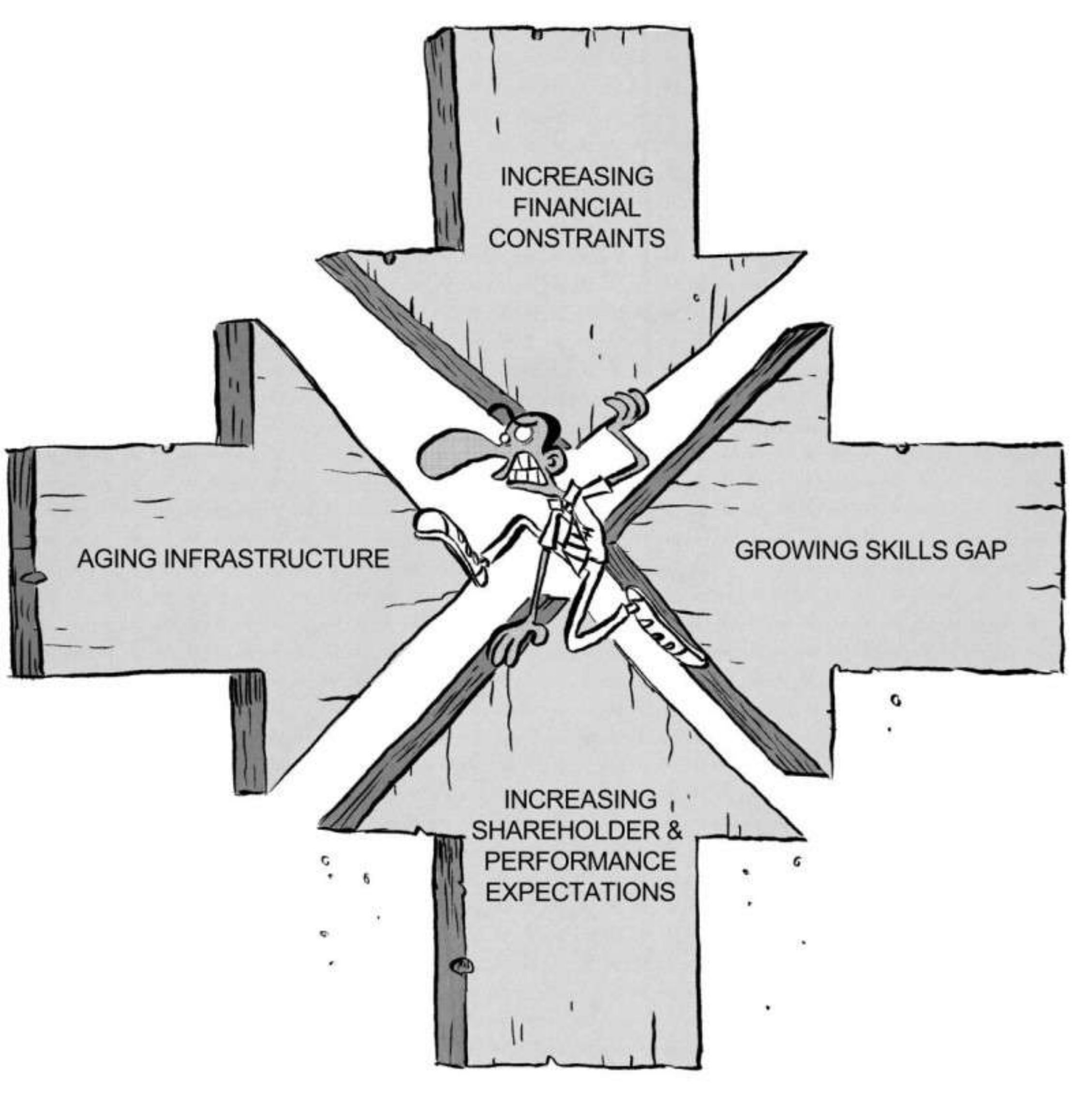
CONDITION ASSESSMENT OF ELECTRICAL APPARATUS: A BUILDING BLOCK FOR ASSET MANAGEMENT



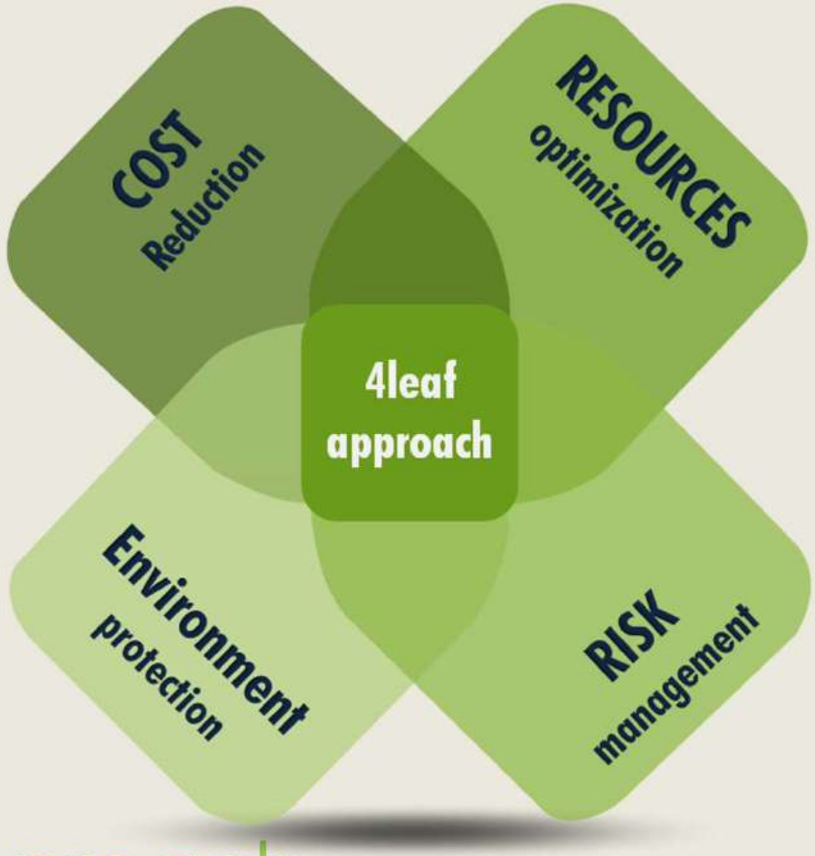
Always under pressure, Asset Managers need unique and unambiguous

ANSWERS

in order to operate infrastructures in the safest and most economic way.

A **GLOBAL approach** to **Asset Management is needed**.

- Risk management
- Resources optimization
- Cost reduction
- Environmental protection



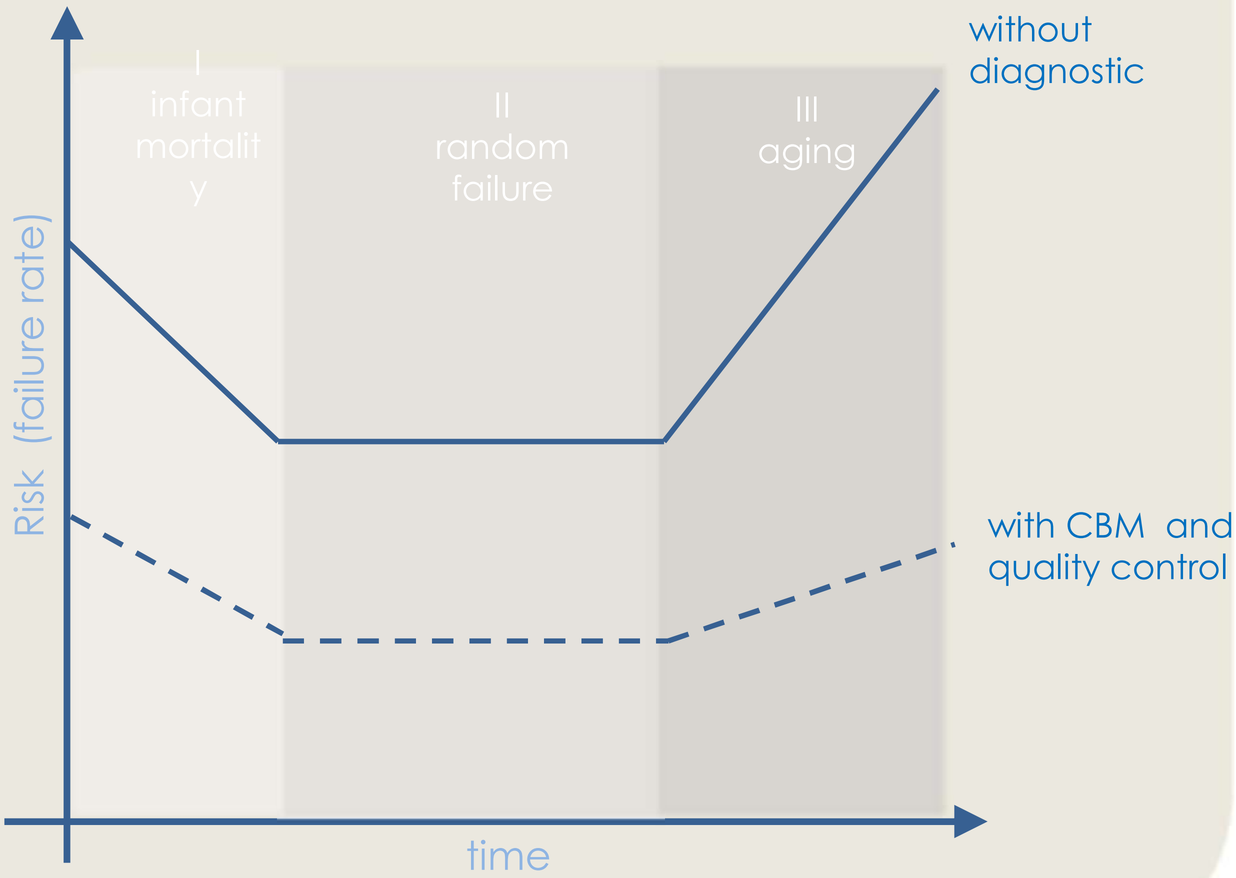
are the main benefits of the 4leaf approach

Risk Management

Why Condition Based Maintenance (CBM)?

Lower failure risk for the whole life.
Extended life!

- failures
- outages
- production losses
- damages
- penalties



"bathtub curve" according to the failure rate

Diagnostic properties

- Bulk diagnosis:
  - Polarization/depolarization currents
  - Dielectric spectroscopy
  - Insulation resistance
  - DGA or furan monitoring
  - Space charge
  - Dissipation factor
  - …

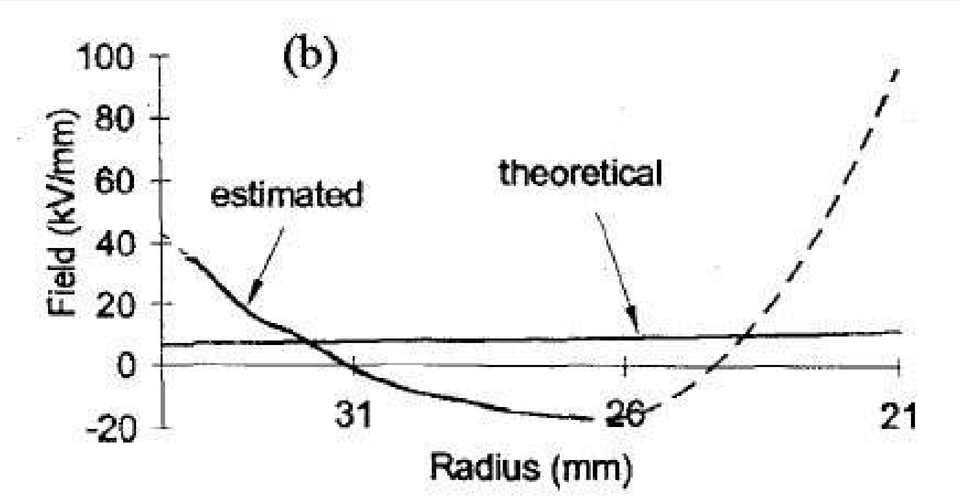
Overall (generally not so fast) degradation processes are evidenced through these techniques

- Local diagnosis
  - Partial discharges
  - Hot spot monitoring
  - ….

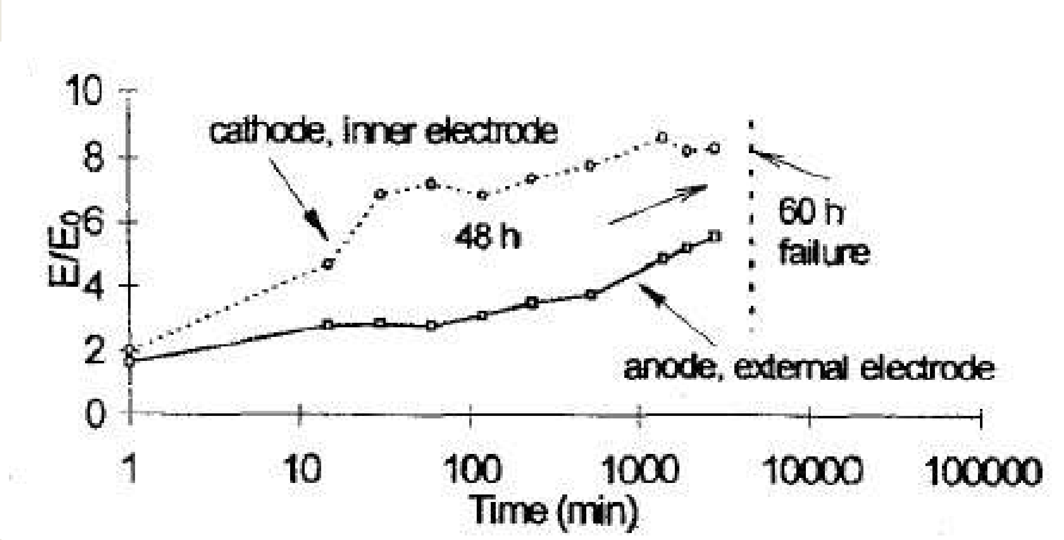
Often fast degradation processes can be evidenced through these techniques
Measure frequently diagnostic markers

Example: space charge measurements

Technique to observe and measure the amount of space charge and electric field profiles in electrical insulation → Crucial for aging and breakdown of DC insulation



Electric field distortion in cable insulation due to space charge accumulation

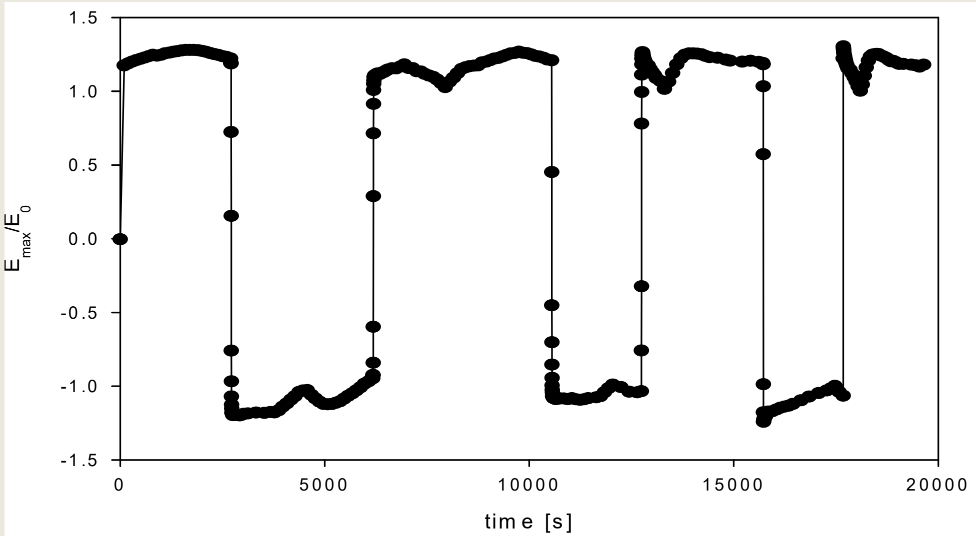


Cathode and anode electric field evolution during polarization until breakdown

Example: space charge measurement

- Space charge and field profile evolution

Space charge pattern as a function of time under DC voltage polarity inversion (warm colors=positive charge, cold colors=negative charge, K=cathode, A=anode)



Time behavior of maximum electric field magnification due to space charge accumulation in a LDPE flat specimen (laplacian field, E_0 = 120 kV/mm).

Why PD as major diagnostic marker

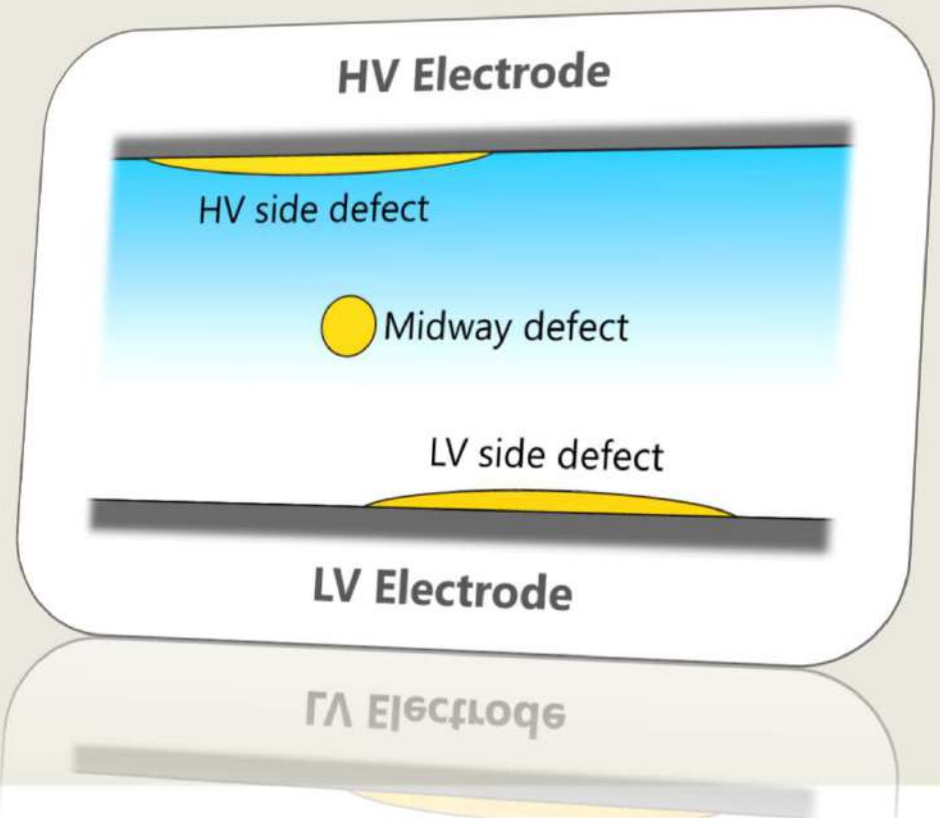
- Diagnostic marker for local defects
- Ageing factor in organic materials
- Often fastest aging mechanism
- Most harmful cause of breakdown

Partial discharge (PD)

Localized electrical discharge that only partially bridges the insulation between conductors and which can or can not occur adjacent to a conductor.

PD normally occurs in gas gaps or on insulation surfaces, due to defects in the insulation system.

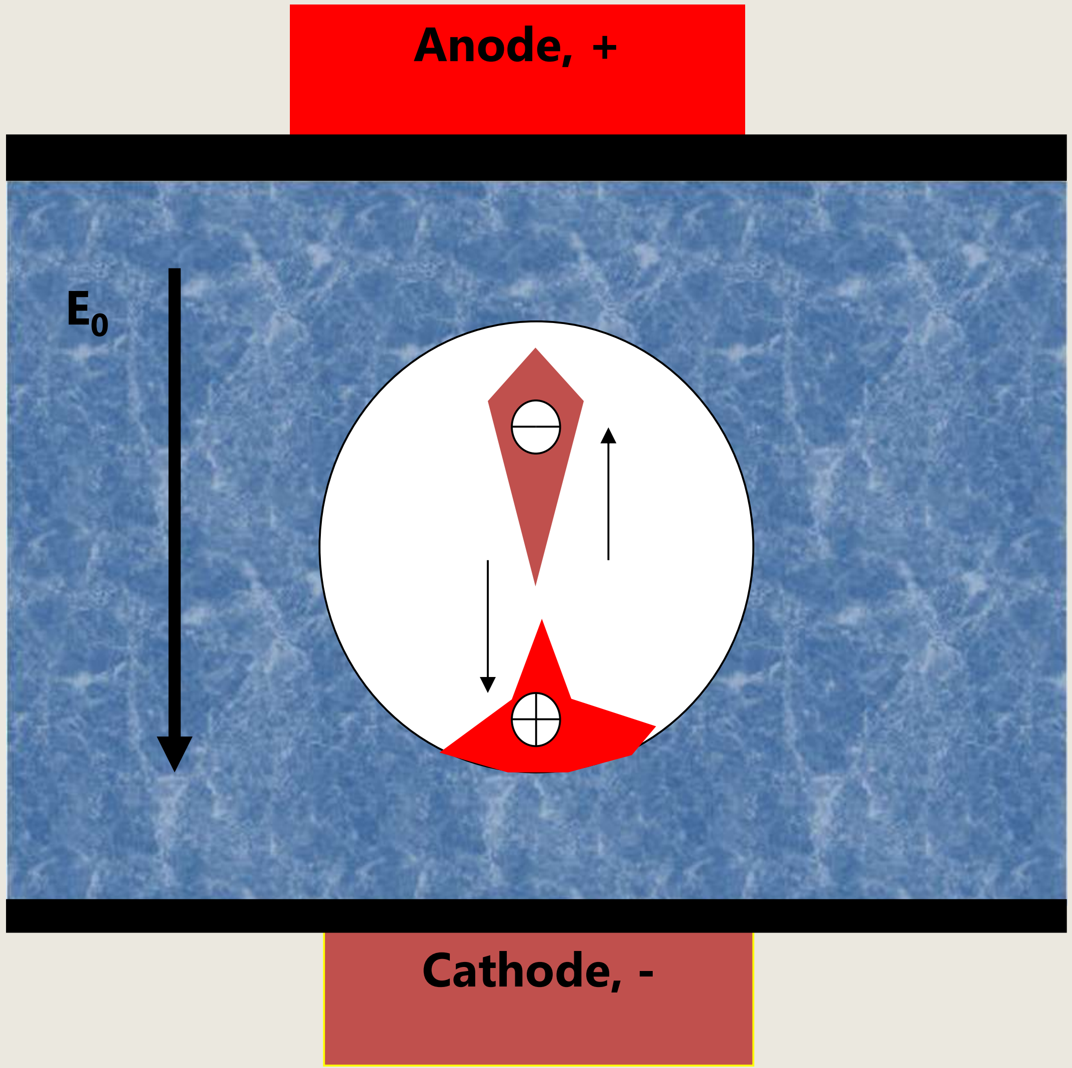
Since PD are related to insulation ageing, they are cause and effect of insulation degradation.



What happens during a PD

The PD transfers:

- Electrons to the cavity surface acting as anode
- Positive ions to the cavity surface acting as cathode

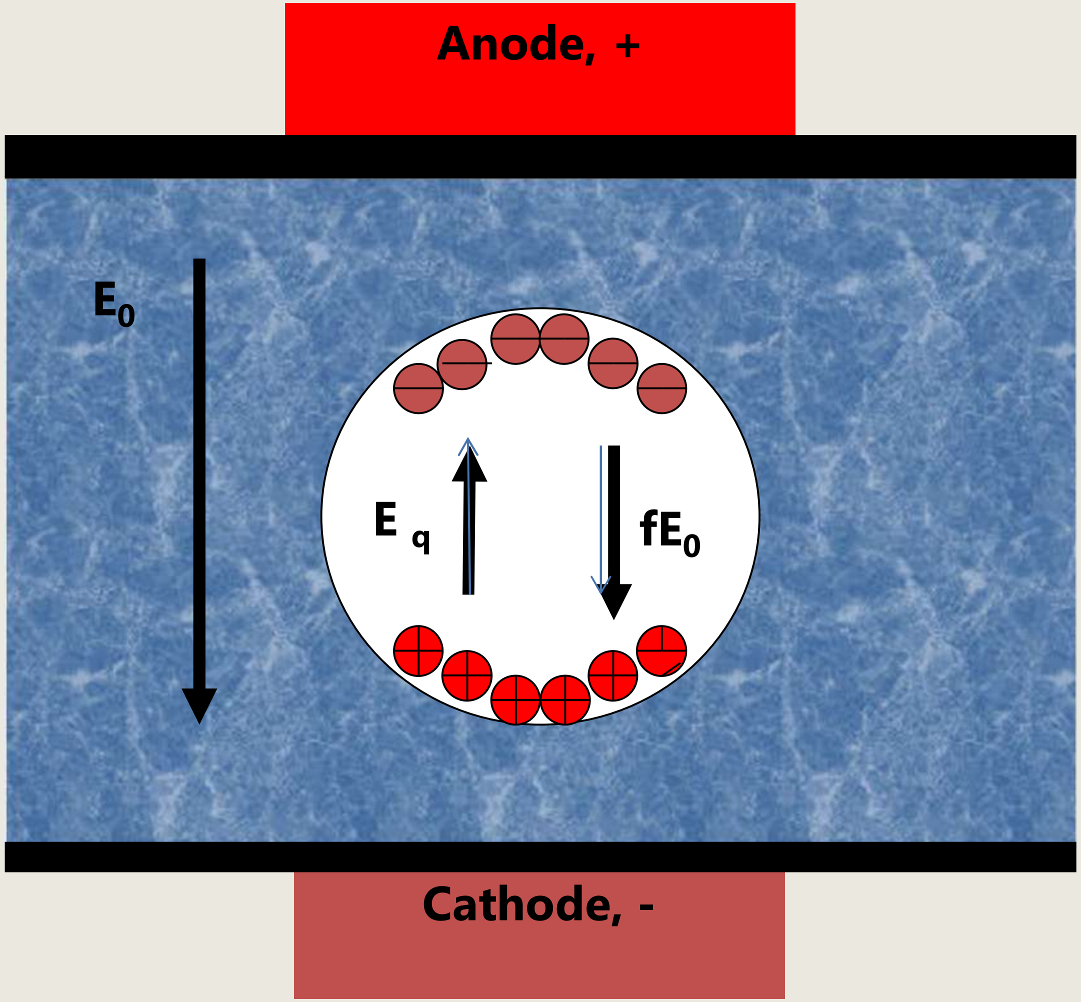


What happens during a PD

This charge distribution generates a local field Eq:

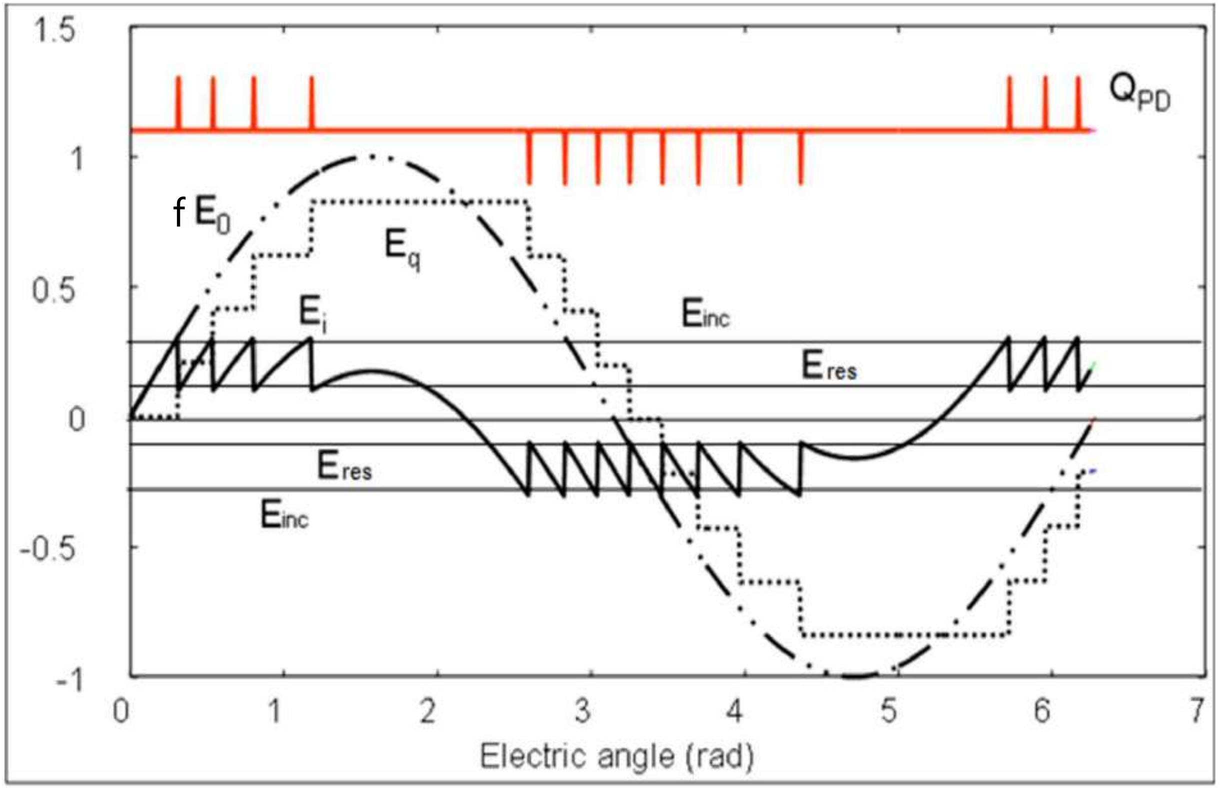
- The local field has opposite sign to the external field (i.e., due to the external source), fE0.
- Thus, the local field reduces the internal field (i.e., the field inside the cavity).

$$E_i = fE_0 - E_q$$



Hypotheses:

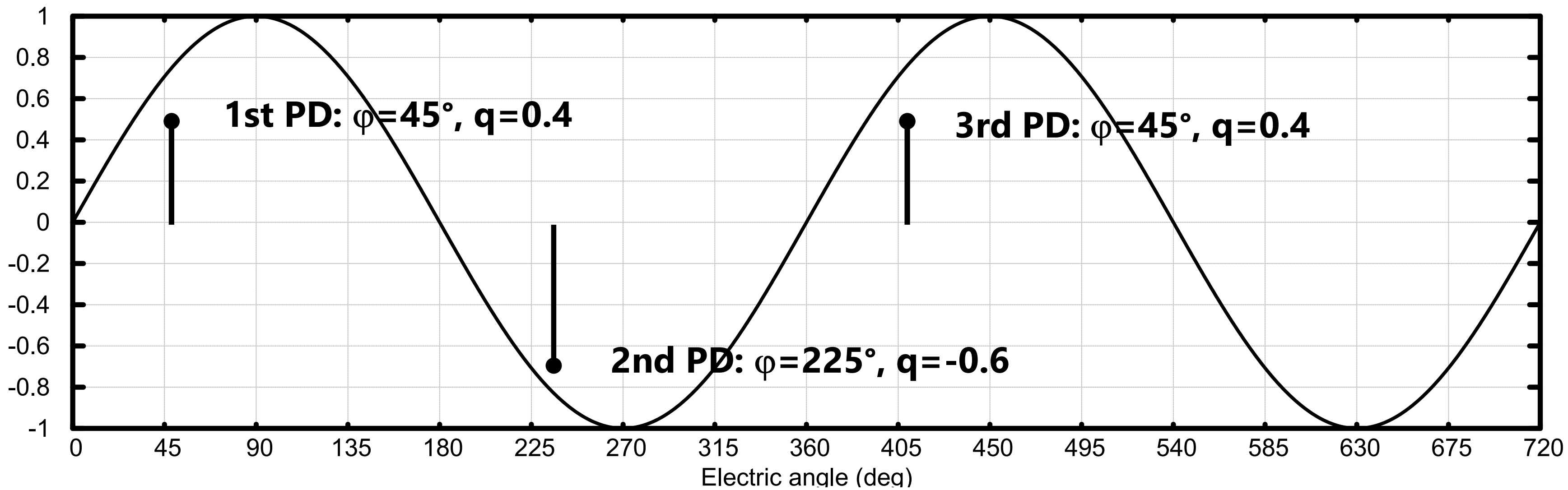
- Infinite electron availability (PD always occur when Ei=Einc)
- No charge diffusion (Eq constant between subsequent PD)

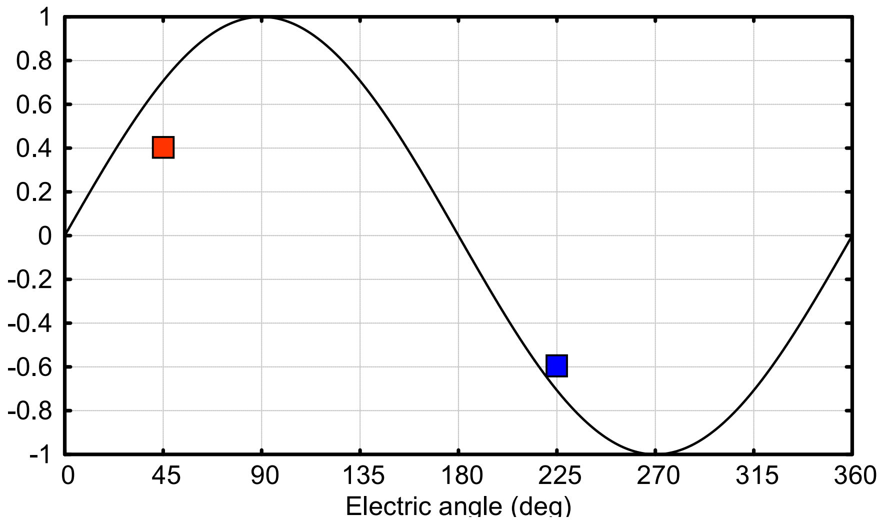


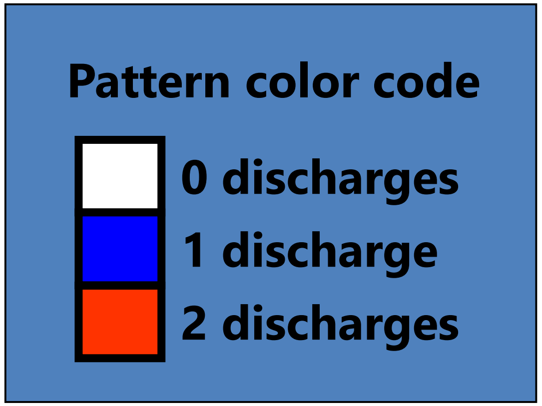
- E_{inc}, inception field
- E_{res}, residual field
- $fE_0 = fE_{max}*\sin(\omega t)$, field due to the applied voltage.
- E_q, local field, due to the charge distribution, changes after each PD.
- $E_i = fE_0 - E_q$, total field inside the cavity

That is why we have negative PD during positive applied voltage and viceversa

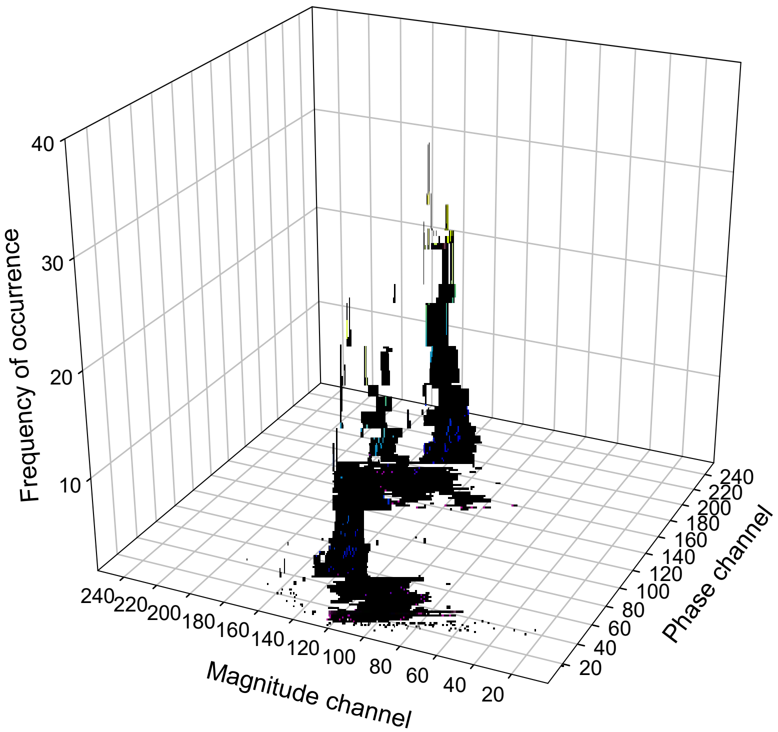
From time-resolved PD acquisition to PD pattern:



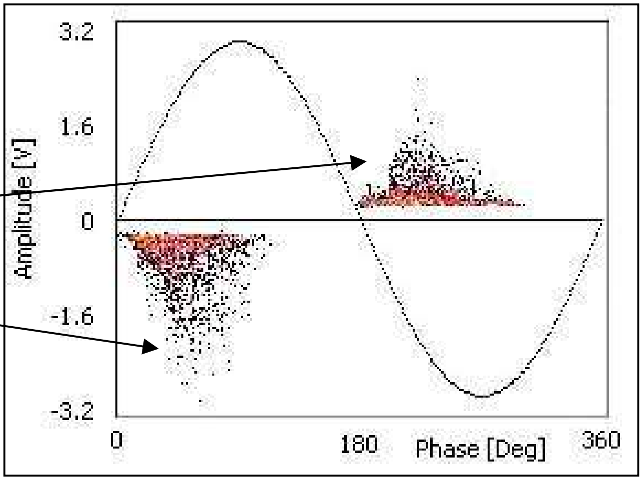




- The PD pattern represents the density of discharges in the phase/magnitude plane (third dimension).
- It is a 3D histogram
- Usually it is represented through a color map

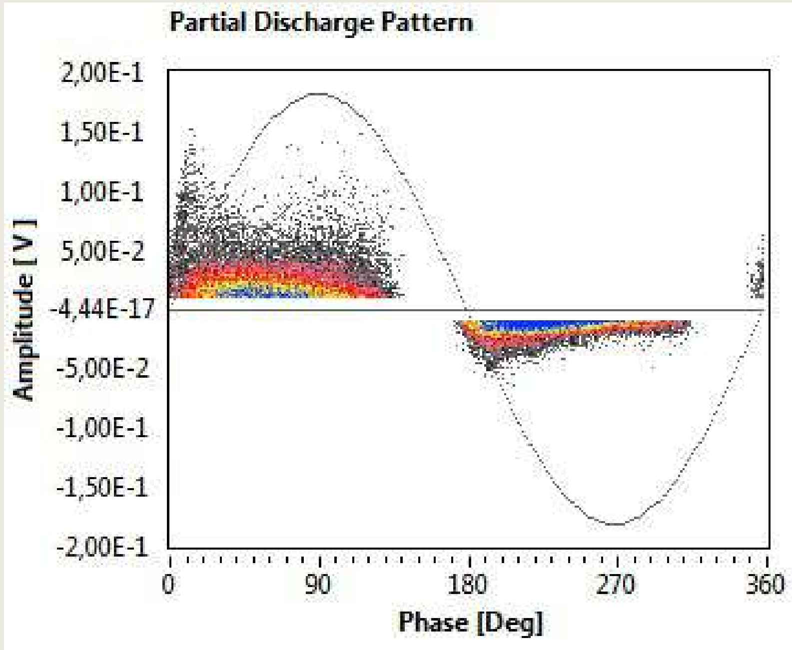


The polarity of PD pulses is also considered in the pattern



Phase Resolved PD Pattern: most common representation of Partial Discharges where Amplitude and Phase position of each collected pulse are represented. PRPD pattern shows repetition rate through a color scale .:

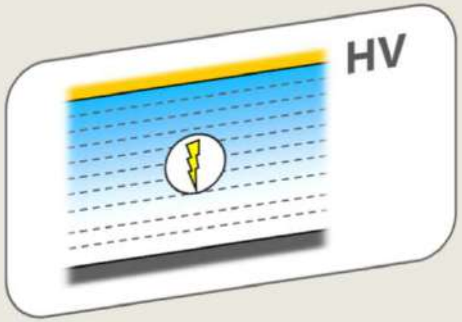
As a matter of fact, the pattern is discrete matrix and more than one dot, i.e. pulse, can be placed inside the same cell of the matrix. According to the color scale, black color means 1 dot only, blue means 40, or more, dots inside the same cell, white color means no dots.

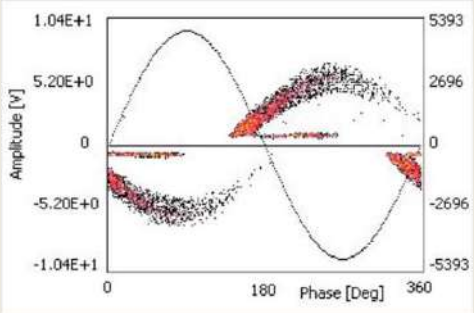


Diagnosis based on pattern → experts

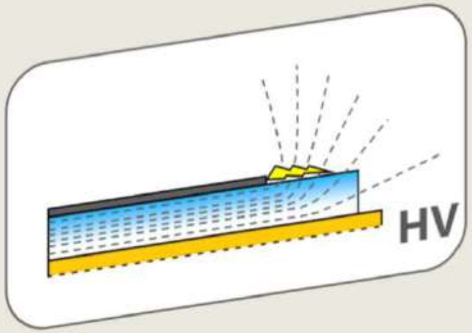
Amplitude consideration: Defect Type

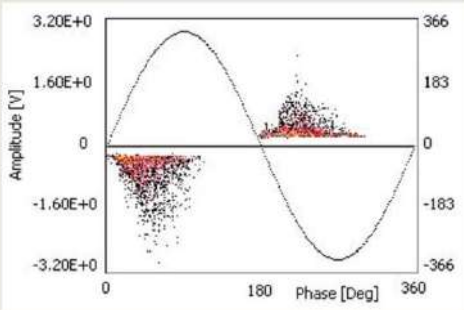
Based on PD Pattern, defect identification can be carried out, since different defect typologies forms different PD pattern shapes.



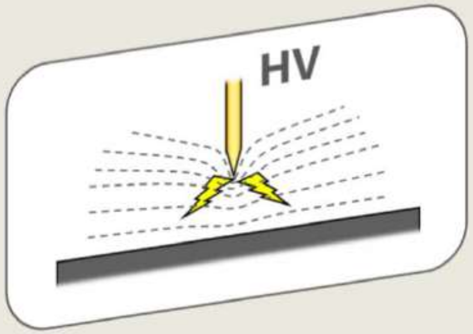


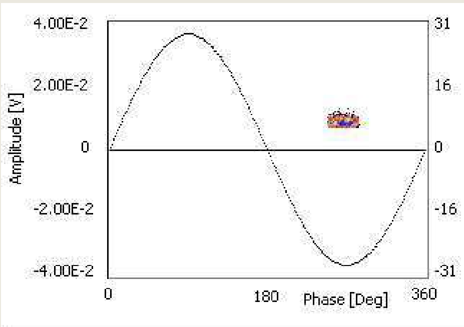
Internal PD





Surface PD



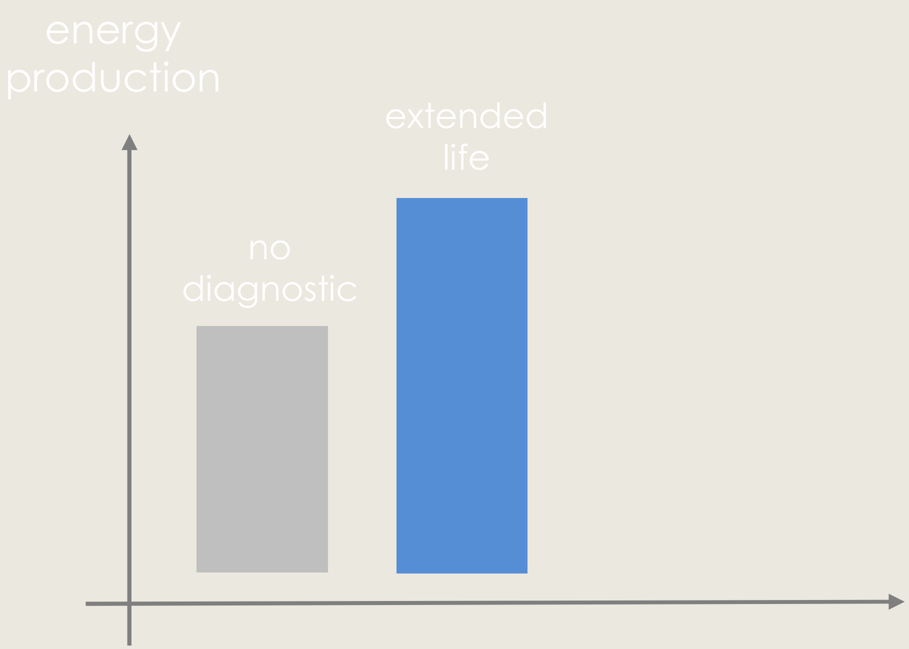


Corona PD

HARMFULNESS

An effective maintenance policy is essential within any asset management approach, mostly for life extension and maintenance programs.

Diagnostic solutions must include hardware and software to assess and prioritizes risk for key assets and to plan maintenance and inspection regimes accordingly.



