-site online test
- On-site offline test

Assets

- Transformer
- Rotating Machines
- Cable

ICM*system*

The better fit for your purpose?

- Universal PD device
- Highest grade of modularity and versatility
- Parallel measurement: Reduces overall testing time with multichannel option
- For complex measurements

Customer groups

- Repair shops
- OEMs
- Power utilities
- Heavy industry
- Service providers
- Test laboratories

Applications

- Factory acceptance test
- On-site offline test
- On-site online test

Assets

- Transformer
- Rotating machine
- GIS
- AIS
- Cable

*more common usage for these customer groups

Our monitoring devices for all your assets

ICM*monitor*

What makes it special?

- Monitor insulation condition (MV & HV)
- Remote access with Monitor Web Server (MWS)

→ Always aware of asset‘s conditions

- Ideal noise handling
- Various versions specified for intended purpose

ICM*monitor* DIN rail with MWS

Customer groups
- Power utilities*
- Heavy industry*
- OEM (indirect customer)

Applications
- Permanent online monitoring
- On-site online test
- On-site offline test

Assets
- Transformer
- Rotating
- GIS
- AIS
- Cable

ICM*monitor* Portable

Why it might a better fit?

- Portable solution of a monitoring system
- Flexibility to monitor one asset after another for a limited period
- With ICM*outlander* (Protective housing) monitoring under all weather conditions and environments

→ Reliable and precise results

Customer groups
- Power utilities*
- Heavy industry*
- Service providers*
- Repair shops

Applications
- Temporary online monitoring
- On-site online test
- On-site offline test

Assets
- Transformer
- Rotating machine
- GIS
- AIS
- Cable

*more common usage for these customer groups

ICMoutlander

- Water resistant (IP65) and dust tight
- Climate controlled -40 C to 85 C outside temperatures
- ICMmonitor portable built-in
- Monitoring Web Server (MWS) built-in
- Accessories and cables in one box

ICMOutlander

Our specialized solutions for GIS

GIS*monitor*

What makes our GIS*monitor* unique?

- Specialized continuous monitoring device for GIS
- Suitable for embedded + external UHF sensors available in the market
  → Allows retrofitting of existing GIS
- Real-time monitoring of multiple assets with multichannel system
- Up to **120** measurement channels in parallel
- Available in different versions

Customer groups
- Power utilities*
- Heavy industry*
- OEM (indirect customer)

Applications
- Permanent online monitoring
- On-site online test

Asset
- GIS

GIS*monitor* Portable

Reasons for the portable version

- Offered as a standardized solution
- Portable monitoring version for GIS
  → For temporary GIS monitoring
- Flexible solution, can be used for several GIS at your site
- Up to 40 measurement channels in parallel

Recommended: HV testing on single or three phase encapsulated GIS

Customer groups
- Power utilities*
- Heavy industry*
- Service providers
- Repair shops

Applications
- Temporary online monitoring
- On-site online test
- On-site commissioning

Asset
- GIS

*more common usage for these customer groups

Other supportive PD solutions

ICM*flex*

How can it support you?

- Measures **partial discharge** and **tan delta simultaneously**
  → Results can be shown on the display at the same time
  → Saves time and cost
- Delivers reliable valid results

Customer groups

- **Repair shops* (on-site)**
- **Service Providers***
- OEM
- Power utilities
- Heavy industry
- Test laboratories

Applications

- Factory acceptance test
- On-Site offline test

Assets

- Rotating machine
- Cable

AIA*compact*

The right additional support

- Light-weight compact instrument for acoustic & electric (UHF) PD
- Easy setup – automatic sensor detection
- Works independently with battery

Customer groups

- Power utility
- Heavy industry
- Service providers
- Test laboratories

Applications

- On-Site offline test
- On-site online test

Assets

- GIS
- Transformer
- Cable accessories

*more common usage for these customer groups

Thank you for your attention!