EMPIR EURAMET Metrology for Future Energy Transmission

19ENG02 FutureEnergy

WP4: Metrology for HVDC grid condition monitoring

4.1 Validation of the PD procedure for qualifying PD analysers used for DC testing in the 1 - 30 MHz range (FFII)

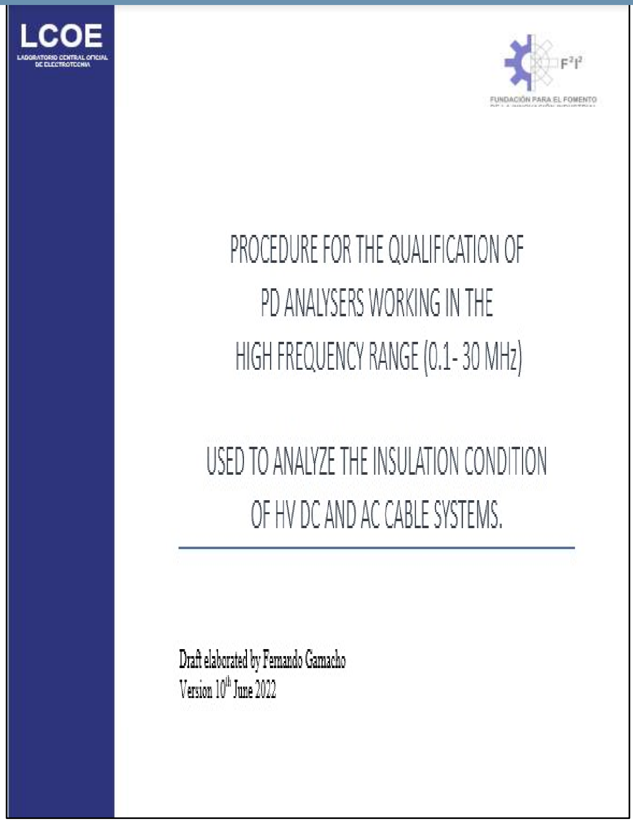
4.2 Procedure for charge evaluation in HVDC GIS using magnetic sensors measuring in the 30 - 300 MHz range (TUDelft)

F²I² LCOE, TU Delft, RISE, Tampere University, Universidad Politécnica de Madrid, DIAEL BlueBOX technology, SuperGrid Institute

Workshop April, 26

Metrology for FutureEnergy Transmission

4.1 Validation of the PD procedure for qualifying PD analysers used for DC testing in the 1 - 30 MHz range


LCOE
LABORATORIO CENTRAL OFICIAL DE ELECTROTECNIA

FUNDACIÓN PARA EL FOMENTO

PROCEDURE FOR THE QUALIFICATION OF PD ANALYSERS WORKING IN THE HIGH FREQUENCY RANGE (0.1- 30 MHz)

USED TO ANALYZE THE INSULATION CONDITION OF HV DC AND AC CABLE SYSTEMS.

Draft elaborated by Fernando Garnacho
Version 10th June 2022

Synhtetic PD Calibrator

Activity number	Activity description	Partners (Lead in bold)
A4.1.1 M04	FFII will collect PD pulses for qualifying of PD analysers working between 1 MHz and 30 MHz from real a.c. cable systems supplied by a collaborator (DIAEL) to analyse their amplitude attenuation (dB/km) versus frequency range , and will perform a statistical analysis of the most representative standard pulses in a.c. cable systems and artificial pulses from 15NRM02 UHV. FFII will work with UPM to extend this statistical study to HVDC cables considering the differences between HVDC cable systems and HVAC cable systems.	**FFII**, UPM
A4.1.2 M15	Using knowledge from 15NRM02 UHV, UPM, with support from FFII, will perform aging for four representative defects in HVDC cable systems: internal void, floating electrode in air, corona in air, and surface discharge in air. These PD results will be compared with at least a thousand PD trains of pulses supplied by a collaborator (DIAEL) from real defects recorded in real HVAC cable systems. UPM will create a database for reference PD pulse trains of PD pattern evolution in typical defects as a function of time that will contain the data collected from the aging process and the data supplied by the collaborator.	**UPM**, FFII
A4.1.3 M22	UPM will develop an artificial intelligence tool for PD pattern recognition of insulation defects. The data saved in the database in A4.1.2 will be used by UPM and FFII for the learning process of the developed artificial intelligence tool for PD pattern recognition.	**UPM**, FFII
A4.1.4 M22	UPM, with support from FFII and TU Delft, will assess the current knowledge level concerning failure modes of converters in HVDC stations by analysing their PD pulse pattern from measurements collected in the past by system operators made available by e.g. collaborator DIAEL. PD High voltage tests will be performed on different semiconductors used in converters to save series of PD pulses associated with defects for classification.	**UPM**, FFII, TU Delft

PD pulses
Attenuation
HVDC grids

Test cells
HVDC
aging

AI Recognition tool

Failure modes in converters

A4.1.5 M18	FFII with support from UPM will define representative standard noises from converters and electronic power sources to be used for qualifying of analysers used on both d.c. and a.c. systems. FFII will collect noise samples obtained from real installations in a.c. and d.c. grids (wind plant, converter stations and PLC), at least two of each type, and classify them into different types of standard noises based on specific representative parameters. A set of adjustable parameters will be defined to enable reproduction of representative noise signals.	**FFII**, UPM	Noise Types
A4.1.6 M25	Using inputs from A4.1.1 – A4.1.5, FFII with support from UPM will validate the calibration procedure to qualify PD analysers working in the frequency range between 1 MHz and 30 MHz developed in 15NRM02 UHV by FFII.	**FFII**, UPM	Procedure
A4.1.7 M26	Using inputs from A4.1.1 – A4.1.6, FFII with support from UPM will design and build an adjustable synthetic calibrator for representative PD defects and noises, i.e., a versatile reference PD source. This calibrator will use adjustable parameters (PD amplitude and PD repetition rate) to simulate the four defects studied in A4.1.2. The PD amplitude will be adjustable between 1 mV to 2 V on 50 Ω input resistor to reproduce representative current pulses defined in A4.1.1 (around 1.5 pC to 3 nC), and the PD repetition rate between 1 pulse per 20 µs and 1 pulse per 2 min. Variable noise signals will have the ability to be mixed with PD pulses using their own adjustable parameters.	**FFII**, UPM	Developing Synthetic PD Calibrator
A4.1.8 M32	FFII, with support from UPM, RISE, TAU and TU Delft will organise a round robin test assessing HF PD analysers of each partner involved, using the developed adjustable PD calibrator from A4.1.7. FFII, UPM, RISE, TAU and TU Delft will participate in the round robin test. The following performances will be evaluated: PD sensitivity for reference PD pulses, PD pattern recognition, PD clustering, noise rejection and PD location.	**FFII**, UPM, TAU, TU Delft, RISE	Round Robin Test
A4.1.9 M36	Using input from the round robin test in A4.1.8, FFII, with support from UPM, RISE, TAU and TU Delft will elaborate a quantitative qualification procedure for a.c. and d.c. analysers, draft a paper on validation of PD method in d.c. grid and send it to the coordinator. Once agreed by the consortium, the coordinator on behalf of FFII, UPM, RISE and TU Delft will submit the paper to a peer reviewed journal and to EURAMET as **D7**: "*Paper on the validation of partial discharge (PD) method in d.c. grid for detection and prevention of insulation failures in HVDC cables, GIS and convertors submitted to a peer-reviewed journal*".	**FFII**, UPM, RISE, TAU, TU Delft	Final version Qualification Procedure And Paper (D7)

4.1 Validation of the PD procedure for qualifying PD analysers used for DC testing in the 1 - 30 MHz range

Deliverable 7

Paper on the validation of partial discharge (PD) method in d.c. grid for detection and prevention of insulation failures in HVDC cables, GIS and convertors submitted to a peer-reviewed journal	Paper	**FFII**, RISE, UPM, TU Delft, TAU	May 2023 (M36)

Paper 1 "Influence of increasing the upper frequency limit f_2 and bandwidth Δf on the wideband PD measuring approach of IEC 60270 used for HVDC grids", FFII. It's already written. To submit to IEEE Magazine.