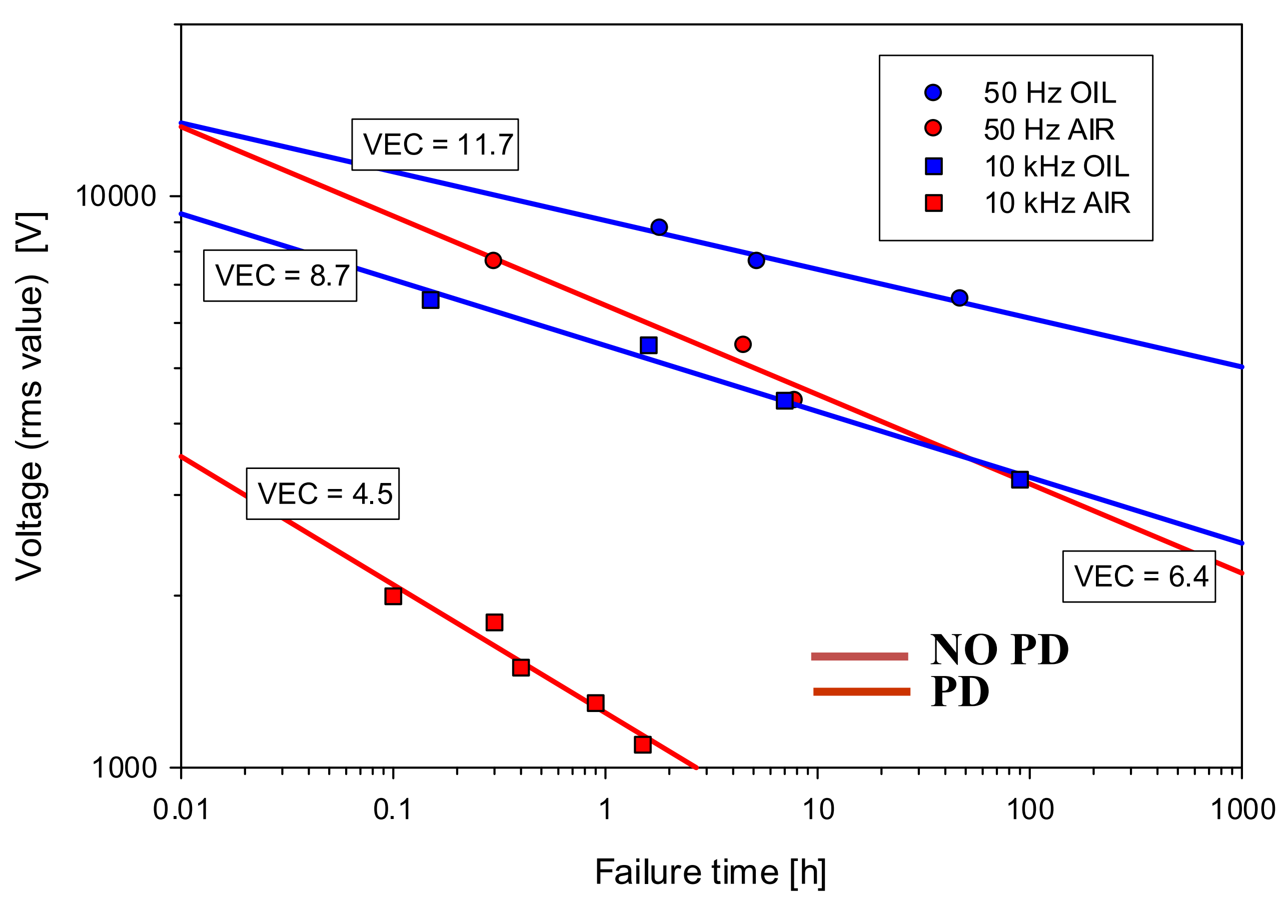
Example: life reduction under power electronics repetitive pulses

Base research work

- Life and VEC decrease at 50 Hz in the presence of PD
- Life and VEC decrease as frequency increases in the absence of PD
- Dramatic life shortening (and VEC decrease) at 10kHz due to PD activity amplification

NO PD $L_{10kHz}=L_{50}/200$

PD $L_{10kHz}=L_{50}/14000$



Life lines for tests performed in air and in oil at 50 Hz and 10 kHz sinusoidal (organic material, #A).

4leaf approach

Environment protection

Environment Protection

- More reliability & efficiency
- Longest life expectancy
- Reduced risk of failures causing environmental damage
- overall cost reduction

provide real environmental benefits!

Cost Reduction

Failure costs = Repair costs + Unavailability costs
+ indirect costs (image, safety, insurance)
+ penalties

REPAIR COSTS (RC)
Average number of failures per year x average repair costs

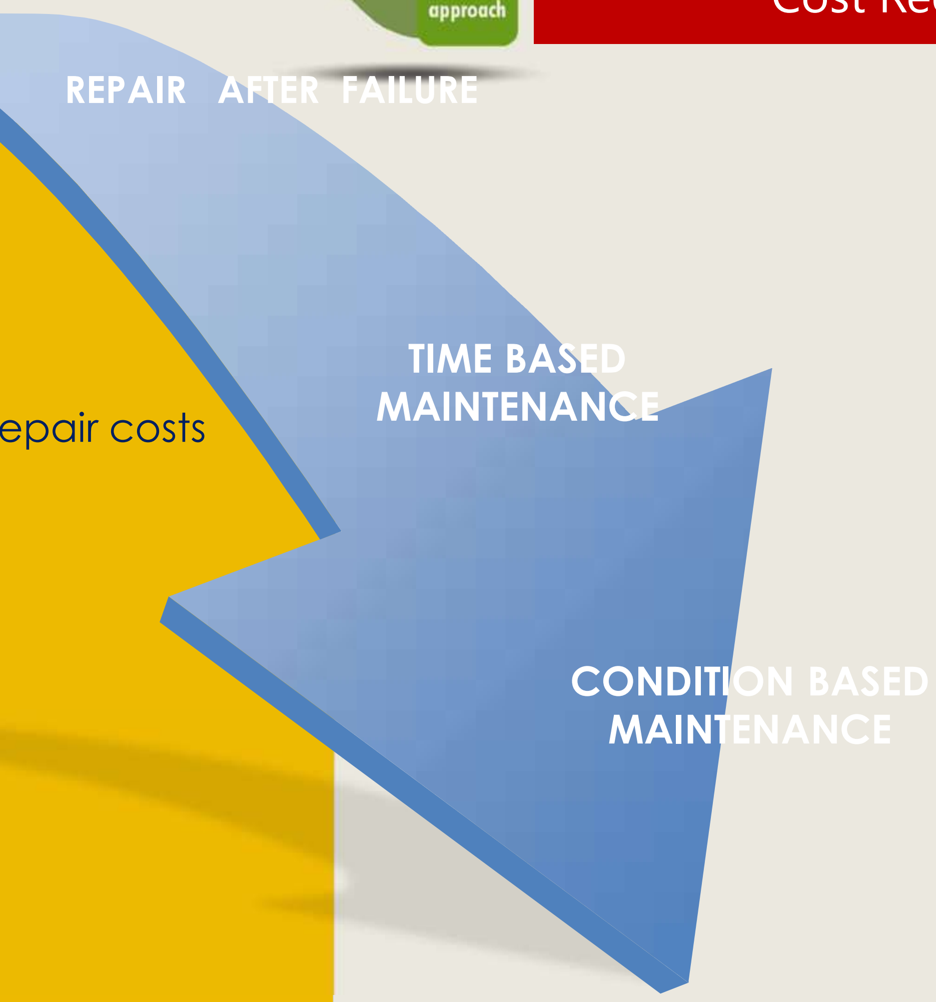
UNAVAILABILITY COSTS (UC)
Energy not supplied (ENS) * energy cost (EC)

ECONOMIC LOSSES (EL) without diagnostics
EL=RC + UC

ECONOMIC LOSSES (EL_D) with diagnostics
$EL_D=(RC \times F)+(UC_D \times F)$ where $F<1$ & $UC_D<UC$
Where F = Probability fault not detected

» $EL > EL_D$

$EL - EL_D$ is what we save with a proper diagnostic quantification for investments in diagnostics



Example: investing in diagnostics (generation plant)

Failure costs = Repair costs + Unavailability costs

Average number of failures per year ⊗ average repair costs

Energy not supplied ⊗ energy cost

Type I | Type II

Energy not supplied (in a year)

$$ENS = \left(\lambda_0 \cdot F_1 \cdot MTTR_1 + h \cdot MTTR_2\right) \cdot \overline{P}$$

Failure rate

Probability fault not detected

MTTR after failure

Number of false alarms/year

Mean time to restore after false alarm

Average power

Type I and Type II errors in diagnostics

Example: investing in diagnostics (generation plant)

- Economic losses (EL) without diagnostics:

$$EL = (\lambda_0 \cdot MTTR_1) \cdot \overline{P} \cdot EC + \lambda_0 \cdot RC$$

EC=Energy Cost
RC=Repair Cost

- Economic losses (EL) with diagnostics

$$EL_D = (\lambda_0 \cdot F_1 \cdot MTTR_1 + h \cdot MTTR_2) \cdot \overline{P} \cdot EC + \lambda_0 \cdot F_1 \cdot RC$$

- $EL-EL_D$ is what we save with a proper diagnostic → **quantification for investments in diagnostics**

- Decision of the Asset Manager: investments in diagnostics, are there problems?

Example: Power Transformers Failure Modes

Common Failures

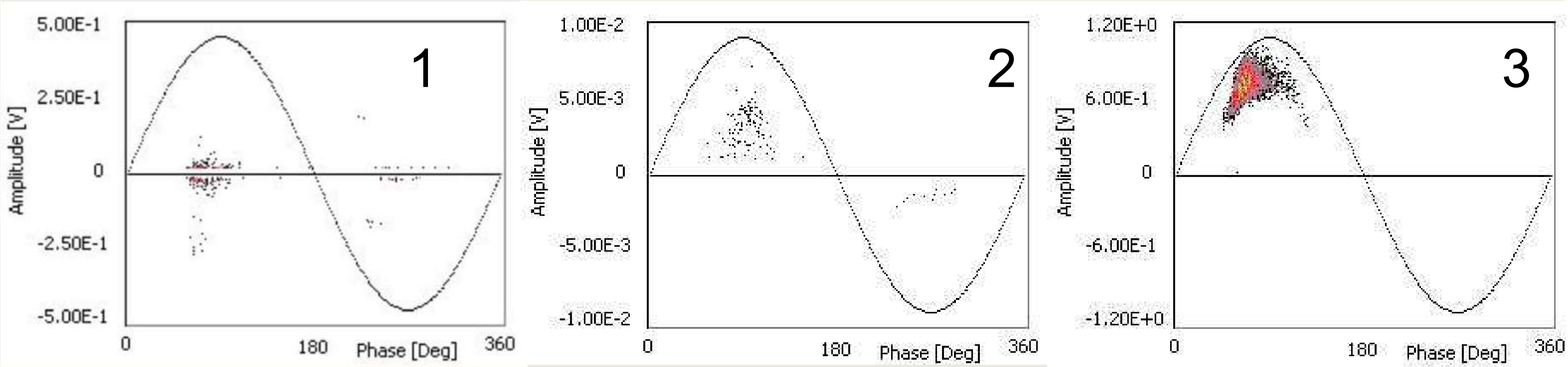
- Partial discharges breaking solid insulation and/or polluting oil → incoming failure.
- Shorted turn due to winding insulation breakdown: local overheating of transformer → end of life
- Reduction of dielectric strength due to moisture ingress, leading to flashover on pressboard barriers→ breakdown
- Deformed windings leading to a reduction in electrical clearance → breakdown
- Lack of cooling resulting in local overheating → rapid overall insulation deterioration (Arrhenius law)
- Arcing/sparking at loose clamping bolts → deterioration of oil strength, risk of flashover.

⇓

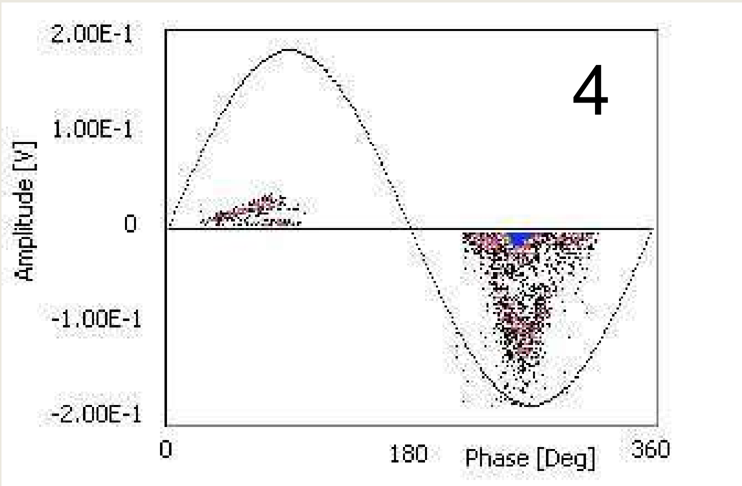
Various diagnostic properties and methods needed

Examples of PD pattern: Corona PD

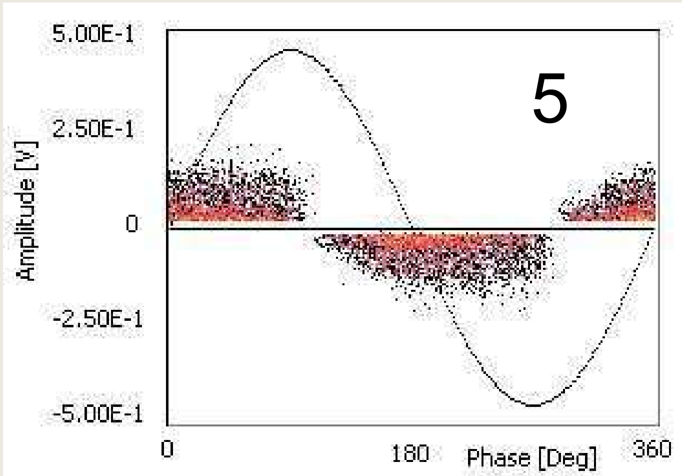
Uncontaminated (dry) oil



H_2O contamination

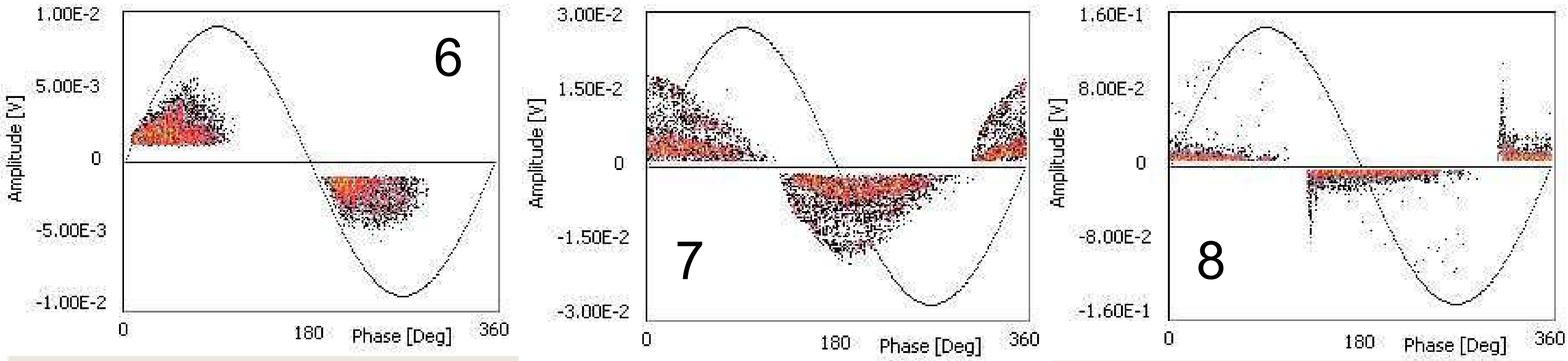


Free metal particles

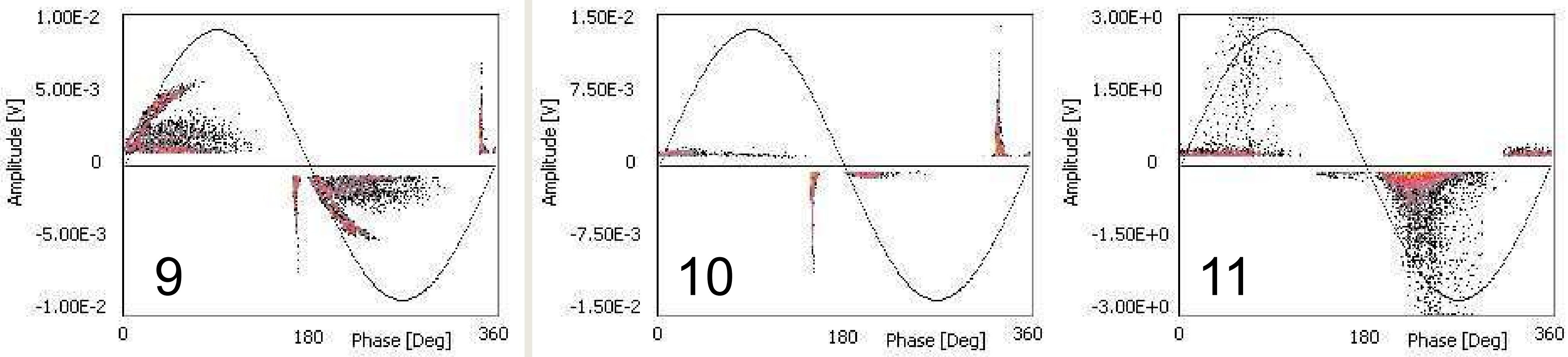


Diagnosis by PD

Examples of PD pattern: Pressboard internal PD

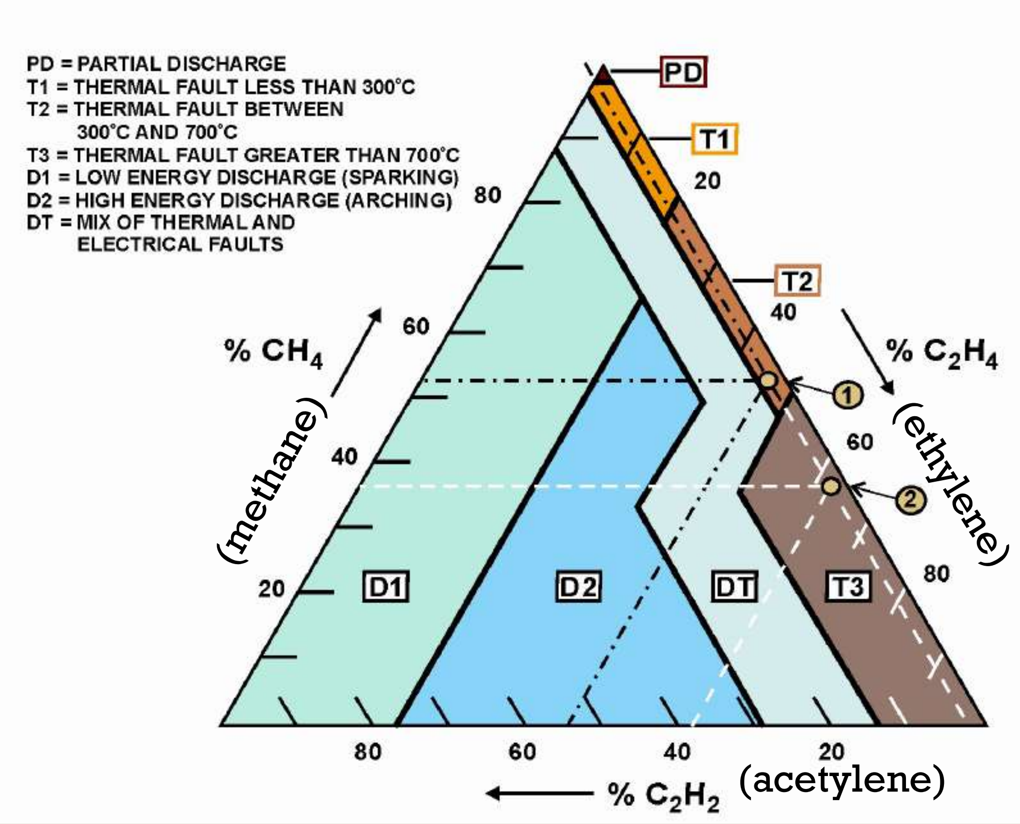


Examples of PD pattern: Surface/internal (mixed) PD on paper



Diagnosis by DGA (Duval Triangle)

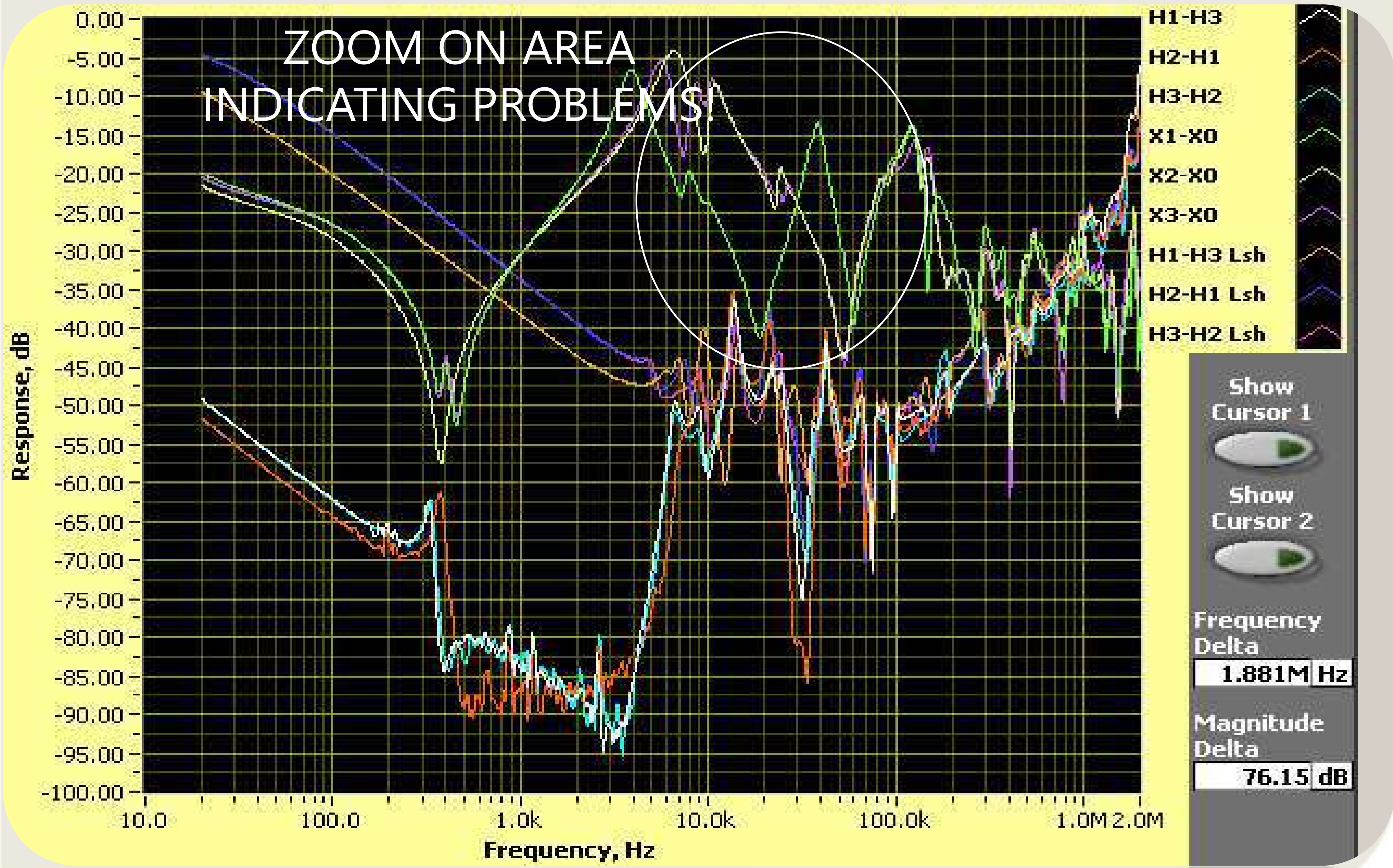
- Once DGA measurements have been carried out, one can use the total accumulated amount of the three Duval Triangle gases (acetylene, ethylene, methane) and **plot the percentages of the total gas to reach a diagnosis**.
- Work only with relative increase amount over time, not total gas.
- In most of the cases Acetylene will be zero, and the result will be a point on the right side of the Duval Triangle.



KEY GAS CONCENTRATION LIMITS (BUREAU OF RECLAMATION)

Gas	Condition ranges				Primary cause
	Good	Fair	Poor	Action	
Hydrogen (ppm)	<100	100 – 999	1000 – 2000	>2000	PD, electrolysis of water
Methane (ppm)	<120	120 – 399	400 – 1000	>1000	Overheated oil
Ethane (ppm)	<64	64 – 99	100 – 150	>150	Overheated oil
Ethylene (ppm)	<50	50 – 99	100 – 200	>200	Very overheated oil
Acetylene (ppm)	<35	35 – 49	50 – 80	>80	Arcing in oil
Carbon Monoxide (ppm)	<350	350 – 569	570 – 1399	>1400	Overheated paper, air pollution
Carbon Dioxide (ppm)	<2500	2500 – 3999	4000 – 9999	>10000	Overheated paper, atmosphere
Oxygen (ppm)	<3500	3500 – 6999	7000 – 9999	>10000	Atmosphere
CO2/CO ratio	>10	10 – 6.1	6 – 4	< 4	Paper degradation
Total combustible gasses (ppm)	>720	720 – 1920	1921 – 4631	<4631	Anomalous condition (look at single gasses)
Score for HI calculation	1	2	3	4	

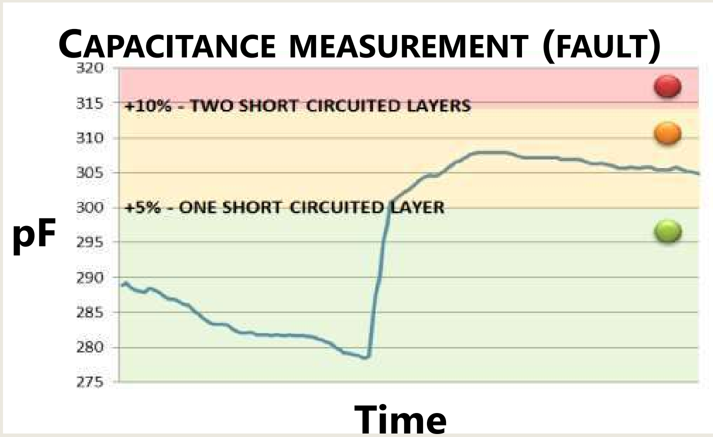
DIAGNOSIS BY SWEEP FREQUENCY RESPONSE ANALYSIS (SFRA)



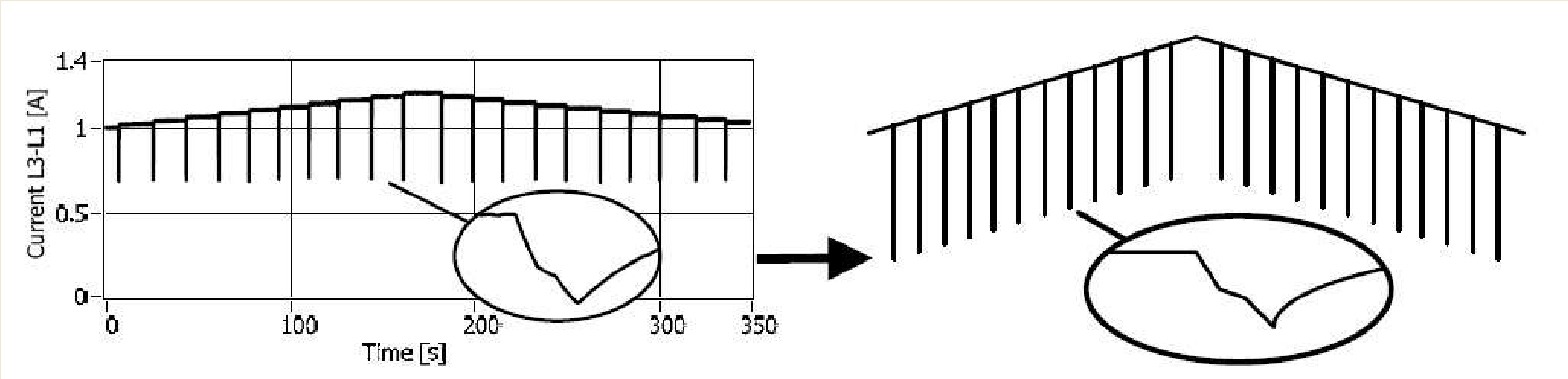
DIAGNOSIS BY ON-LINE MONITORING BUSHING TESTS

Real time evaluation of the behavior of capacitance and tanδ parameters. This is of outmost importance in case of “fast failure modes”, like a short circuited layer or PD in bushings..

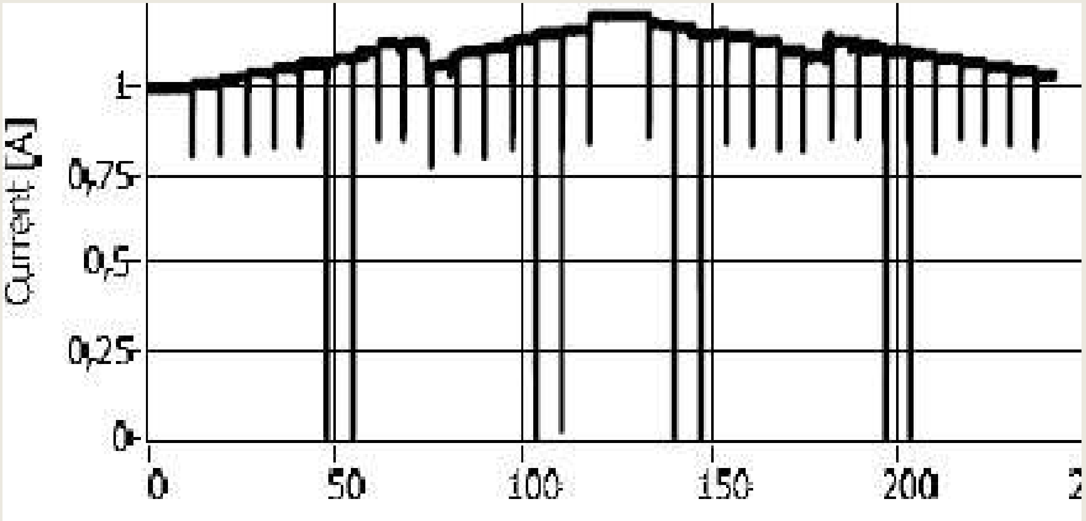
Time trend is fundamental to decide the proper maintenance time (on line monitoring)



DIAGNOSIS OF TAP CHANGER BY DYNAMIC RESISTANCE MEASUREMENTS



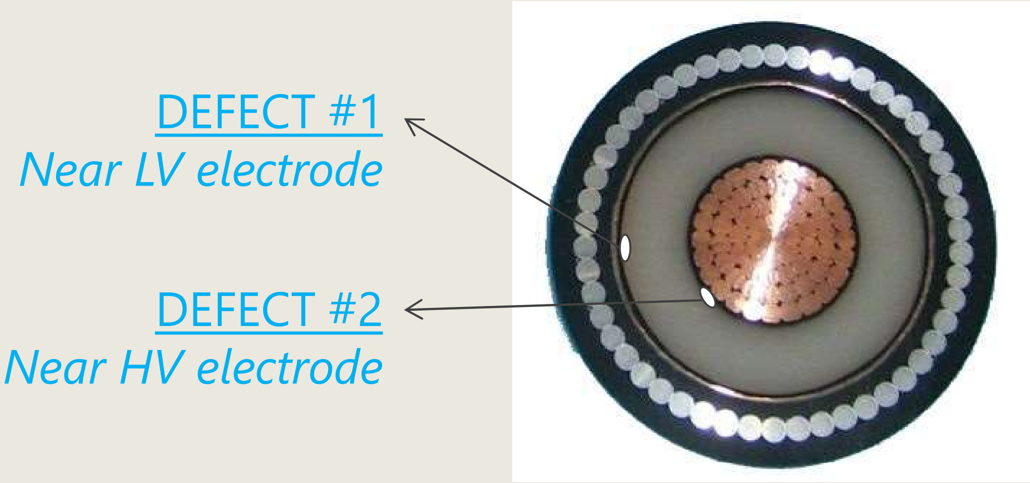
Example of Healthy Tap Changer



Example of Unhealthy Tap Changer

Example: cable. PD Amplitude vs Defect Positioning

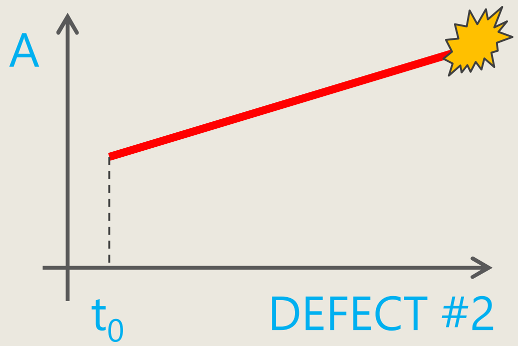
Amplitude alone during a spot PD measurement is not able to give any indication on degradation rate.



Considering same location and same amplitude…

Are these defects equally harmful?

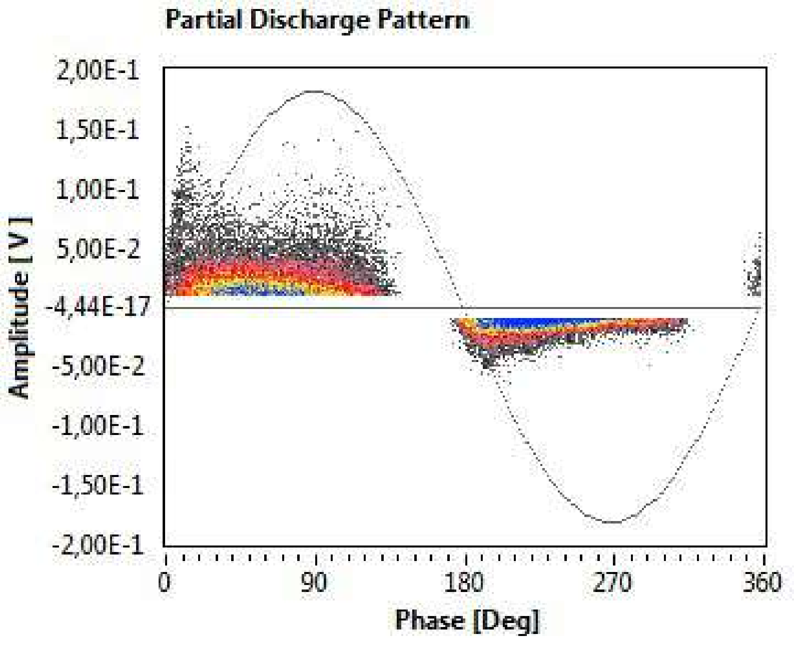
NO! Since the defects are located in regions subjected to different electric fields, amplitude behavior over time may be different.



Example: cable. Amplitude trend evaluation

PD measurement campaign regarding a MV network. The campaign consisted in repetitive PD measurements on defined circuits.

Many circuits found with PD at rated voltage did not show any amplitude or repetition rate increase: rely only on amplitude is not enough!



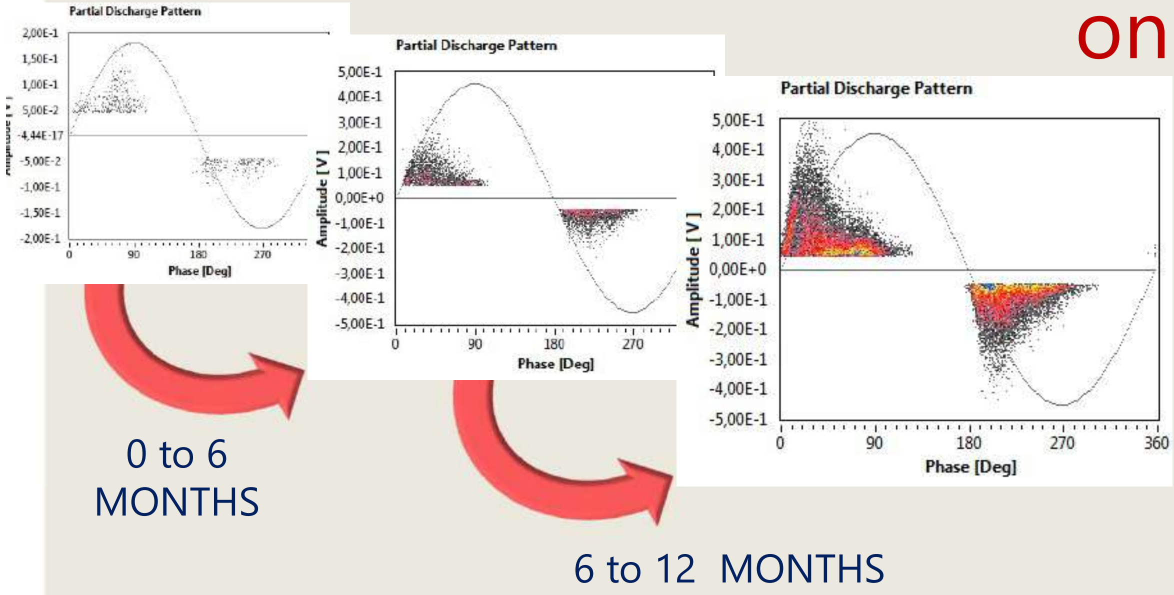
Example:

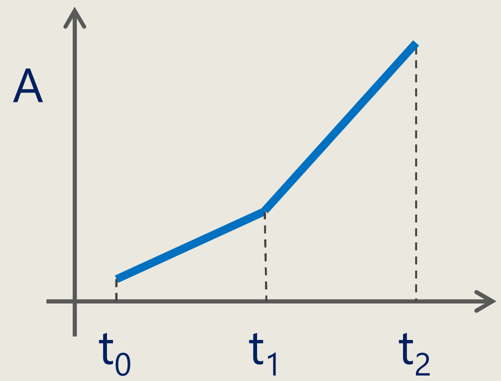
- 15kV single core XLPE cable
- 1,4 km (PD located 950 m far from PD measurement point)
- On-line test in 2008-2009-2010
- Off-line Test result > 500 pC
- During 2012 cable still in service!

Example: cable. Amplitude trend evaluation

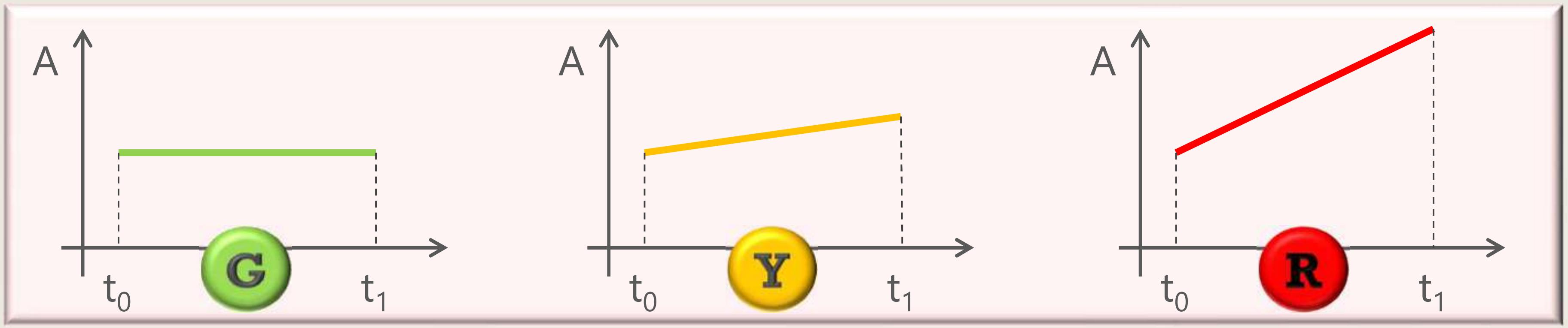
A correct Asset Management should take in consideration this trending over time of PD activity, for planning maintenance...

only at the right moment!





MAINTENANCE REQUIRED



Asset management and monitoring

Need of (on line) diagnostic quantity monitoring, BUT

ABLE TO PROVIDE EASY AND STRAIGHTWFORWARD INPUTS TO ASSET MANAGER (e.g. go, not go, maintenance time)

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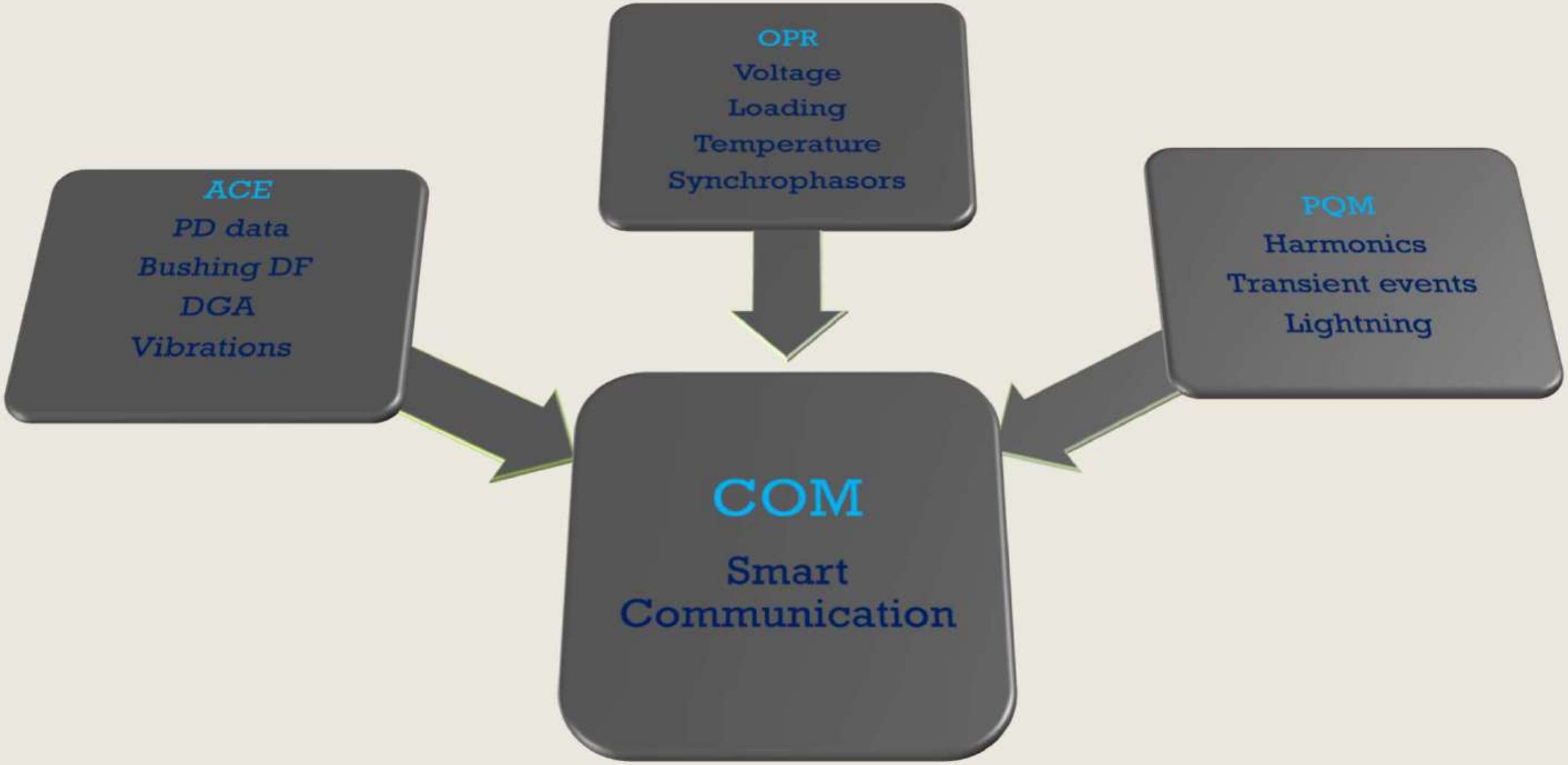
Make it Smart and Bridge the Gap

Global monitoring systems for electrical apparatus

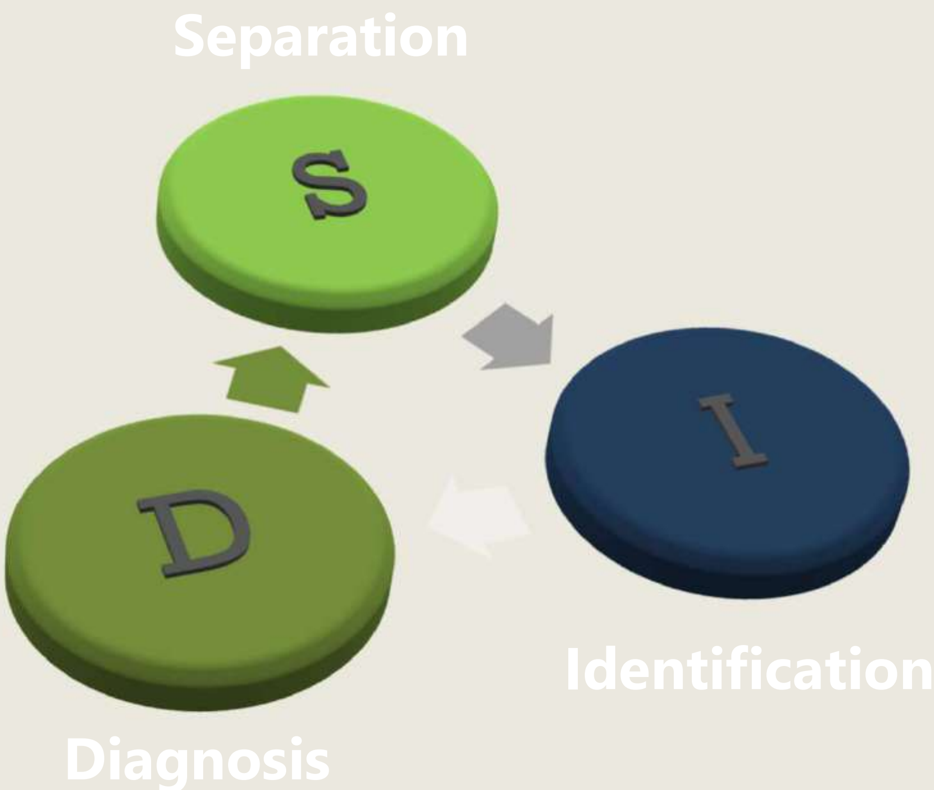


- Advanced noise rejection, artificial intelligence, data storage, alerting, communication tools are needed

ACE: Asset Condition Estimator

ACE: Why Advanced Technologies for Diagnosis?

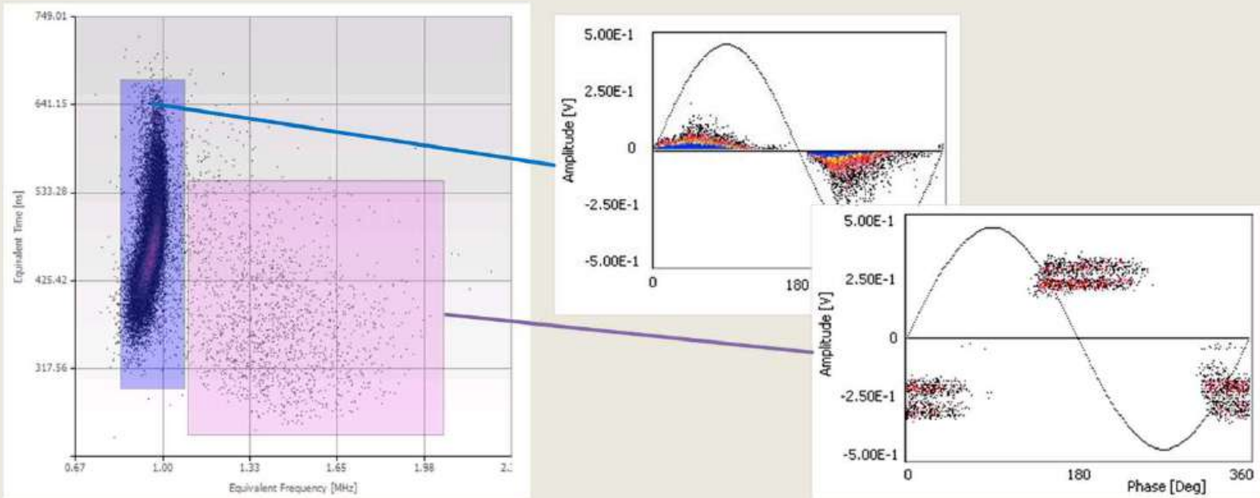
SID approach is fundamental for PD diagnosis



- Separation of the different PD sources and noise rejection
- Identification of PD Type based on PD Pattern and consequent harmfulness
- Knowing number and type of defects, Diagnosis is accurate and effective

PD data processing scheme

- PD source separation/noise rejection (TF map)



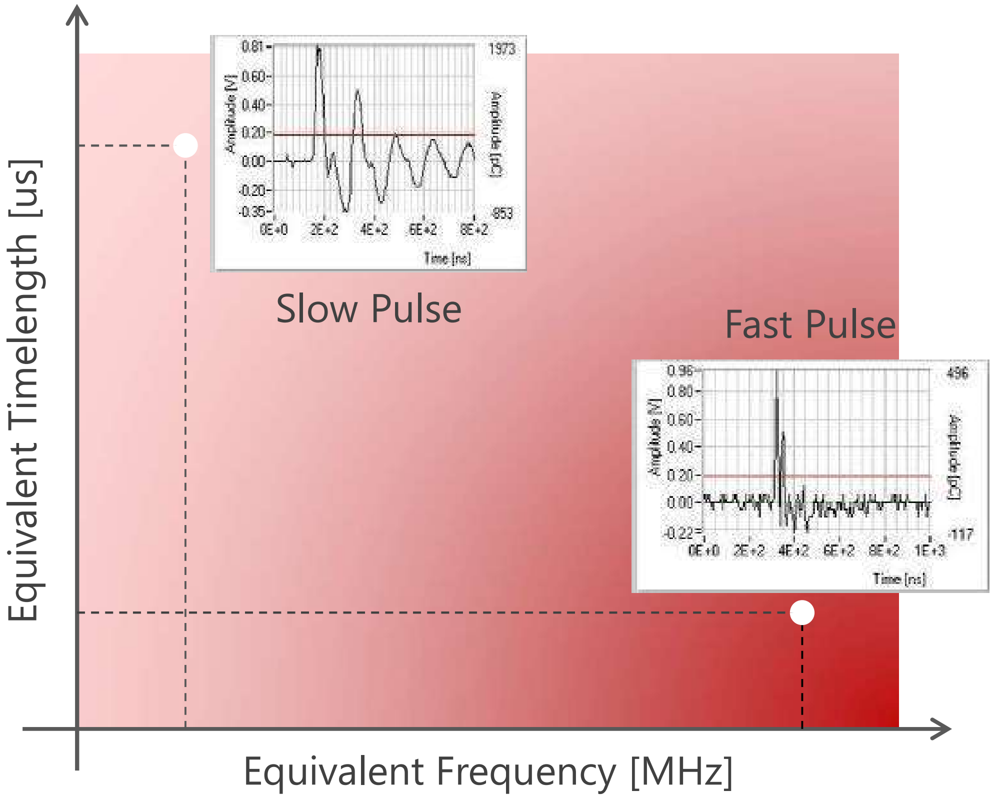
- Individual PD source identification (artificial intelligence):
  - Stress Grading / Multiple Voids / Distributed Microvoids / Embedded Delamination/Slot/Conductor Delamination/ B2B etc
- Smart alarm management

Noise rejection: T-F Separation Map

For each pulse the FFT is calculated. On the base of such Fourier Transform two quantities are calculated and plotted on the T-F Map:

•Equivalent Time length

•Equivalen Frequency

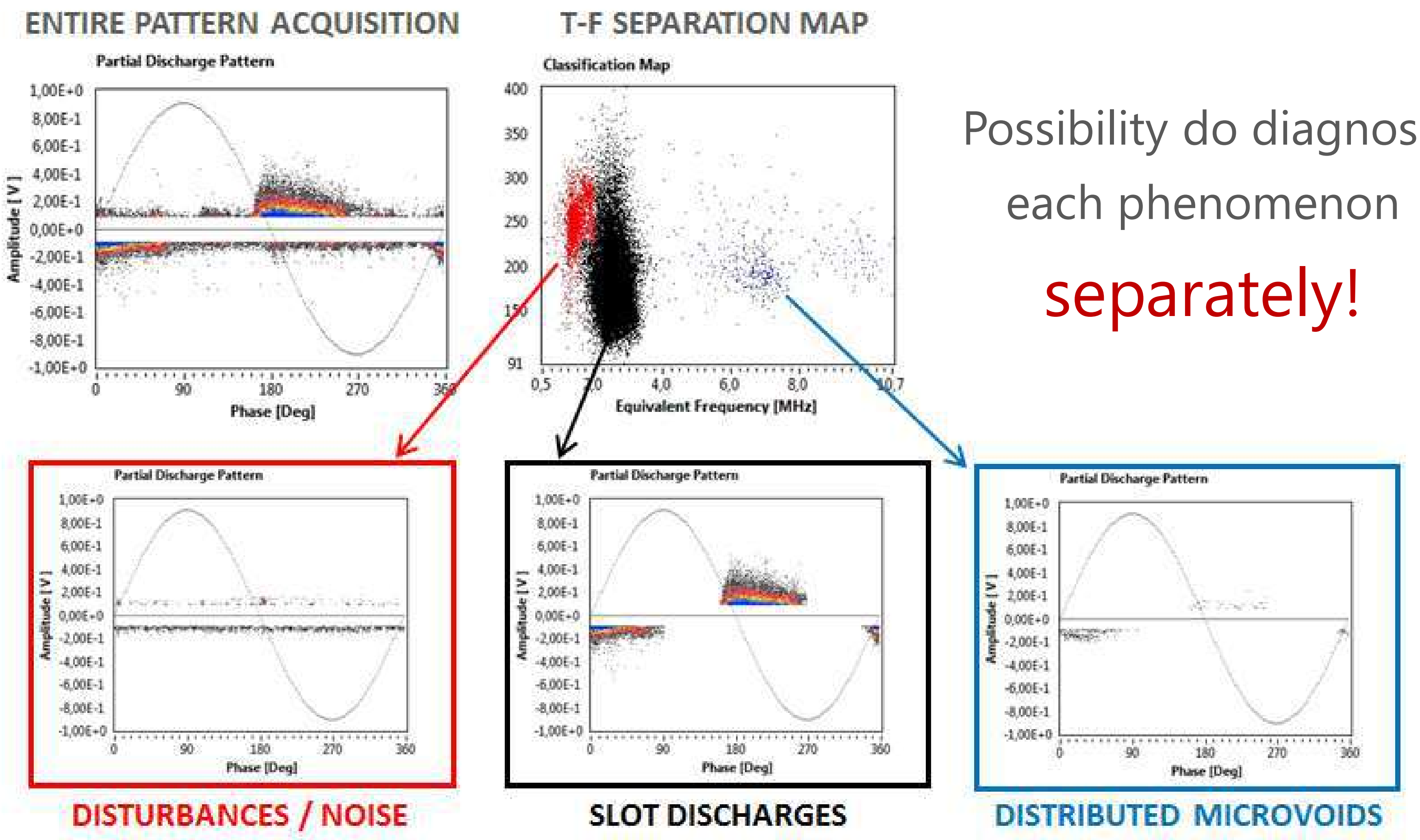


Having different waveforms, different phenomena either PD or noise will be located in different parts of the T-F map, allowing

separation!

Example of Separation and Identification

This is an example of separation coming from a Rotating Machine, but the principle is the same for every EUT tested.

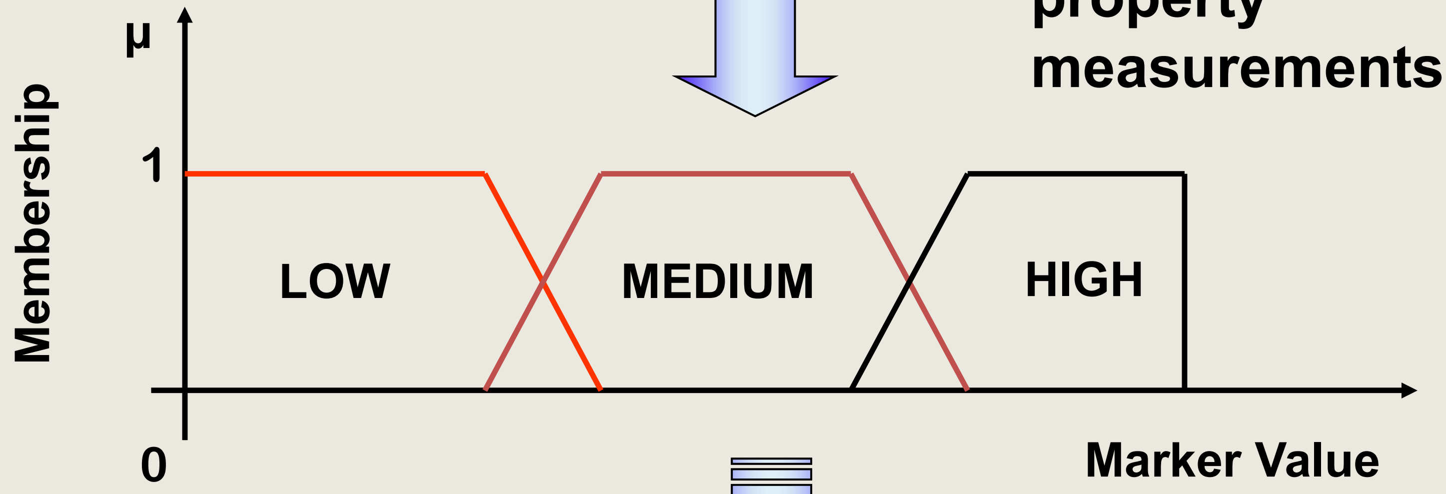


Possibility do diagnose each phenomenon **separately!**

Identification through artificial intelligence (AI) techniques

Φ_{min} Φ_{mean} $\Delta\varphi$ β Sk ND

Identification markers (from diagnostic property measurements)

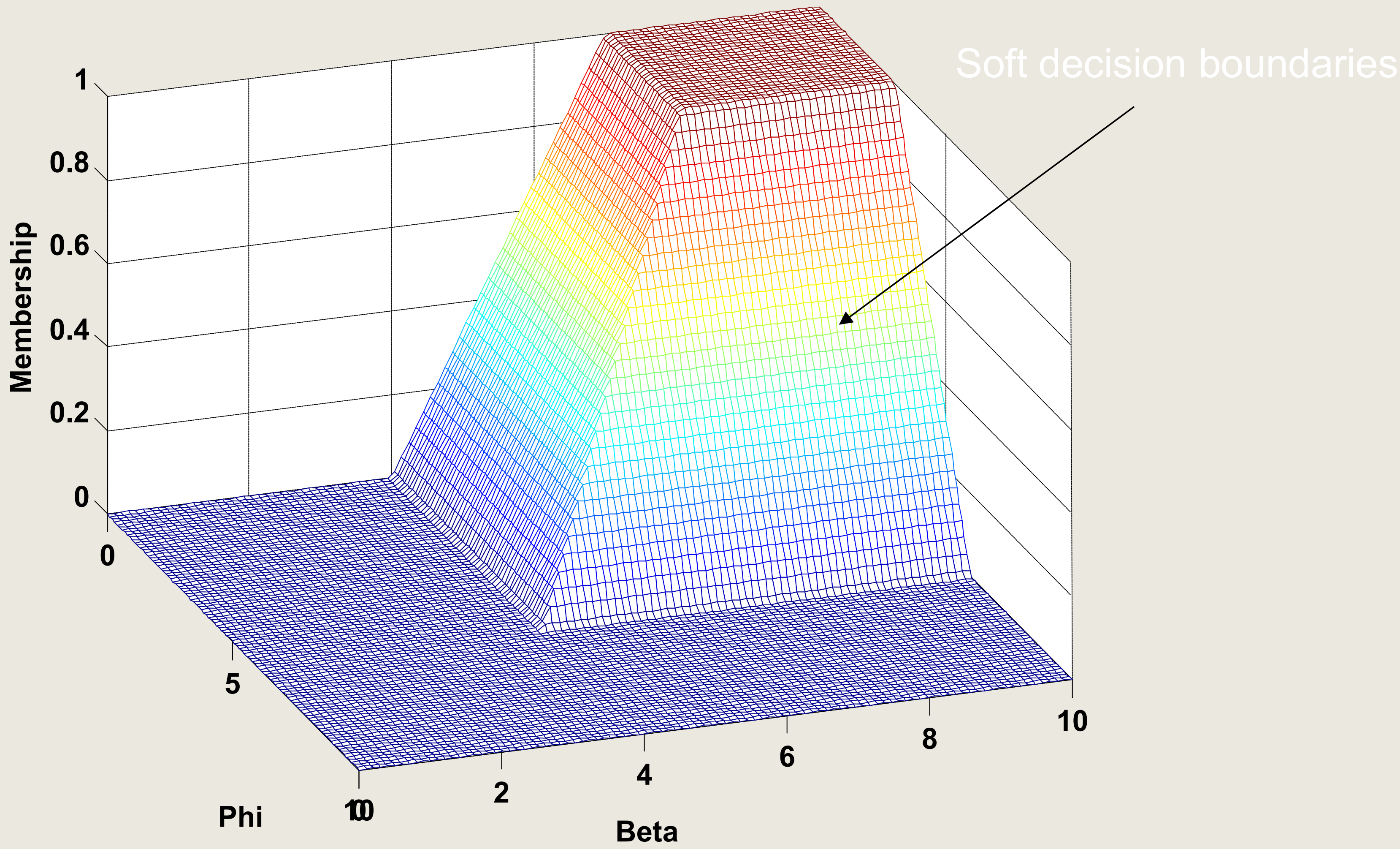


LINGUISTIC RULES

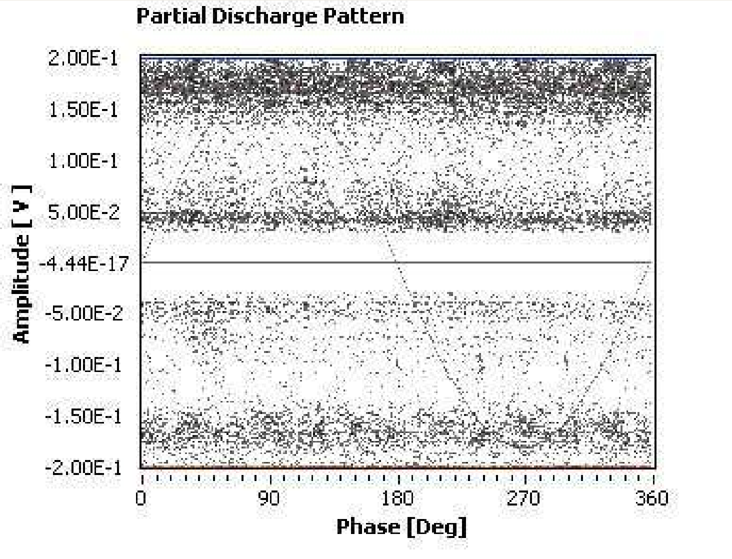
(e.g., **IF** (Φ_{min} is **small)**, **AND** (β is **large)** **THEN** INTERNAL)

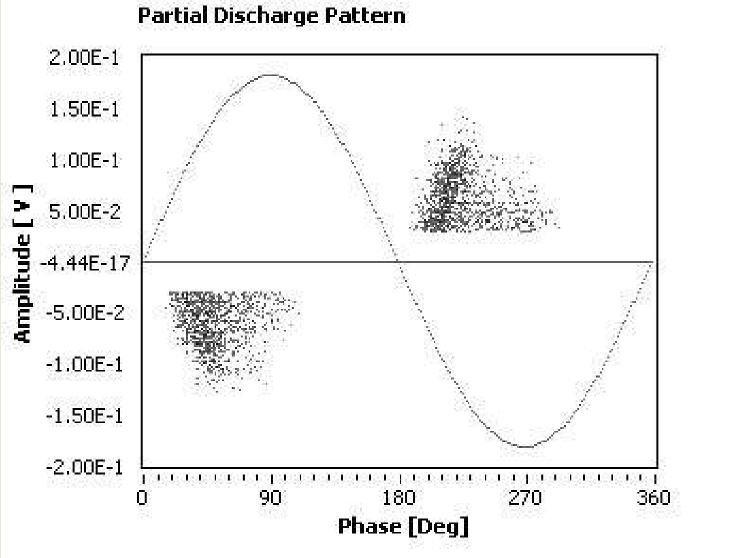
Identification through artificial intelligence (AI) techniques

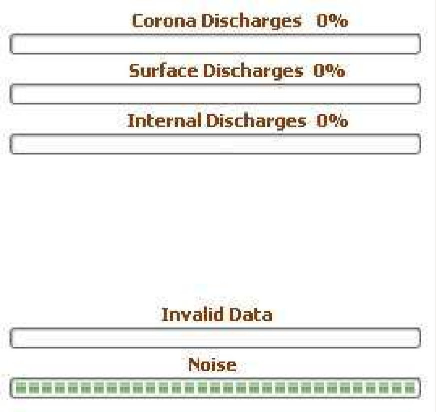
IF (Φ_{min} is **small**), **AND** (β is **large**) **THEN** INTERNAL)

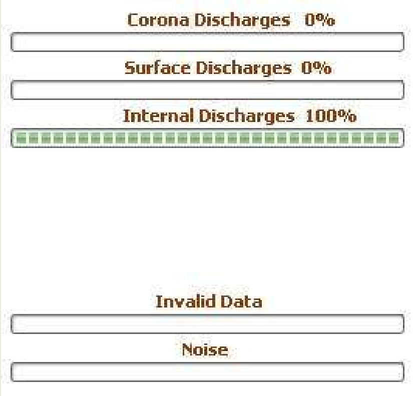


EXAMPLE noise rejection and identification









Smart Communication and Alarms

A. DATA ANALYSIS

- The data are downloaded from each PD detector manually or automatically and saved in a PC
- The customer can:
  - Analyze the data using PDProcessing
  - Send data to Expert

OFFERED ITEMS	
HARDWARE	Sensors
	Acquisition Box
	Laptop
SOFTWARE	PDManager
	PDProcessing

B. Local ALARMS

- Same of A.
- The only difference is that Qmax and Nw trend are sent to a SCADA using MODBUS communication from each PDdetector
- In addition dry contacts can be used for local alarms or sent to the SCADA

OFFERED ITEMS	
HARDWARE	Sensors
	Acquisition Box
	Laptop
SOFTWARE	PDManager
	PDProcessing
	PDCheck control

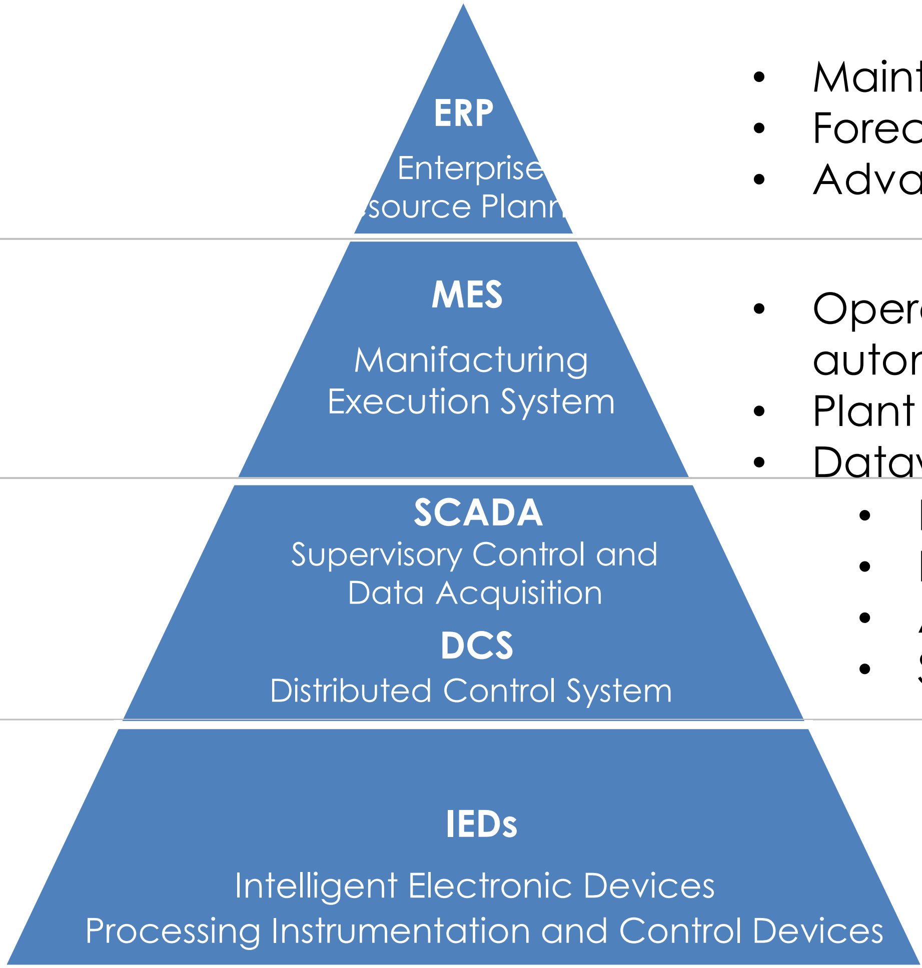
C. Alarm Manager

- All data are sent AUTOMATICALLY to a SERVER
- The Alarm Manager system is tuned by Experts
- Automatic alarms with traffic light logic
- WEB APPLICATION
- Watch DOG

OFFERED ITEMS	
HARDWARE	Sensors
	Acquisition Box
	Server
SOFTWARE	TIMS Software Suite (PDMManager, Alarm Manager, Web App)

Global TiSCADA - Architecture

TiSCADA designed on a Service Oriented Architecture (SOA)
Software design based on structured collections of discrete software modules, known as services, that collectively provide the complete functionality of the software application. Each service that makes up an SOA application is designed to provide a tightly defined set of functions.



Enterprise (4th Level)

- Maintenance
- Forecasting
- Advanced datawarehouse

Plant (3rd Level)

- Operation and monitoring automation
- Plant Design
- Datawarehouse

Process (2nd Level)

- Data collection
- Historian
- Alarm management
- Supervision and Control

Sensors and Actuators (1st Level)

- Data acquisition
- Issuing commands
- Alarm calculation

Alarm management

- Green Light: no PD inside the apparatus or recorded PD are not potentially harmful.

- Yellow Light the PD activity is a phenomenon with fast degradation rate, but the trend is constant or changing slowly.

- Red Light the probability of failure in the apparatus may be high.

PD data processing
Magnitude processing

- **Q_{max}**: 95th percentile of magnitude distribution
- Threshold values for Q_{max}:
  - $Q_{maxth\text{-}YELLOW}$ (Green/Yellow)
  - $Q_{maxth\text{-}RED}$ (Yellow/Red)
- Thresholds depend (for a type of apparatus) on:
  - Sensor sensitivity
  - Source type

Source type	**Risk weigth**
Slot Discharges	High
Embedded Delaminations	High
Distributed Microvoids	Medium
Stress Grading	Low
Bar to Bar / Bar to Ground	Very Low

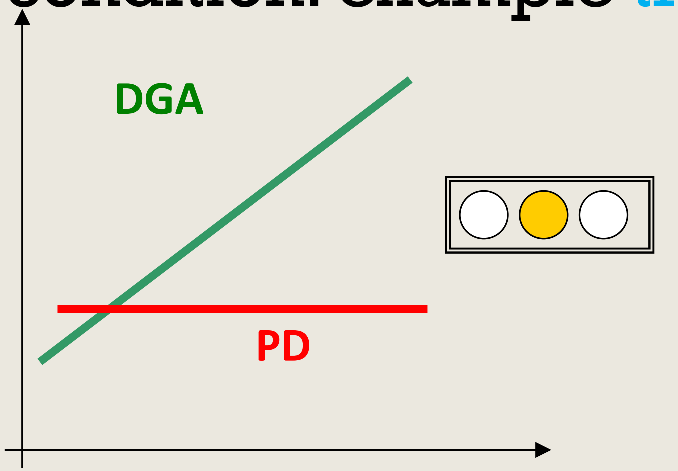
PD data processing
Repetition rate processing

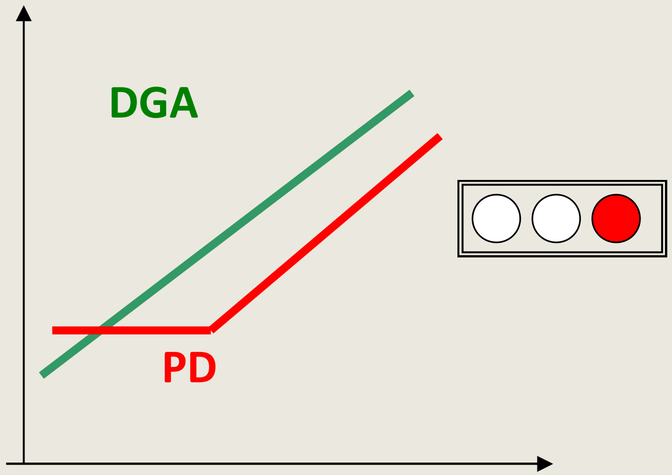
- Similar to Qmax
- Then, indications are combined based on TREND evaluation (after SEPARATION and IDENTIFICATION)

		Q_{max}		
		G	Y	R
N_s	G	G	G	Y
	Y	G	Y	R
	R	Y	R	R

Evaluation of time trending

- Trending different properties is the basis to give COMBINED alarms and assess broadly insulation condition: example transformer





- BUT: Meaningful trending! Not influenced by external disturbances or other PD!

Summarising diagnostic information

Dynamic Health Index

DEFINITION OF HEALTH INDEX

Health Index is based on diagnostic properties. If, for the sake of simplicity, a single diagnostic marker *X* is considered (in a real case *X* would be a function of a number of elementary diagnostic markers), the Health Index can be defined as:

$$HI = 1 - \Pr(F|X)$$

The last part is the conditional probability of Failure given a level of the diagnostic marker X at the time t.

The diagnostic marker *X* would be defined having:

- **Initial value** at $t = 0$ and ageing $A = 0$
- **Limit value**, reached when the ageing is $A = A_L$

  N.B. Limit value not necessary reached when $t = L_D$ *(design life)*

DIFFERENCE BETWEEN AGE AND AGEING

There is often misunderstanding about fundamental definitions of Age and Ageing for electrical equipment:

- **Age:** time under stress or operation time (hours/days/years)
- **Ageing:** irreversible change of insulation properties which can affect service operation and reliability due to service stresses

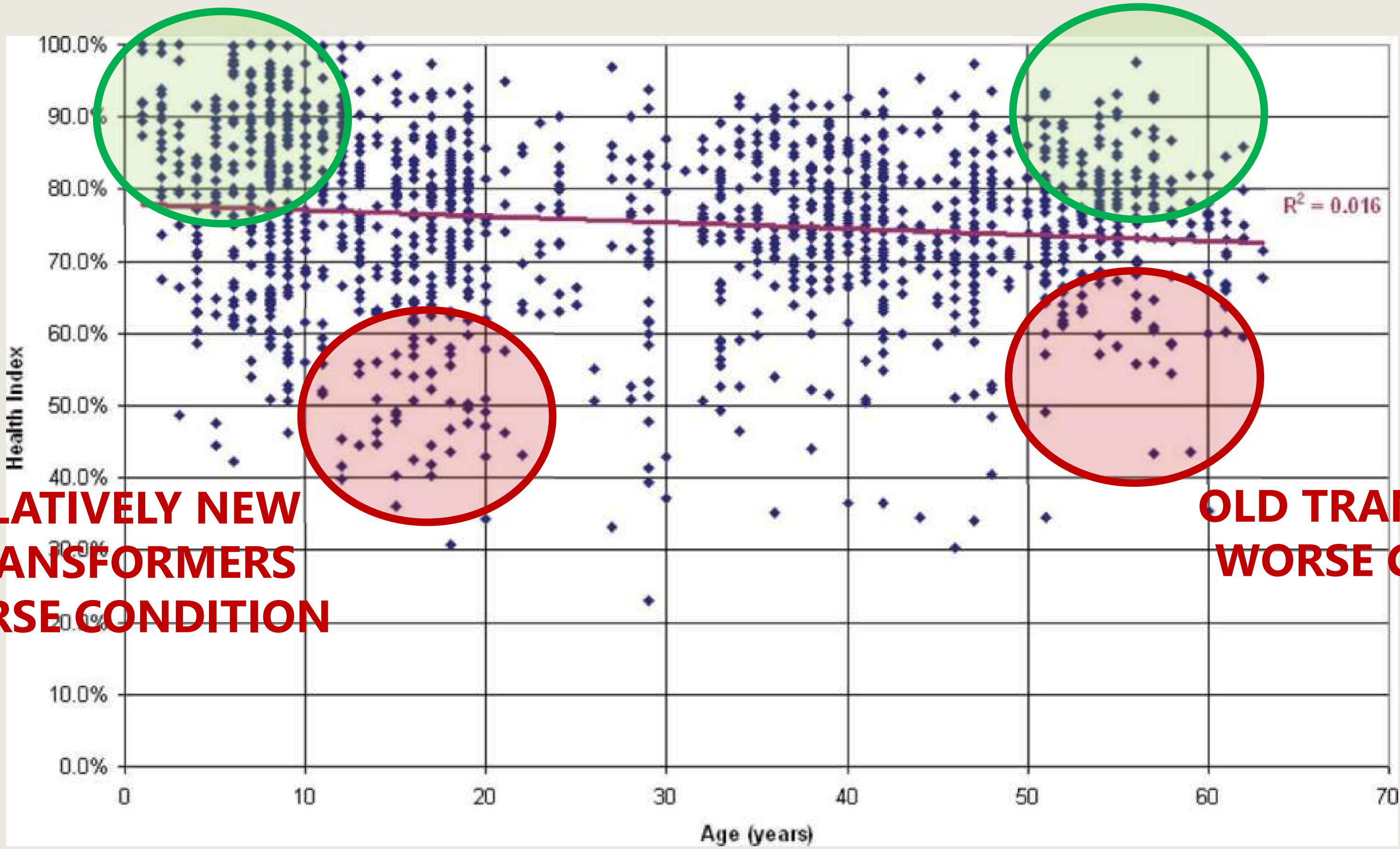
Some papers speculate that there is little correlation between equipment condition and Age:

Jahromi, A.; Piercy, R.; Cress, S.; Service, J.; Fan, W., "An approach to power transformer asset management using health index," Electrical Insulation Magazine, IEEE , vol.25, no.2, pp.20,34, March-April 2009

DIFFERENCE BETWEEN AGE AND AGEING

NEW TRANSFORMERS GOOD CONDITION

OLD TRANSFORMERS GOOD CONDITION



RELATIVELY NEW TRANSFORMERS WORSE CONDITION

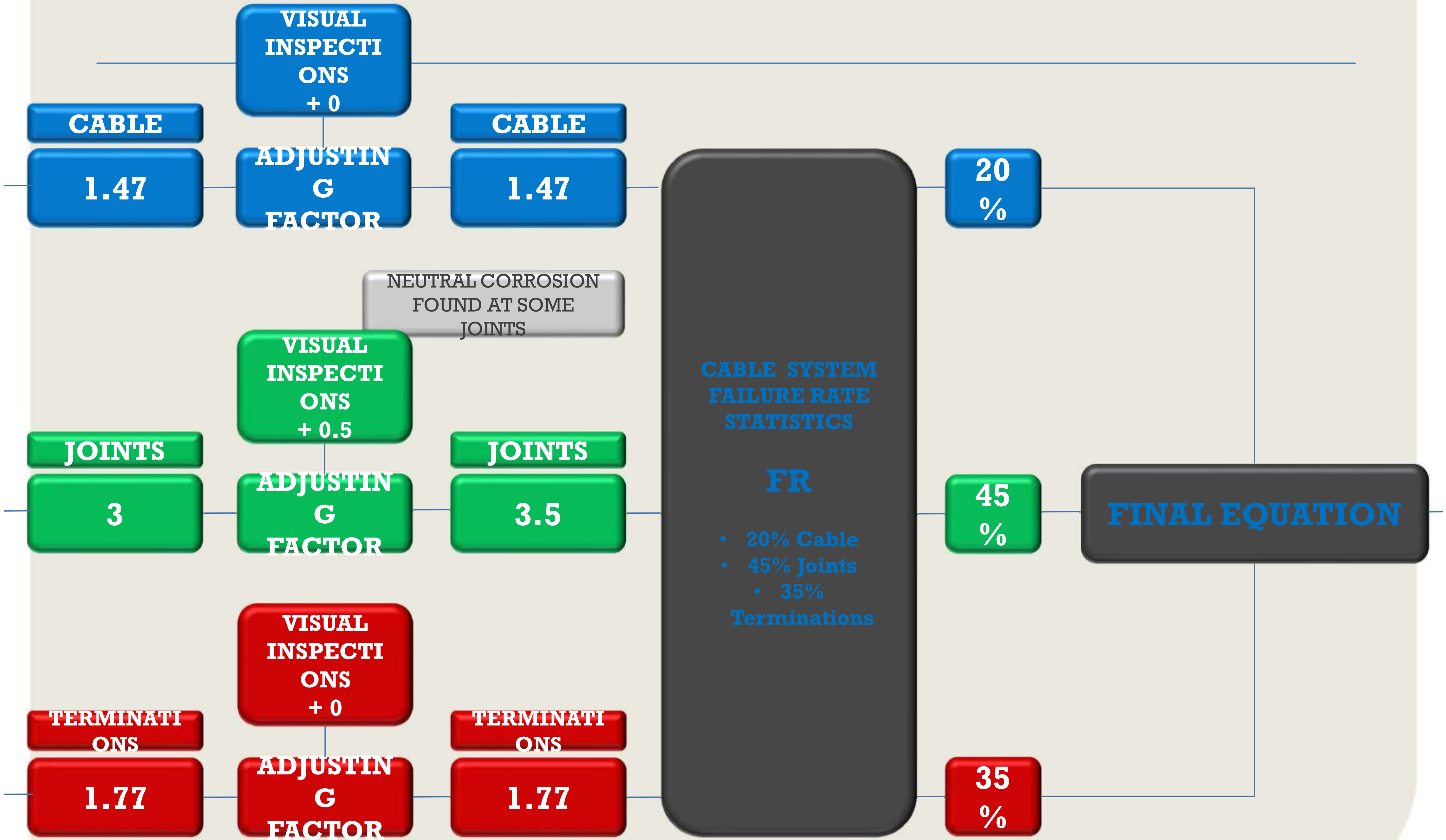
OLD TRANSFORMERS WORSE CONDITION

EXAMPLE OF HI CALCULATION FOR A CABLE

SCORE (1=GOOD,…,4=BAD)

CABLE					
PARTIAL DISCHARGE	NO PD ACTIVITY IN THE CABLE	1	8	$W_{AVERAGE}$	1.47
DISSIPATION FACTOR	DISSIPATION FACTOR SMALL INCREASE	2	7		
THERMOGRAPHY	NOT AVAILABLE	N/A	5		
JOINTS					
PARTIAL DISCHARGE	MEDIUM/HIGH PD ACTIVITY IN ONE JOINT	3	8	$W_{AVERAGE}$	3
THERMOGRAPHY	NOT AVAILABLE	N/A	5		
TERMINATIONS					
PARTIAL DISCHARGE	NO PD ACTIVITY IN THE TERMINATIONS	1	8	$W_{AVERAGE}$	1.77
THERMOGRAPHY	HOT SPOT IN ONE TERMINATION	3	5		

EXAMPLE OF HI CALCULATION FOR A CABLE



THE FINAL EQUATION FOR HI CALCULATION

The final equation can be expressed as:

$$HI = 100 - \sum_{i=1}^{N} \frac{FR_i \cdot (PSC_i - SC_{min})}{SC_{MAX} - SC_{min}}$$

Where:

- ***N*** number of subcomponents
- ***FR_i*** failure rate of the subcomponent *i*
- ***PSC_i*** partial score of the subcomponent *i*
- ***SC_{MAX}*** *max score value*
- ***SC_{min}*** *min score value*

THE FINAL EQUATION FOR HI CALCULATION (SEMPLIFICATION)

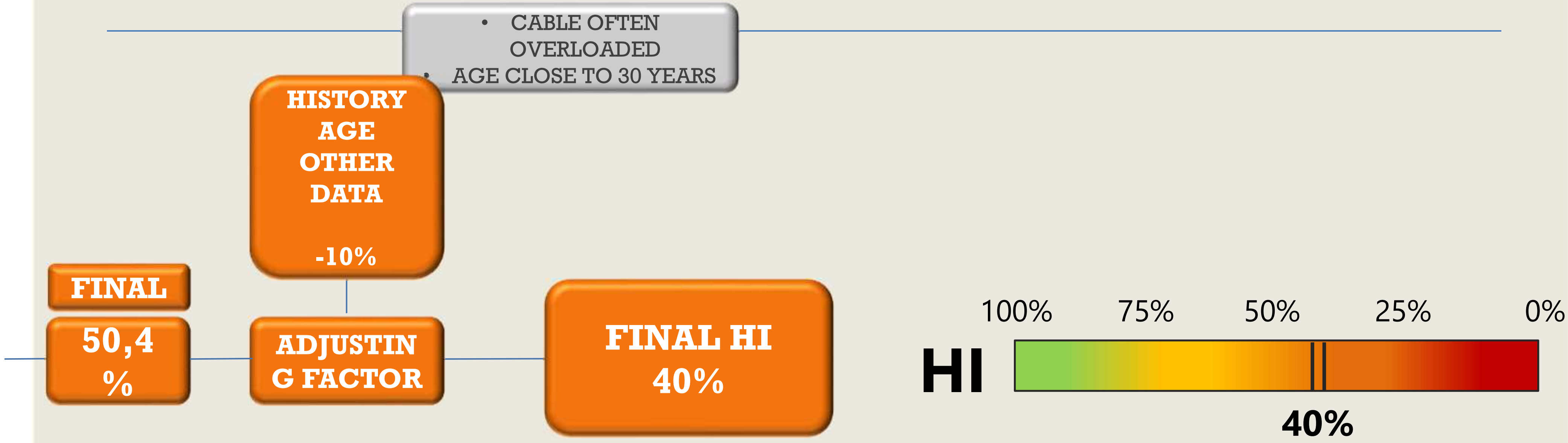
In our case:

- ***N*** number of subcomponents → 3
- ***FR_i*** failure rate of the subcomponent *i*
- ***PSC_i*** partial score of the subcomponent *i*
- ***SC_{MAX}*** *max score value → 4*
- ***SC_{min}*** *min score value → 1*

The final equation can be simplified as:

$$HI = 100 - \sum_{i=1}^{3} \frac{FR_i \cdot (PSC_i - 1)}{3}$$

EXAMPLE OF HI CALCULATION FOR A CABLE



This is not the end of the process. User can decide to perform extraordinary maintenance in order to decrease the final score, increasing the HI.

Example: Substitution of the joint having lower reliability will bring final score from 40% to 70%!!!

Example of HI Calculation for a Cable

- **GOOD - 100%-75%:** Asset in good overall condition. Continue operation without restrictions. It is anyhow suggested to repeat the condition assessment process as in order to spotlight any degradation mechanism inception due to ageing or anomalous operating conditions.

G

- **FAIR - 75%-50%:** Asset in fair overall condition. Continue operation, but perform minor re-evaluation of operation and maintenance practices. Pay particular attention to those components which show lower Health Index. Minor probability of failure in the short time. Repeat this condition assessment process after a certain amount of time depending on technical-

F

Example of HI Calculation for a Cable

- **BAD - 50%-25%:** Asset in poor overall condition. Continue operation with major re-evaluation of operation and maintenance practices. Conduct an economic assessment of risk and start to plan replacement or maintenance. Medium probability of failure in the short time. Repeat this condition assessment process after a certain amount of time depending on technical-financial considerations. Time should be shorter than “FAIR” case.

B

- **ACTION - 25%-0%:** Asset in critical condition. Handle operation with care or take apparatus out of service. Start replacement/rehabilitation process.