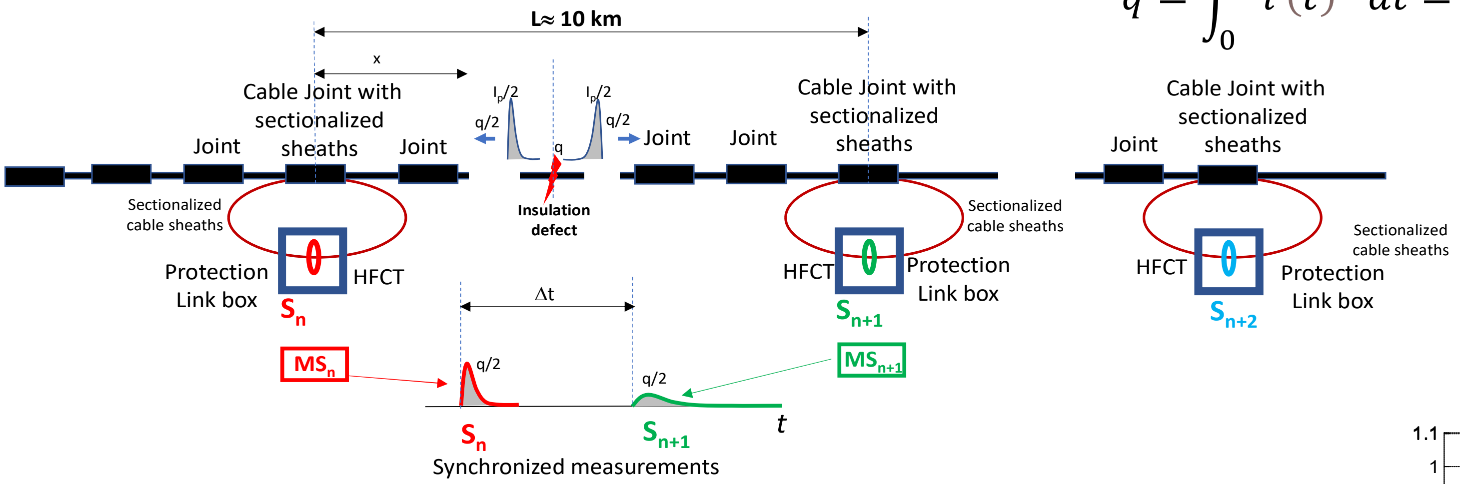
Paper 2 "Validation of PD analyzers for insulation diagnosis of HVDC and HVAC grids by means of a new synthetic PD calibrator", FFII. It's already written. To submit to Sensors Journal.

Paper 3 "Metrological Qualification of PD Analysers for Insulation Diagnosis of HVDC and HVAC grids" FFII, UPM, RISE, TUDelft, TAU. It's already written (final version). To submit to Sensors Journal.

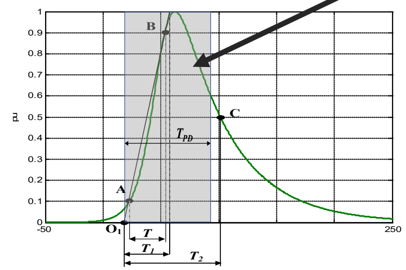
Paper 4 "Functionality Test for Qualification of PD Analysers used for insulation diagnosis of HVDC and HVAC Grids" FFII, UPM, RISE, TUDelft, DIAEL, TAU. (final version in the 1st week of May). Sensors?

Why is the charge quantity important for PD monitoring in HVDC Cable Systems ?

PD Monitoring in HVDC Cable systems



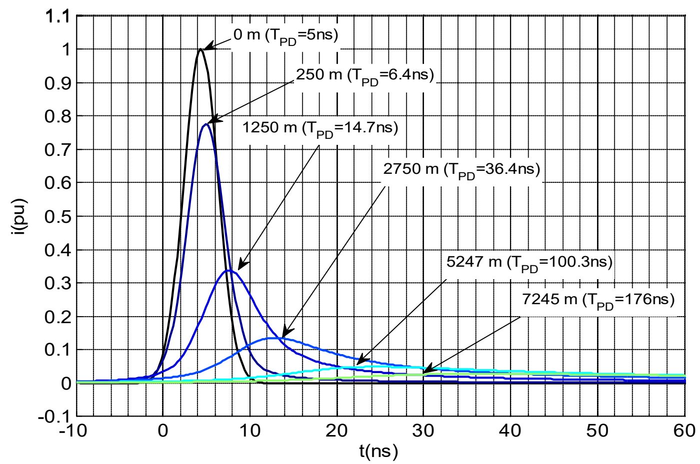
$$q = \int_0^\infty i\,(t)\cdot dt = i_{peak}\cdot\int_0^\infty i_{pu}\,(t)\cdot dt = i_{peak}\cdot T_{PD}$$



$$I_x(\omega) = I_0(\omega)\cdot e^{-\gamma(\omega)\cdot x} \qquad \gamma(\omega) = \sqrt{(r + j\cdot\omega\cdot l}\cdot\sqrt{(g + j\cdot\omega\cdot c}$$

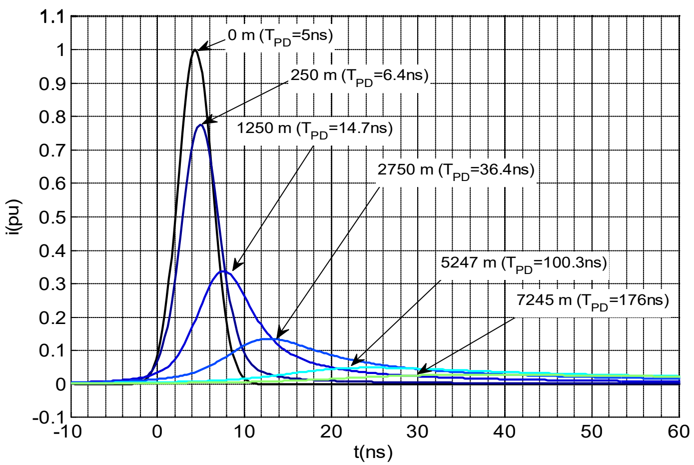
$$\underline{q_x = I_x(0)} = I_o(0)\cdot e^{-(0)\cdot x} = q_o\cdot e^{-\sqrt{r\cdot g}\cdot x}$$

$$\boldsymbol{q_{10km} = q_o\cdot e^{-0.0039} = 0.996\cdot q_o}$$

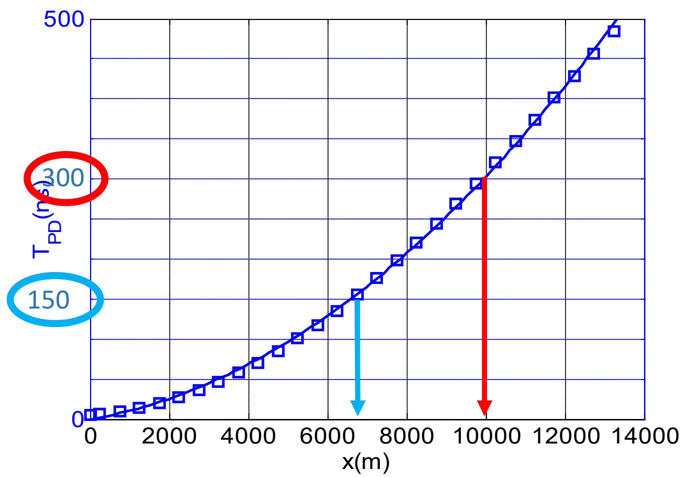


What are the differences between HVAC and HVDC cable systems in relation to PD Pulse Width (T_{PD})?

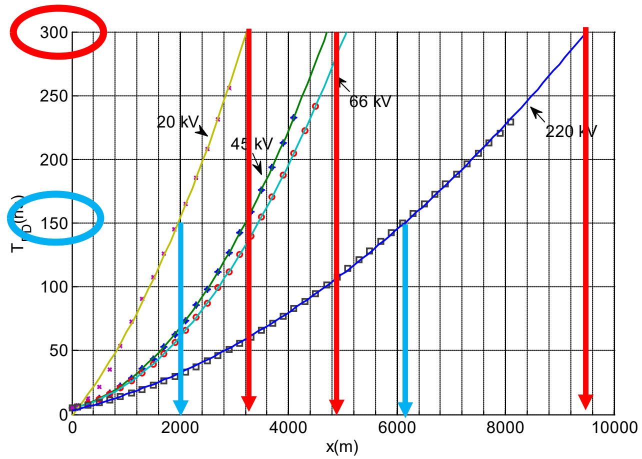
HVDC Cable Systems 320 kV



HVDC Cable System 320 kV



HVC Cable Systems 20 kV – 220 kV

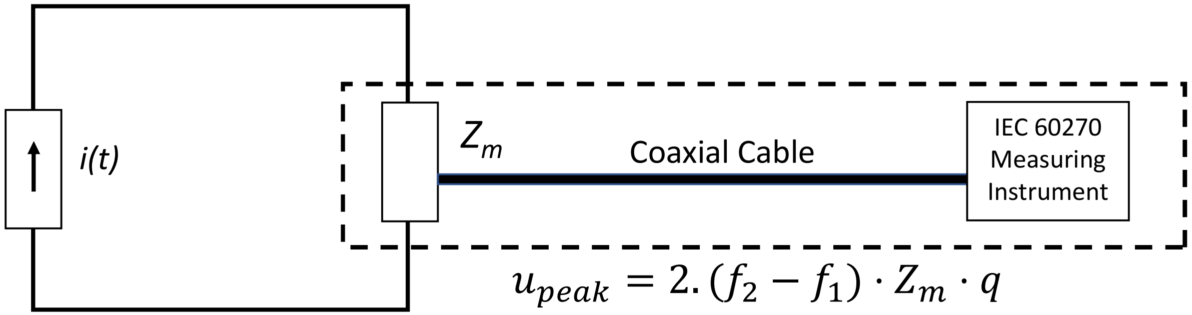


PD Measuring Systems approaches

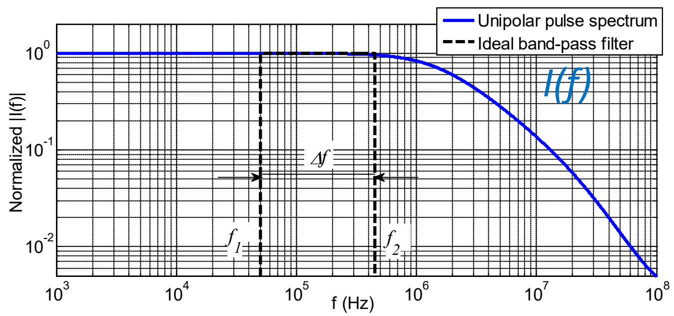
$$q(t)=\int_0^t i(t)\cdot d\tau \qquad Q(s)=I(s)/s$$