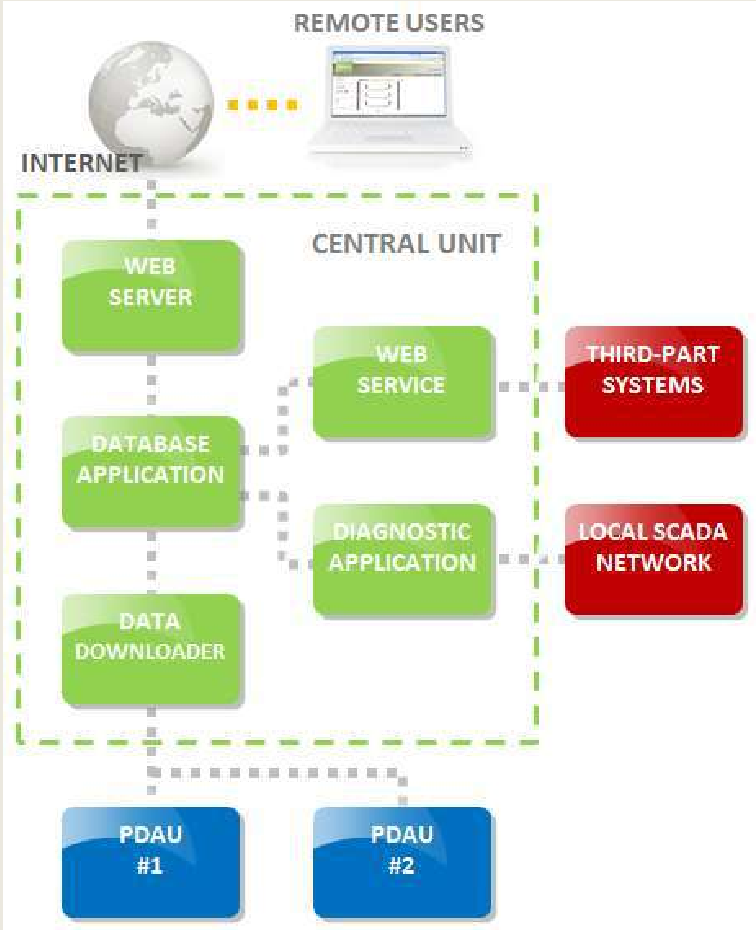
A

Tayloring the strategy: T&D&G, Distribution

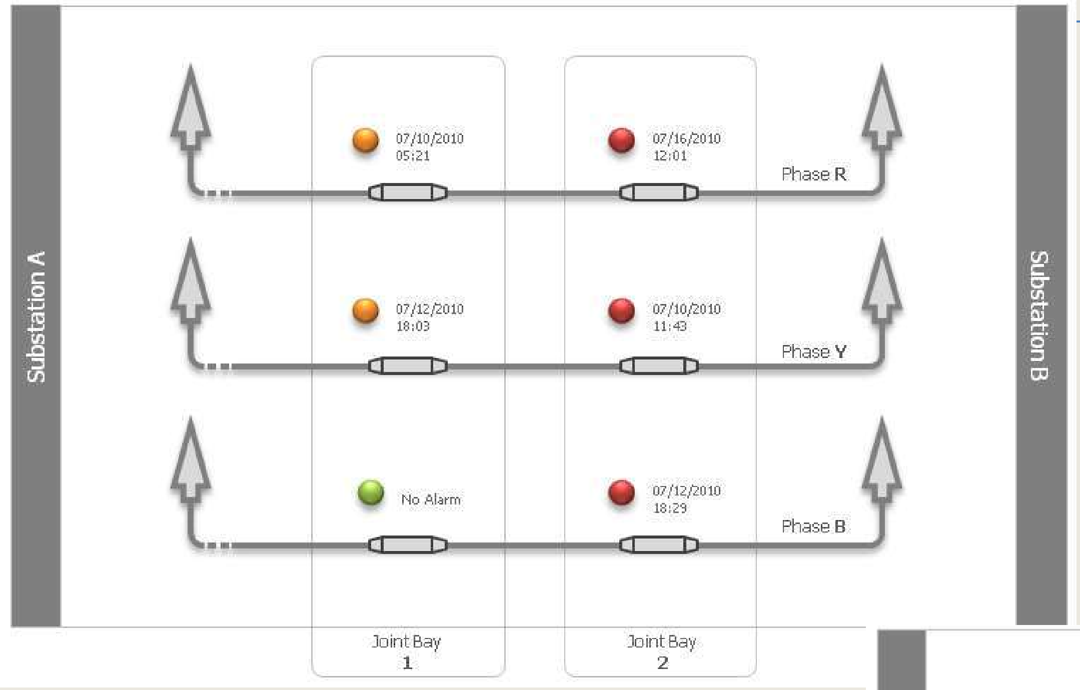
T&D&G

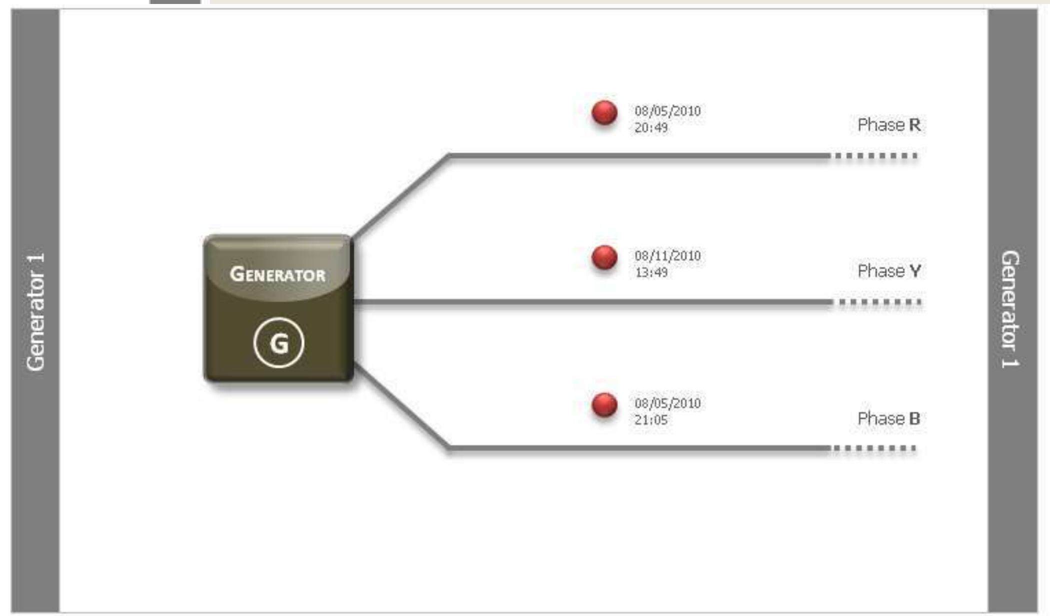
Different system layers

- **High sensitivity, type I and II errors to be minimized, long maintenance time (forecast)**
- **Data Downloader to** manage Diagnostic Unit, PDAU (severe noise rejection), **Database** (storage and management, artificial intelligence, thresholds, alerts , **Communication** (web service, provides data and alerts to remote users in a simple way (traffic light))



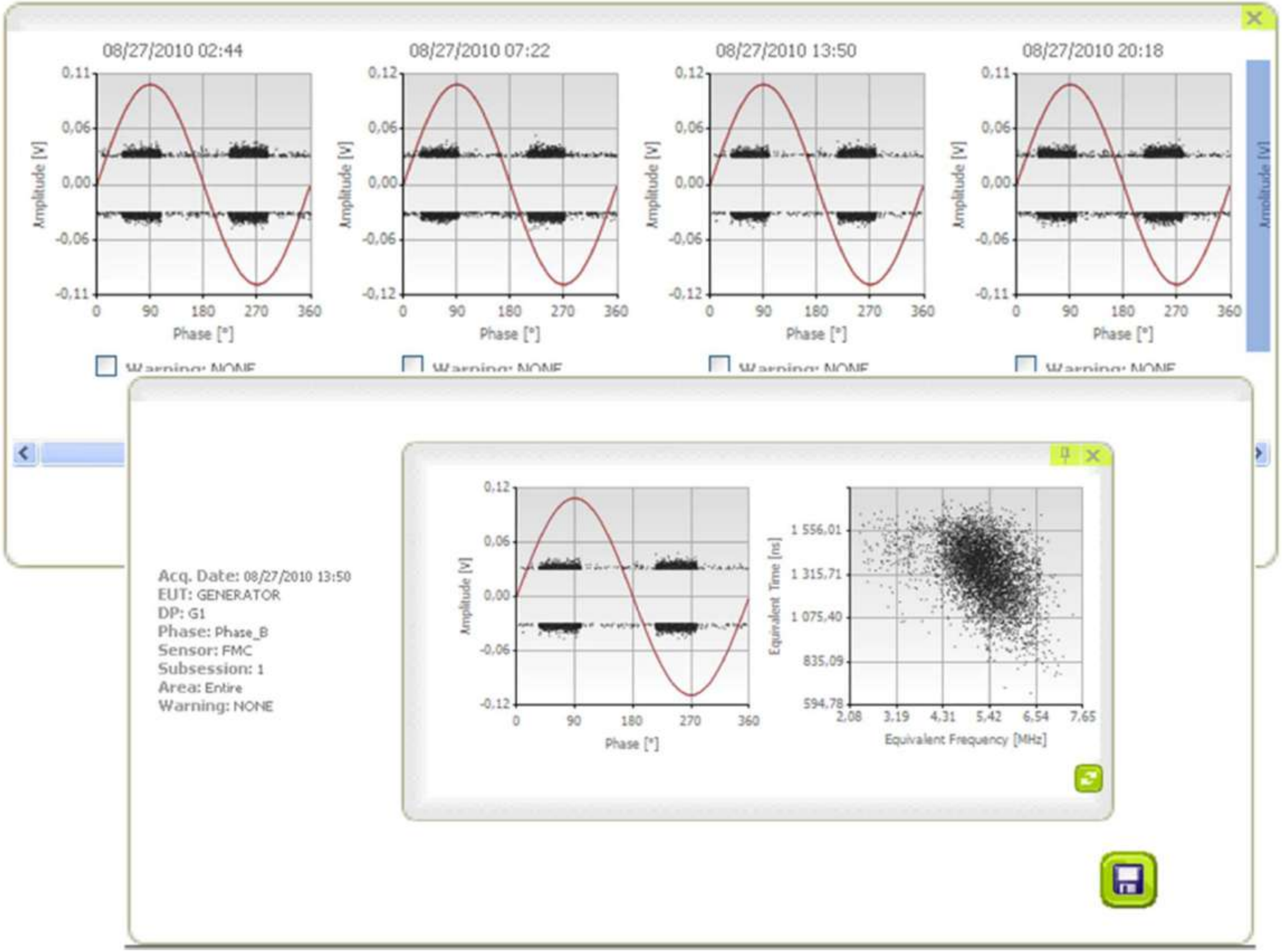
The different system layers: Web service





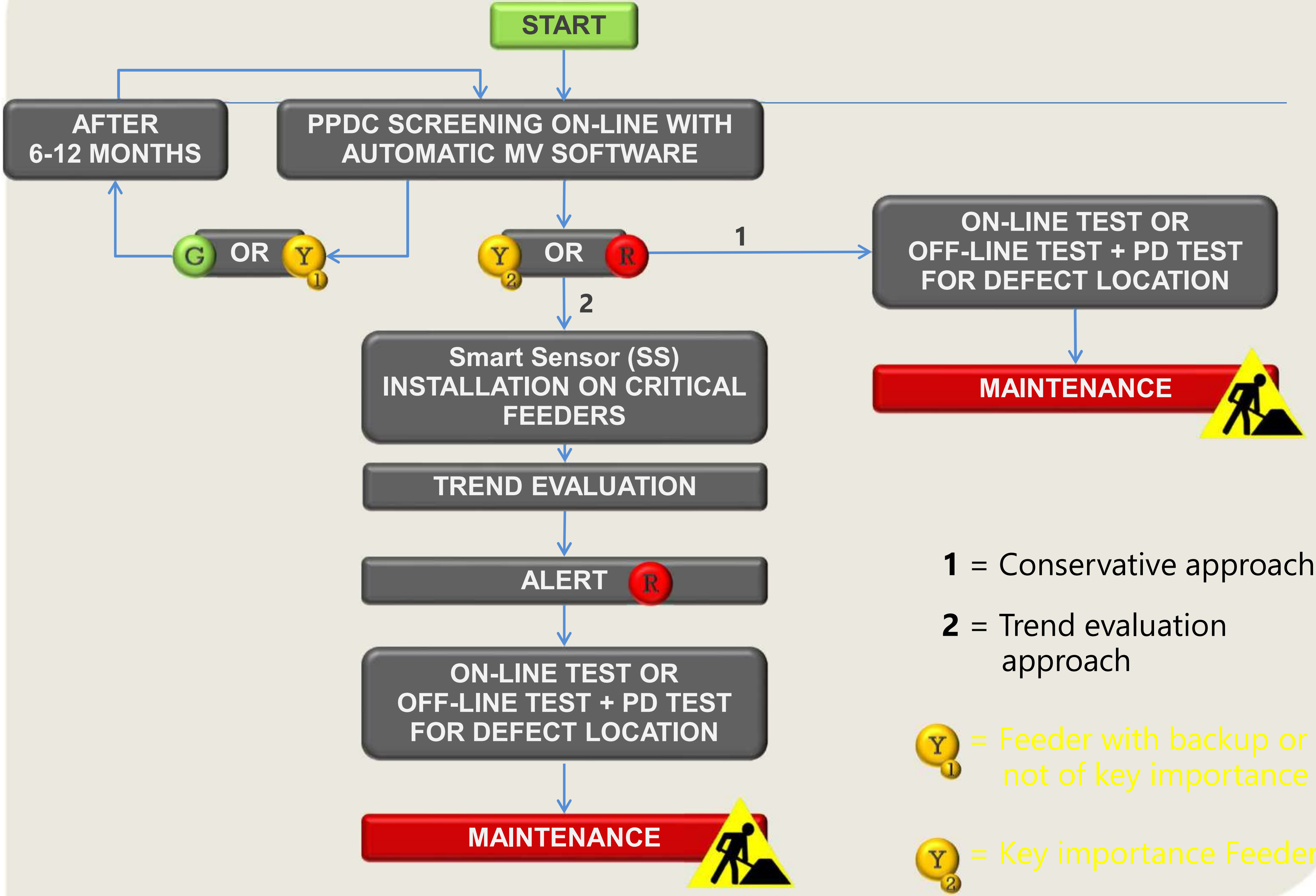
- One can see the trending associated with each sensor in each phase of each equipment.
- One can see the recorded data and patterns… one can play e.g. with the T-F map and set up PD alarms properly (based on amplitude/trend/repetition rate).

- Folders containing the stored data can be opened when alarms are raised and patterns associated with the PD activities (or what else among Diagnostic Properties DP) can be seen immediately



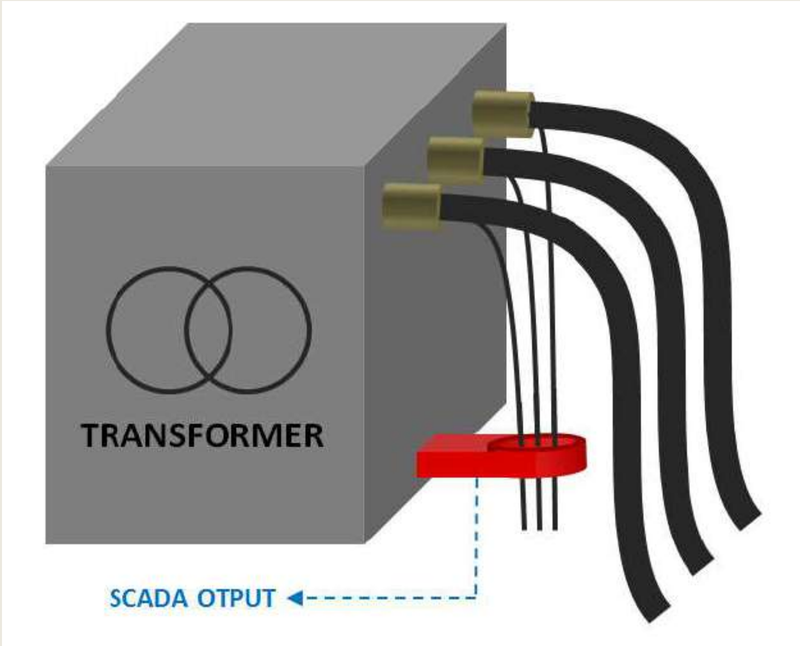
DISTRIBUTION

Smart approach for the MV grid



Smart Sensors (SS)

- Low cost
- Reliable
- Distributed intelligence
- Smart alarm management



Strategy

- Highlight possible weak points by:
  - Age
  - Technology
  - Recent repair operation (infant mortality due to bad manufacturing)
  - On-line PD screening
- Equip apparatus with low cost SS
- Diagnostic quantity (PD) trending and Alert management
- Repair only if and when needed
- NO NEED OF EXPERTS

400 kV Transformer

CASE STUDY #1

Background

- A 250 MVA autotransformer experienced immediately after installation a significant increase of Hydrogen
- According to the IEC and IEEE specs, the level and the trend of H2 were critical after only few months. After one year the H2 level exceeded 1000 ppm
  - ***Possible PD according to IEC60599 based on Duval Triangle***
  - ***Condition 2 according to IEEE C57.104: Exercise caution-Analyze for individual gases-Determine load dependence***
- BUT:
  - Is this gas increase actually due to thermal or electrical problems?
  - Is the PD activity, if present, harmful or not?
  - Which type of PD and where is this located?
  - Which is the degradation rate?
  - Which is the best action to be taken reducing costs and increasing reliability?

Actions

1. OIL TREATMENT

2. MONITOR PD+GAS+Bushing Tandelta before oil treatment and after

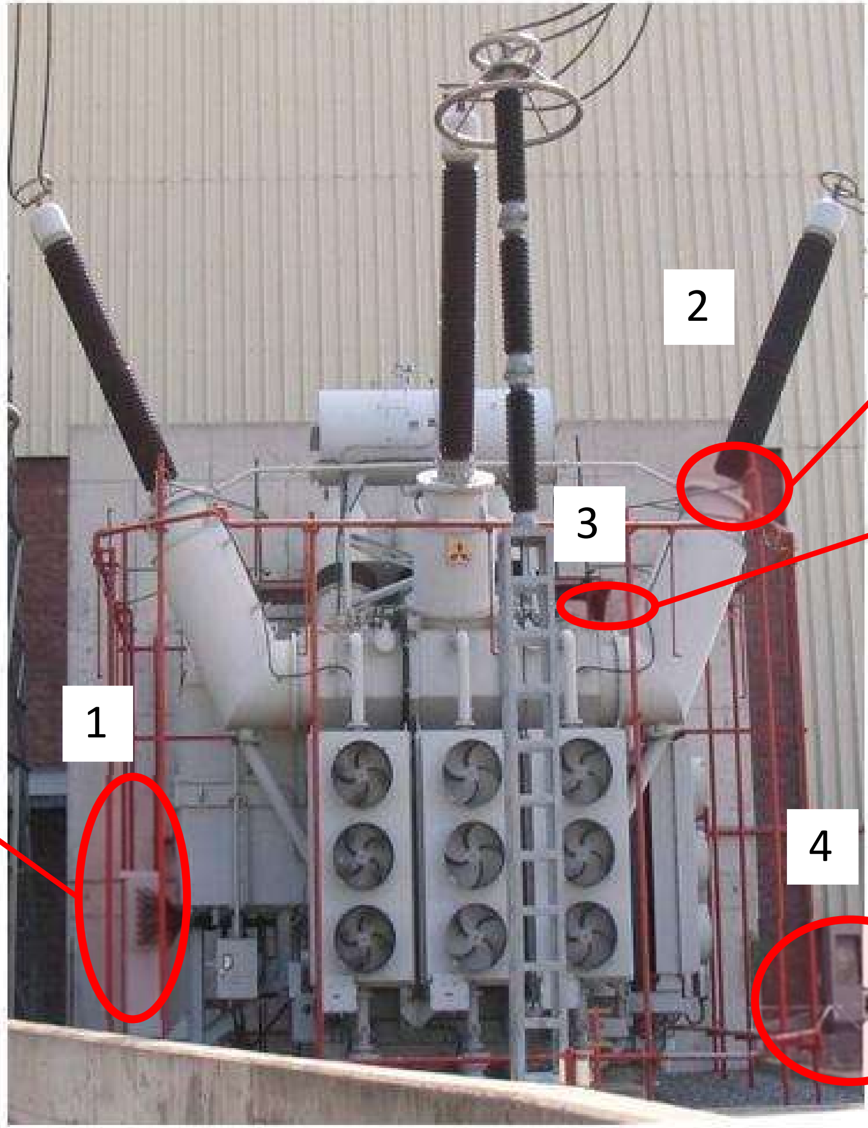
SCOPE OF THE MONITORING SYSTEM INSTALLATION:

- MONITOR THE TRANSFORMER TO AVOID UNEXPECTED FAILURES
- ASSESS THE PD HARMFULNESS
- GIVE A PROBABILITY OF FAILURE WITHIN THE GUARANTEE TIME

SGGMS main characteristics

- PD
  - UWB detector (16kHz-35 MHz)
  - 6 sensors (Tap Adapters)
  - Time -Frequency Map Separation algorith
- DGA
  - 2 Gas (H_2,CO) + Moisture + Temperature
  - Membrane technology/electrochemical sensors
- Bushing Tandelta/Capacitance
  - Leakage Current
  - Dissipation factor
  - Insulation Resistance

GLOBAL MONITORING LAYOUT



1: Acquisition Box

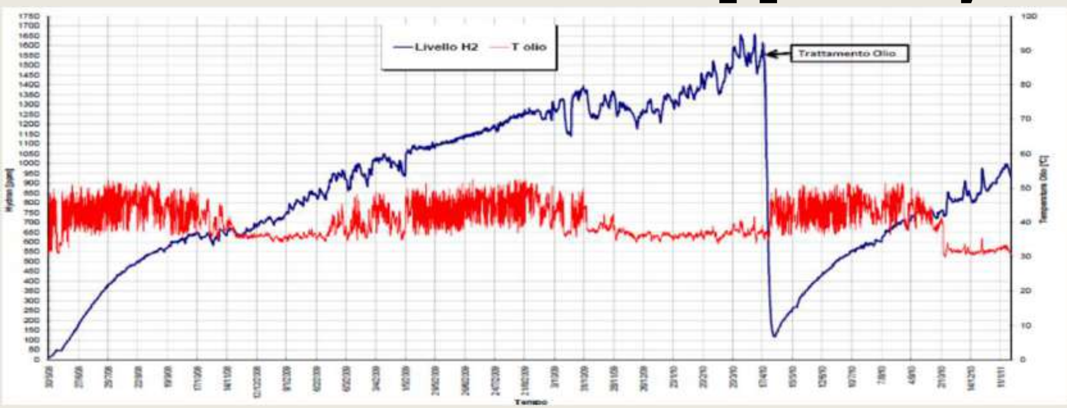
2: Tap Adapter for both PD and TanD acquisition

3: TD Sensor

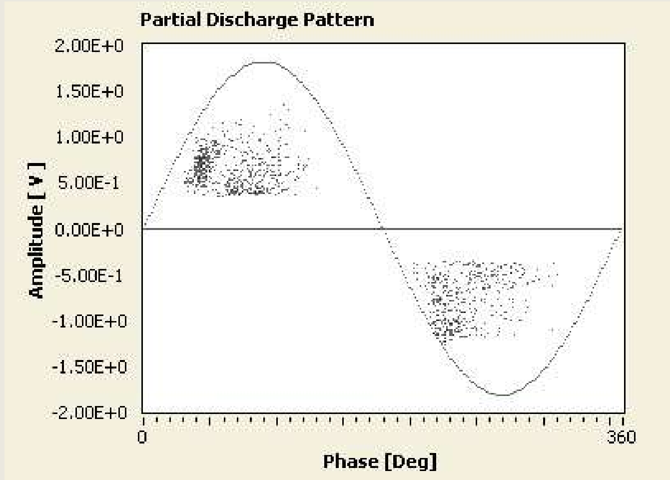
4: DGA

Results before oil treatment

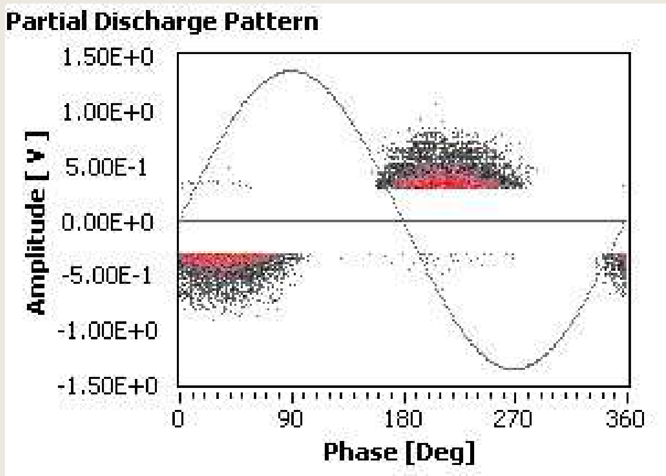
- TWO PD phenomena were detected on-line:
  - A sporadic activity due to small gas bubbles in the oil. This activity was intermittent.
  - A smaller, but persistent, activity detected in all the HV phases, identified as mixed internal/surface PD.
- H2 level increase about 5 ppm/day



Bubble PD



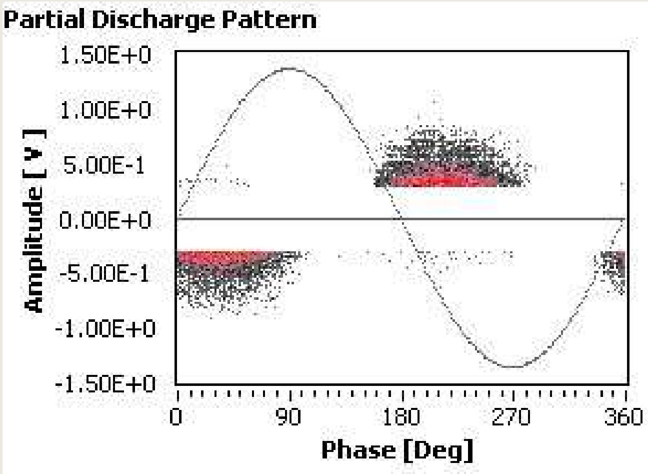
Surface/Internal PD



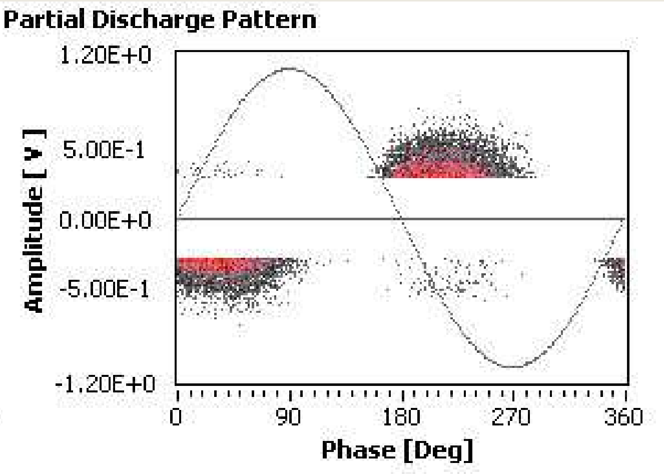
Main results after oil treatment

- The first activity, due to the bubbles, disappeared after the oil treatment.
- Second activity was still there, in all three phases at HV side (230 kV)

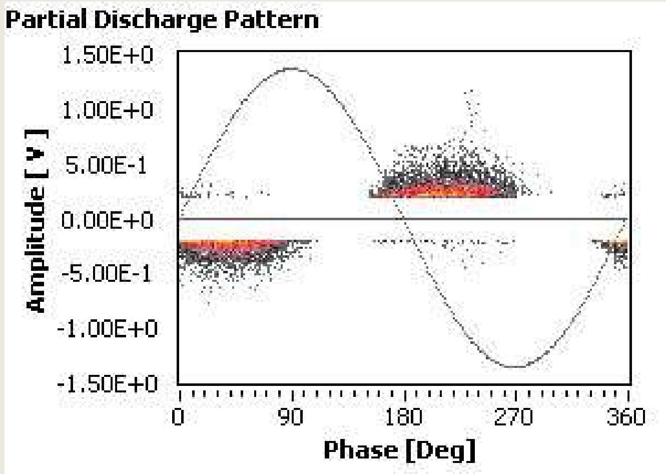
Phase 4

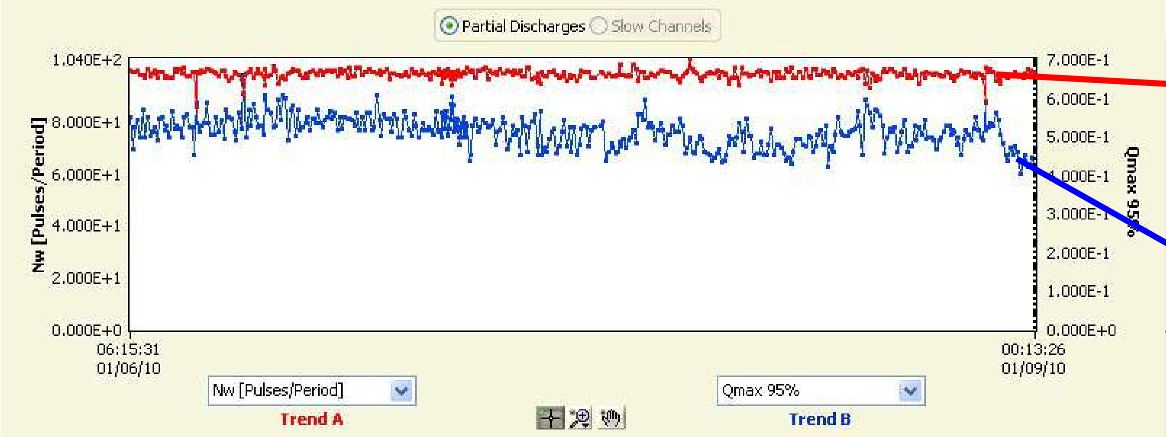


Phase 8



Phase 12



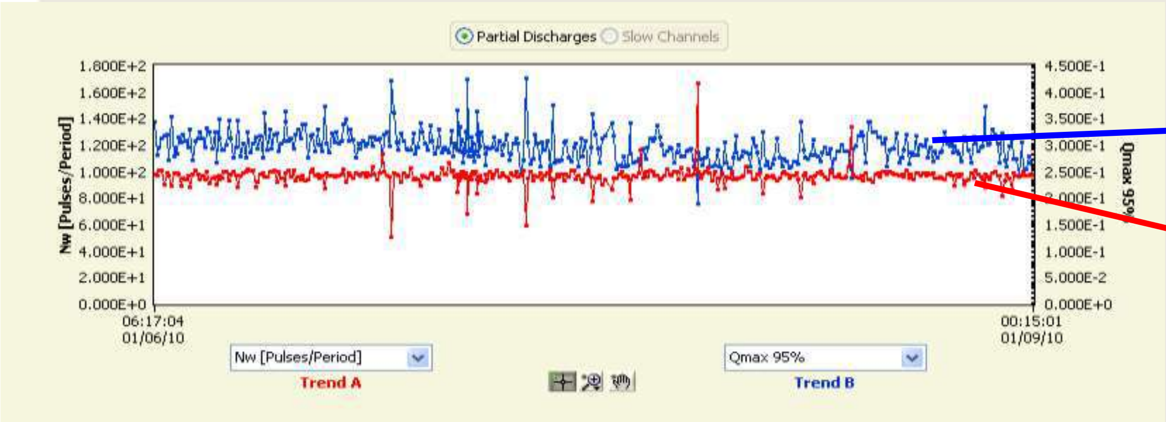


Nw > 80

PD Trend

Phase 4

Qmax>500 mV

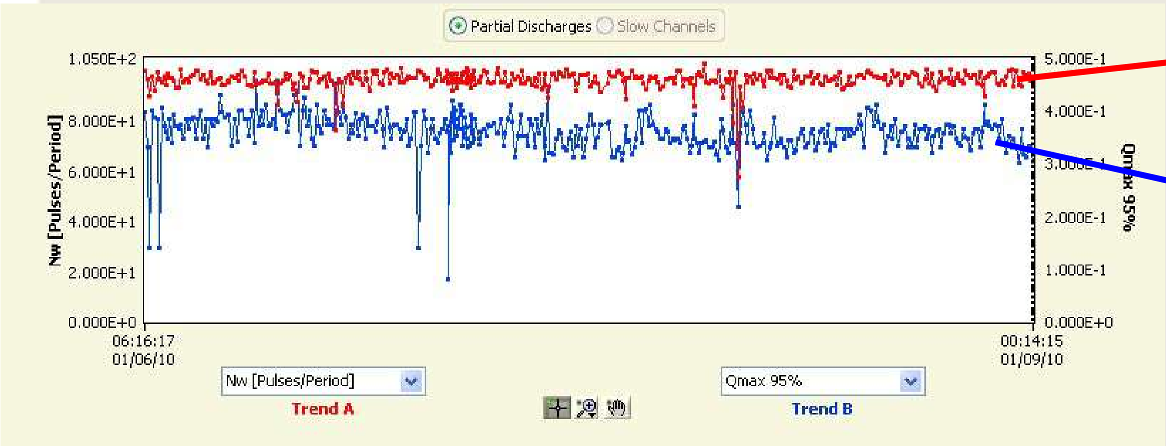


Qmax>250 mV

PD Trend

Phase 8

Nw > 100



Nw > 80

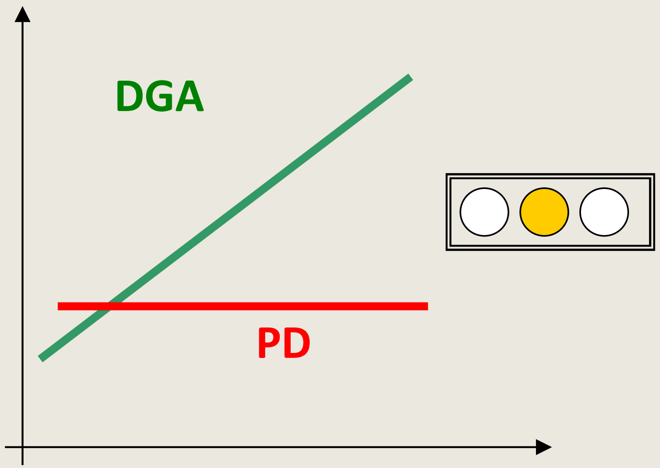
PD Trend

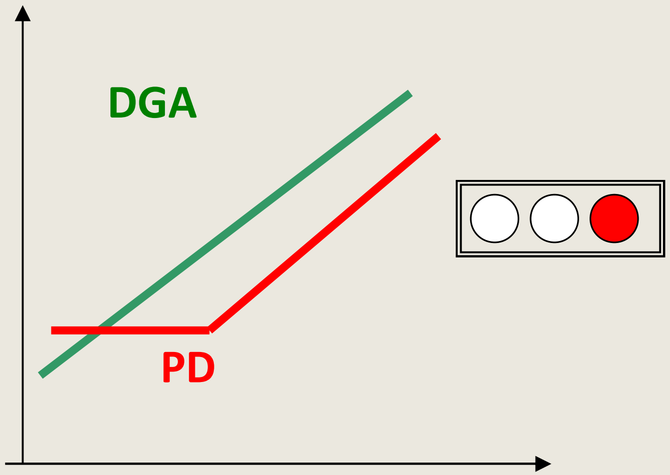
Phase 12

Qmax>300 mV

Evaluation of trending

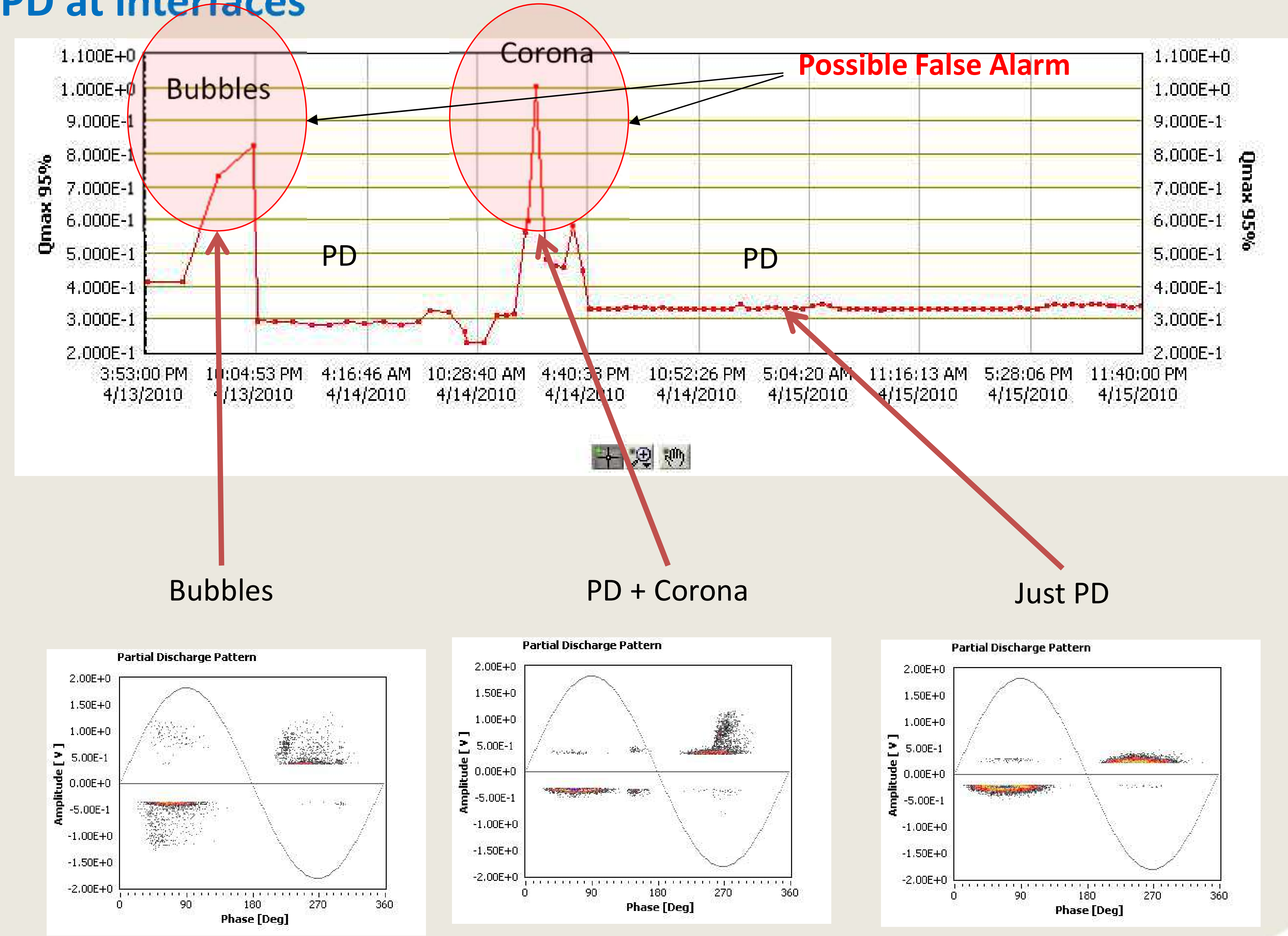
- Necessary to give COMBINED alarms and assess insulation condition



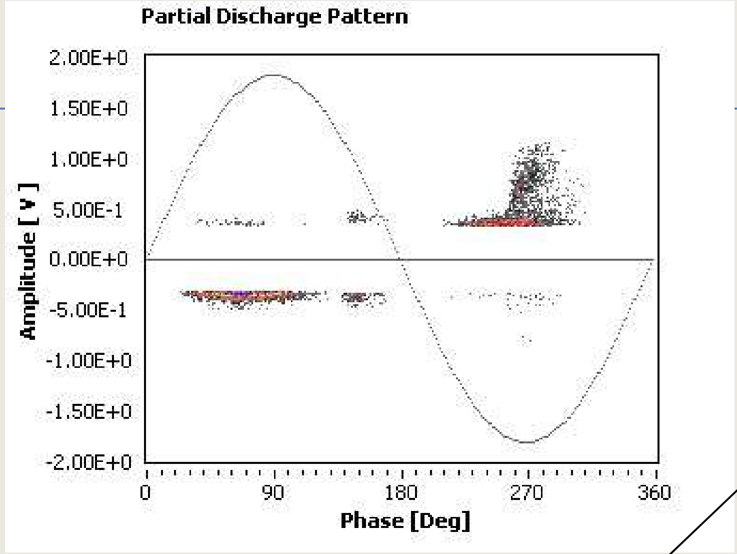


Yellow light provided

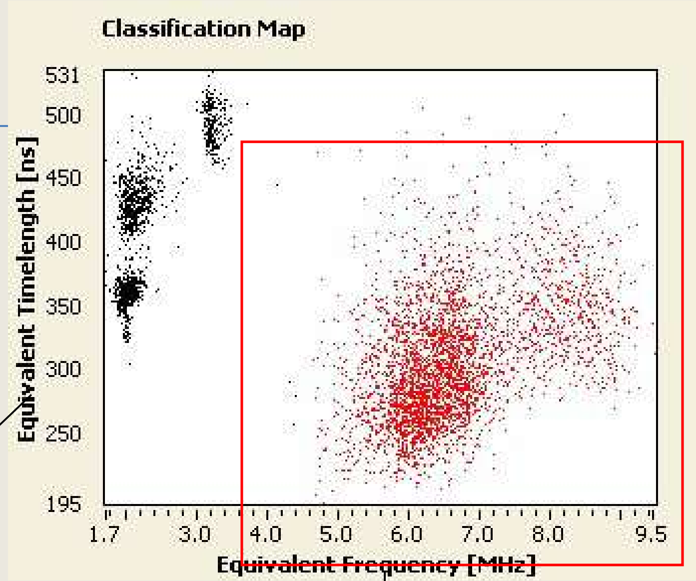
Qmax Trend of Phase 4 without separation of **Corona** and **Bubble** from **PD at interfaces**



TF FILTERING: Smart Alarm setting

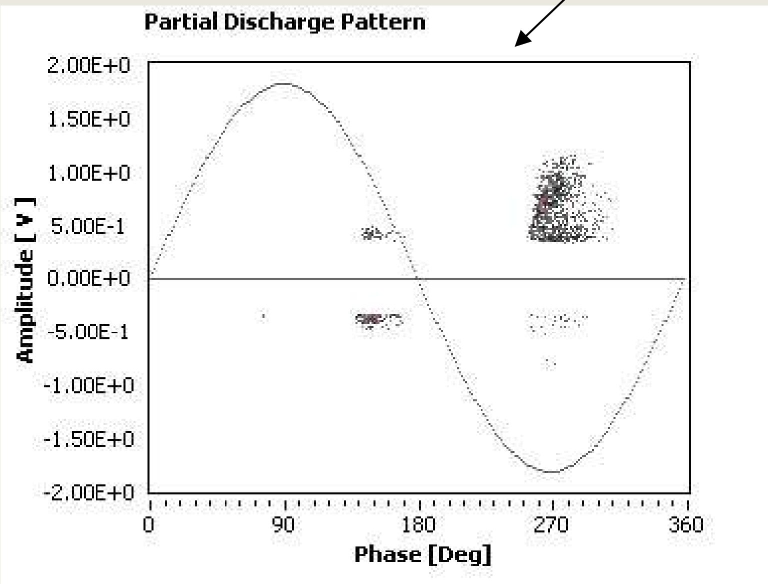


CORONA + PD

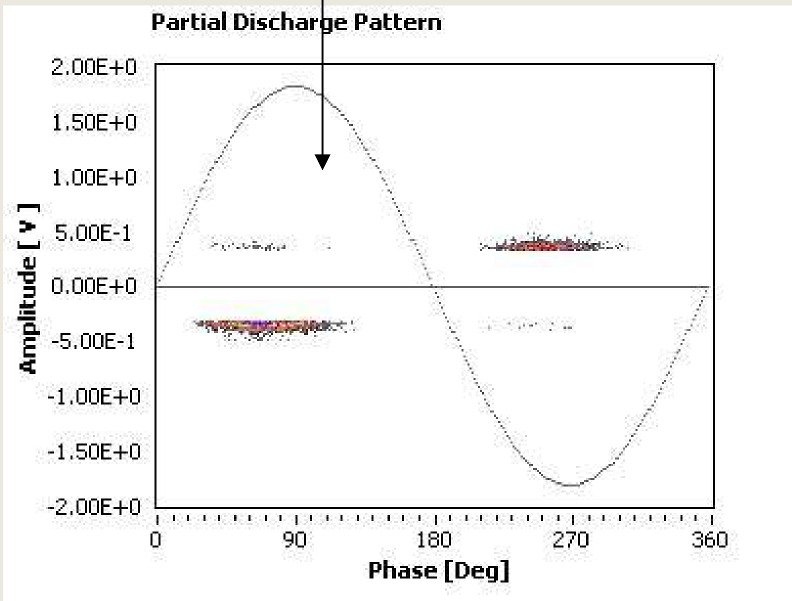


TF FILTERING:

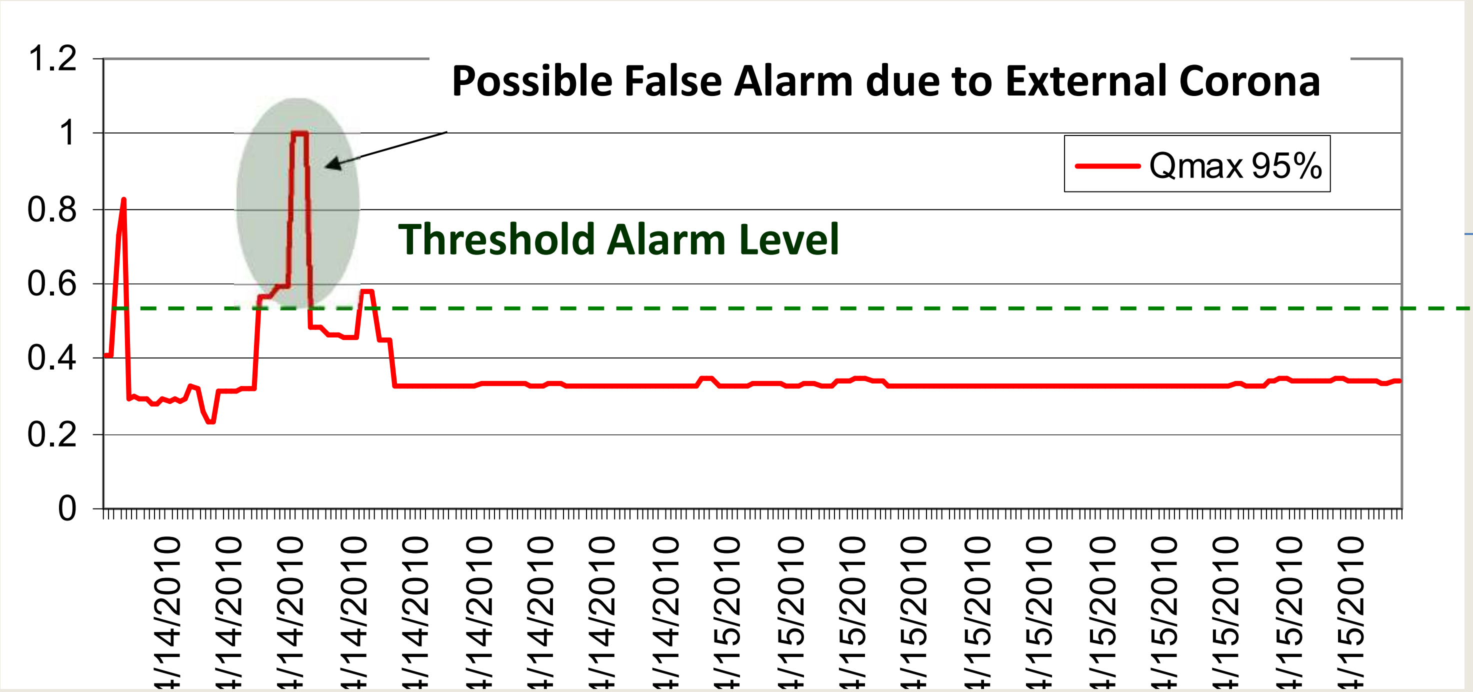
Trending evaluated only in this region of the map!!



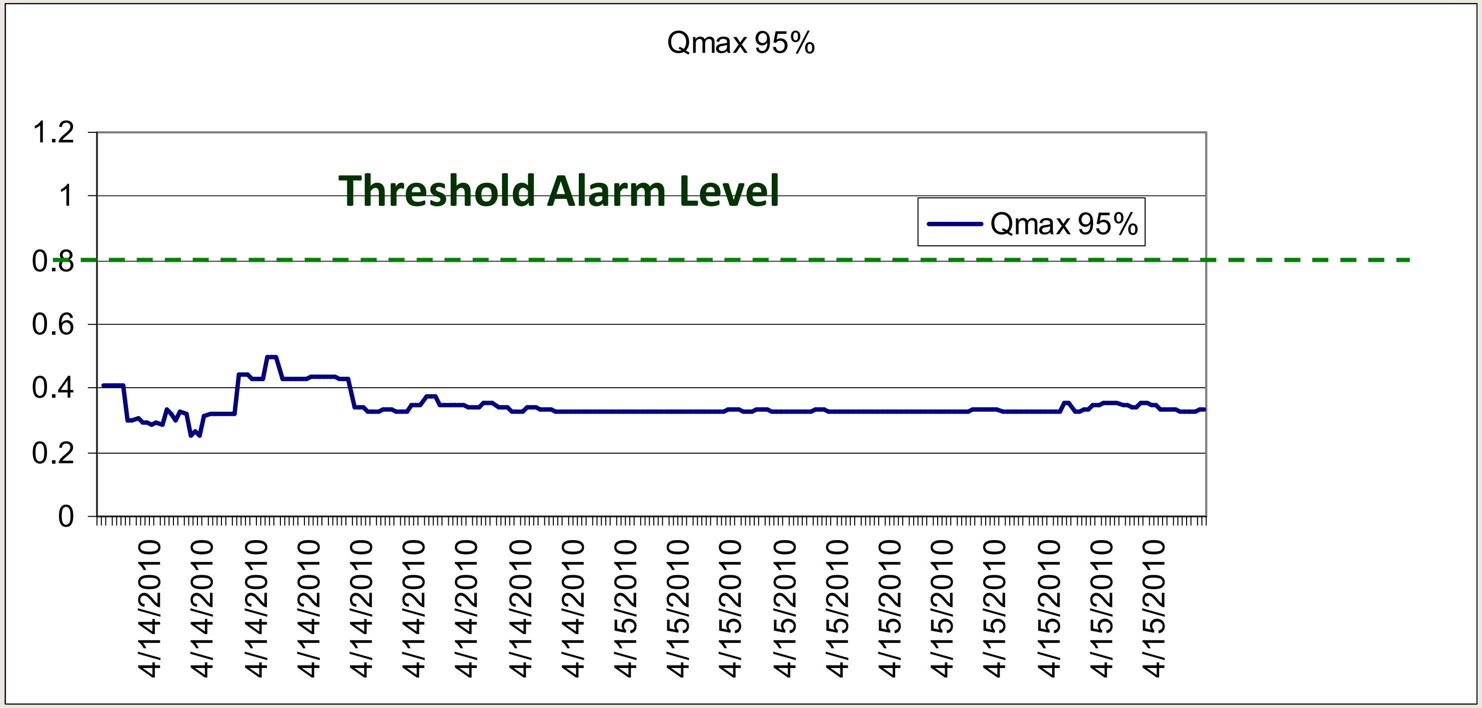
CORONA



PD



Trending without TF filtering



Trending after having TF filtered external corona

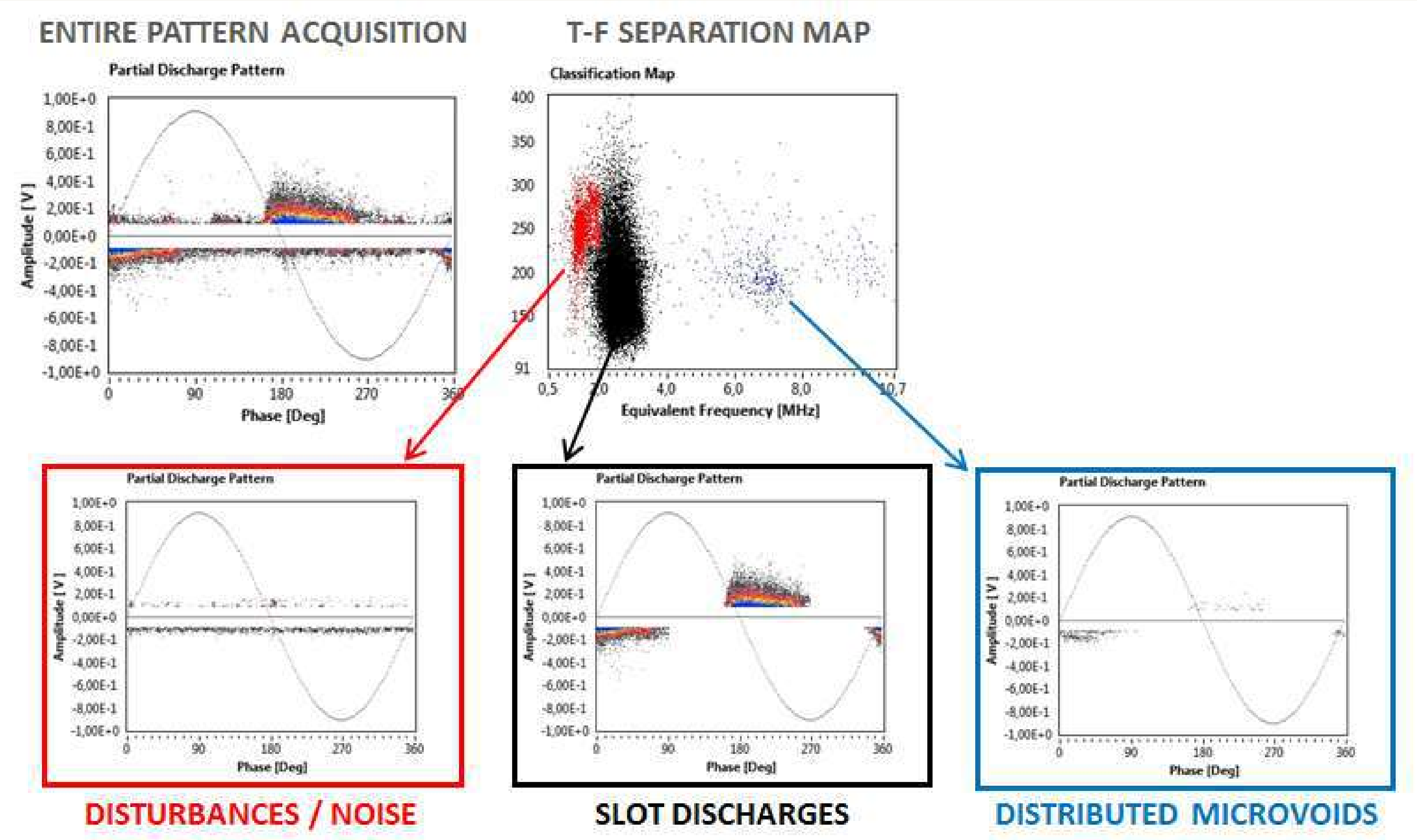
FACTS after 6 months monitoring

- No significant changes in bushing tandelta values were noted over the monitoring period (6 months)
- Polarity of detected PD indicated that PD source was not located inside the bushings.
- The H2 gas levels increased during the monitoring period with average rate of 5 ppm/day. No significant changes in the rate was noted. constant rate.
- PD activities were detected continuously for 6 months , demonstrating that gas increase was due to PD
- PRPD pattern investigations suggested that
  - There are three defects: one each phase, in the upper part of transformer

13kV air-cooled generator monitoring

CASE STUDY #2

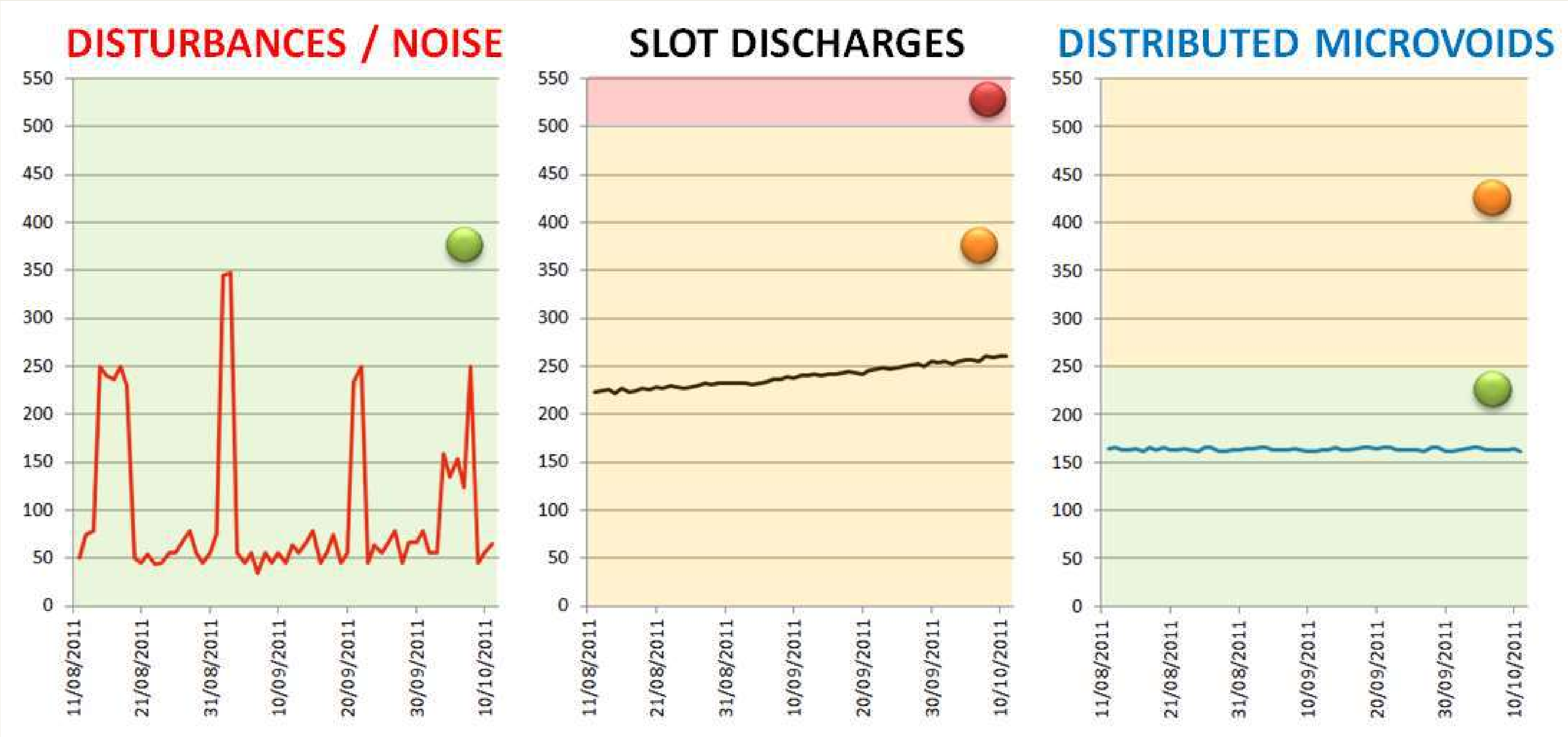
PD pattern separation example



Easy?

- Apparently a dominant phenomenon
- Magnitude monitoring could probably work in this case (is it monitoring even needed?)
- Maybe, but is noise/disturbance stationary?
- Not really…
- Let us look at the trend of the three phenomena separately (separation achieved by defining zones on the TF map)

Monitoring results



- Disturbance can become larger than slot PD
- This could generate false alarms → record data based on TF map as pre-trigger

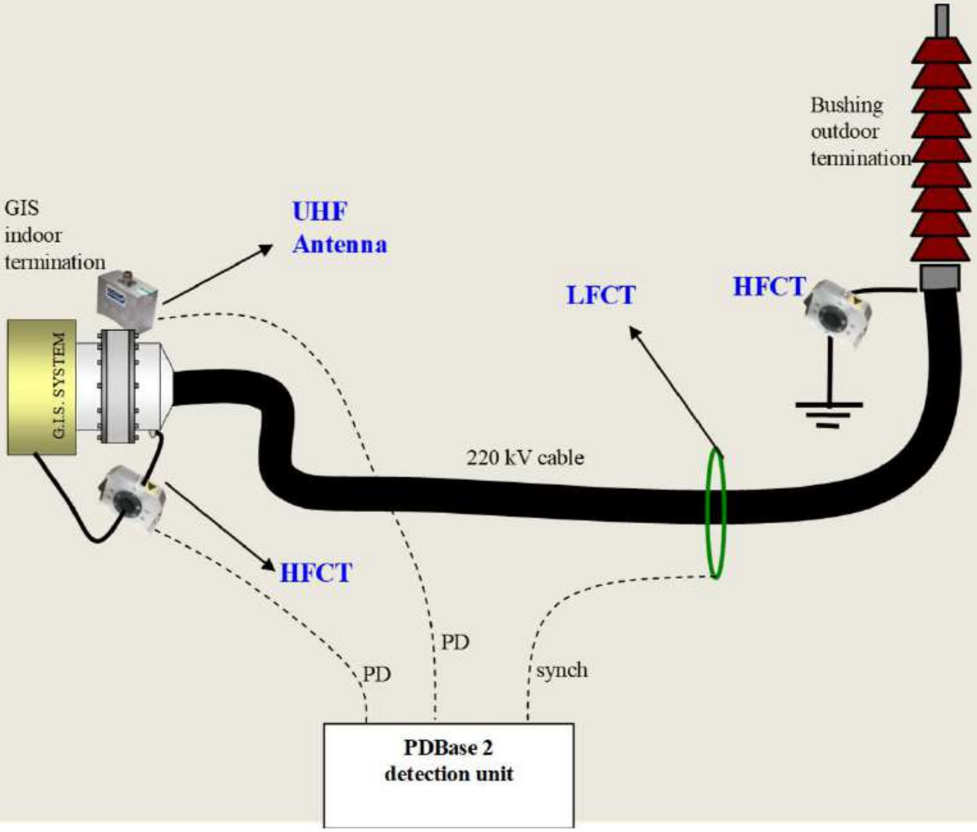
HV Cable and GIS

CASE STUDY #3

PD below the noise, Separation, Identification, Location, Alerting. 220kV, Europe.

Techimp UHF Antenna

Techimp HFCT Sensor

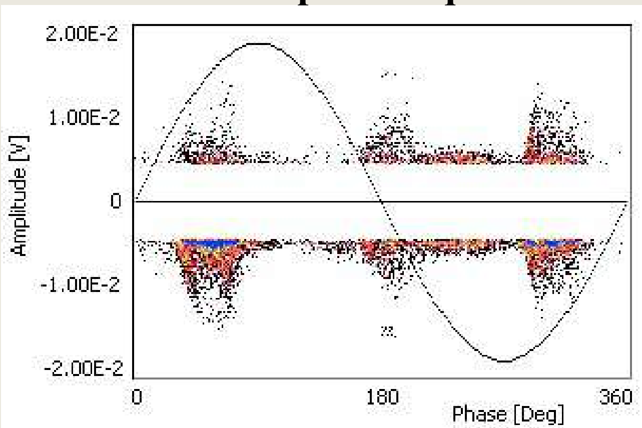


Measurement Set Up:

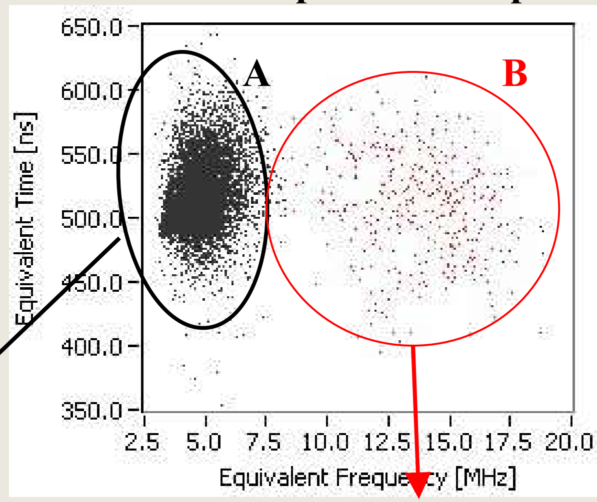
•Techimp PD Base II
•Techimp UHF Antenna
•Techimp HFCT Sensor

- **PD acquisition in correspondence of a 220kV cable-GIS termination**
- **Apparently only disturbance are present**

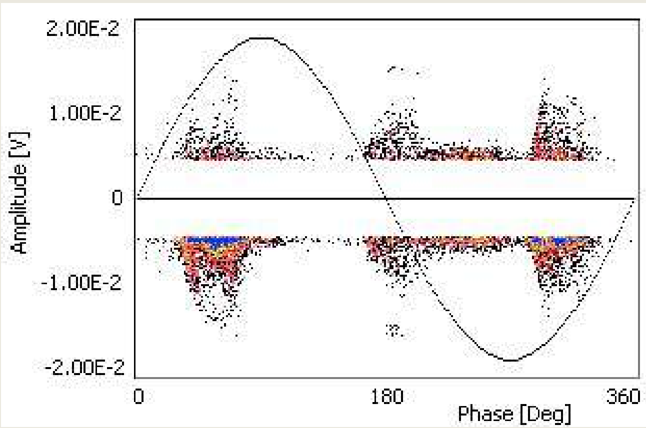
PD Pattern – Complete Acquisition



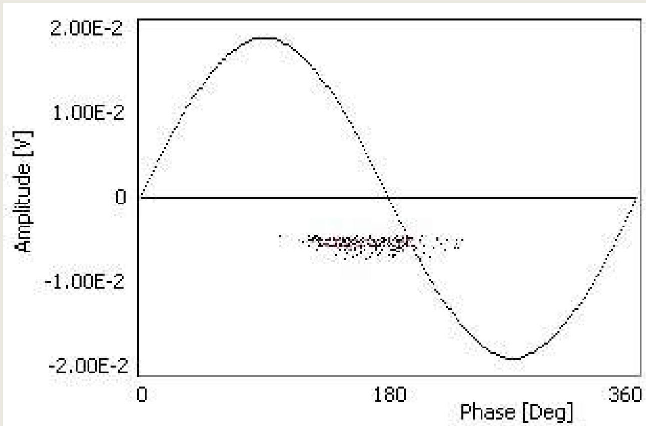
T-F Separation Map



Sub pattern A: Disturbances



Sub pattern B: PD due to internal cavity



Separation allows dangerous PD to be detected below the noise level (effective on-line testing) !

AVOIDING FALSE ALARM !
EFFECTIVE MAINTENANCE !

HV Cable

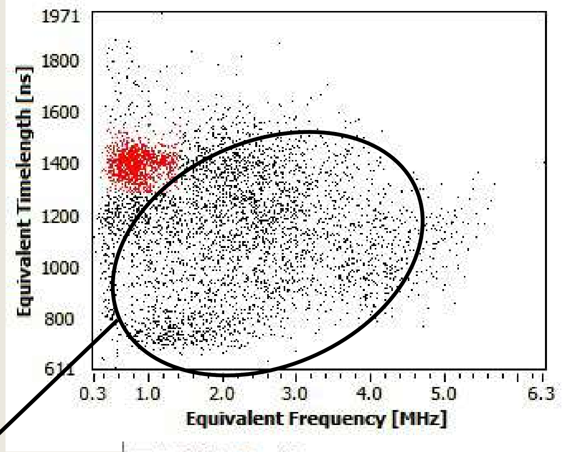
CASE STUDY #4

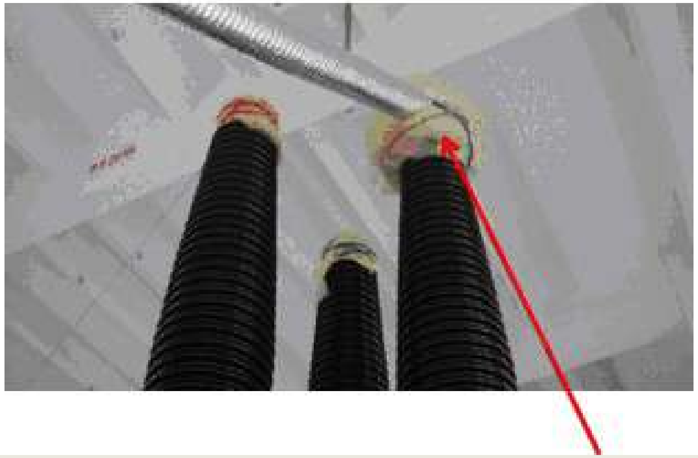
Identification and Pass/No Pass: Lab Tests.

- PD acquisition on a 220kV cable system during After Laying PD Test
- High-amplitude signals are detected (up to 700 pC !!!). **PASS / NO PASS ?**

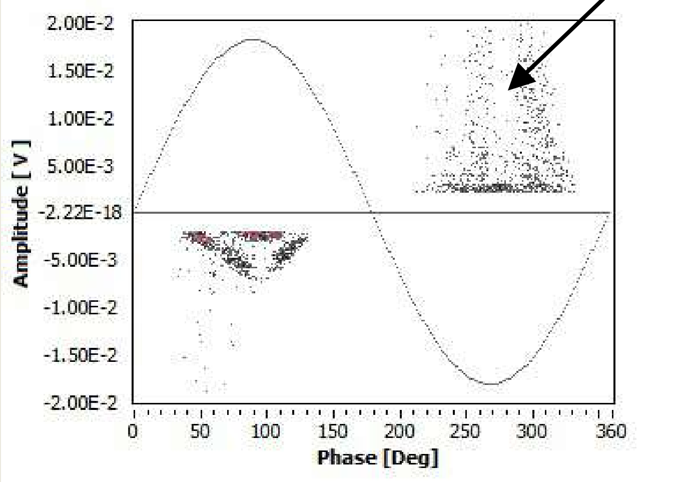
PD Pattern – Complete Acquisition

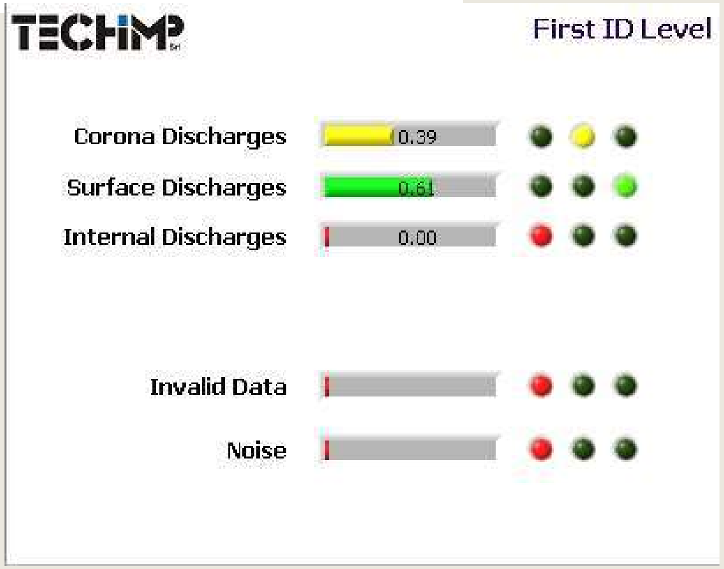
T-F Separation Map





Sub Pattern (Black cluster)





Plastic cover of HV bushing for RTS connection to GIS cable termination !!!

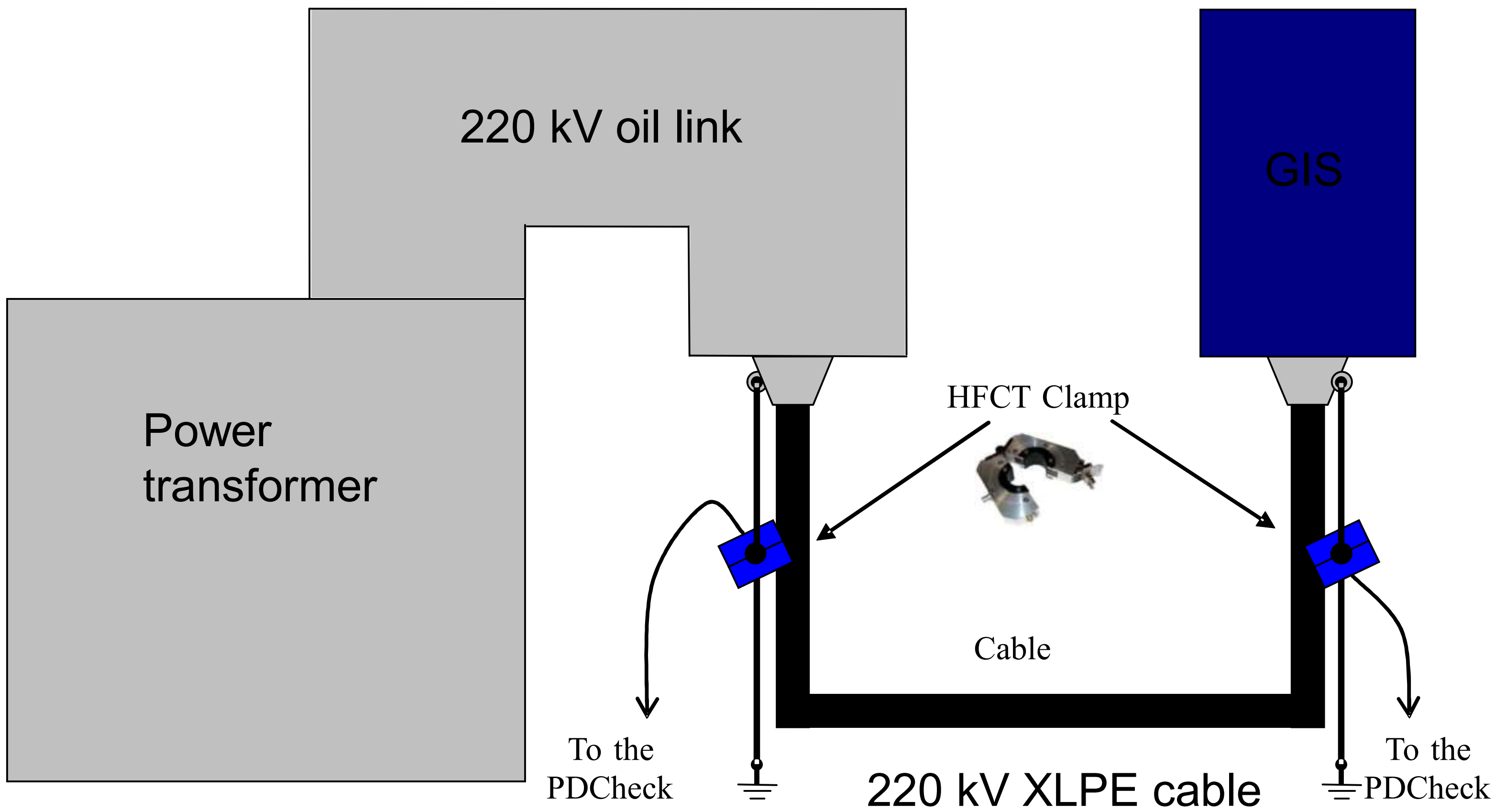
Pass / no pass criterion shall not be based on PD amplitude, but, first of all, on IDENTIFICATION of the detected PD phenomena.

HV Transformer and GIS

CASE STUDY #5

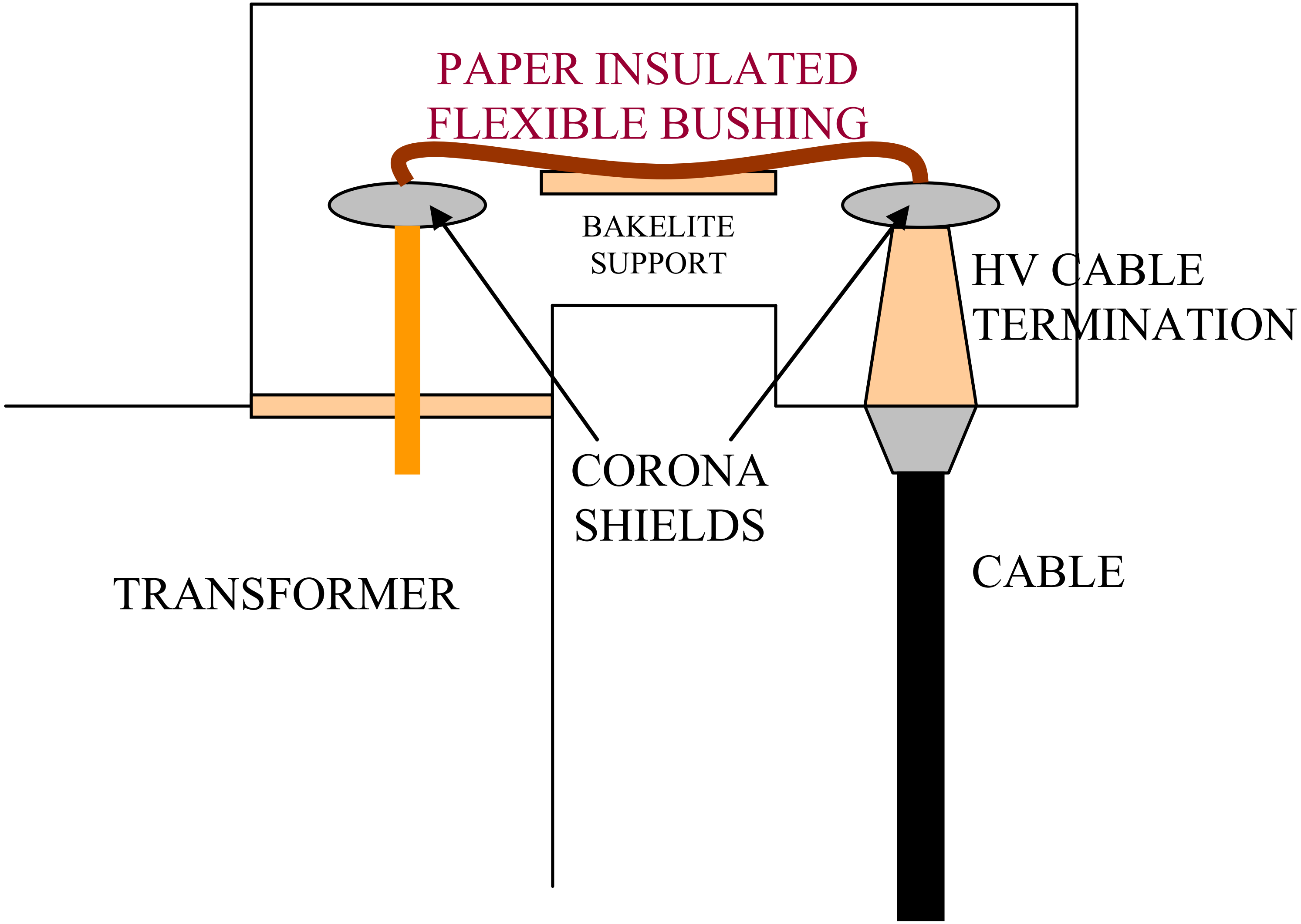
Separation and Location. 220 kV, Europe.

On line PD test on Transformer/Cable: **PD measurement layout**



On line PD test on Transformer: **Insulation technology**

OIL FILLED LINK between Transformer and HV cable

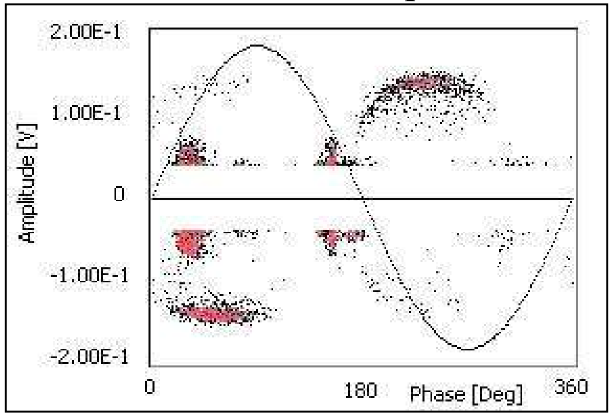


On line PD test on Transformer:

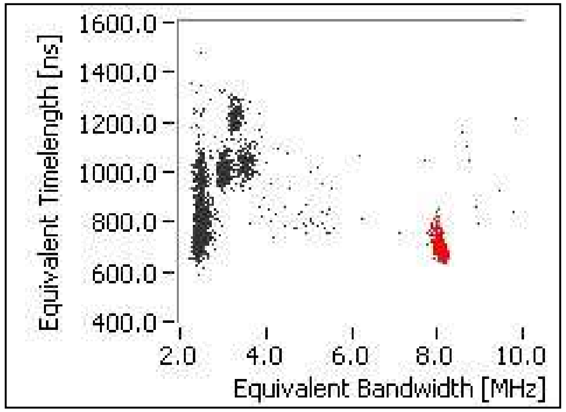
PD measurement results
Phases 0 and 4

Typical acquisition from phases 0 and 4:
PD FREE

Entire Pattern acquisition

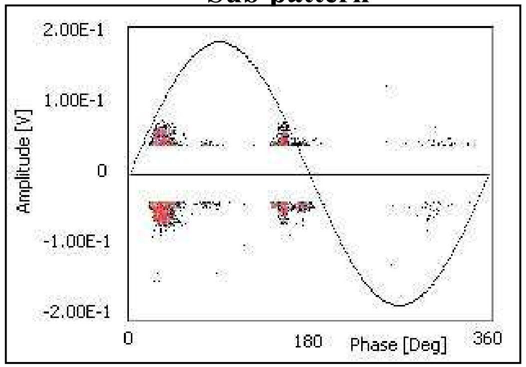


Classification Map

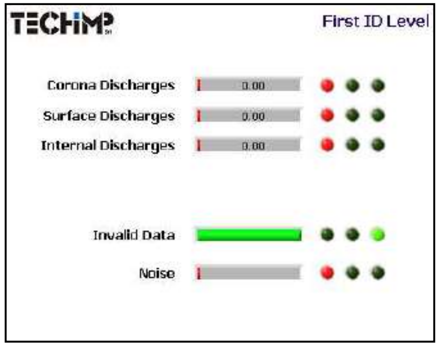


Black phenomenon (3-phase corona)

Sub-pattern

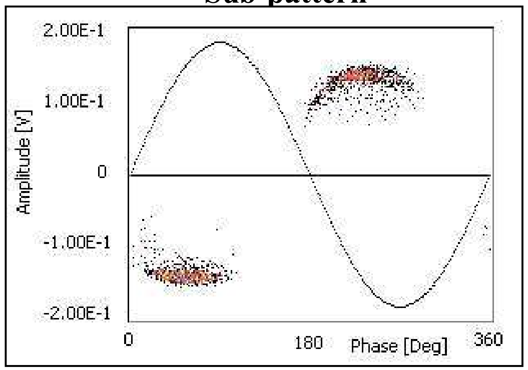


Identification

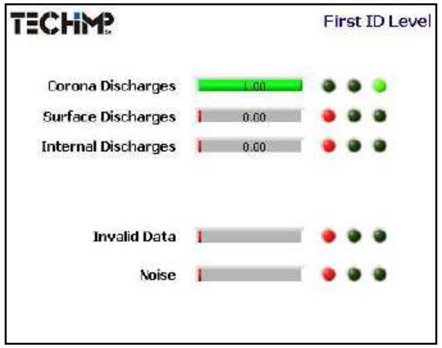


Red phenomenon (Corona)

Sub-pattern

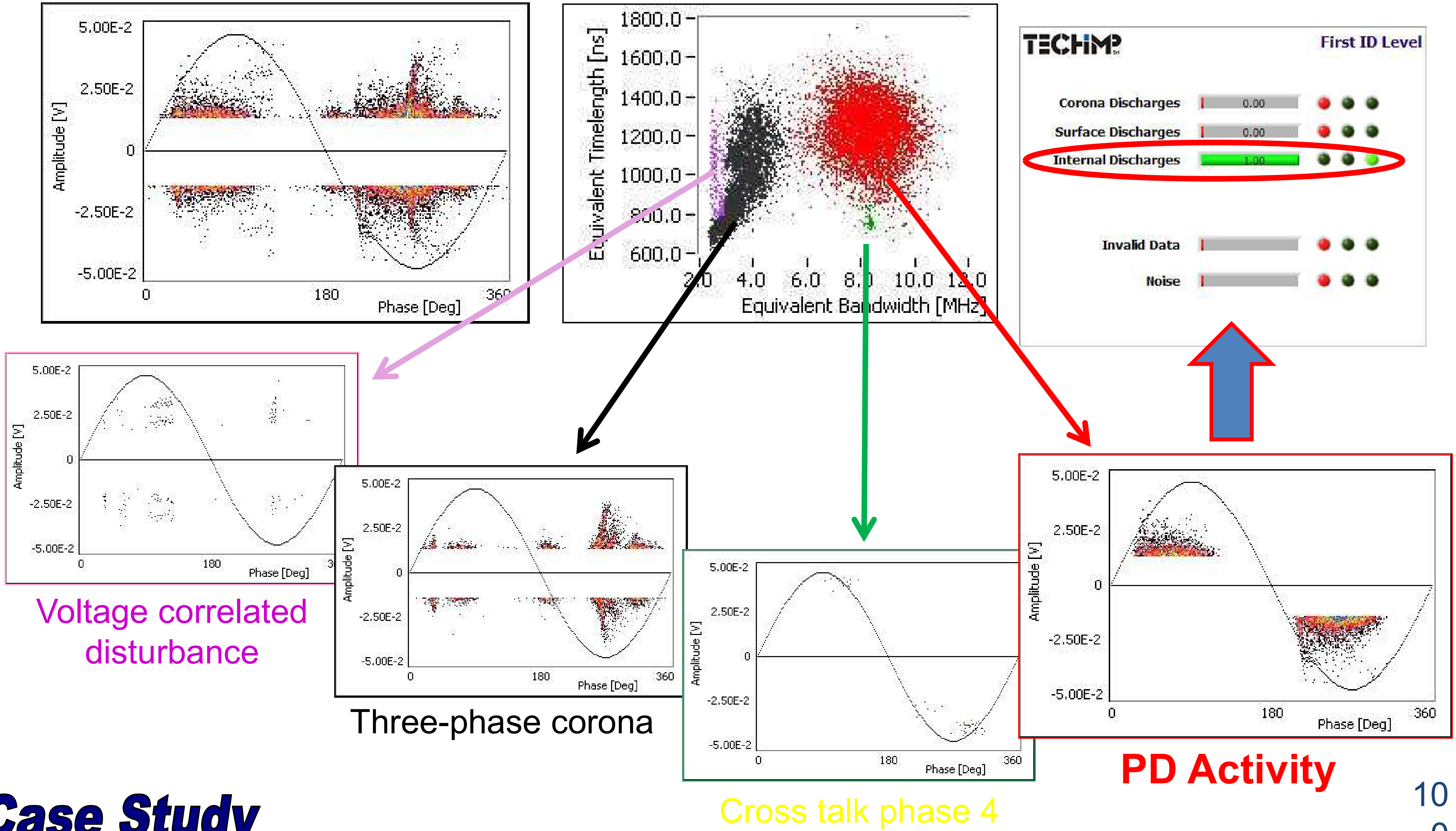


Identification



Case Study

On line PD test on Transformer: **PD measurement results – phase 8**

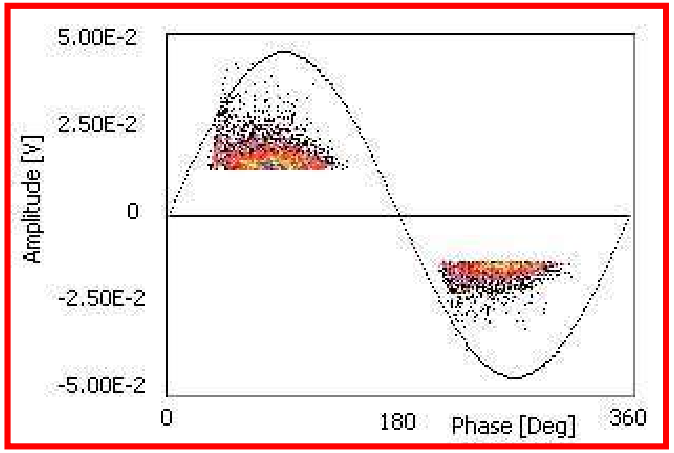


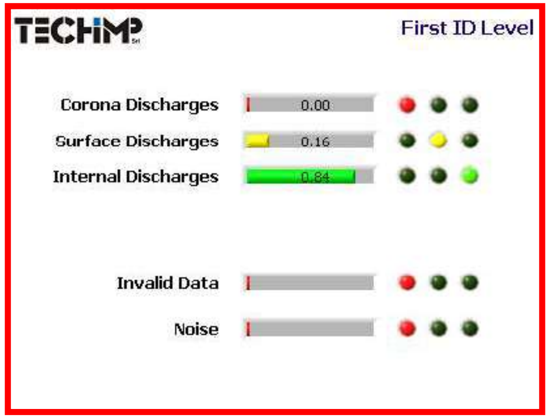
On line PD test on Transformer: **PD measurement results**

internal/surface discharge occurring on paper surface and interface cavities of bushing of phase 8.

Red phenomenon PD activity

Sub pattern





…. Customer's decision: to replace bushing

Finding of bushing inspection: TRACKS IN PAPER!!!

PD INFERENCE RESULTS TO BE EFFECTIVE!!!

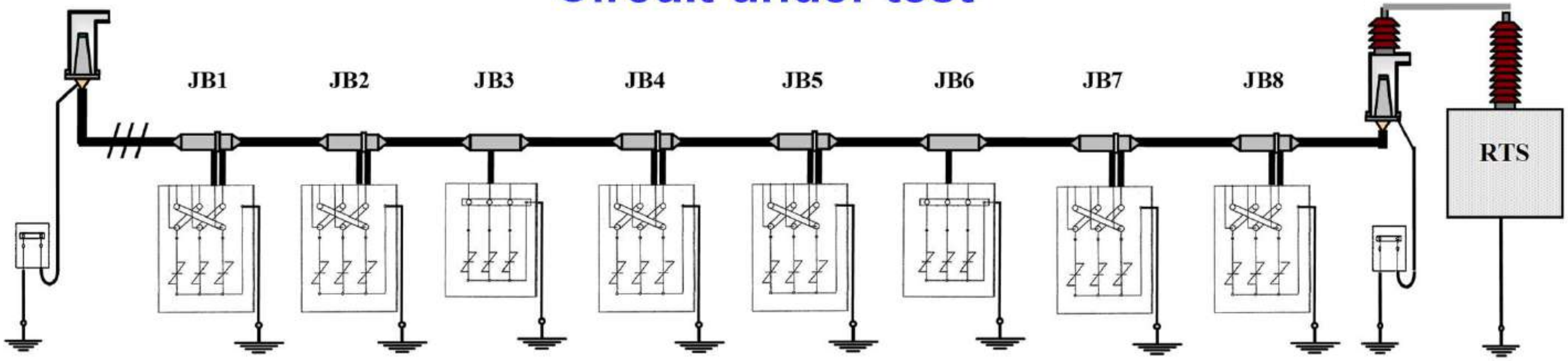
Case Study

HV Cable Commissionig

CASE STUDY #6

Quality Control. 400 kV, ME.