$$q_\infty=\int_0^\infty i(t)\cdot d\tau$$

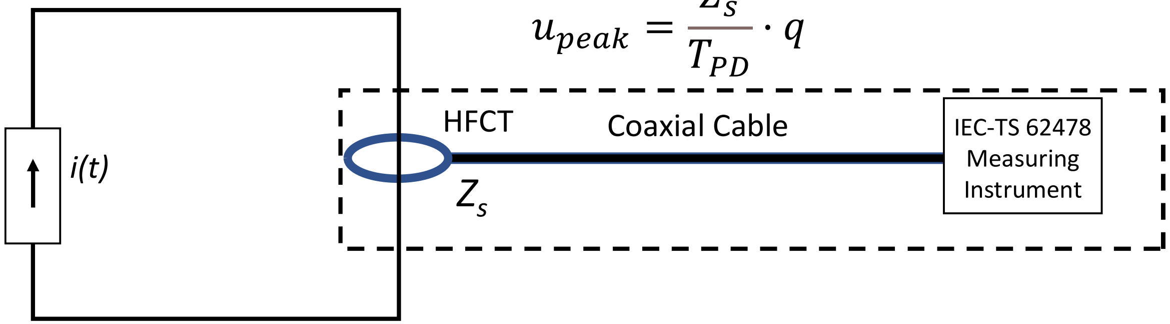
$$q_\infty=\lim_{s\to 0}\left[s\cdot Q(s)\right]=\lim_{s\to 0} I(s)=I(0)$$



$$u_{peak}=2.(f_2-f_1)\cdot Z_m\cdot q$$

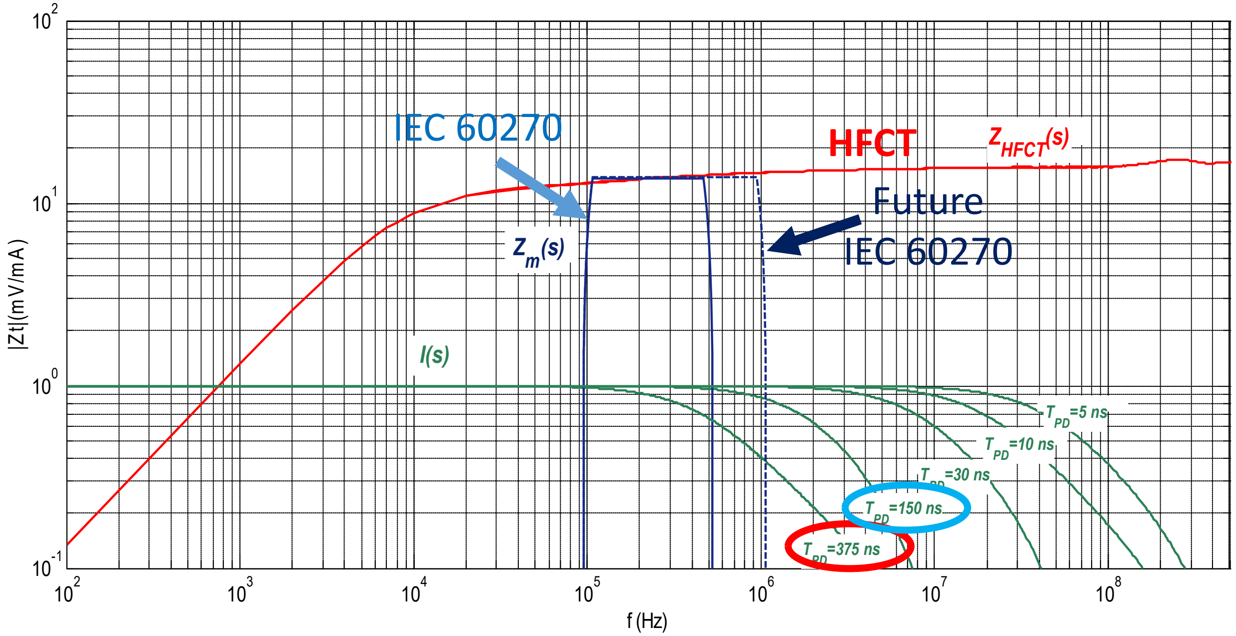


$$u_{peak}=\frac{Z_s}{T_{PD}}\cdot q$$



What is the limitation of the IEC 60270 for off-line PD measurements ?

HFCT
Transfer impedance
(Ω)

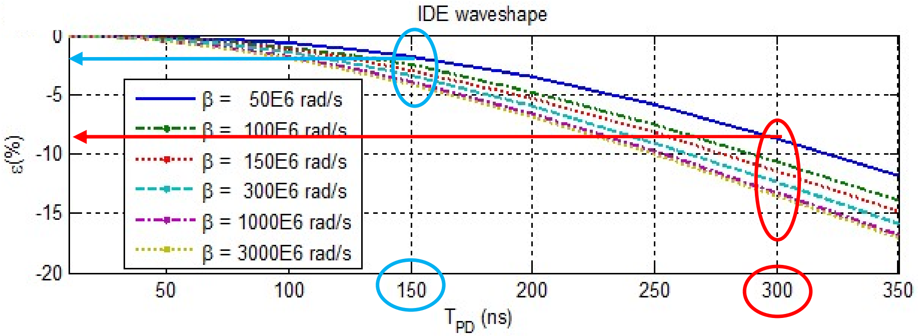


What is the limitation of the IEC 60270 for off-line PD measurements ?

$$i(t) = i_{peak} \cdot k \cdot \frac{1}{e^{\alpha \cdot t} + e^{-\beta \cdot t}}$$

T_{PD}=300 ns -> $Error_{min}$ ~ 8% < 10%

T_{PD}=150 ns -> $Error_{min}$ ~ 3% < 10%

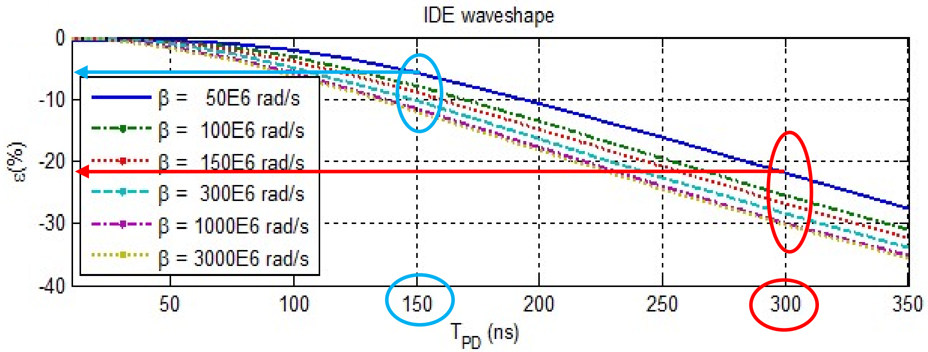


Current IEC 60270 Standard

$$30\text{ kHz} \le f_1 \le 100\text{ kHz};$$
$$f_2 \le 500\text{ kHz};$$
$$100\text{ kHz} \le \Delta f \le 400\text{ kHz}.$$