Circuit under test



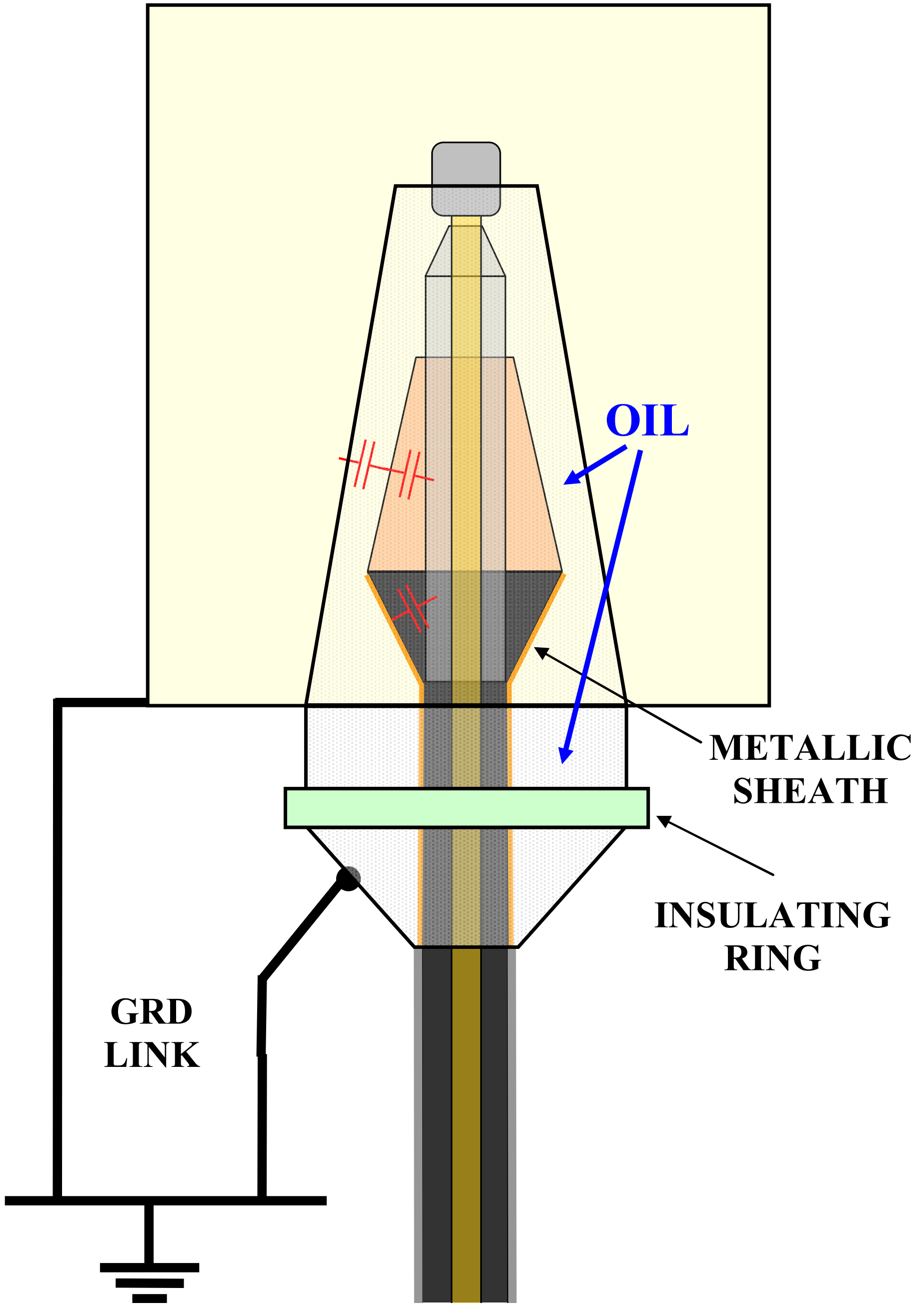
Sensors connection at terminations

Sensors connection at link boxes

Case Study

Insulation technology of terminations:

•EPR stress cone
•immersed in oil



Case Study

1° PD measurement

Results:

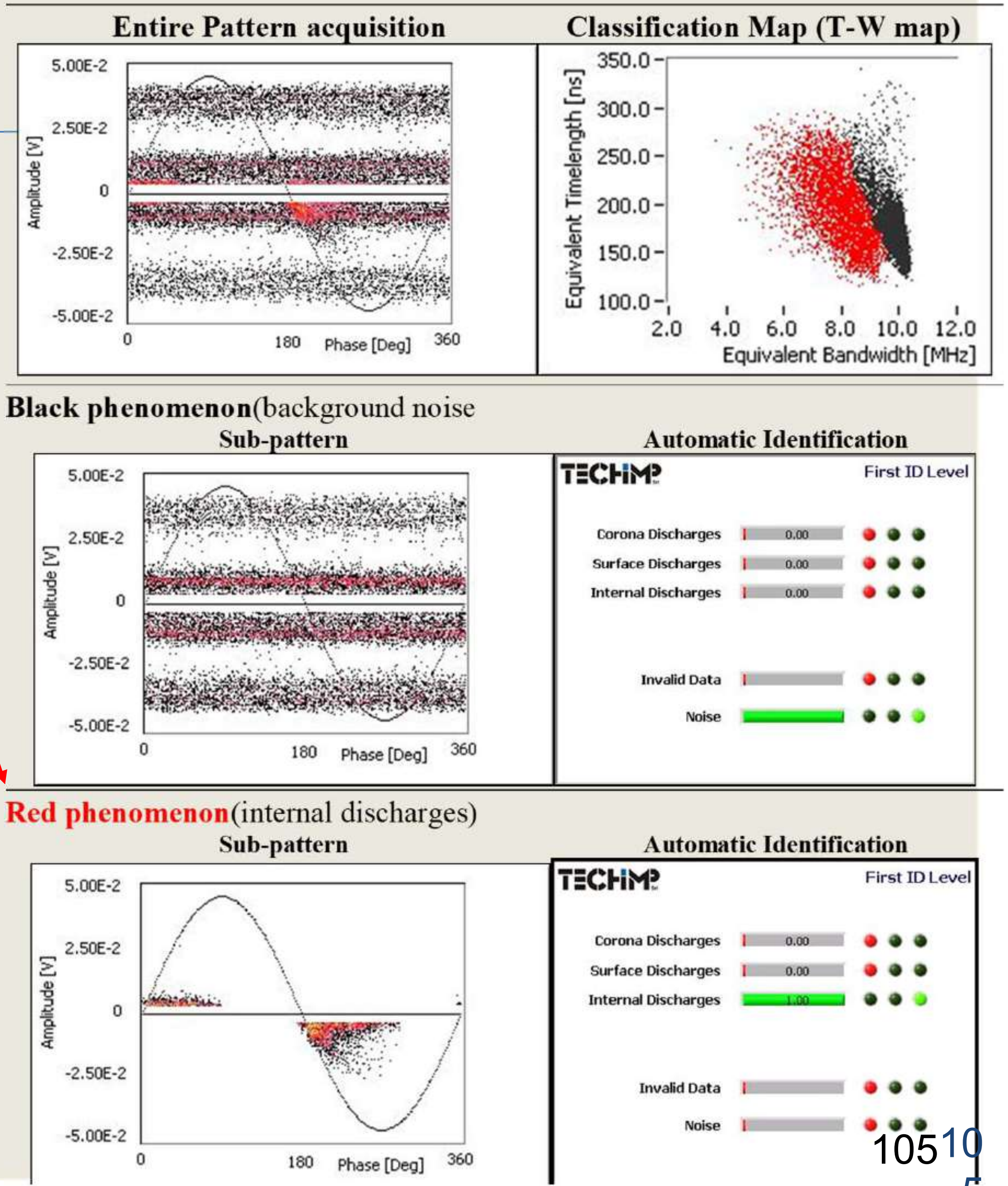
•**PD activities** detected at one side terminations of yellow and blue phases

Taken action:

•inspection and **cleaning** of the outer part of the insulation system of two terminals

Re-installation..

…2° PD measurement…



Case Study

2° PD measurement

Results:

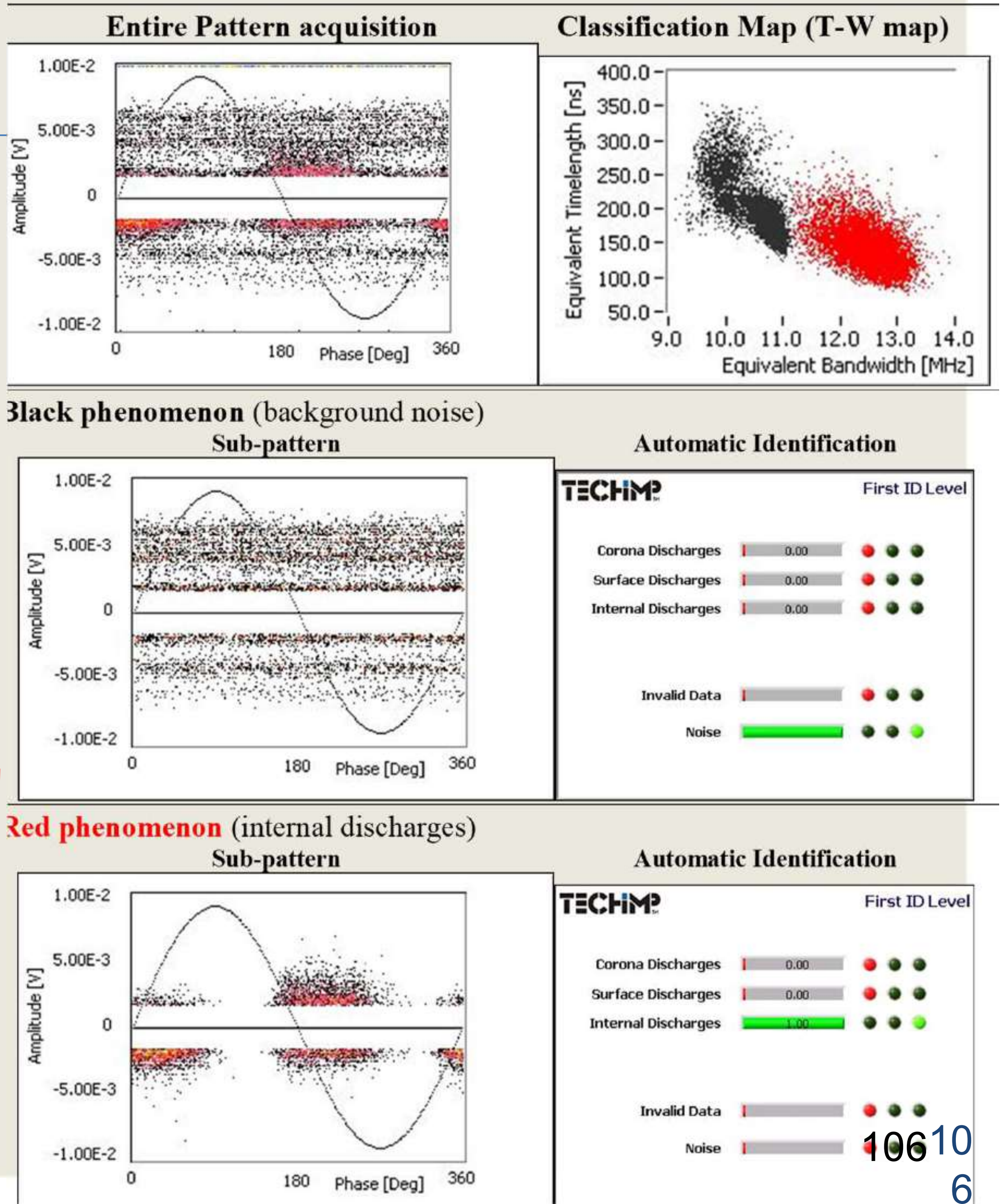
•Again PD activities detected at the same terminations of yellow and blue phase

Taken action:

•To replace terminations!!!

After replacement..

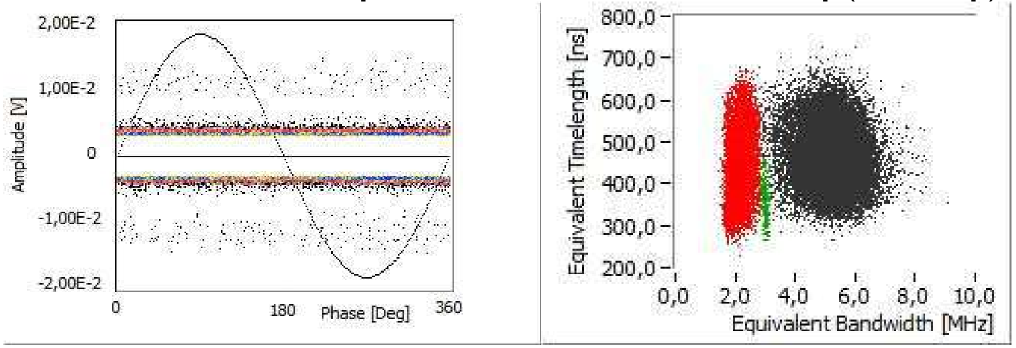
…3° PD measurement…



Case Study

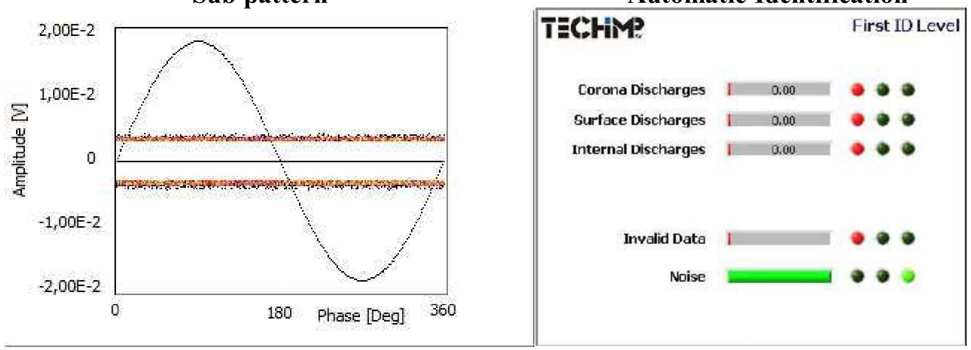
…3° PD measurement after terminals replacement…. → **PD FREE!!** → **…**

Entire Pattern acquisition | **Classification Map (T-W map)**



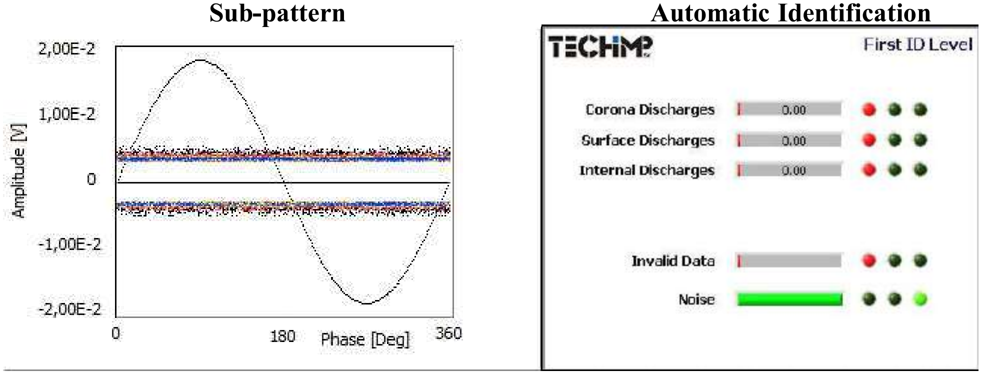
Red cluster (background noise)

Sub-pattern | **Automatic Identification**



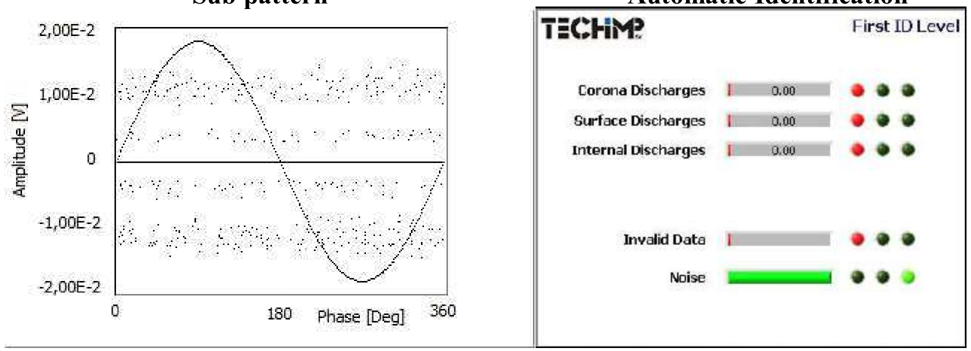
Black cluster (background noise)

Sub-pattern | **Automatic Identification**



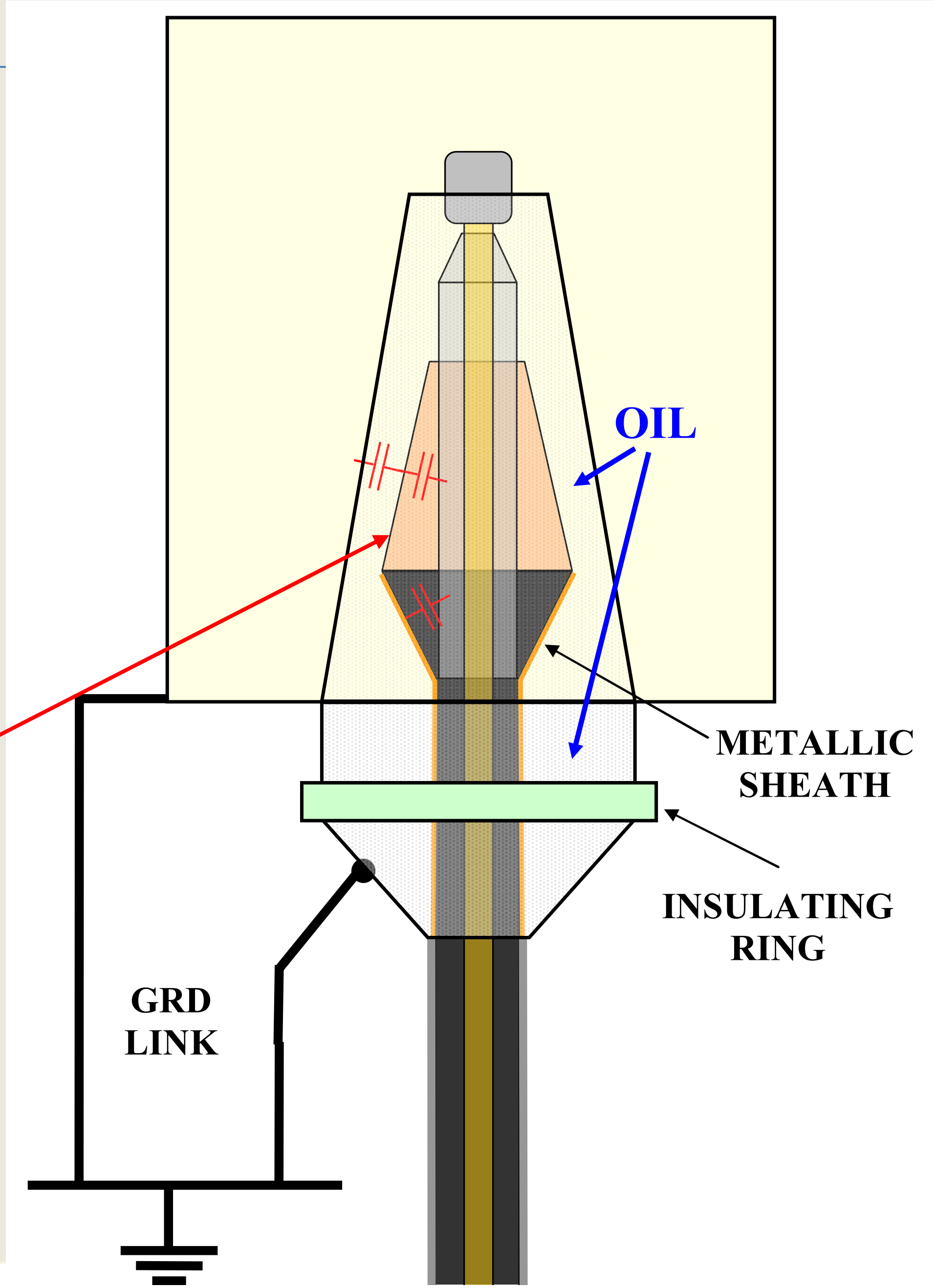
Green cluster (background noise)

Sub-pattern | **Automatic Identification**



PD inference resulted to be effective:

during inspection a defect was found in the stress cone immersed in oil

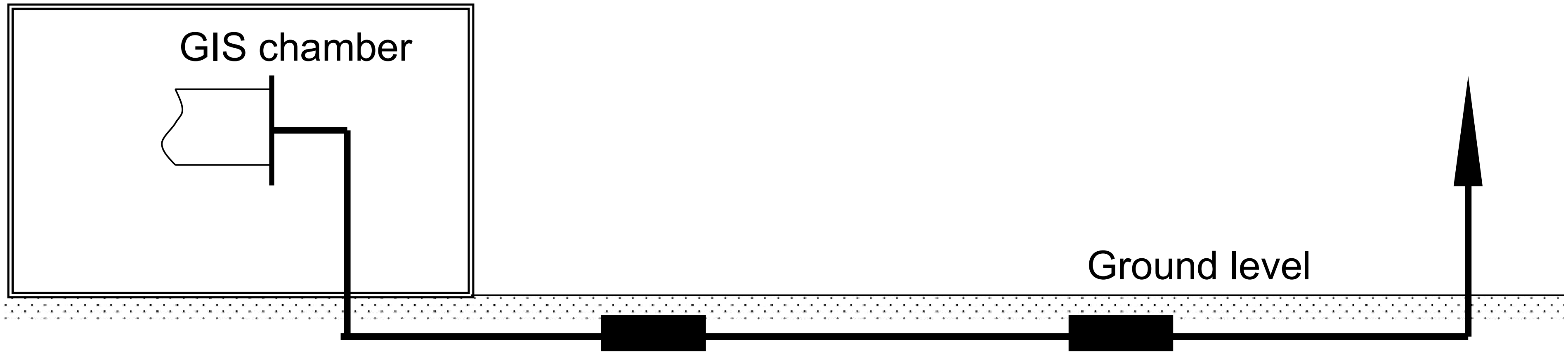


Case Study

H V Cable On-line Testing

CASE STUDY #7

use of the TF map for trending and alerting. 400 kV, Europe.

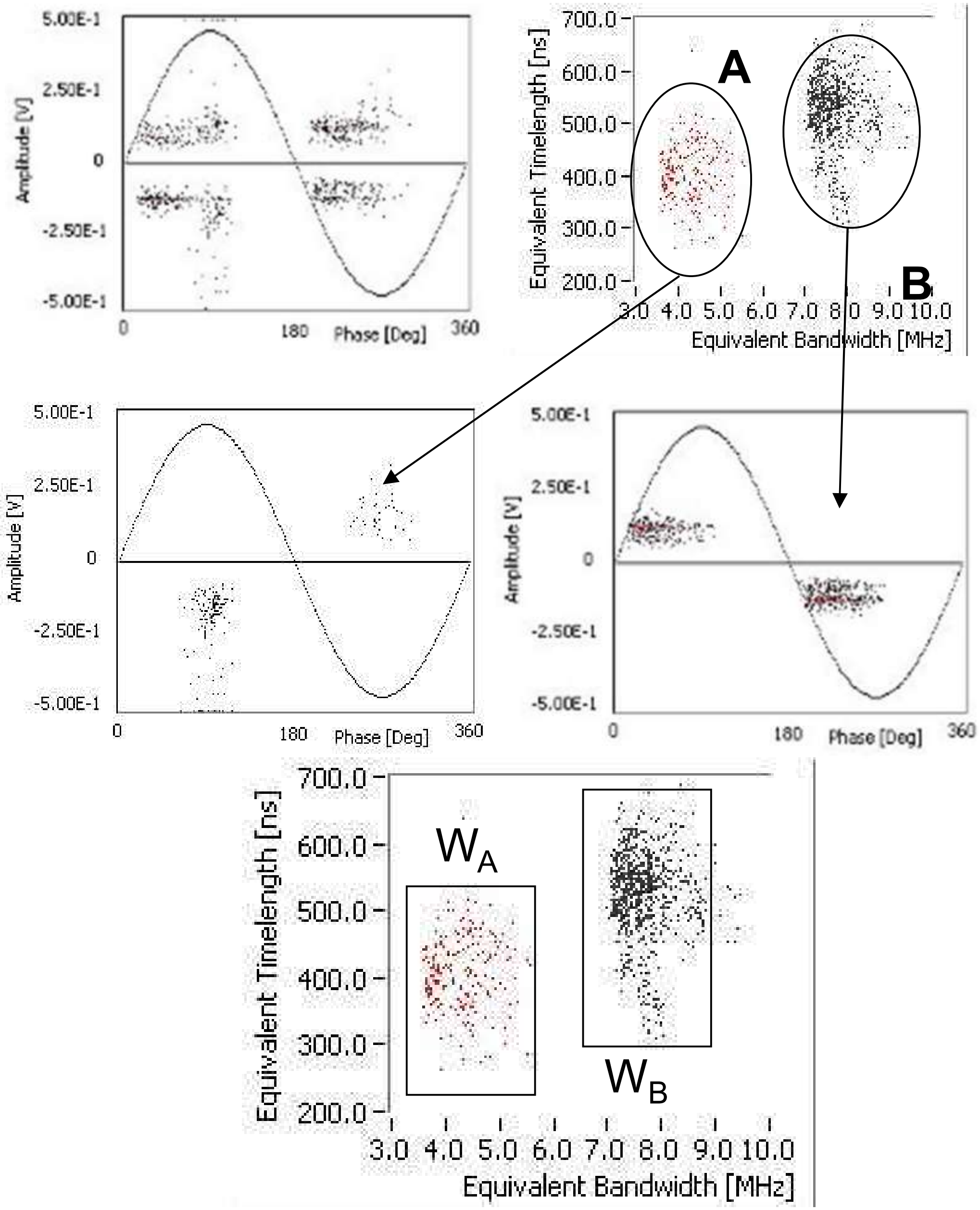


- Cable system:
  - 400 kV XLPE
  - One indoor termination
  - One outdoor termination
  - Two joints.
- PD signal detection:
  - HFCT clamped on grounding leads of terminations.
  - Joints equipped with capacitive taps

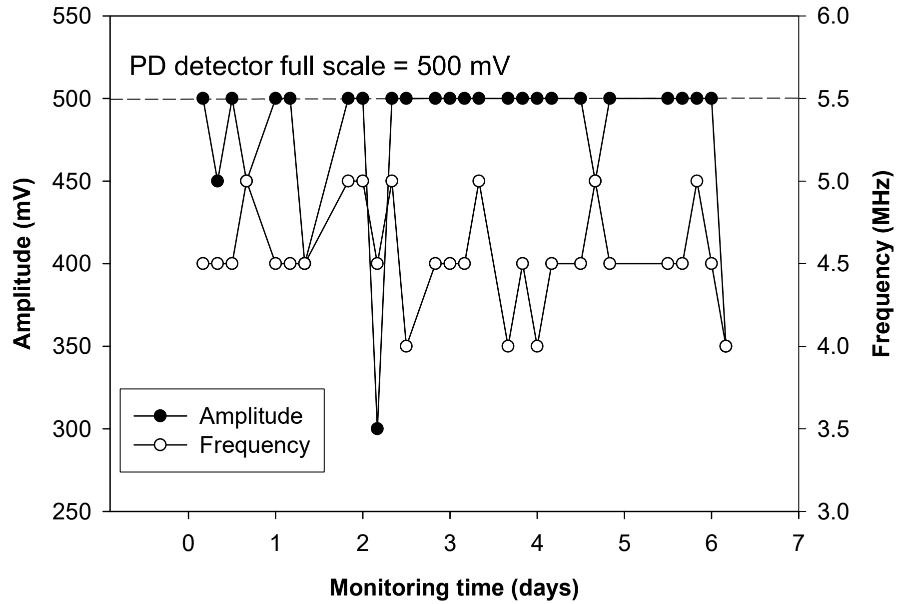
Case Study

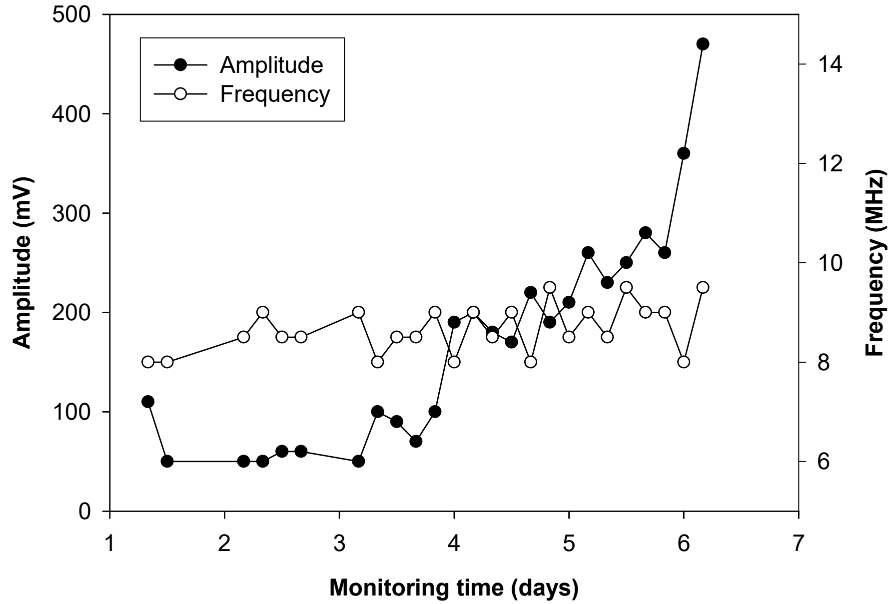
- Two phenomena were detected in the cable system by measuring at a joint capacitive tap.
  A. Discharges on the external surface of outdoor termination
  B. Discharges internal to the joint

- Monitoring diagnostic strategy:
  - Define two windows, W_A and W_B, on the TF map
  - Track pulses in W_A and W_B separately.



- Phenomenon A:
  - Large magnitude
  - Does not evidence a trend
- Phenomenon B:
  - Lower magnitude
  - Evidences a trend till breakdown
- The only way to accurately monitor PD harmfulness is track A and B separately.





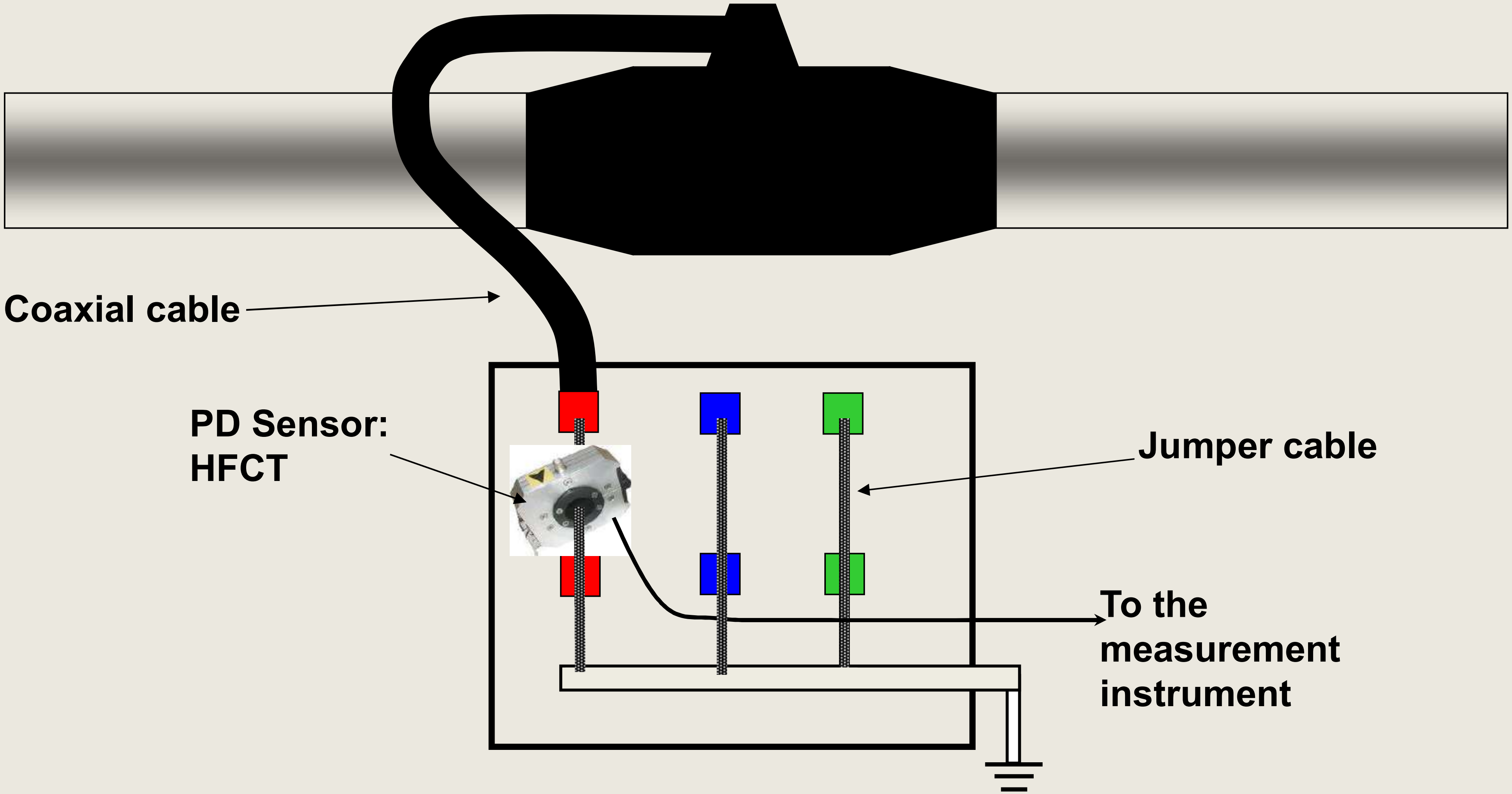
Case Study

H V Cable On-line Testing

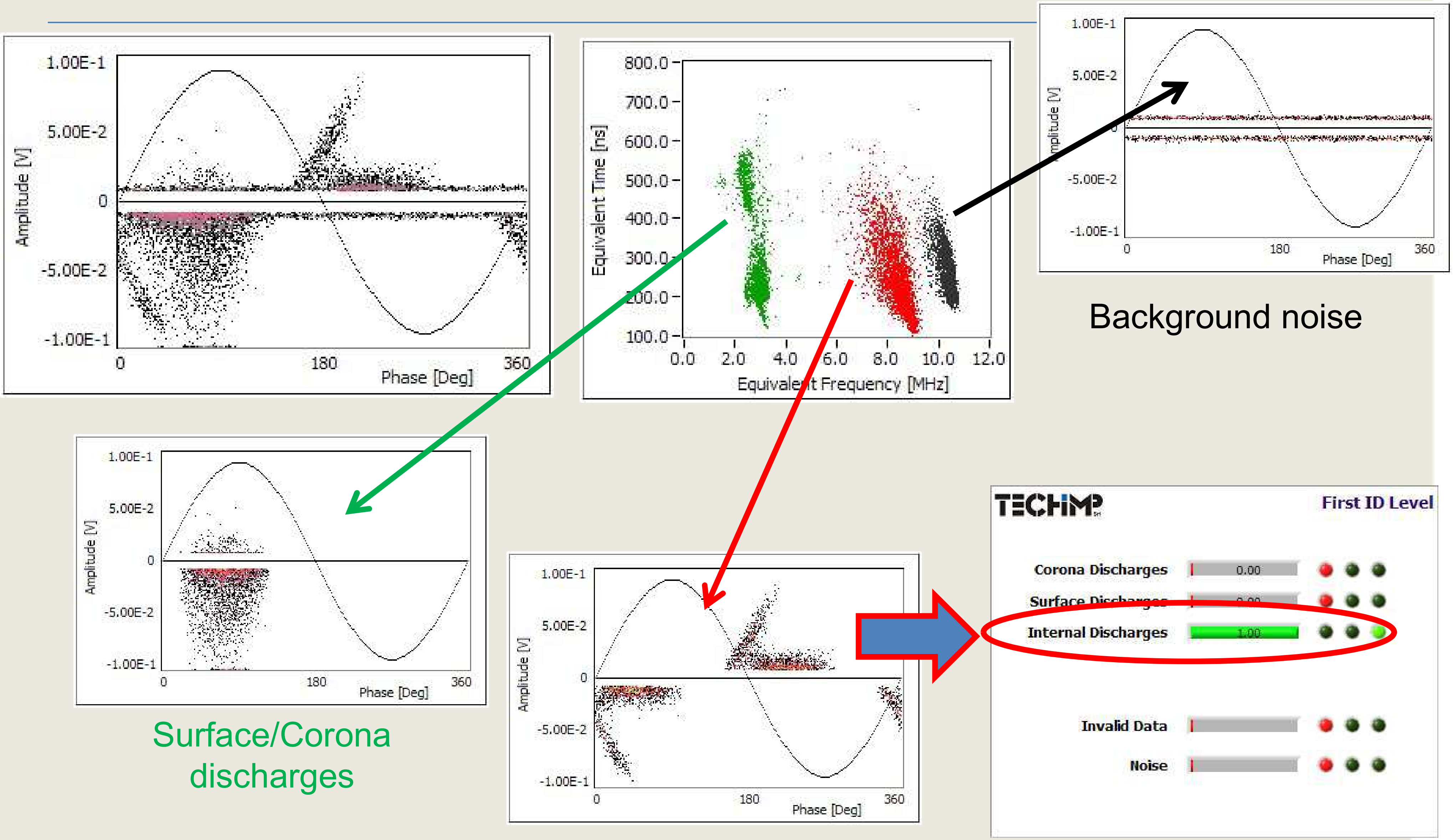
CASE STUDY #8

use of the TF map for separation and location. 220 kV, Europe.

On line PD test on EHV Cable: **PD detection**

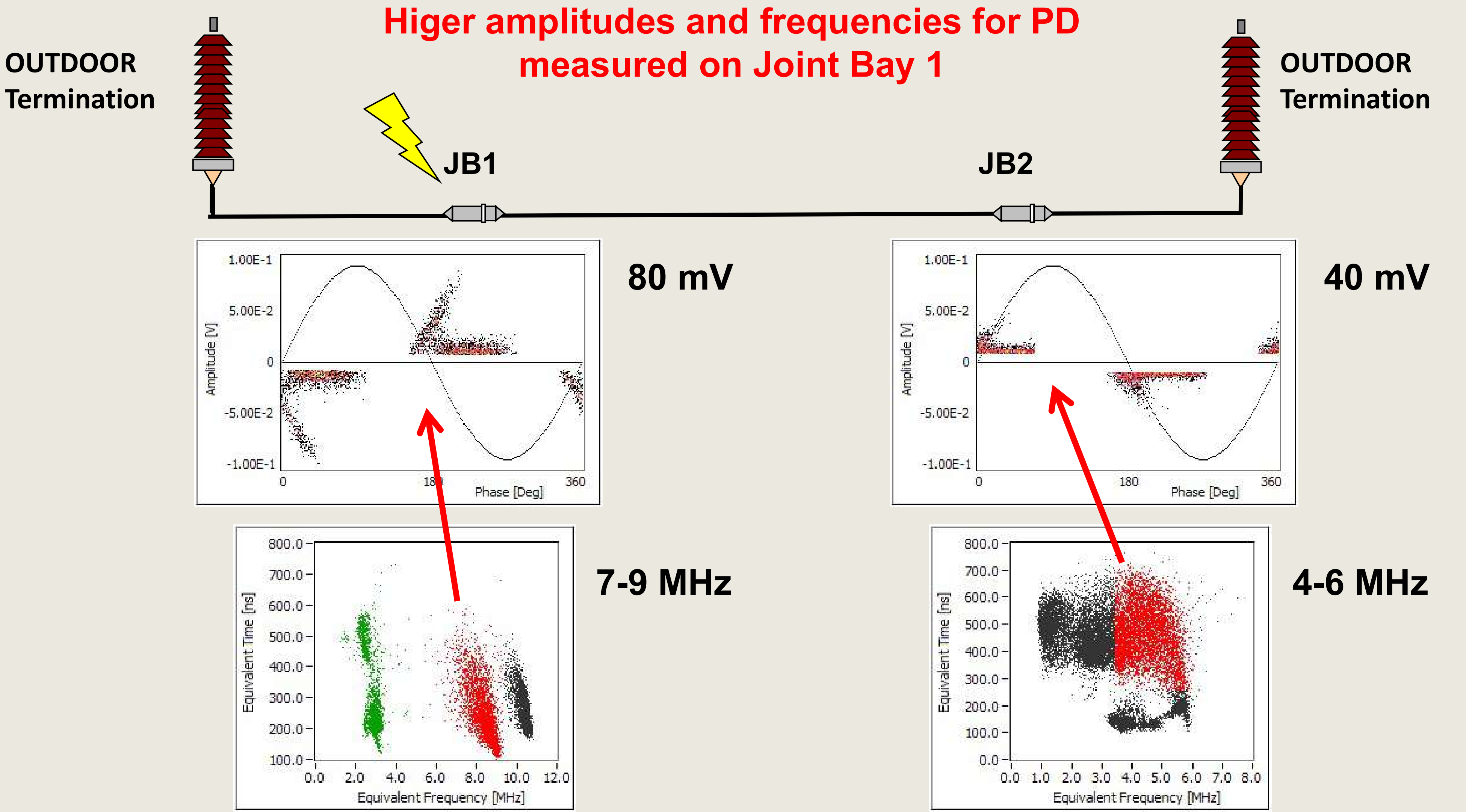


On line PD test on EHV Cable: **PD measurement results**



Internal discharges

On line PD test on EHV Cable: **PD measurement results and location**



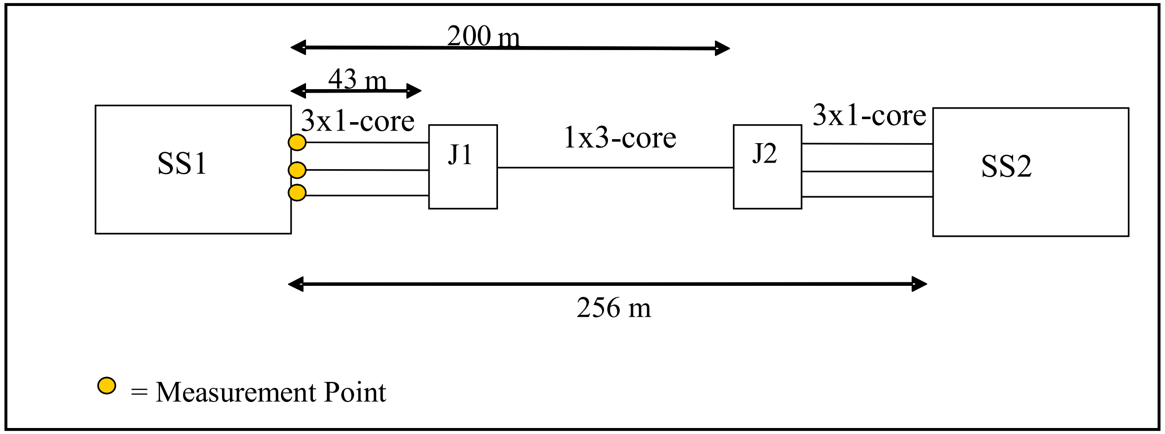
Case Study

MV Cable On-line Testing

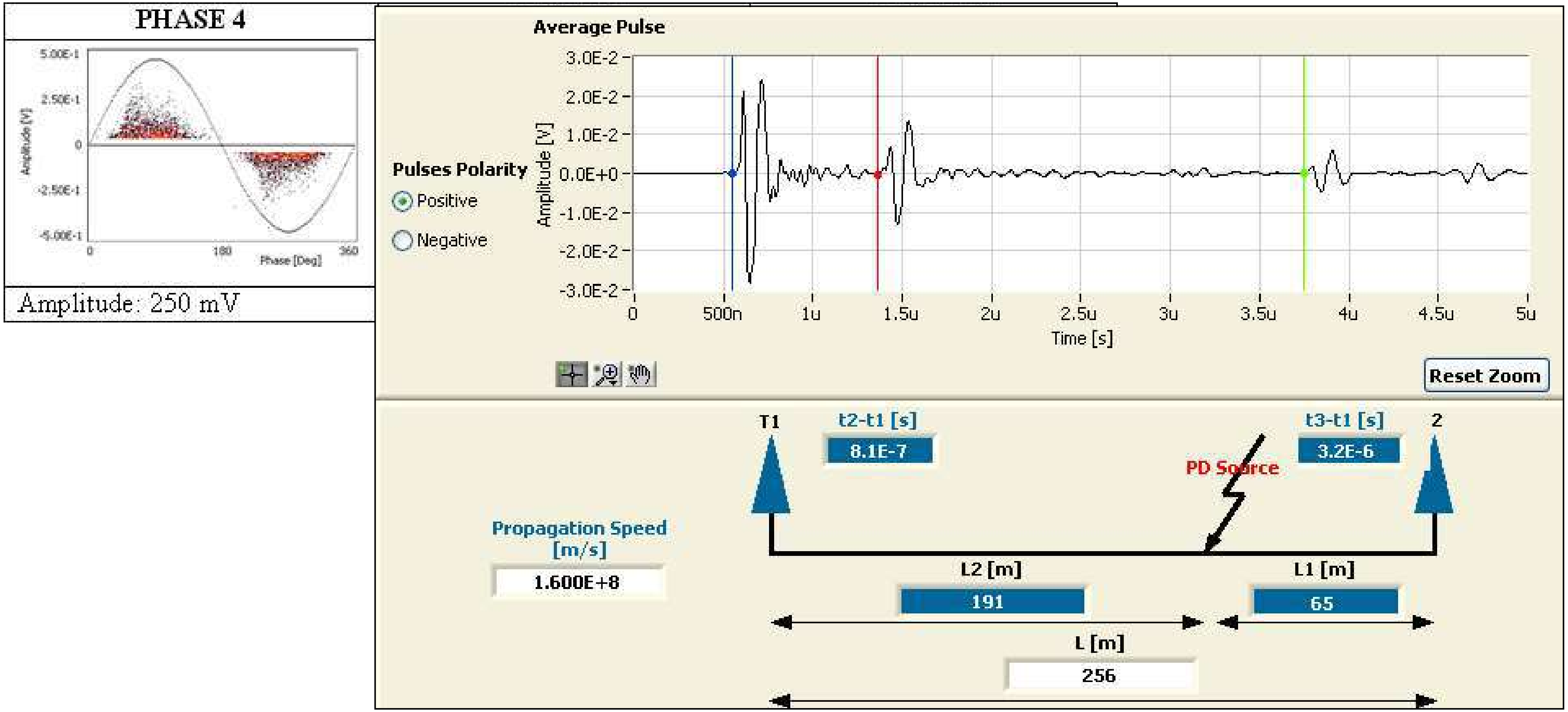
CASE STUDY #10

use of the TF map for separation and location, trend-based alert.
20 kV, Europe.

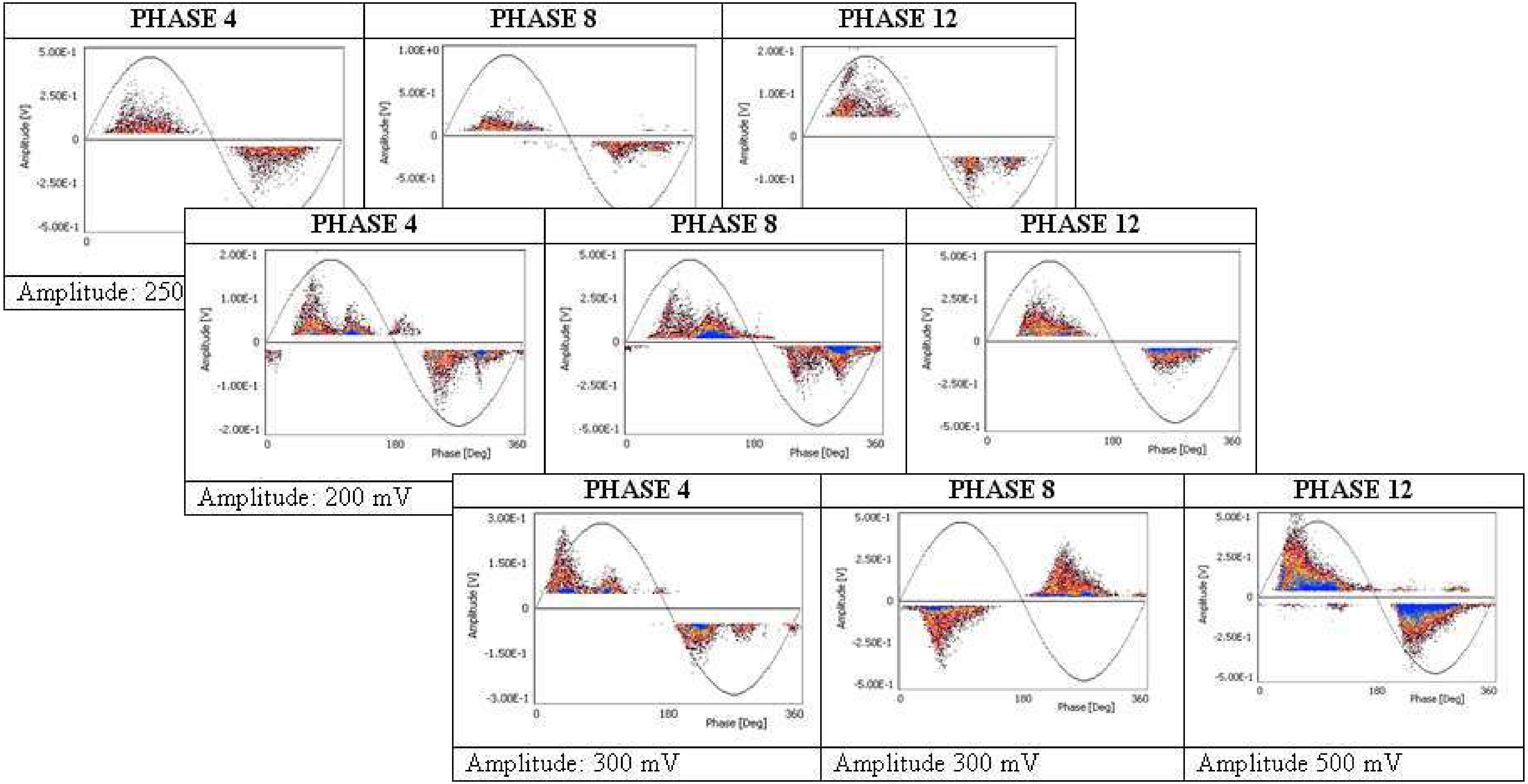
On line PD test on MV Cable: **System layout**



On line PD test on MV Cable: **PD measurement results.**
Internal PD detected in all the phases.

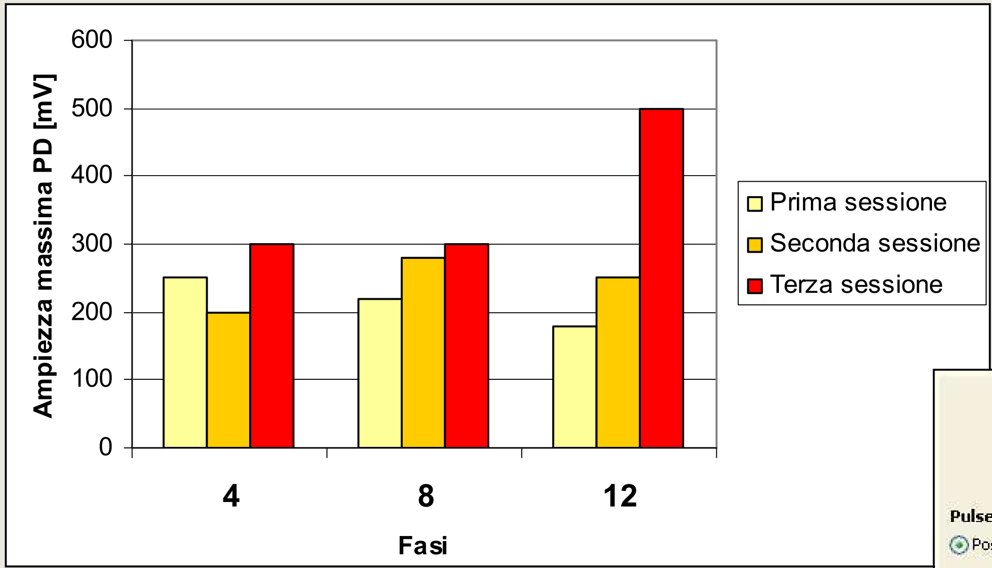


On line PD test on MV Cable: **PD measurement results.**
Internal PD detected in all the phases.

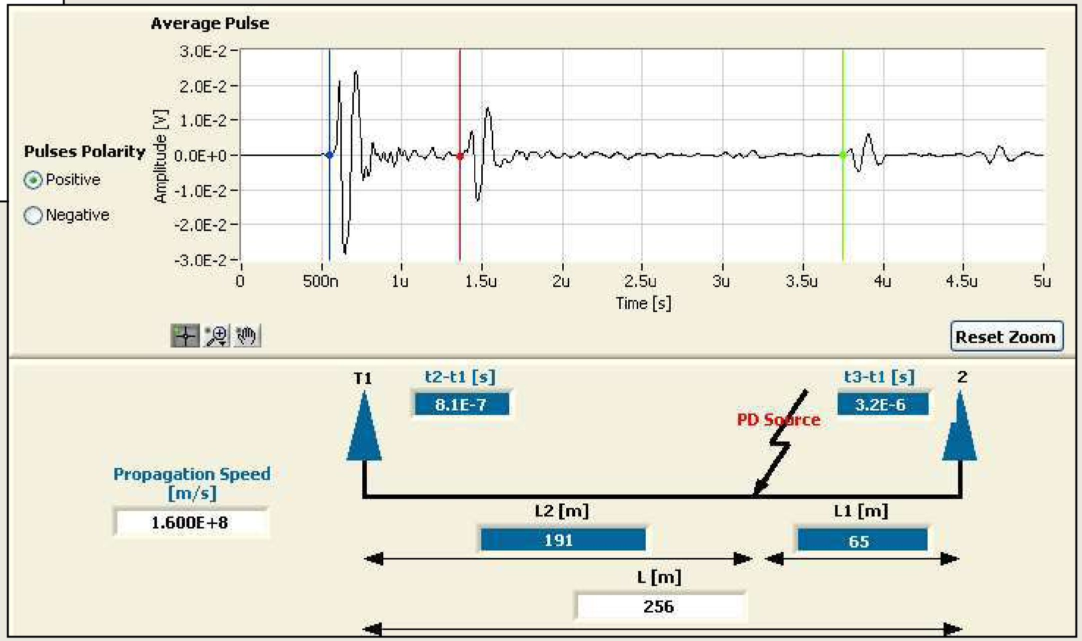


MV distribution cable online test

On line PD test on MV Cable: **PD trend and location.**



Internal PD increased its amplitude very fast.



Localization through reflectometric techniques highlight that the source was located in joint 2.

During a DC test phase 12 had a breakdown. Online PD measurement and trend analysis were effective!!!

Permanent Monitoring solution: PD data together with LOAD information are sent to the CU

Primary Substation

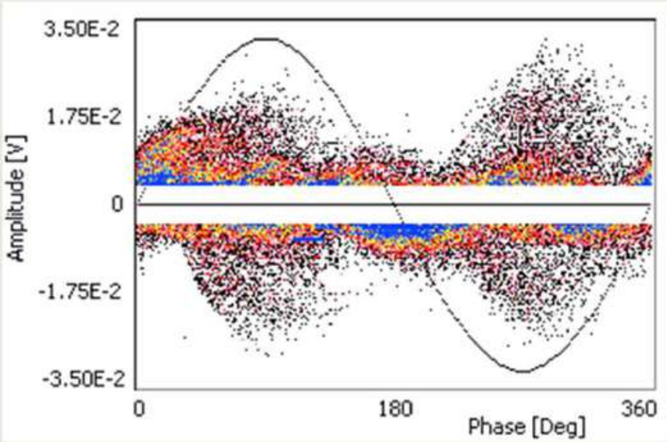
CASE STUDY #10

use of the TF map for separation, identification and location, switchboards, Far East.

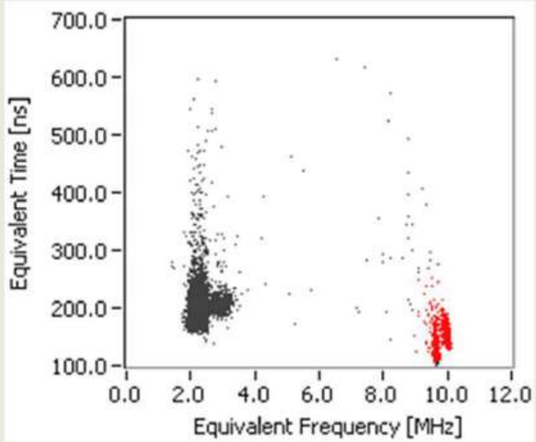
- Main characteristics:
  - No T-Joints
  - No branches
  - Cables shorter than 2 km
  - Voltage up to 33 kV

L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	L15

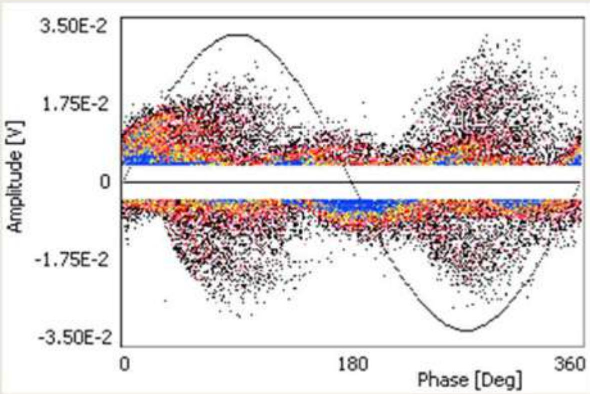
PRPD pattern: Entire acquisition



Classification map



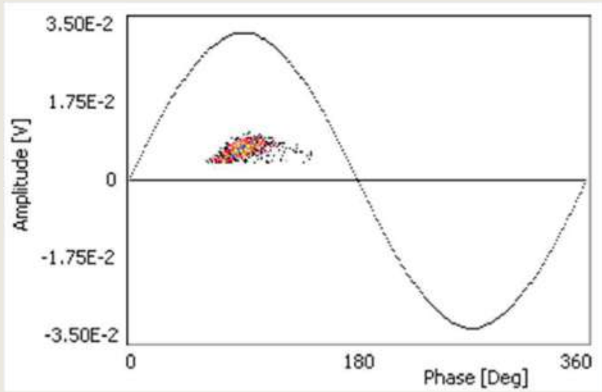
Black class: Internal discharges in MV cable



PD Amplitude: 32mV

PD Frequency: 2-4MHz

Red class: PD activity in a panel in Switchgear room

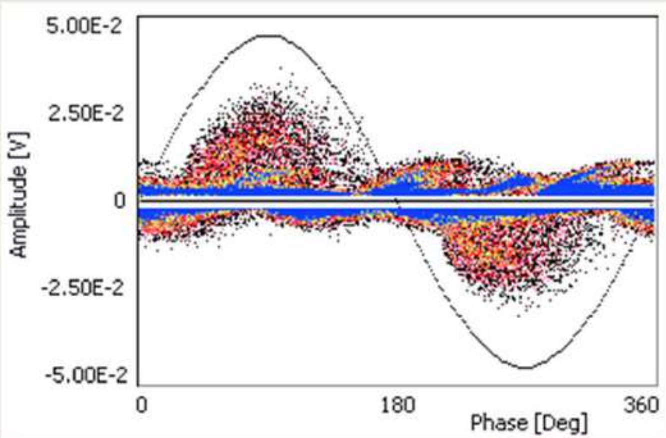


PD Amplitude: 8mV

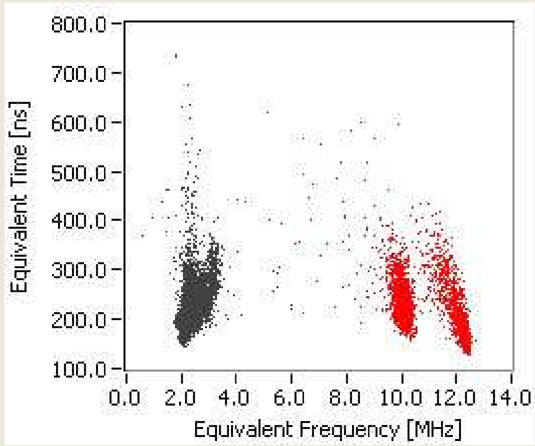
PD Frequency: 9-10MHz

L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	L15

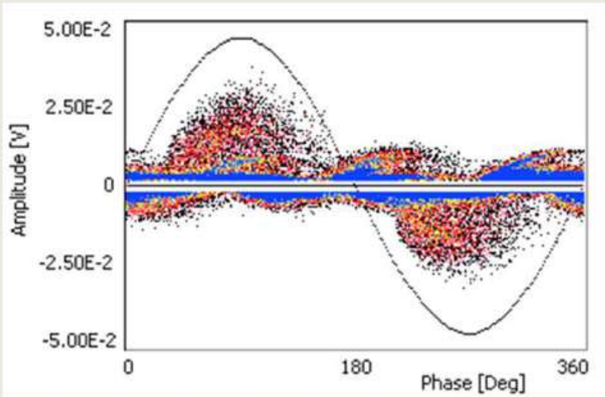
PRPD pattern: Entire acquisition



Classification map



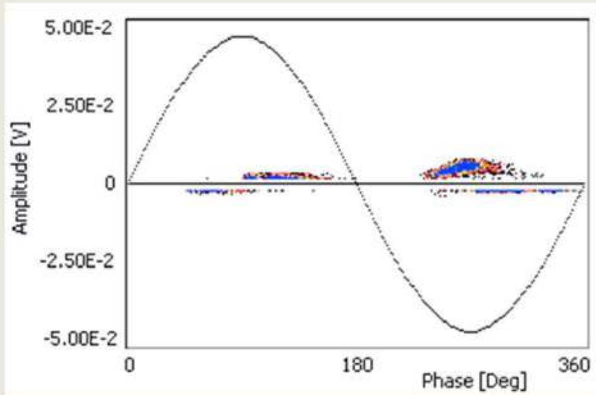
Black class: Internal discharges in MV cable



PD Amplitude: 36mV

PD Frequency: 2-4MHz

Red class: PD activity in a panel in Switchgear room

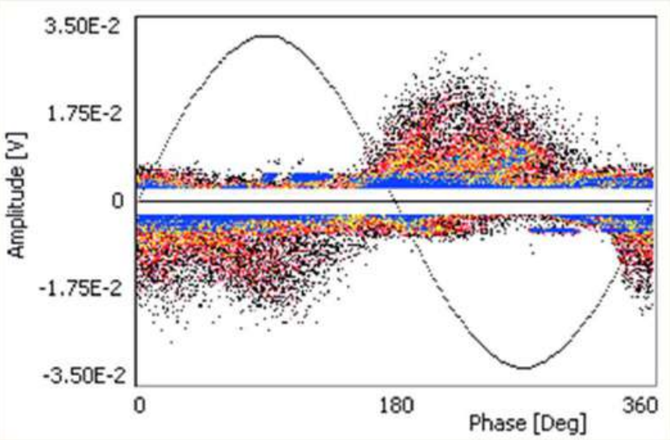


PD Amplitude: 8mV

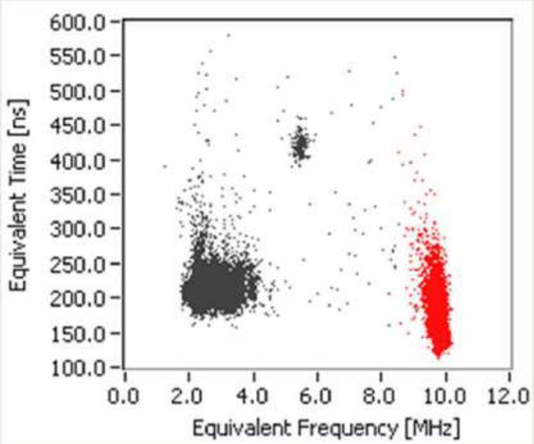
PD Frequency: 10-12MHz

L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	L15

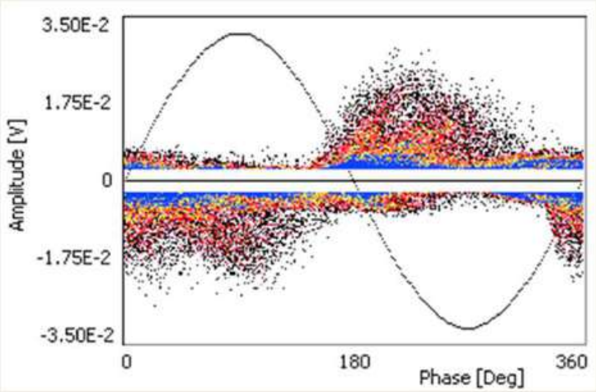
PRPD pattern: Entire acquisition



Classification map

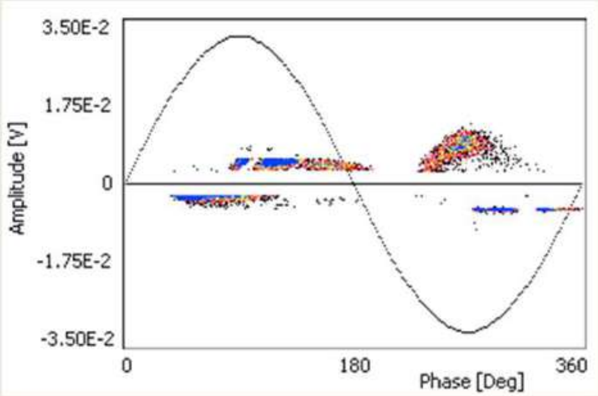


Black class: Internal discharges in MV cable



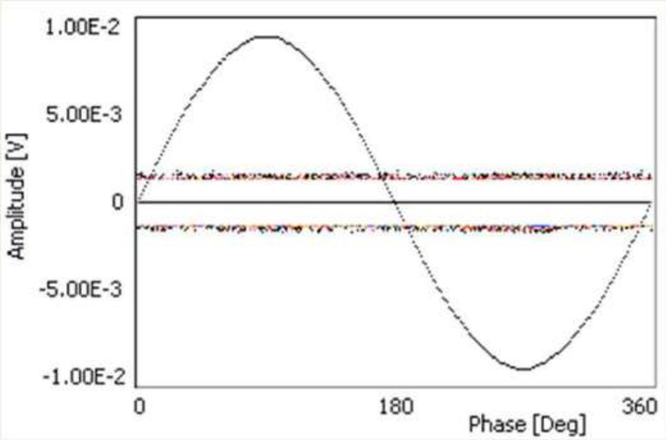
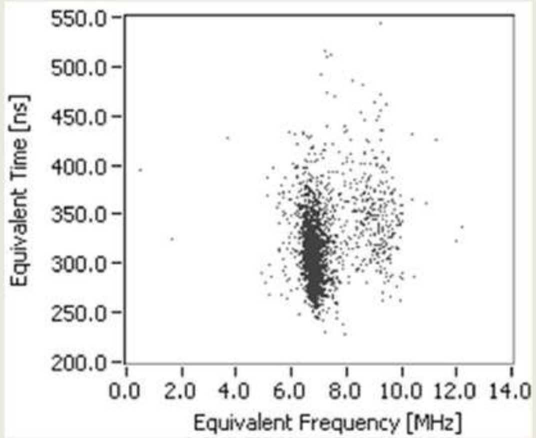
PD Amplitude: 28mV
PD Frequency: 2-4MHz

Red class: PD activity in a panel in Switchgear room



PD Amplitude: 12mV
PD Frequency: 10MHz

L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	L15

PRPD pattern: Entire acquisition - noise	Classification map
	

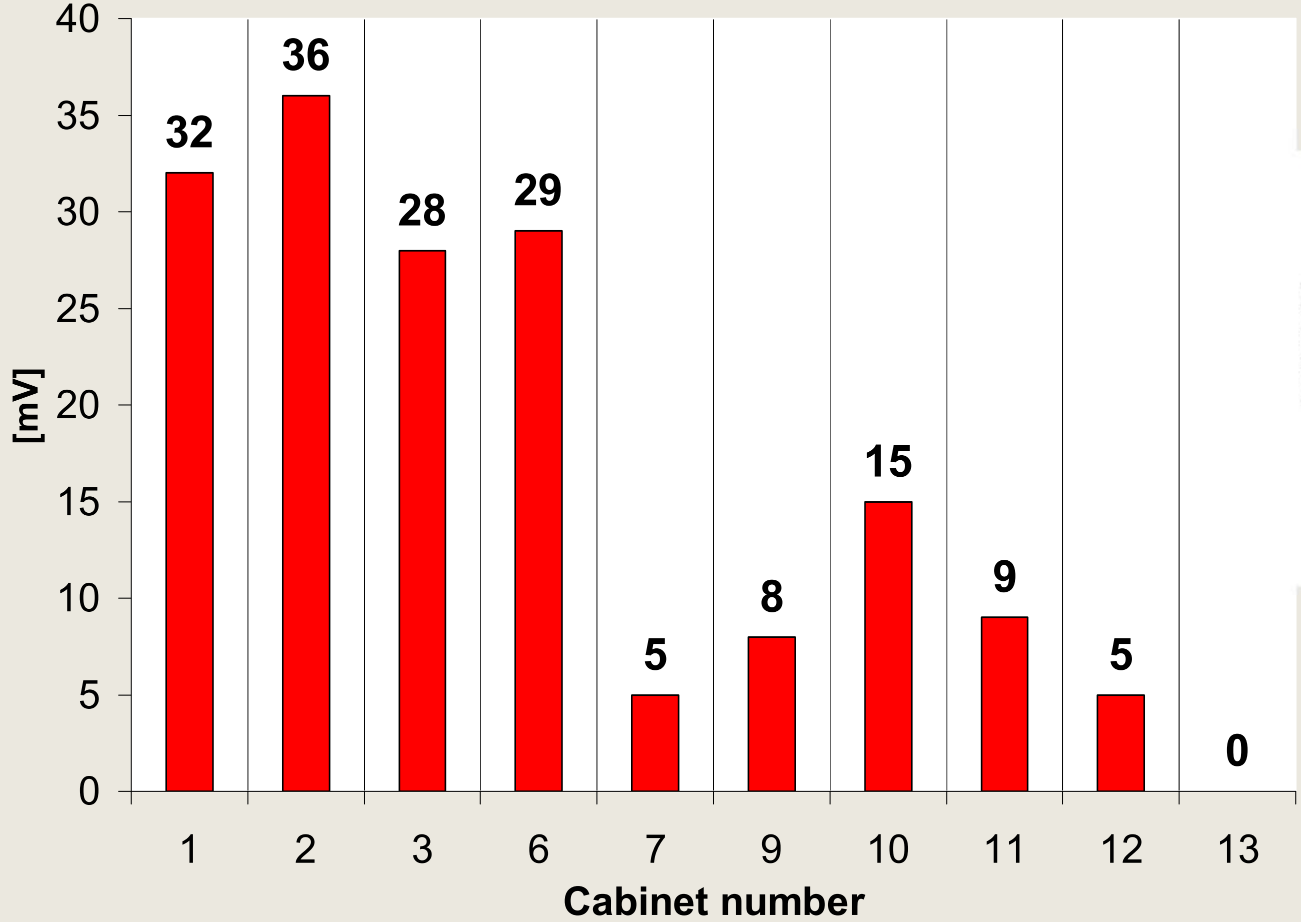
PD DETECTION RESULTS – **SUBSTATION A**

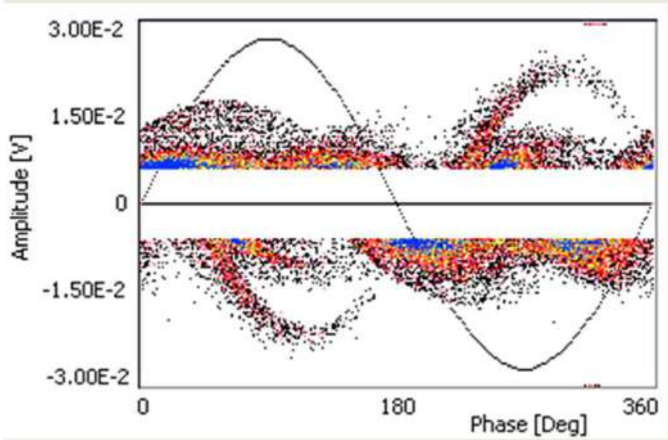
Different PD activities were detected in Substation A using HFCT around the MV cables:

- **Internal PD:** Were detected in almost all the cables with variable amplitude and low frequency bandwidth. This kind of discharges come from outside the Switchgear. A localization is necessary to know if the PD source is inside the cable or inside the device supplied by the cable (e.g. motor, pump, compressor…);

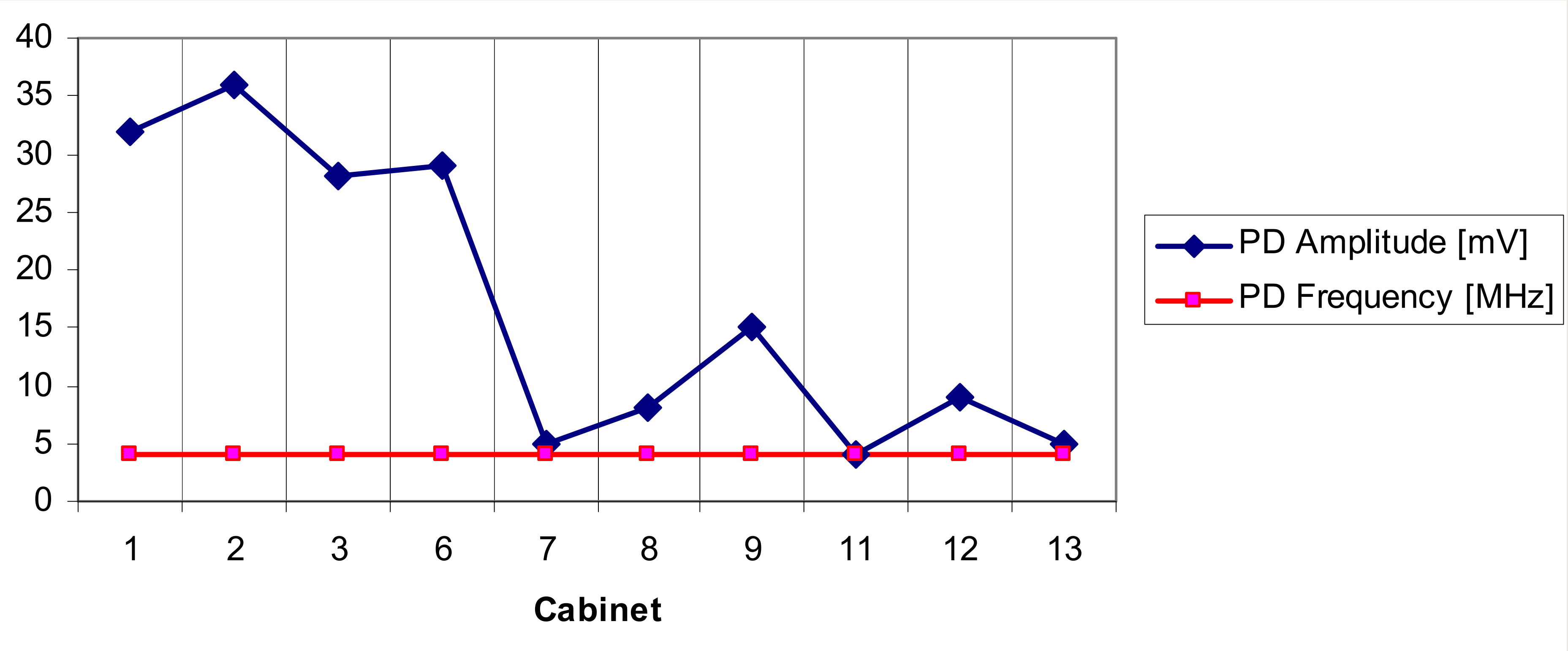
- **Surface/Corona PD:** Coming from inside the panels, were detected propagating in many Switchgears with variable amplitude and frequency. In some cabinets the frequency spectrum was very high.