T_{PD}=300 ns -> $Error_{min}$ ~ 22% > 10%

T_{PD}=150 ns -> $Error_{min}$ ~ 5% < 10%

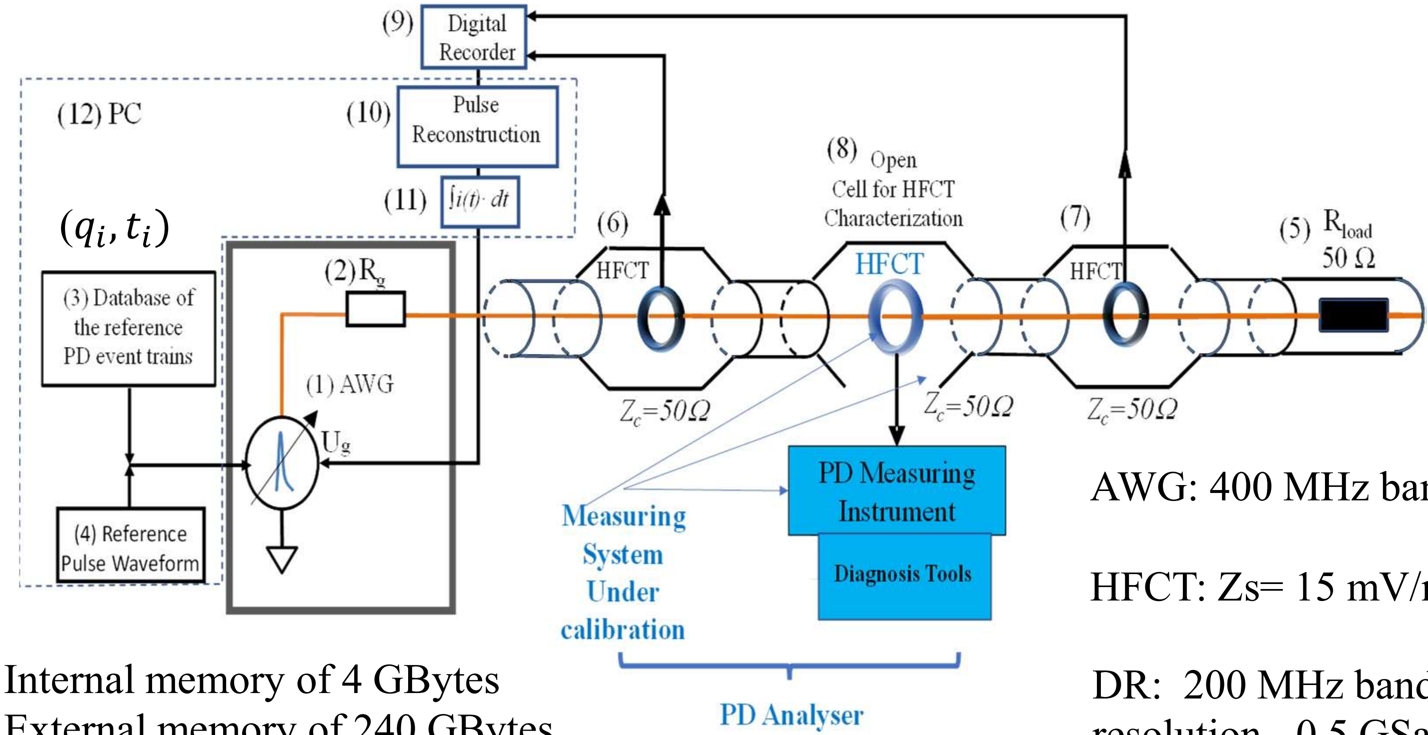


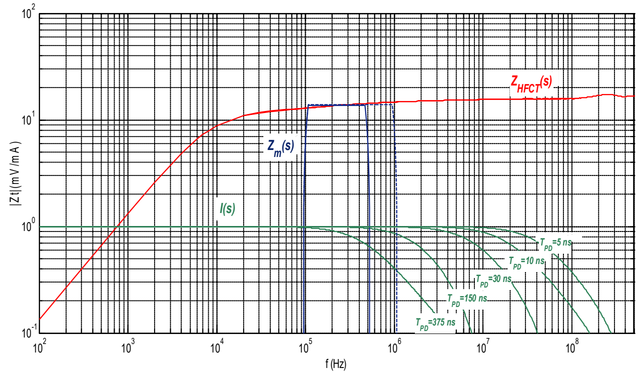
New IEC 60270 Standard

$$30\text{ kHz} \le f_1 \le 100\text{ kHz};$$
$$f_2 \le 1\text{ MHz};$$
$$100\text{ kHz} \le \Delta f \le 900\text{ kHz}.$$

Therefore: IEC 60270 for off-line PD measurements T_{PD}> 150 ns is not a good approach

PD calibrator electric circuit





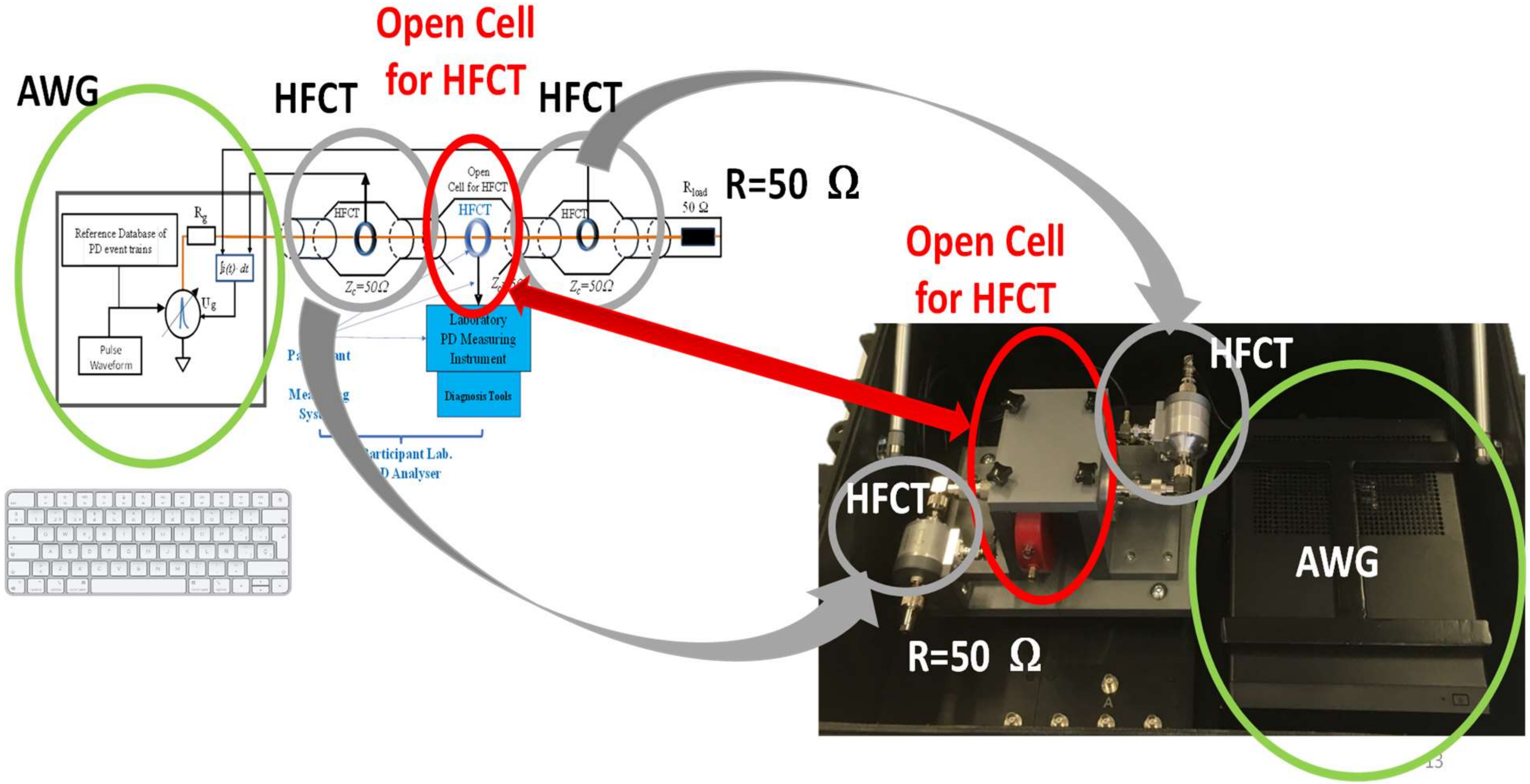
Internal memory of 4 GBytes
External memory of 240 GBytes.

AWG: 400 MHz bandwidth, 1.25 Giga-Samples/s and 50 Ω

HFCT: Zs= 15 mV/mA; 30 kHz – 500 kHz

DR: 200 MHz bandwidth (1 Giga-Sample/s with 8 bits resolution - 0.5 GSamples/s with 12 bits resolution)

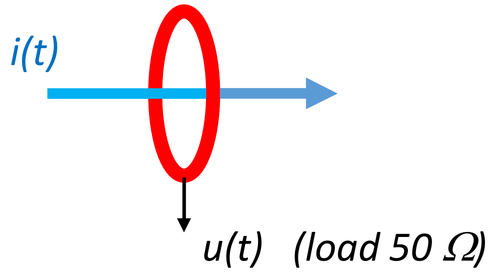
Implementation of the PD Synthetic Calibrator

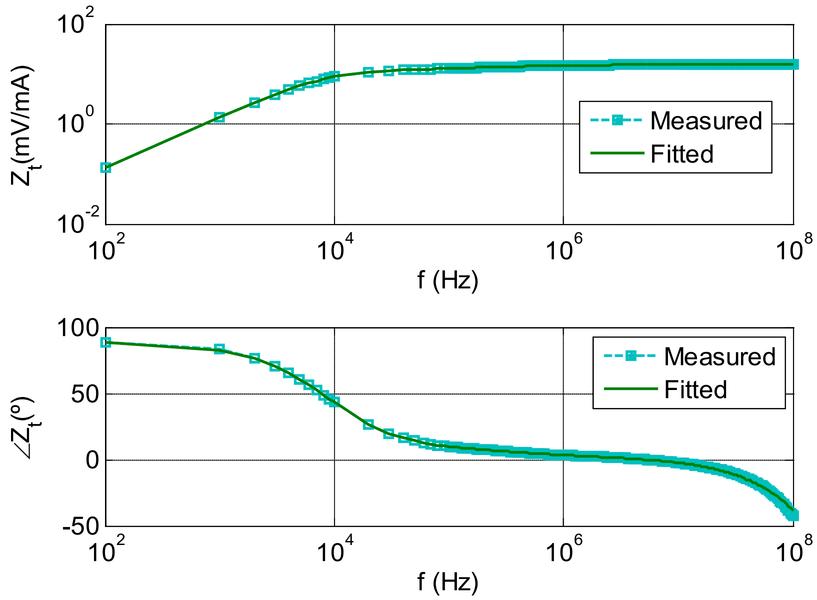


Signal Reconstruction

$$Z_t(s) = \prod_{i=1}^{n} \frac{s - z_i}{s - p_i}$$

$$Z_t(s) = \sum_{i=1}^{n} \frac{r_i}{s-p_i} + r_0$$





Continuous-time system

$$\dot{x}(t) = A \cdot x(t) + B \cdot i(t)$$
$$u(t) = C \cdot x(t) + D \cdot i(t)$$