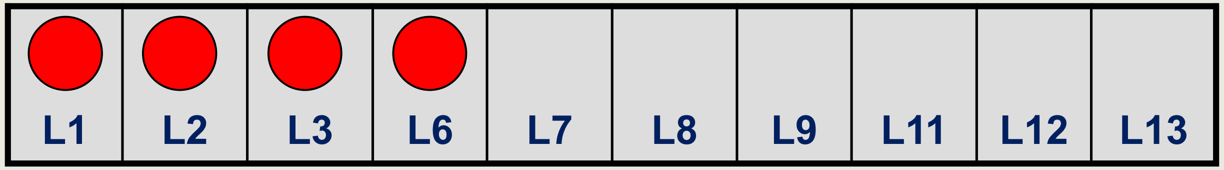
INTERNAL PD LOCALIZATION



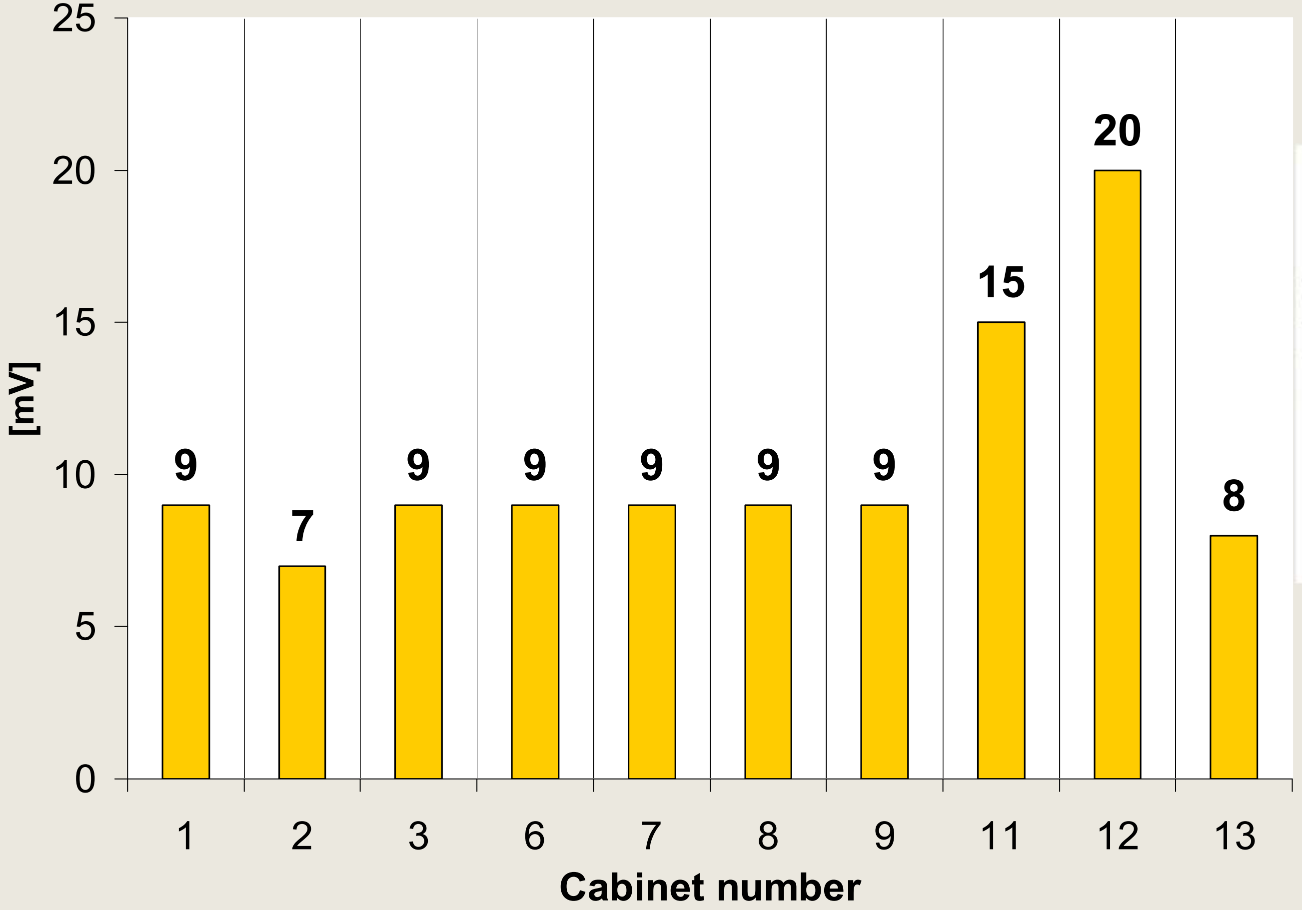


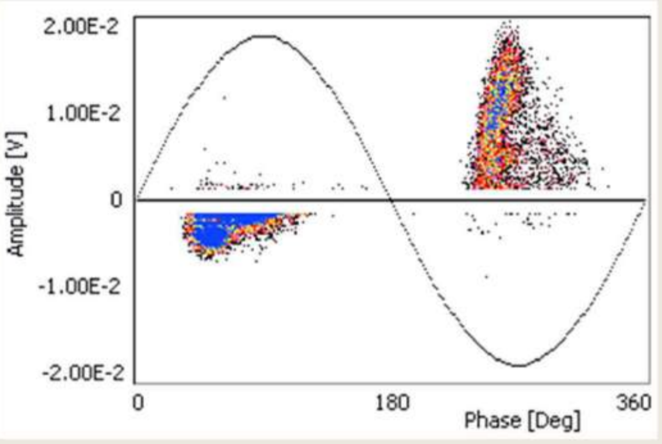
INTERNAL PD LOCALIZATION

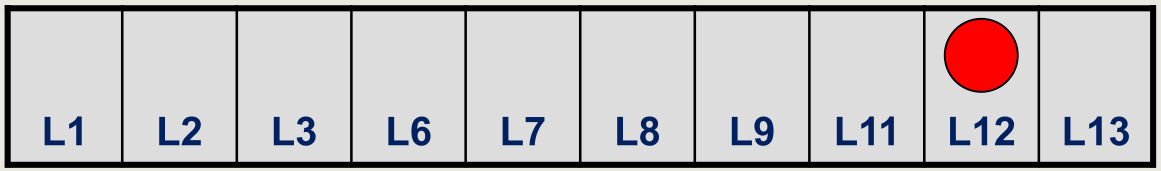




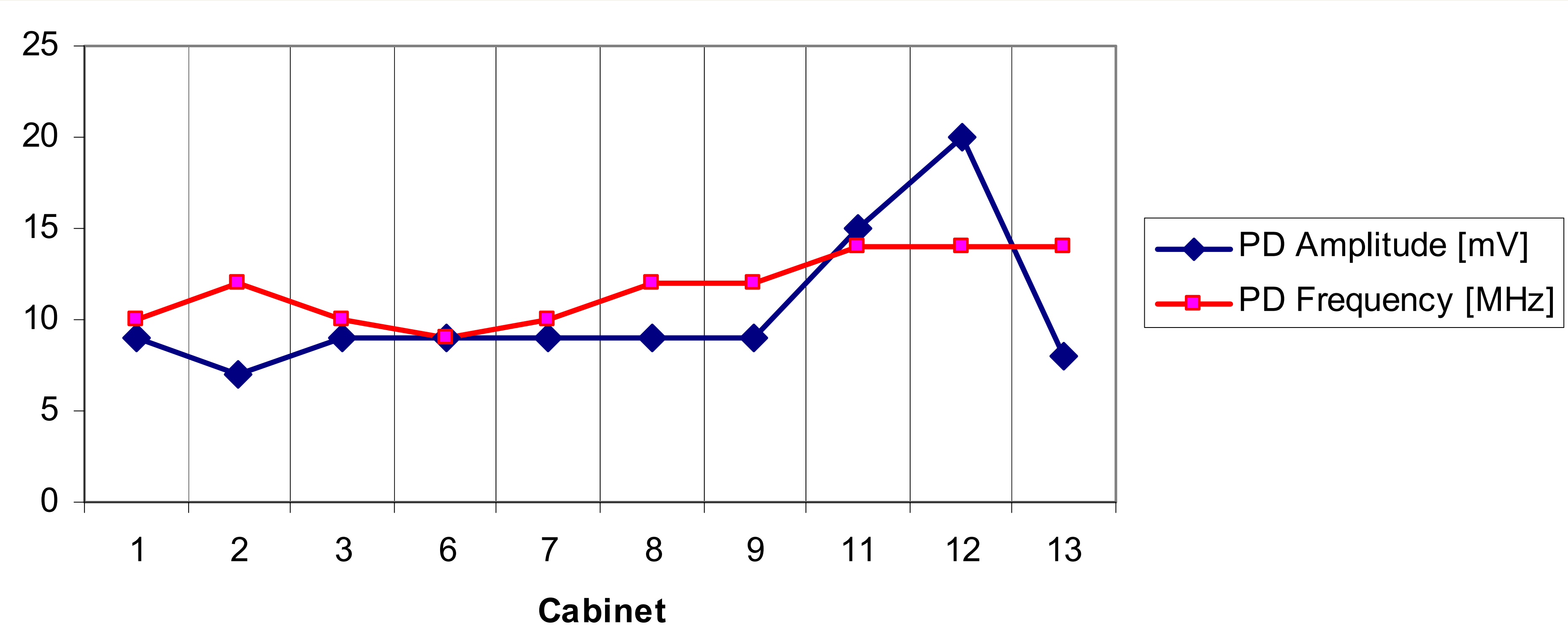
SURFACE PD LOCALIZATION

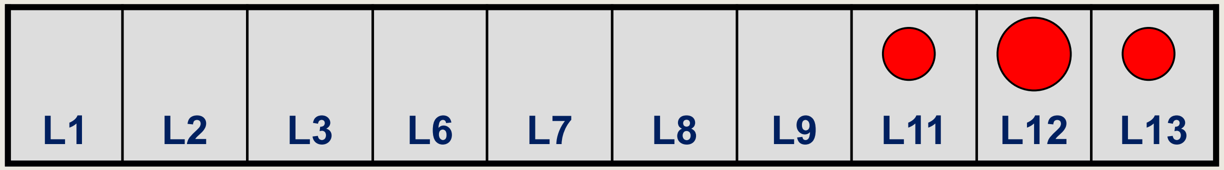




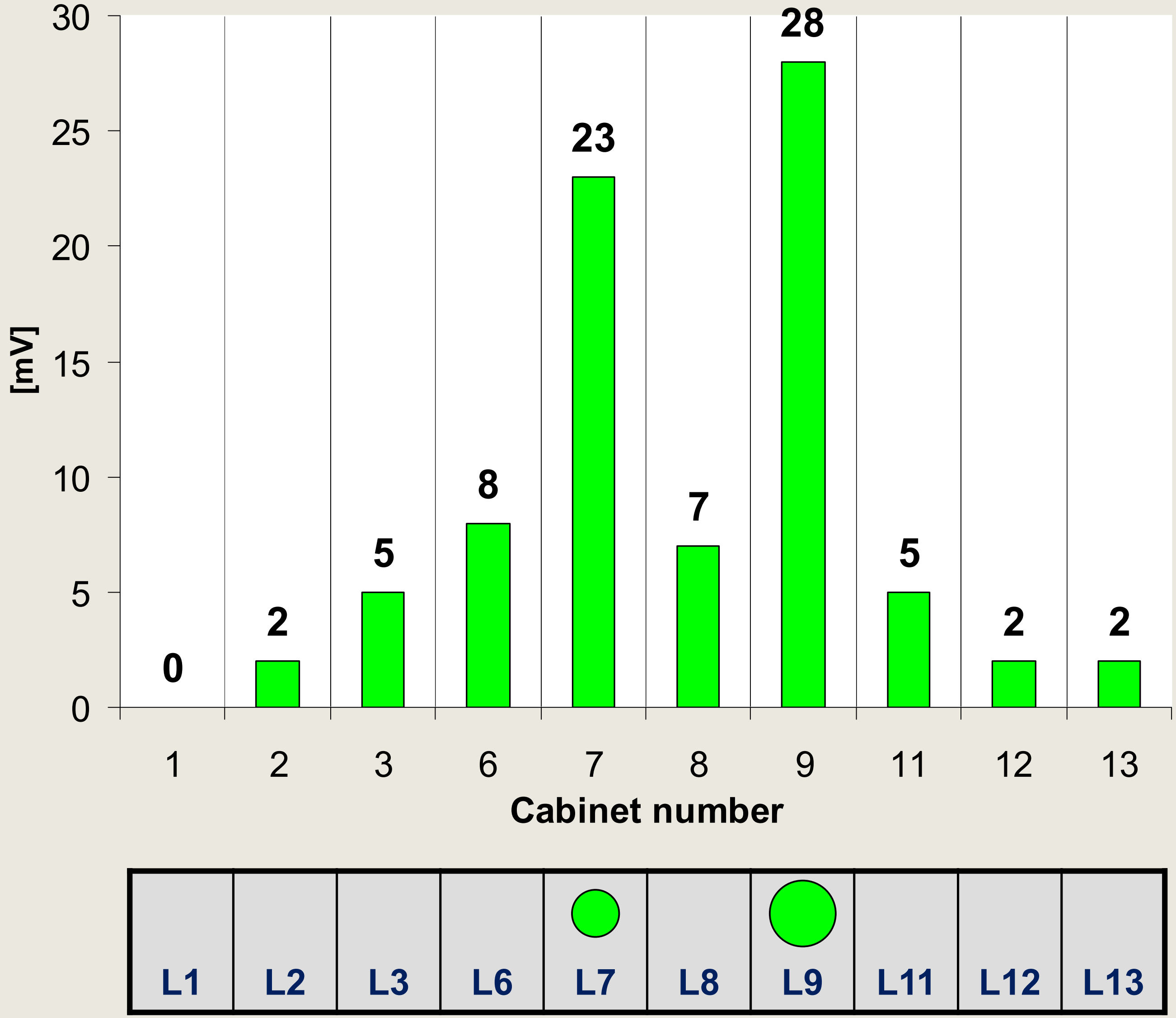


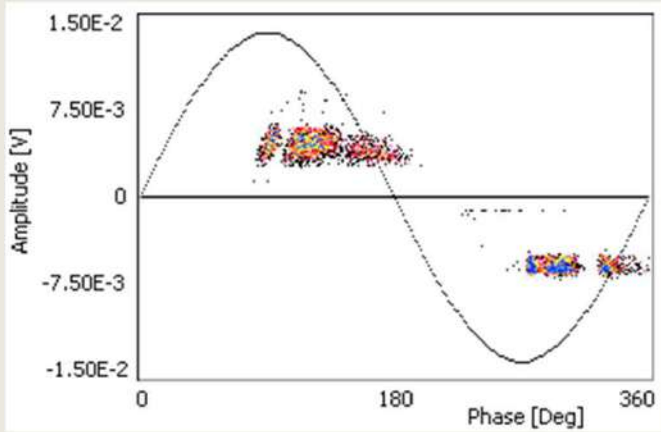
SURFACE PD LOCALIZATION



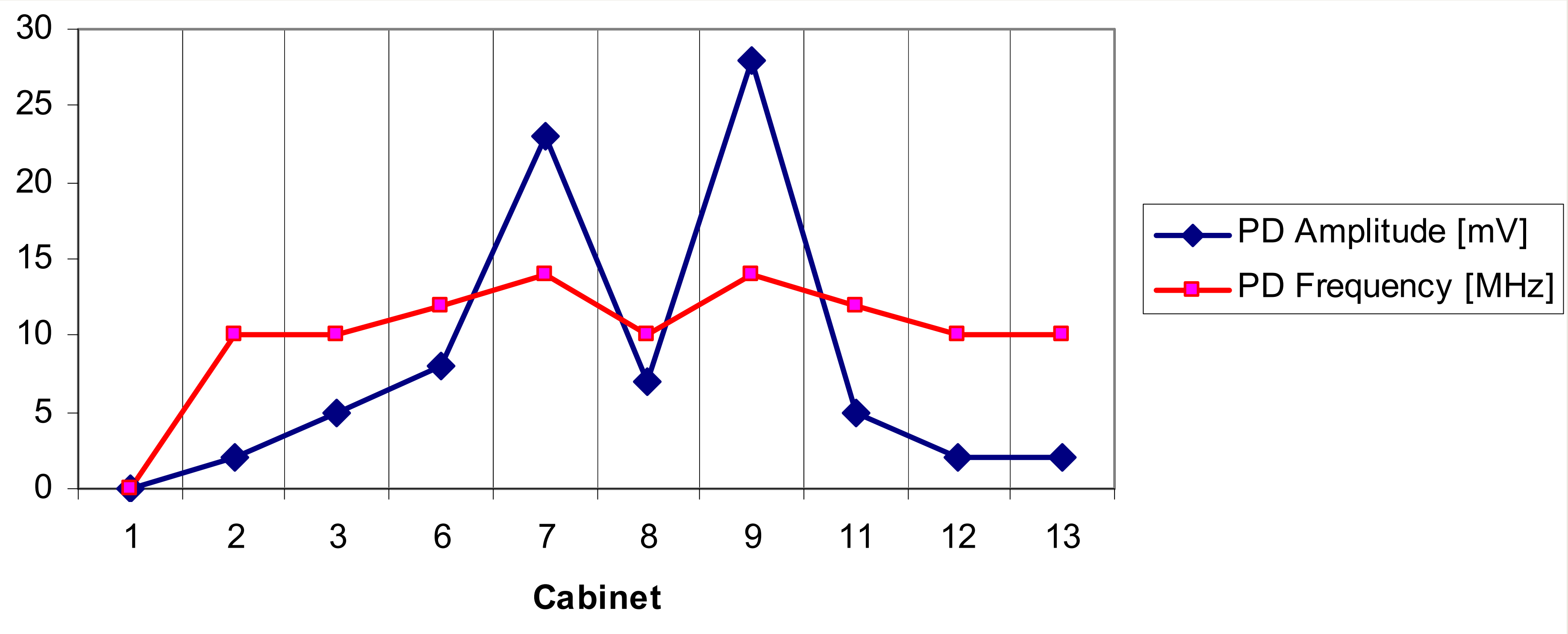


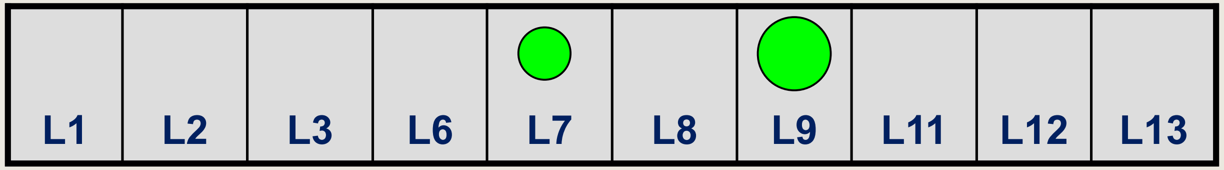
CORONA PD LOCALIZATION





CORONA PD LOCALIZATION





MV Transformers

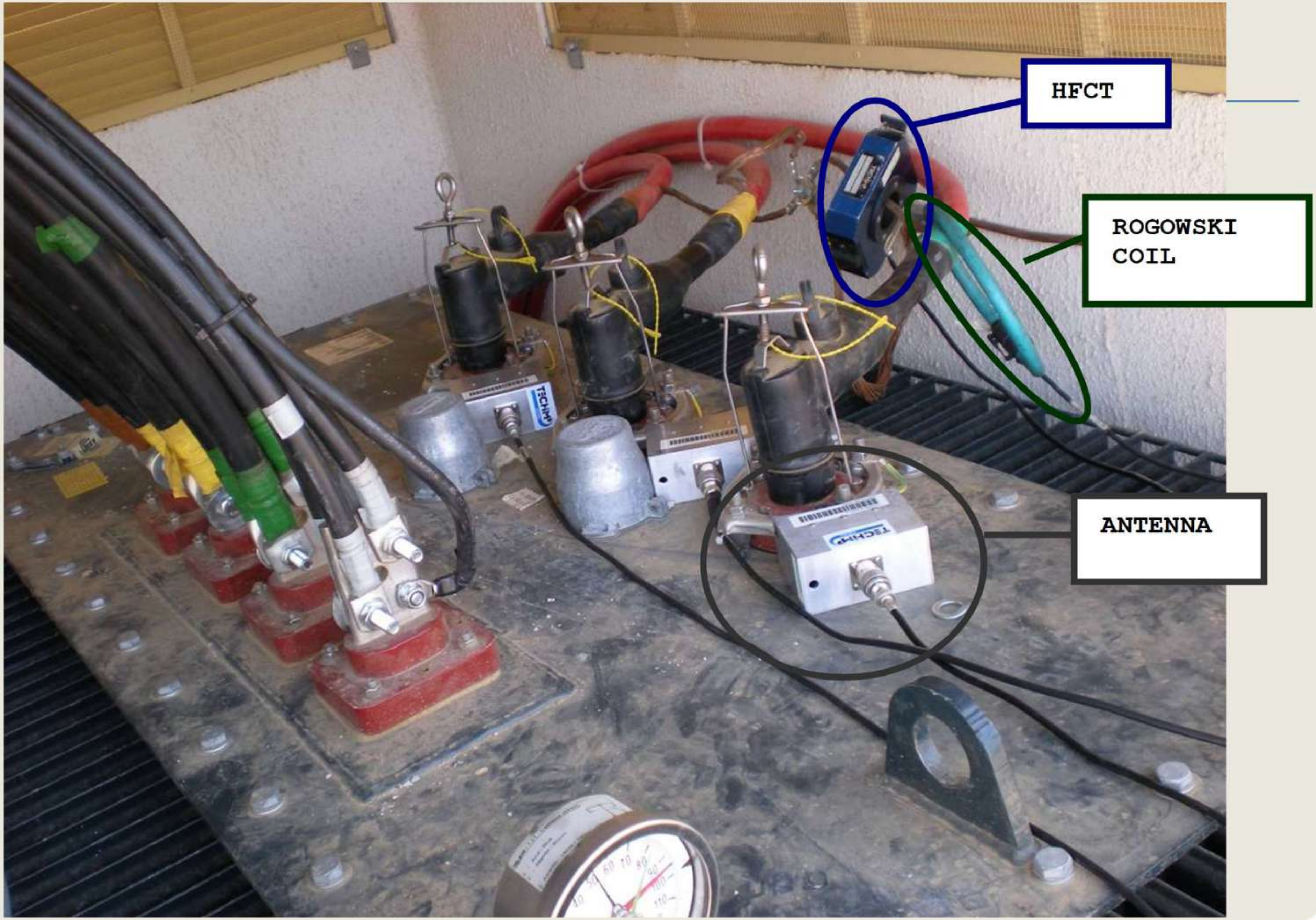
CASE STUDY #11

use of various sensors. Photovoltaic Plant. Europe.

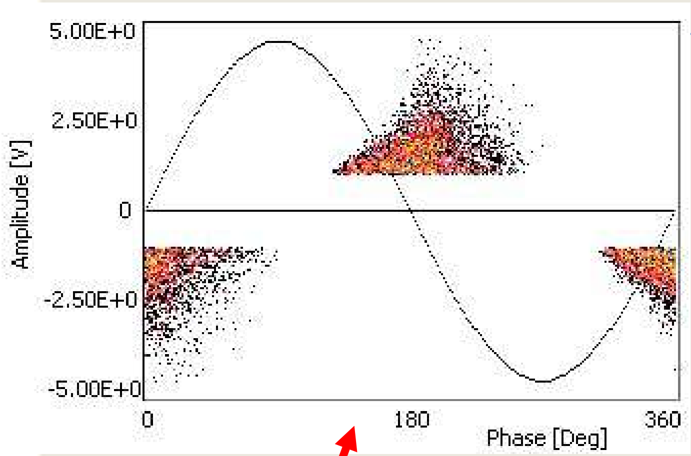
- **Techimp HFCT sensor:** installed around cable ground lead or directly around cables. Monitoring of PD activities within both switchgears and cables

- **Techimp FMC sensor:** tied to the cable. Monitoring of PD activities within both switchgears and cables

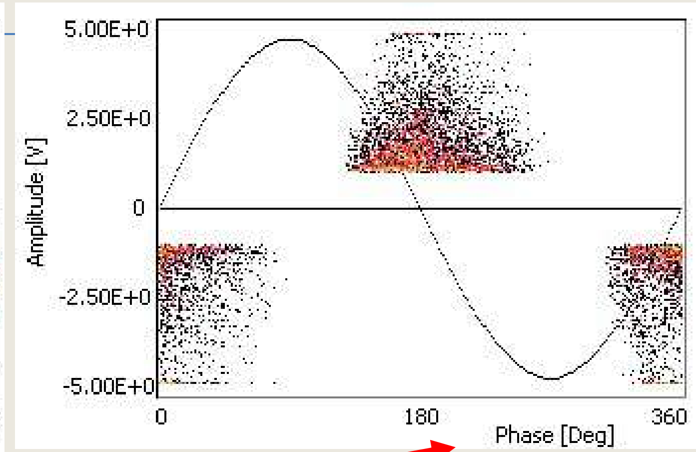
- **Techimp UHF Antenna sensor:** close to cables entrance on the transformer top. Monitoring of PD activities within cable termination and inside transformer


HFCT
ROGOWSKI COIL
ANTENNA

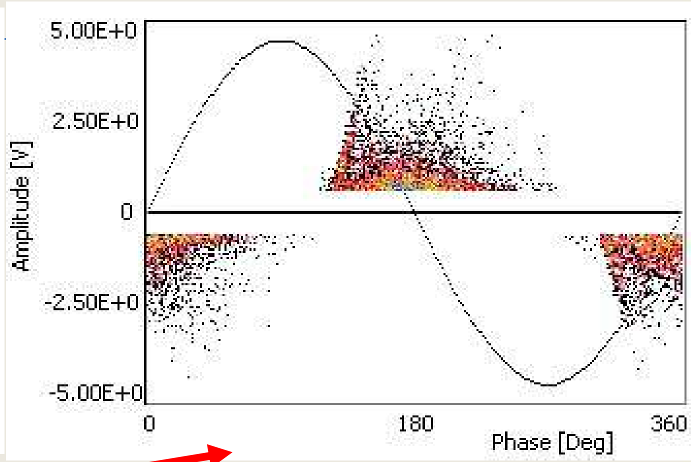
Interfaces PD in Phase Red



Interfaces PD in Phase Yellow

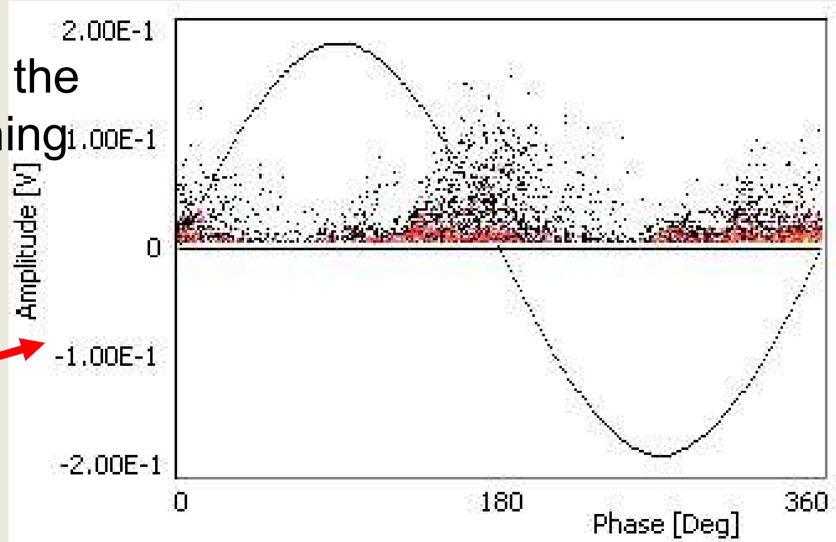


Interfaces PD in Phase Green



Techimp HFCT clamped around cable ground lead

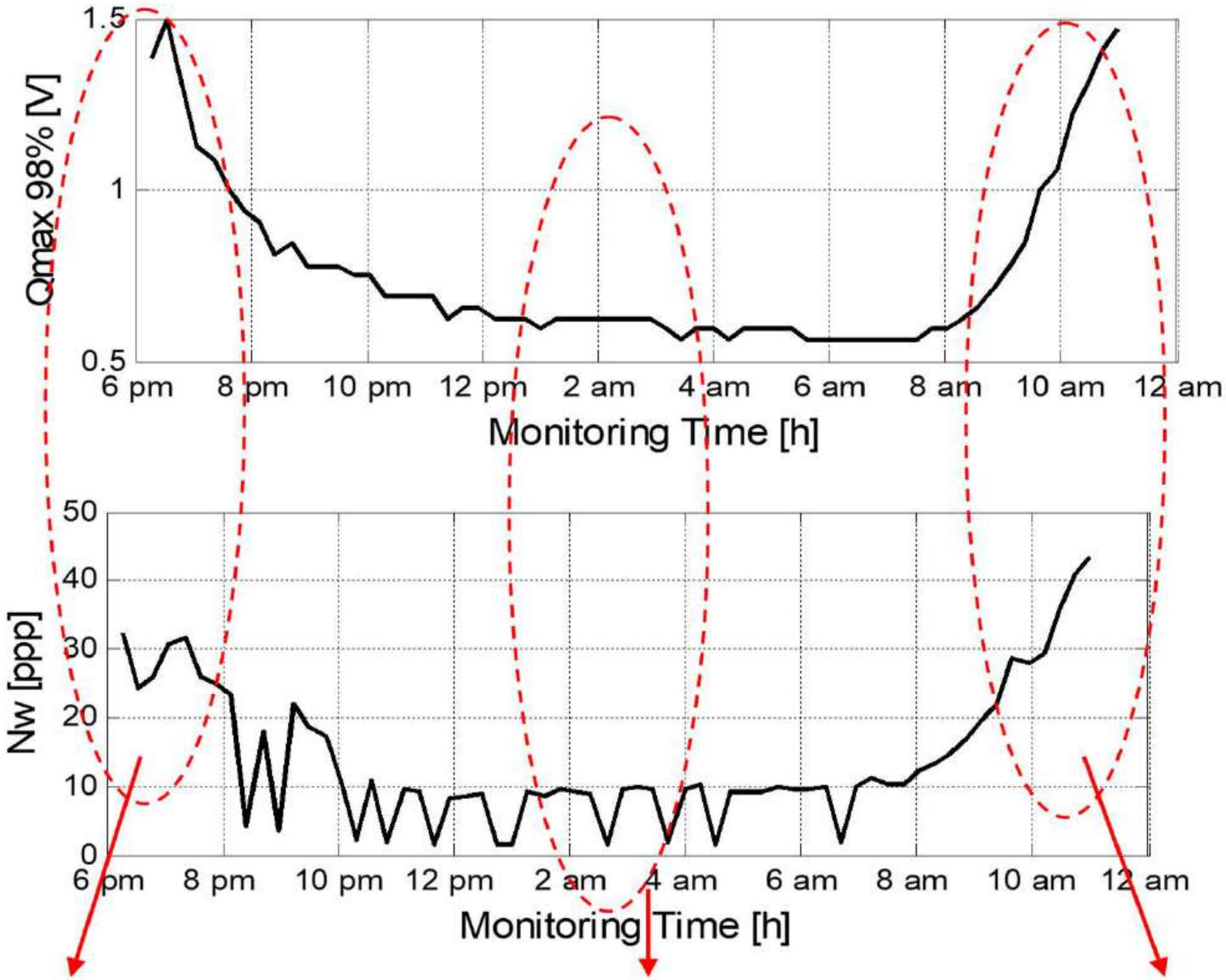
Techimp UHF Antenna close to the transformer bushing

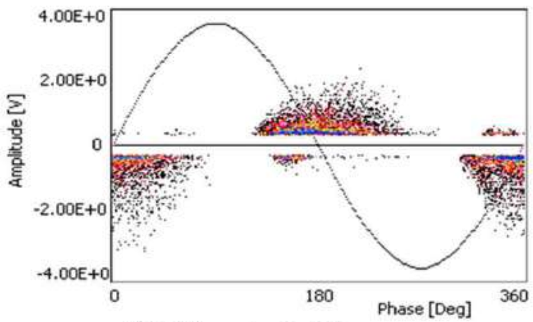


Same transformer was continuously monitored for 18 hours.

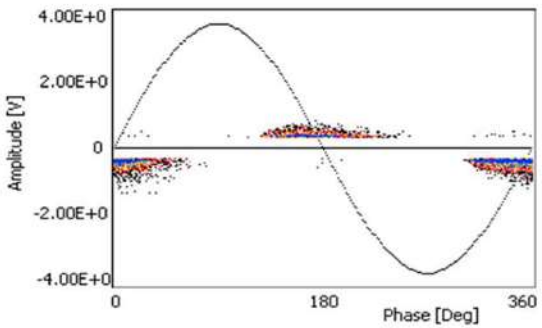
By analyzing the magnitude and repetition rate TREND it is possible to assess the risk associated with the PD activities and, thus,

PREVENT THE FAILURE!

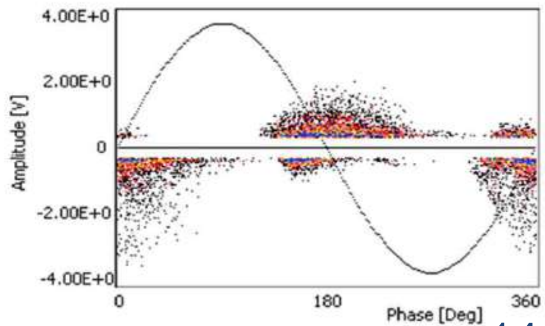




02 Sept: 6:00 pm



03 Sept: 1am



03 Sept: 11 am

MV Cables. On-line Screening

CASE STUDY #12

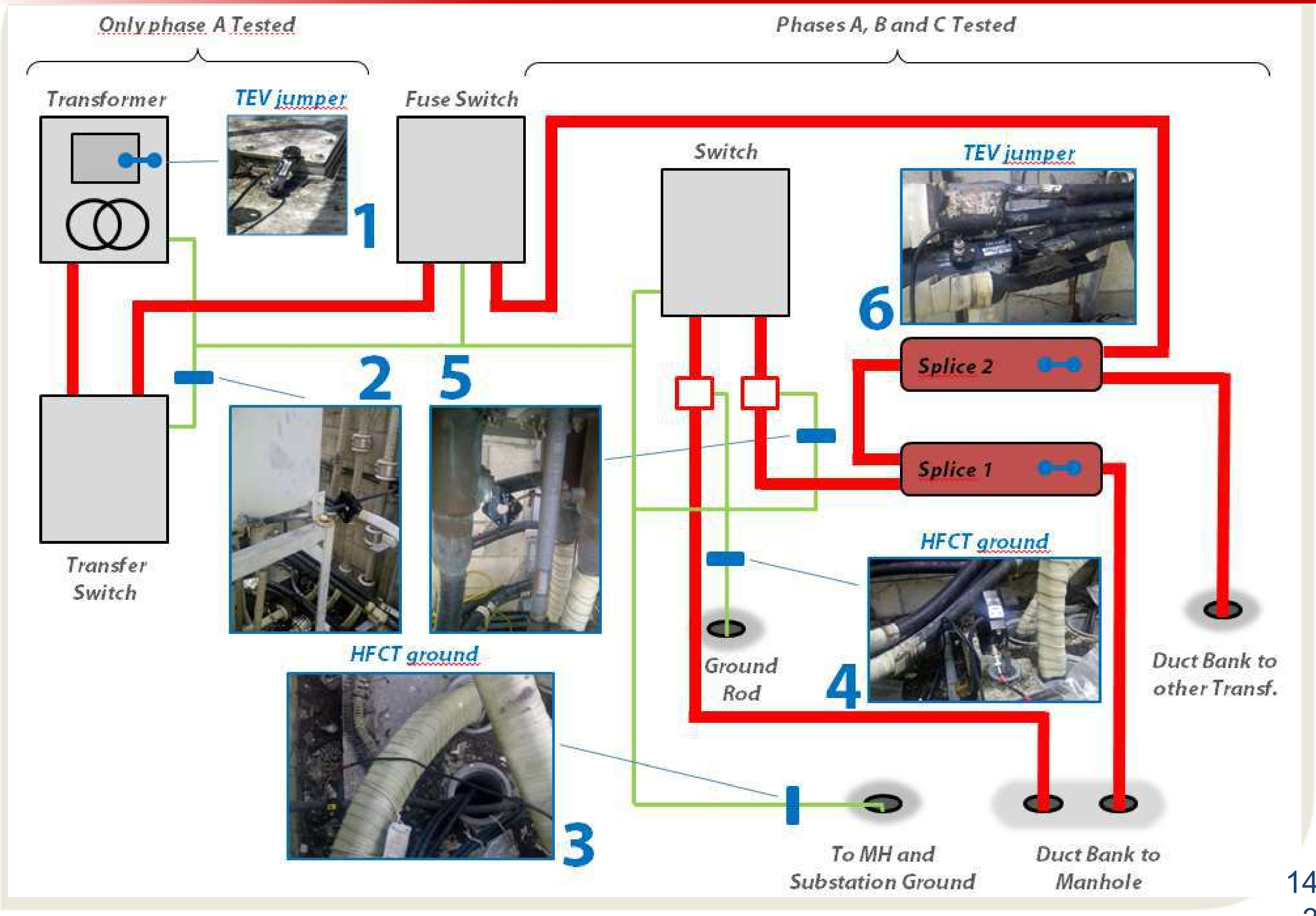
Identification and location. MV grid. USA.

- PD was found on B phase of a single core PILC splice with on-line PD measurements using Techimp PPDC inside a manhole without de-energizing the cable circuit

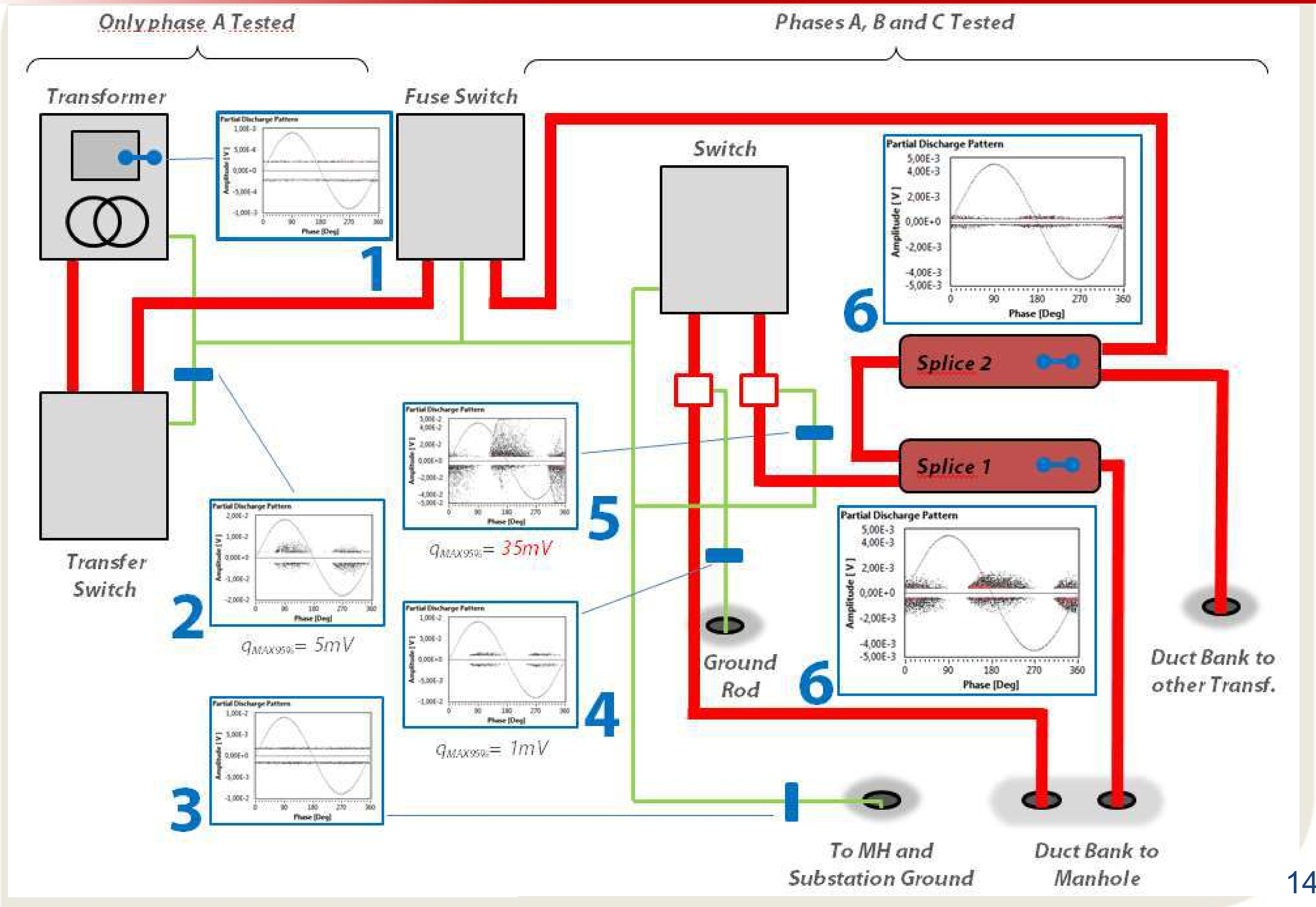
- Splice was cut and re-tested in the laboratory with different voltage levels till breakdown

- Then, the splice was dissected to find PD evidence

PILC SPLICE – ON-LINE SENSORS SETUP



PILC SPLICE – ON-LINE PD RESULTS

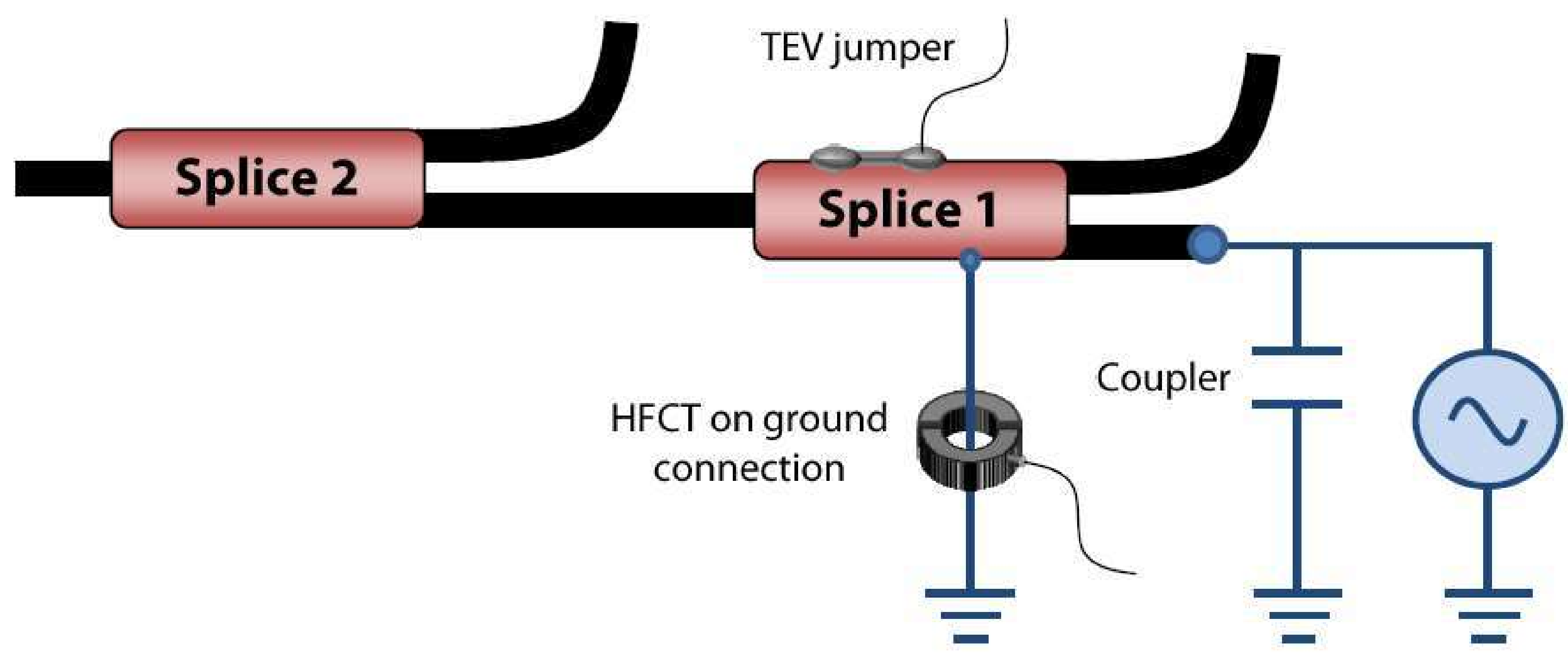


PILC SPLICE – ON-LINE PD RESULTS

- No PD was found inside the MV Transformer in the manhole
- Interface PD phenomenon was detected with HFCT sensor in B phase, propagating in the ground connections of the manhole
- Highest PD amplitude detected with HFCT sensor was on the ground connection near the two PILC splices. PD is likely generated inside one of the splices
- TEV jumper sensor placed on the two splices highlights that PD is coming from B phase of Splice#1
- The two splices were cut and tested in laboratory.

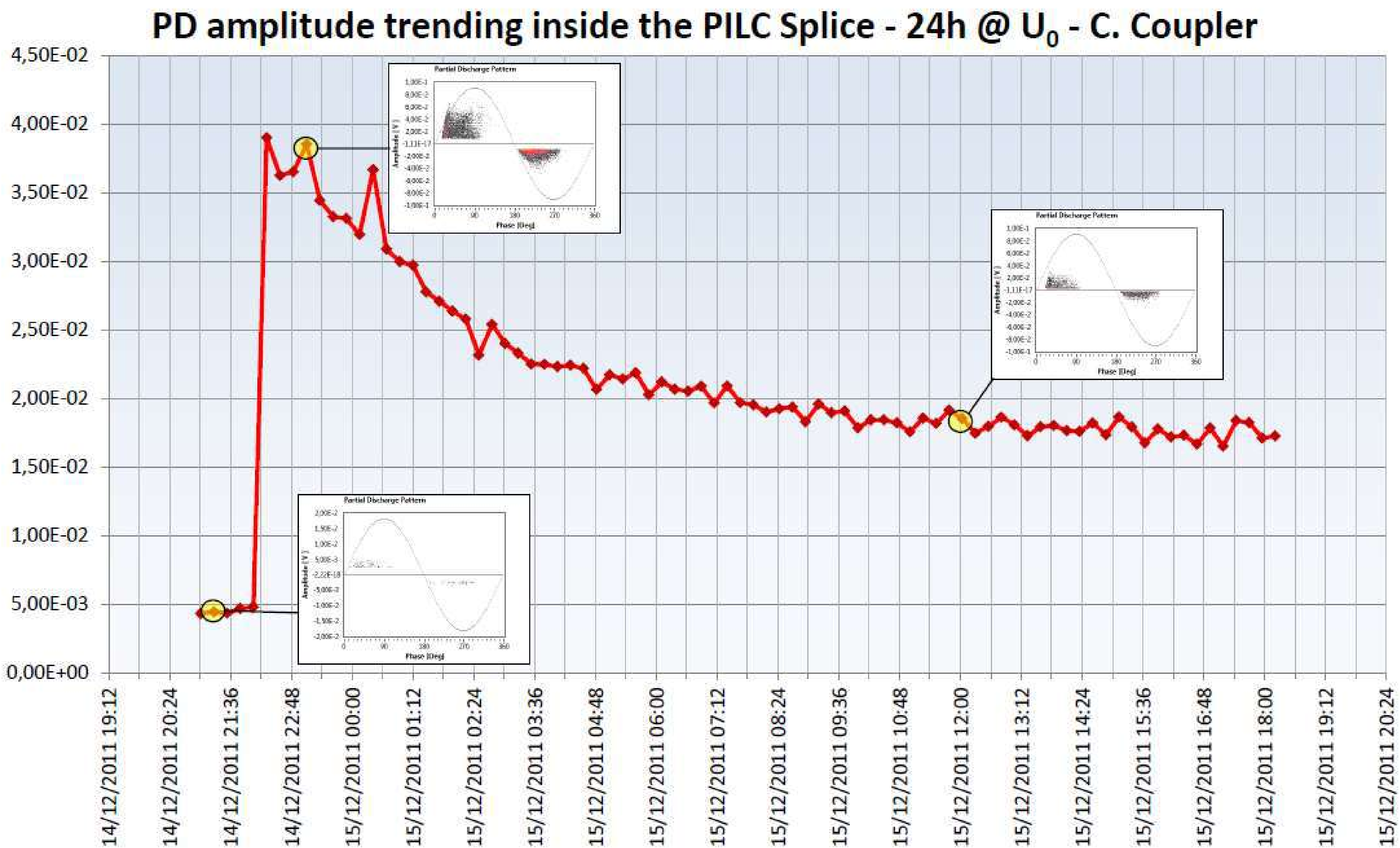
PILC SPLICE – LABORATORY TEST

Laboratory test layout



- A PD Monitoring session was performed using Techimp PPDC at rated voltage for 24h (PD recorded every 15 minutes)
- PD results from Capacitive Coupler are presented

PILC SPLICE – MONITORING TEST



PILC SPLICE – MONITORING TEST

- Interface PD inside the splice was incepted 1 hour after the test start

- Higher amplitude right after inception. PD amplitude decreasing and stabilizing to 18-19 mV.

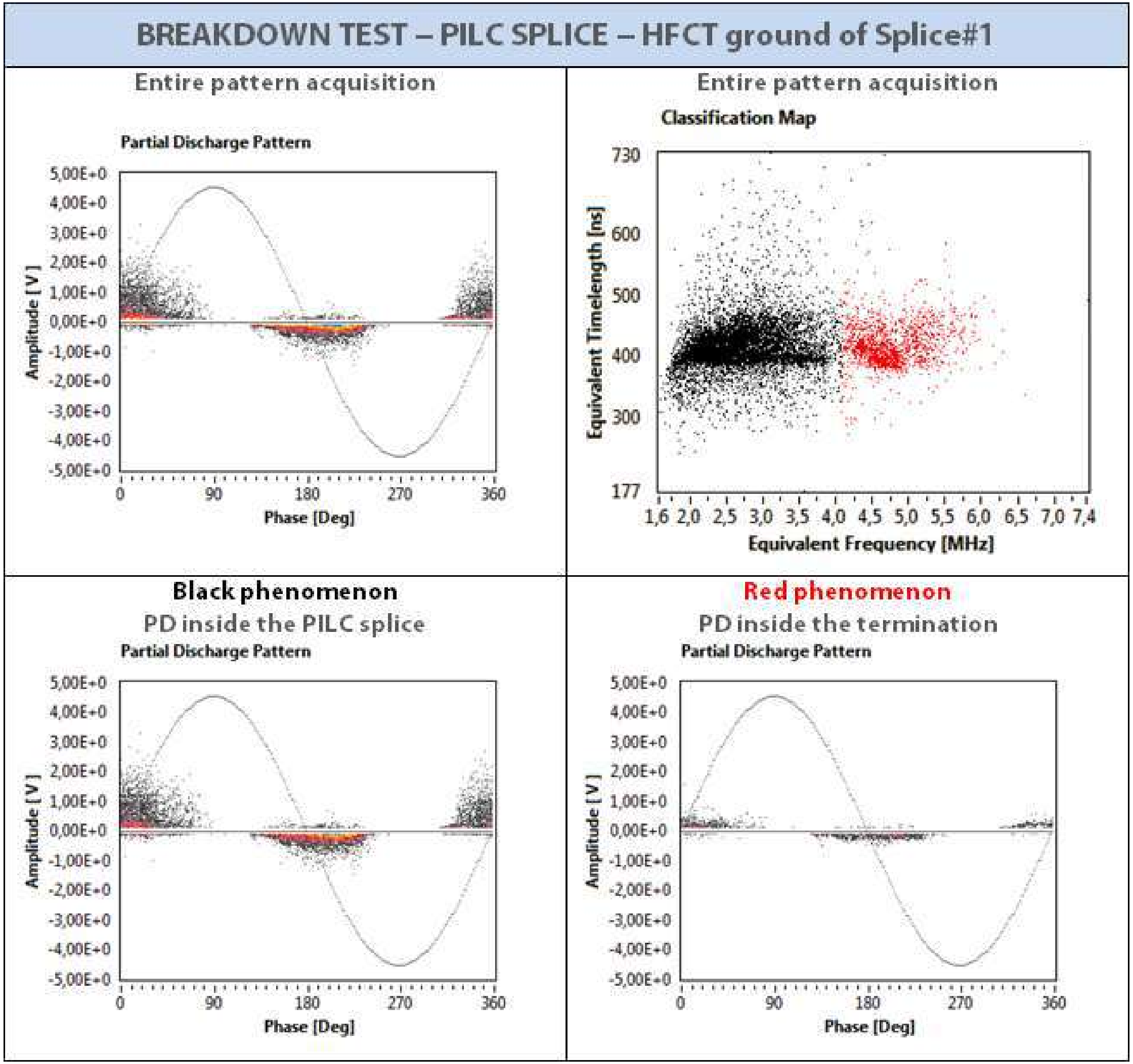
- The defect, an Interface PD, is likely located at the interface between different materials , i.e. semiconductive tape and insulating material.

- PD inside the PILC splice detected On-line confirmed by laboratory tests!

- With the same sensors configuration it was decided to increase the voltage till breakdown. Voltage increased from 2 U0 by steps of 0.5 U0 every 30 minutes (PD recorded every 5 minutes).

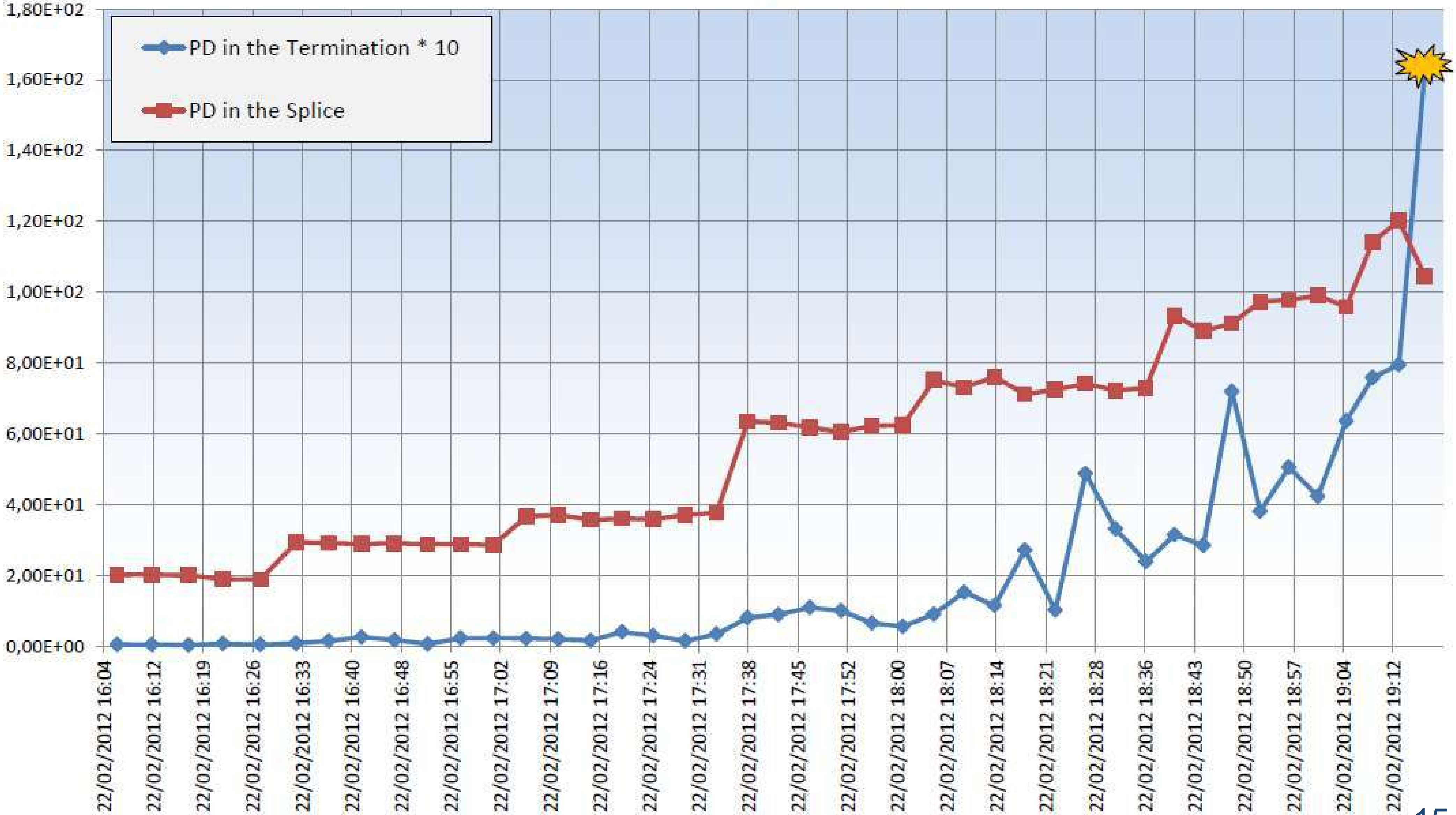
- At 7 U0 the termination failed, not the splice.

PILC SPLICE – BREAKDOWN TEST



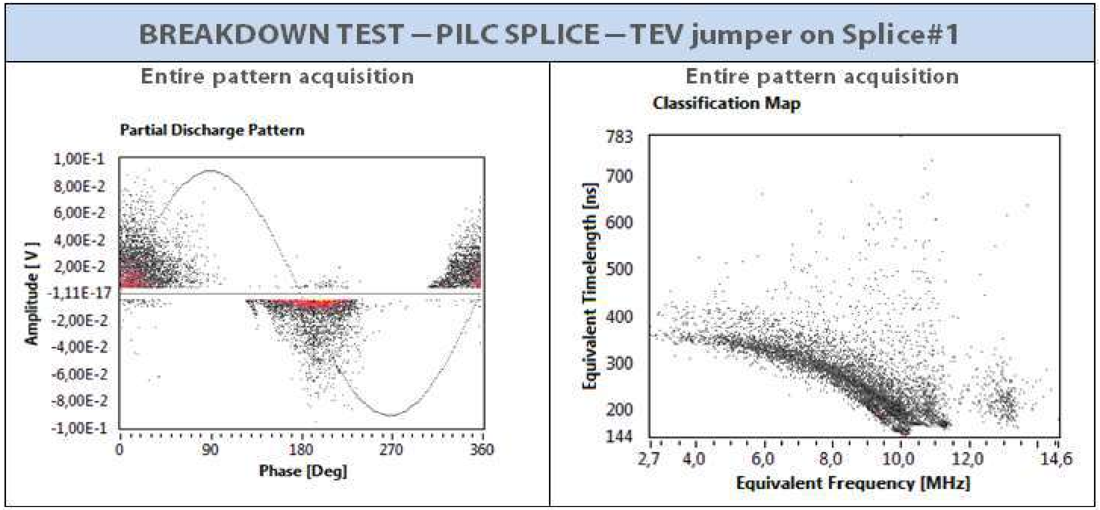
PILC SPLICE – BREAKDOWN TEST

PD ($q_{MAX95\%} * N_W$) trending of PD inside the PILC Splice and inside the Termination at different and increasing voltage levels with HFCT ground



PILC SPLICE – BREAKDOWN TEST

- ($q_{MAX95\%}$*N_W) is related to the damage associated with the PD phenomenon (PDDF = PD Damage Factor)
- PILC splice PDDF is high but it did not show a fast increase with voltage increases
- Termination PDDF is much lower than that for the splice but it showed a very fast increase, especially in the last voltage steps
- Looking only at amplitudes it can be speculated that PD inside the splice is the most harmful, but the breakdown was at the termination, where a smaller PD had a very bad trending



PD results with TEV jumper placed directly on Splice#1 **confirms PD activity inside**

PILC SPLICE – BREAKDOWN TEST

- This is to confirm that PD amplitude is in general associated with damage size, but it cannot be associated often with the degradation rate which is the only thing related to the remaining life of the cable or splice.

A VERY IMPORTANT RESULT OF THIS TEST IS TO SHOW THAT

PD AMPLITUDE TRENDING

IS THE MOST IMPORTANT FACTOR TO BE CONSIDERED IF A MEANINGFUL ANALYSIS ON AN ELECTRICAL APPARATUS HAS TO BE CARRIED OUT

Conclusions

Asset Management is a key issue for any electrical asset. It must be faced using innovative technologies and acquiring skill, but it can offer huge advantages for companies, significant research and education work for reasearch institution. The future of energy management is there