$$\boldsymbol{A} = \begin{bmatrix} \boldsymbol{p}_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \boldsymbol{p}_n \end{bmatrix} \qquad \boldsymbol{B} = \begin{bmatrix} \mathbf{1} \\ \cdots \\ \mathbf{1} \end{bmatrix}$$

$$\mathrm{C} = [r_1 \quad \ldots \quad r_n] \qquad D = r_0$$

discrete system

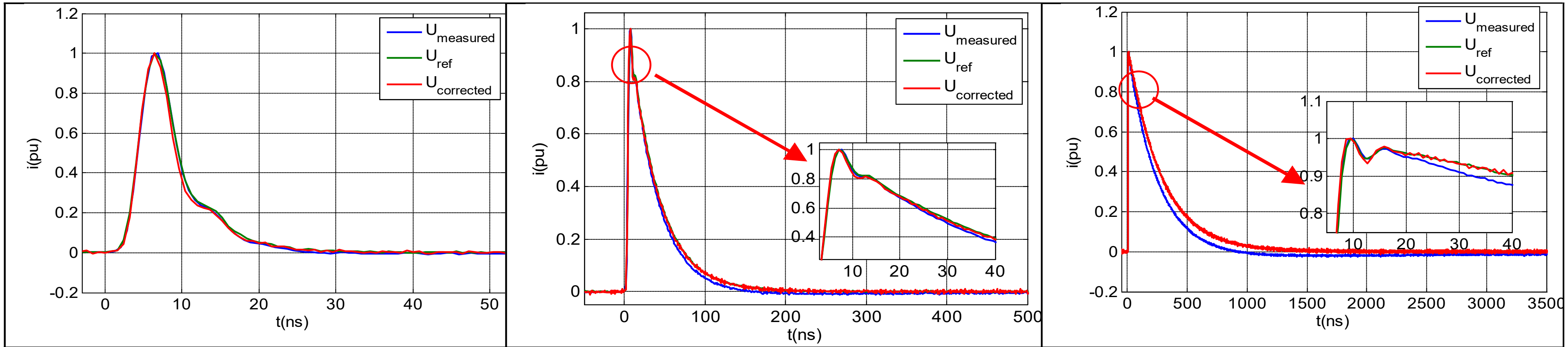
$$i_k = \frac{[u_{k+1} - (C \cdot F) \cdot x_k]}{(C \cdot G) + D}$$

$$x_{k+1} = F \cdot x_k + G \cdot i_k$$

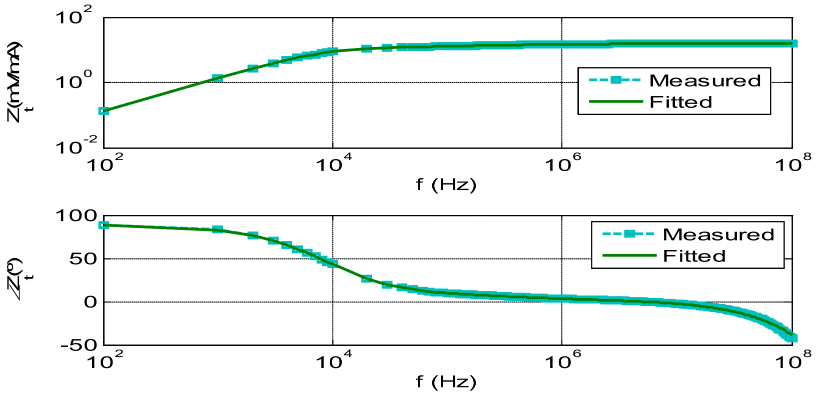
$$x_0 = 0$$
$$F = exp(A \cdot h_s)$$
$$G = (F - I) \cdot A^{-1} \cdot B$$

I: n x n identity matrix

Signal reconstruction

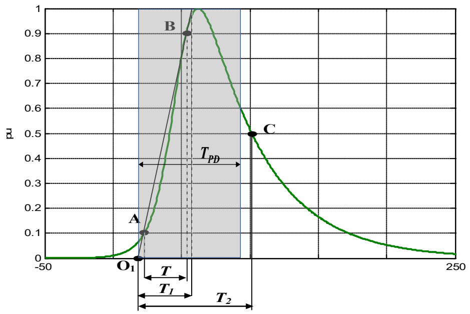


T_{PD}= 7 ns	T_{PD}= 37 ns	T_{PD}= 300 ns



Maximum and minimun magnitudes to be meausred by the Synthetic PD Calibrator

T_{PD} (ns)	q_{max} (pC)	q_{min} (pC)
8.0	320	2.0
16.0	640	2.0
37.5	1.500	2.0
75.0	3,000	2.0
150	6,000	4.0
375	15.000	10.0



T_{PD} of 75 ns $\rightarrow T_1/T_2$= 31,2 /76 ns

For example for T_{PD}=75 ns

q_{min}

Minimum peak value to be measured by the recorder of 0.4 mV_{peak}

$q_{min}=U_{min} / Z_{HFCT} \times T_{PD}$=0.4 mV / 15 mV/mA x 75 ns (pC/mA) =2 pC

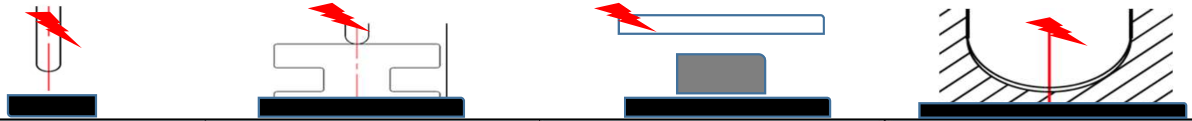
q_{max}

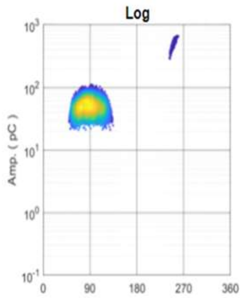
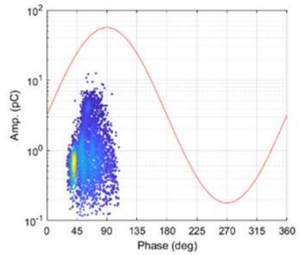
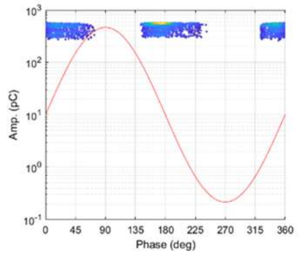
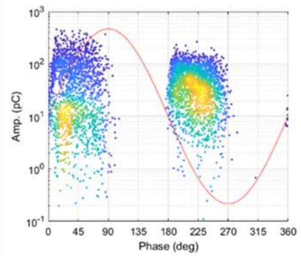
Maximum Current to be generated= 4V/ 100 Ω =40 mA_{peak}

$q_{max}=I_{max} \times Z_{HFCT}$ =40 mA x 15 mV/mA = 3,000 pC

Reference Data Base of PD event trains (q_i, t_i)

For diagnostic Tests (HVAC and HVDC): Test cell of 20 kV(AC) 30 kV(DC)



	Corona (+)	Surface (+)	Floating	Cavity (+)
PRPD Pattern				

Aging > 1 year

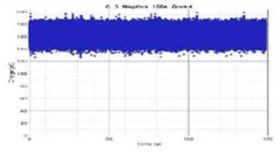
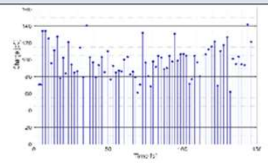
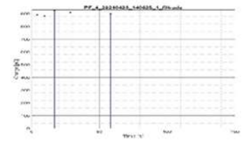
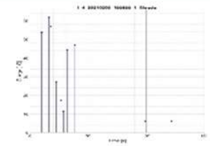
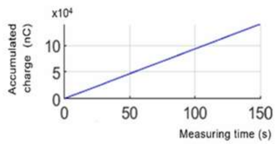
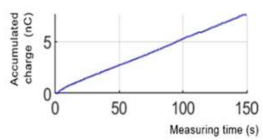
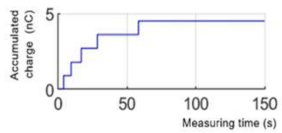
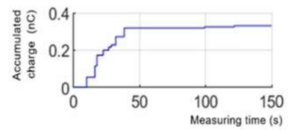
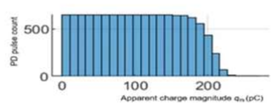
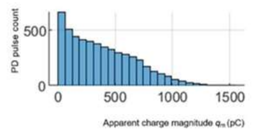
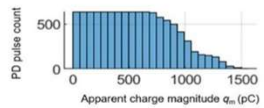
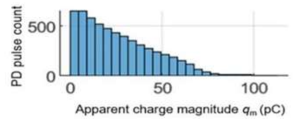
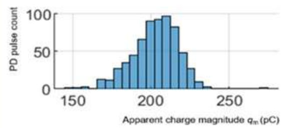
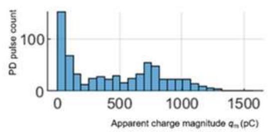
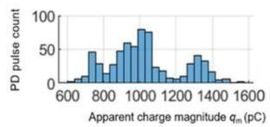
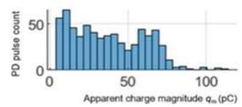
A data base of at least 1000 different reference PD pulse trains of each representative insulation defects (cavity, surface on air, floating potential, and corona) is available. The 95 % of the total PD pulse trains generated by test cells were used for training AI recognition tool.

The remaining 10% (at least 50 pulse trains for each PD defect) were reserved PD recognition test and PD clustering test.

Reference Data Base of PD event trains (q_i, t_i)

PD graphs for HVDC

Aging > 1 year

Constant direct voltage			Changing direct voltage. $u(t) = Uo \cdot (1-e^{-t/\tau})$; $Uo = 30\ kV$; $\tau = 16\ s$		
PD Pattern	**Corona (-)**	**Surface (-)**	**PD Pattern**	**Floating (-)**	**Cavity (-)**
Apparent charge of individual PD pulses 150 s			Apparent charge of individual PD pulses at a voltage change		
Accumulated apparent charge 150 s			Accumulated apparent charge at voltage changes		
Monotonous decreasing PD histogram m=650 p			Monotonous decreasing PD histogram at voltage changes		
Charge intervals PD histogram m=650 p			Charge intervals PD histogram at voltage changes		

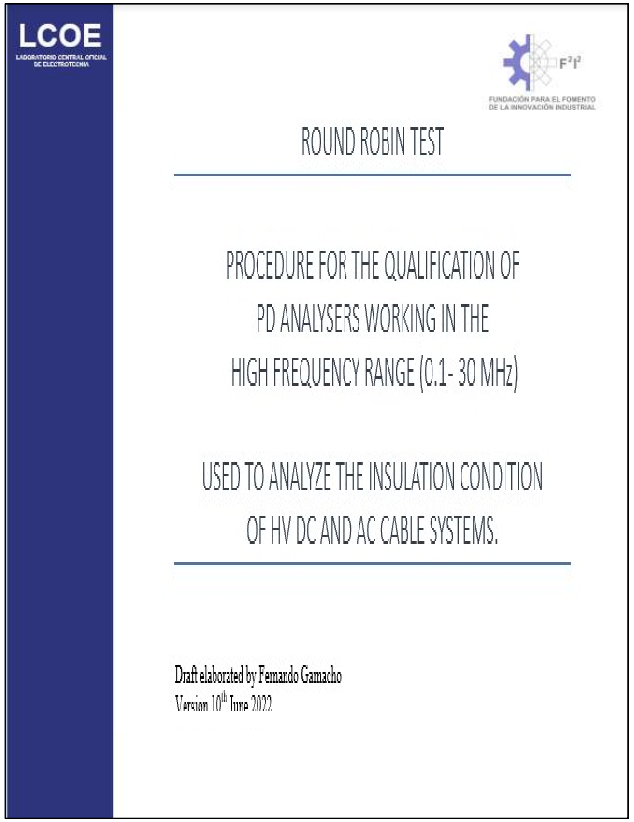
Reference Data Base of PD event trains (q_i, t_i)

Diagnostic Tests
PD pulse trains for HVDC

PD pulse trains of 150 s (2.5 min)

Defect	Polarity	Nº Trains	Figures per PD pulse train		
			m (pulses)	q (pC)	qa(nC)
Cavity	**(+)**	**538**	11,1	75,2	0,8
	(-)	**569**	8,8	72,0	0,6
Floating	**(+)**	**371**	3,4	899,5	3,1
	(-)	**195**	3,2	1108,5	3,6
Corona	**(+)**	**657**	110718,5	7115,6	787829,1
	(-)	**609**	1611509,5	272,1	438558,0
Surface	**(+)**	**427**	93,4	560,9	52,4
	(-)	**343**	124,0	312,5	38,7

A 4.1.8. Round Robin Test (August 2022 - January 2023)



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ROUND ROBIN TEST

PROCEDURE FOR THE QUALIFICATION OF
PD ANALYSERS WORKING IN THE
HIGH FREQUENCY RANGE (0.1- 30 MHz)

USED TO ANALYZE THE INSULATION CONDITION
OF HV DC AND AC CABLE SYSTEMS.

Draft elaborated by Fernando Garnacho
Version 10th June 2022

PD Simulator


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ROUND ROBIN TEST

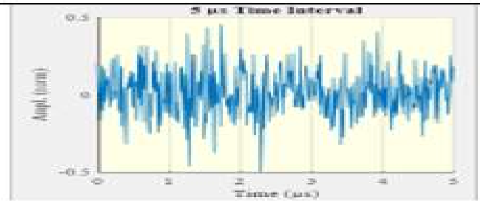
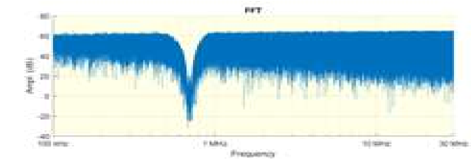
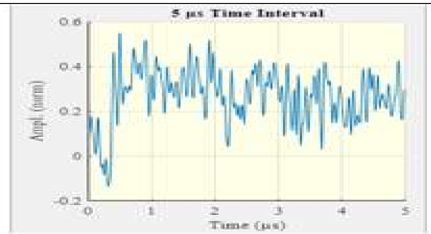
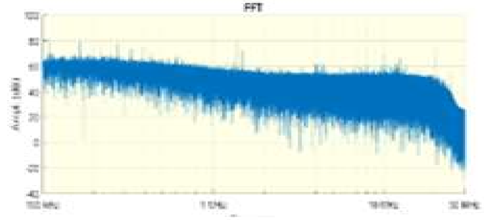
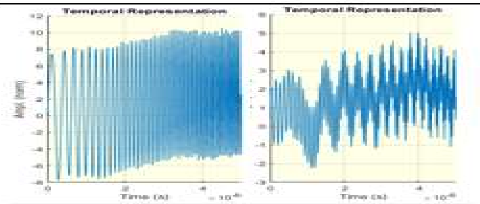
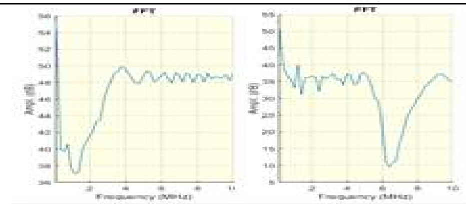
PROCEDURE FOR THE QUALIFICATION OF PD ANALYSERS WORKING IN THE HIGH FREQUENCY RANGE (0.1-30 MHz)

USED TO ANALYZE THE INSULATION CONDITION OF HV DC AND AC CABLE SYSTEMS.

Validation of the Calibration Procedure to qualify PD

For Noise #1: A wideband PD instrument tunned in f_1=610 kHz f_2=770 kHz was the recommended PD measuring approach to mitigate the noise spectrum #1.

Noise types

	Time domain	Frequency domain
a) Invariable Noise #1 for PD Measurements according to IEC 60270		
b) Invariable Noise #2 for On-site PD Measurements according to TS IEC 62478		
c) Variable Noise #3 for Continuous PD Monitoring according to TS IEC 62478	 $t = t_1$ $t = t_2$	 $t = t_1$ $t = t_2$

4.1.8. Round Robin (Aug-22 to Jan-23)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ROUND ROBIN TEST

PROCEDURE FOR THE QUALIFICATION OF
PD ANALYSERS WORKING IN THE
HIGH FREQUENCY RANGE (0.1- 30 MHz)

USED TO ANALYZE THE INSULATION CONDITION
OF HV DC AND AC CABLE SYSTEMS.

Qualification	IEC 60270	Invariable noise TS IEC 62478	Variable noise TS IEC 62478
1) Noise rejection	Yes	Yes	Yes
2) Linearity (2 pc - 2,4 nC)	Yes	Yes	Yes
	Yes	Yes	Yes
3) Resolution time t_{res}	Yes	Yes	Yes
4) Error due to pulse width (T_{PD}=8 ns -150 ns)	Yes	Yes	Yes
A) PD Recognition	Not	Yes	
B) PD Clustering	Not	Yes	
C) PD Location	Not	Yes	

4.1.8. Round Robin (Aug-22 to Jan-23)


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ROUND ROBIN TEST

PROCEDURE FOR THE QUALIFICATION OF PD ANALYSERS WORKING IN THE HIGH FREQUENCY RANGE (0.1-30 MHz)

USED TO ANALYZE THE INSULATION CONDITION OF HV DC AND AC CABLE SYSTEMS.

a) Apparent charge Measurements

Measuring systems that work according to IEC 60270

The IEC 60270 requirement and statement related to noise level are as follows.

- "The apparent charge threshold level shall be adjusted to at least twice the background noise."
- The uncertainty for a PD Measuring System that complies the standard requirements is ± 10% or ±1pC, whichever is greater.

Considering these above sentences, if the noise level is not more than 50% of the apparent charge value, the charge error should not be more than 10%.

Measuring systems that work according to TS IEC 62478

There is no standardized limit for PD amplitude error when performing PD measurements according to TS IEC 62478 (measuring frequency > 1 MHz). Considering that the PD charge measurement will be done in service, the noise level should be higher than in laboratory measurements and the maximum permissible error should also increase. Applying the same principle as IEC 60270 with respect to noise, it is proposed that the error should not be greater than ±3 dB (±30%) when noise is 200% of the PD charge value.

4.1.8. Round Robin (Aug-22 to Jan-23)


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ROUND ROBIN TEST

PROCEDURE FOR THE QUALIFICATION OF PD ANALYSERS WORKING IN THE HIGH FREQUENCY RANGE (0.1-30 MHz)

USED TO ANALYZE THE INSULATION CONDITION OF HV DC AND AC CABLE SYSTEMS.

b) Measurements of PD pulse repetition frequency

Measuring systems that work according to IEC 60270

For every value of the pulse repetition frequency, the recorded number of pulses as observed during the defined time interval shall be within ±2 % of the known number of calibration pulses applied (clause 7.3.5 of future edition 4 of IEC 60270). Therefore, applying the same criteria as the charge errors, if the noise level is less than 50% of the PD load value, the maximum permissible error should not be greater than 2%.

Measuring systems that work according to TS IEC 62478

No limitation is stated in TS IEC 62478 for the error of PD pulse repetition frequency. Applying the same criteria as the charge errors, if the noise level is not more than 200% of the PD charge value, the maximum permissible error for the pulse repetition frequency should not be greater than 2 %.

4.1.8. Round Robin (Aug-22 to Jan-23)

1) Noise rejection Test


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ROUND ROBIN TEST

PROCEDURE FOR THE QUALIFICATION OF
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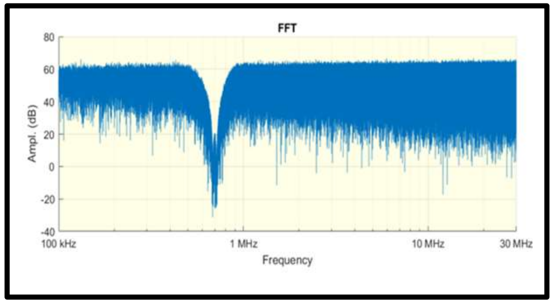
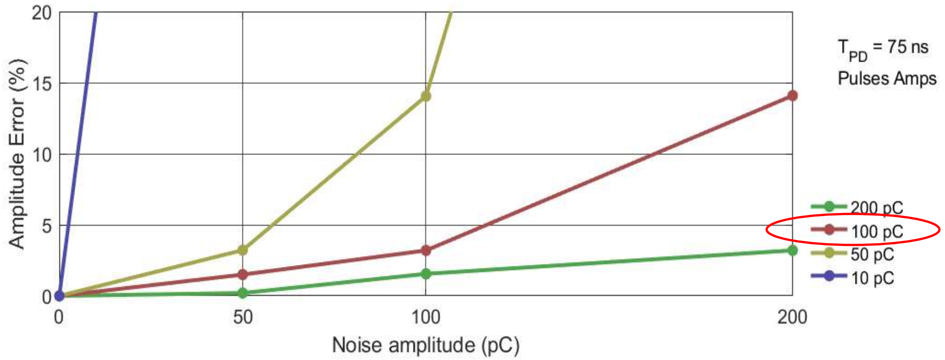
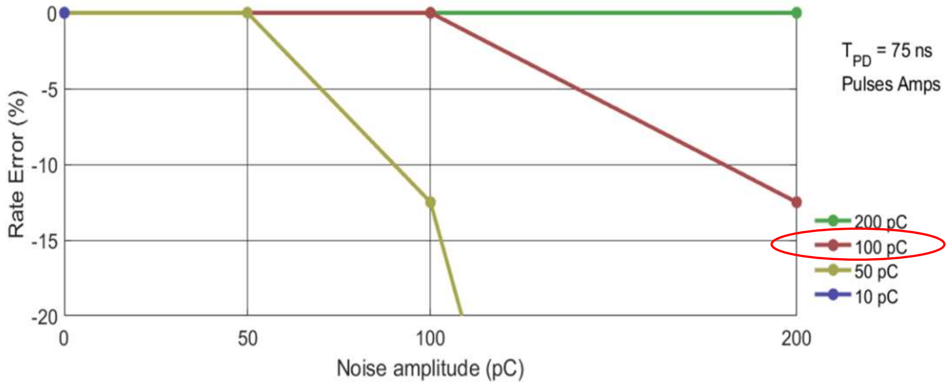
Draft elaborated by Fernando Garnacho



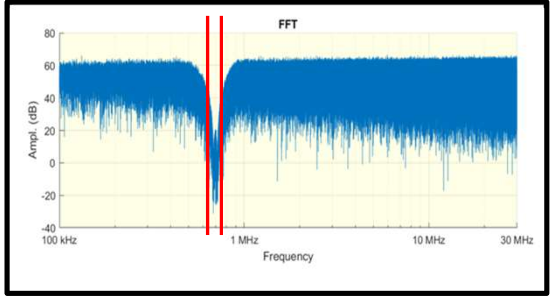




4.1.8. Round Robin (Aug-22 to Jan-23)

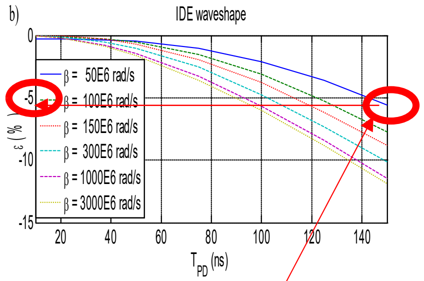
Summary for Noise #1

a) Invariable Noise #1 for PD Measurements according to IEC 60270



PD Analyser for off-line Measurements		PD Analyser A-1	PD Analyser A-2	PD Analyser A-3
f_1-f_2 (kHz)		40 – 400	40 – 800	610 – 770
Δf (kHz)		360	760	160
Charge measurement method		Quasi-integration	Quasi-integration	Quasi-integration
Filtering Method		None None	Manual Selection of f_1, f_2 and	trigger level
Metrological tests		Charge & PD repetition rate errors v.s. noise level Requirements Max ABS(ε_q) ≤ 10%; Max ABS(ε_n) ≤ 2% under 50% noise level		
Noise Rejection q=100 pC	Noise range (%)			
	200	ε_q=248%	ε_q=151%	ε_q=61.9%
		ε_n>1000 %	ε_n>1000 %	ε_n=-0,4%
	100	ε_q=104.3%	ε_q=53,9%	ε_q=32.0%
		ε_n>1000 %	ε_n>1000 %	ε_n=-0,4%
	50	**ε_q=27%**	**ε_q=26%**	**ε_q=2.6%**
		ε_n>1000 %	**ε_n>1000 %**	**ε_n=-0,4%**
	20	ε_q=7,8%	ε_q=9,6%	ε_q=0,5%
		ε_n>1000%	ε_n=496%	ε_n=-0,4%
Linearity under 35% noise	**Charge range (pC)**	**Linearity error = (Max error – Min error) / 2 Requirement ≤ 5% under 35% noise level**		
	50 to 2.400	± 16,3%	± 6,2%	± 2,9%
	10 to 2.400	>100%	± 6,2%	± 2,9%
T_{PD} influence under 35% noise q=200 pC	**Pulse width T_{PD} range (ns)**	**T_{PD} error = (Max error – Min error) / 2 Requirement ≤ 30% under 35% noise level**		
	8 to 150	± 2,5%	± 2,5%	± 2,7%
Resolution Time under 35% noise q=200 pC	**t_{res} range (µs)**	PD repetition rate error Requirement ≤ 2% under 35% noise level		
	2,500 – 10	2.5 ms ; ε_n>2.0 %	2.5 ms ; ε_n>2.0 %	10 µs ; ε_n=1.3 %

wideband apporach

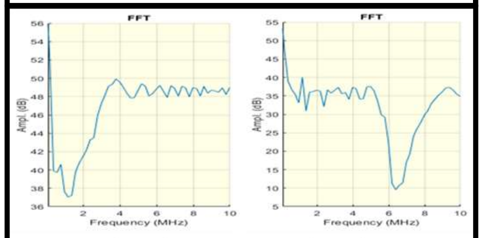


Max-Min=5,4%

4.1.8. Round Robin (Aug-22 to Jan-23)

Summary for Noise #3

c) Variable Noise #3
for Continuous PD Monitoring
according to TS IEC 62478



$t = t_1$ $t = t_2$

PD Analyser for Continuous PD monitoring		PD Analyser B-1	PD Analyser B-2	PD Analyser B-3	PD Analyser C
HFCT bandwidth f_1-f_2 (MHz)		0,2 – 20	0,08 -61	0.004 – 1,100	0,2 – 20
Charge measurement Method f_1-f_2 (MHz)		Quasi-integration f_1=1.0, f_2= 4.0	Direct reading of HFCT (1)	Integration in time domain	Quasi-integration f_1=2.45, f_2=3.95
Digitizer: Bandwidth (Sampling rate)		30 MHz (60 MS/s)	50 MHz (100 MS/s)	20 MHz (1.25 GS/s)	50 MHz (100 MS/s)
Filtering Method f_1-f_2 (MHz)		Passband filter Manual Selection of f_1, f_2 and trigger level f_1=1.75, f_2= 3.25	4th order passband filter Butterworth f_1=0,05, f_2= 45 (hardware)	8th order lowpass filter f_2= 20 (hardware)	Automatic Wavelet Filter to recognise PD pulses and pulsating noises
Metrological tests		Charge error & PD repetition rate errors v.s. noise level Requirements Max ABS(ε_q)≤ 30%, Max ABS(ε_n)≤ 2% under 200% noise level			
Noise Rejection q=100 pC	Noise range (%)				
	200	**ε_q= 4.1 %**	**ε_q=-0.4 %**	**ε_q=-40,0%**	**ε_q=-11,7%**
		ε_n=0.0 %	**ε_n=0.0 %**	**ε_n=0.7 %**	**ε_n=-0,0%**
	100	ε_q=0.8 %	ε_q=0.0 %	ε_q=16,5%	ε_q=-1,6%
		ε_n=0.0 %	ε_n=0.0 %	ε_n=0.7 %	ε_n=-0,0%
	50	ε_q=-0.1%	ε_q=0.1 %	ε_q=8,7%	ε_q=1,7%
		ε_n=0.0 %	ε_n=0.0 %	ε_n=0.0 %	ε_n=-0,0%
	20	ε_q=0,0 %	ε_q=0.2 %	ε_q=3,5%	ε_q=1,7 %
		ε_n=0.0 %	ε_n=0.2 %	ε_n=0.0%	ε_n=-0,0%
Linearity under noise	Charge range q(pC)	Linearity error = ± ABS(ε_l)= ± ABS (Max error – Min error) / 2 Requirement ≤ 5% under 35% noise level			
	50 to 2.400	± 0.1%	± 0.5%	± 2.0 %	± 0.2%
	10 to 2.400	± 0.7%	± 11.0%	± 85.0 %	± 0.8%
T_{PD} influence under noise q=200 pC	T_{PD} range (ns)	T_{PD} error = ± ABS(ε_{TPD})= ± ABS (Max error – Min error) / 2 ABS(ε_{TPD}) ≤ 30% under 35% noise level			
	37.5 t0 150	± 24.1 %	± 2,1 % (*)	± 0.8 %	± 25. 5%
	8 to 150	± 28.7%	Not applicable	± 1.5 %	± 29.8%
Resolution Time under noise q=200 pC	t_{res} range (µs)	PD repetition rate error for decreasing time interval between PD pulses Requirement ≤ 2% under 10% noise level			
	2,500 – 10	10 µs, ε_n=0.0 %	20 µs, ε_n=0.0 %	2.5 ms, ε_n=0.5 %	10 µs,ε_n=0. %

4.1.8. Round Robin (Aug-22 to Jan-23)

Diagnostic Tests

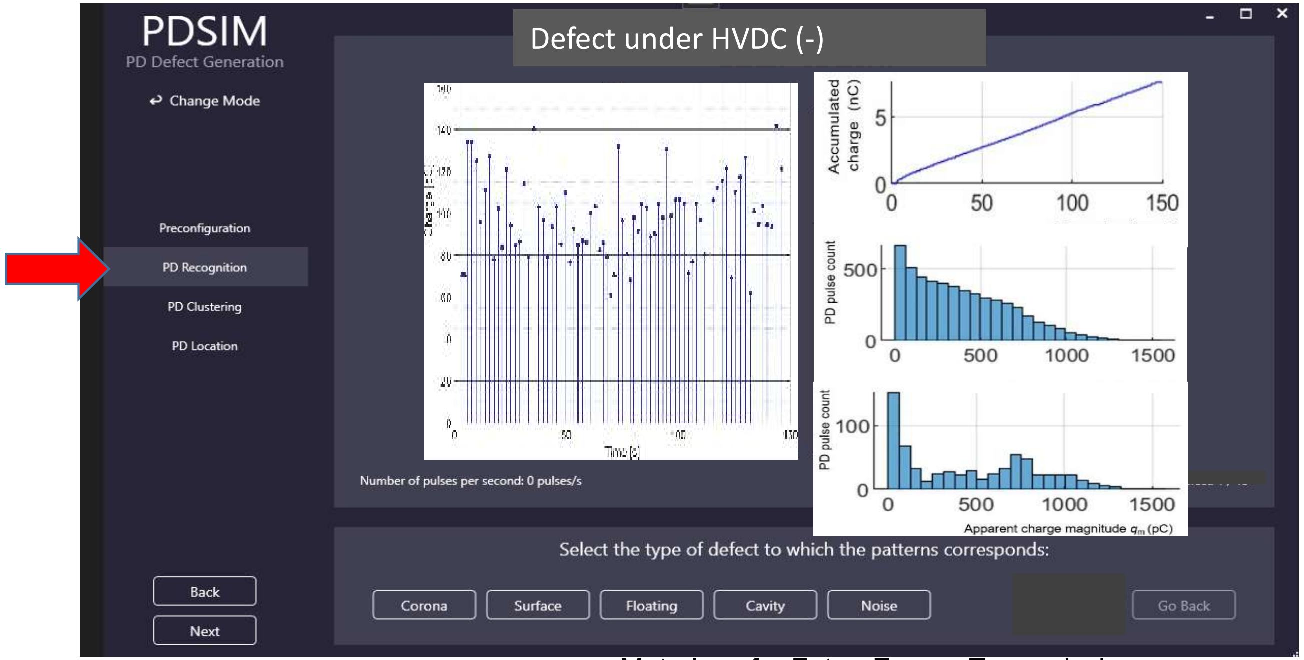
Qualification	IEC 60270	Invariable noise TS IEC 62478	Variable noise TS IEC 62478
A) PD Recognition		Yes	
B) PD Clustering		Yes	
C) PD Location		Yes	

4.1 Validation of the PD procedure for qualifying PD analysers used for DC testing in the 1 - 30 MHz range

A4.1.8 Round Robin Test

A4.1.6. Validation of the Calibration Procedure to qualify PD analysers (Apr 2022 - Jul 2022)

1. PD recognition capability for DC software files :



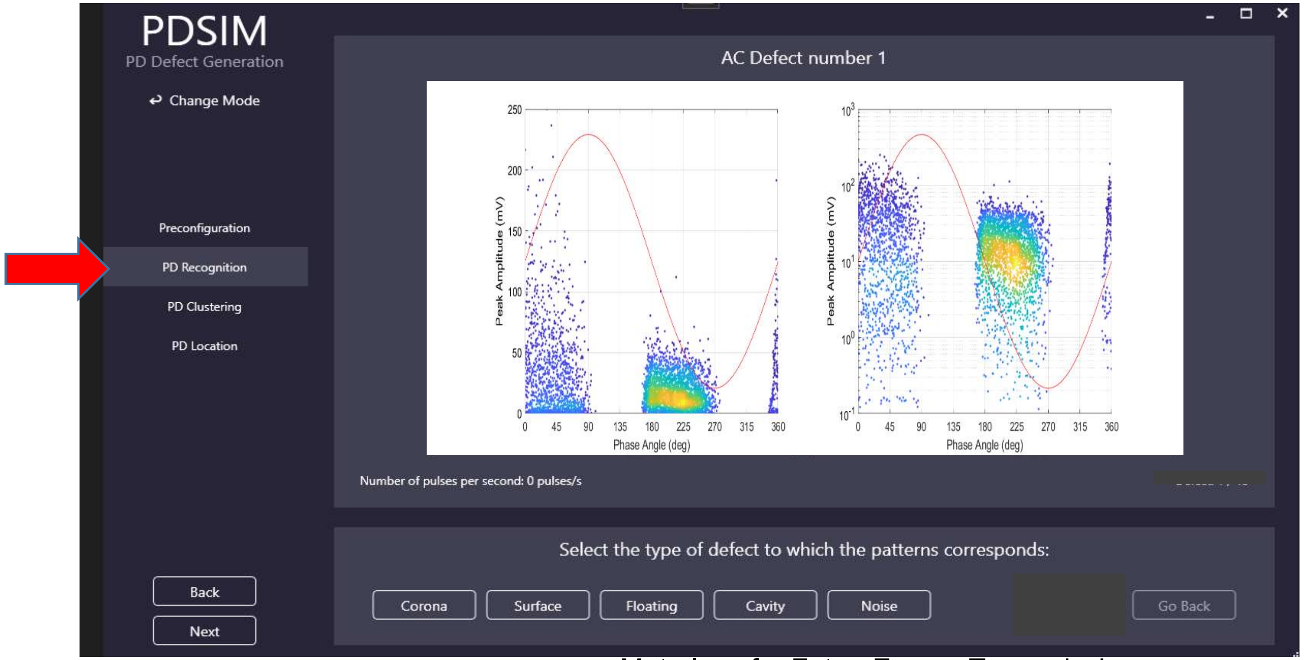
AC:
- **-Corona in air,**
- **-Surface in air,**
- **- Floating Potential in air,**
- **- Cavity in solid,**
- **- Mobile Particles SF6,**
- **- Protussion in SF6,**
- **- Surface in SF6.**

DC:
- **Corona in air,**
- **Surface in air,**
- **Floating Potential in air,**
- **Cavity**
- **Mobile Particles SF6**
- **Protussion in SF6,**
- **Surface in SF6**

4.1 Validaton of the PD procedure for qualifying PD analysers used for DC testing in the 1 - 30 MHz range

A4.1.8 Round Robin Test

A) PD recognition capability for AC and DC (software files):

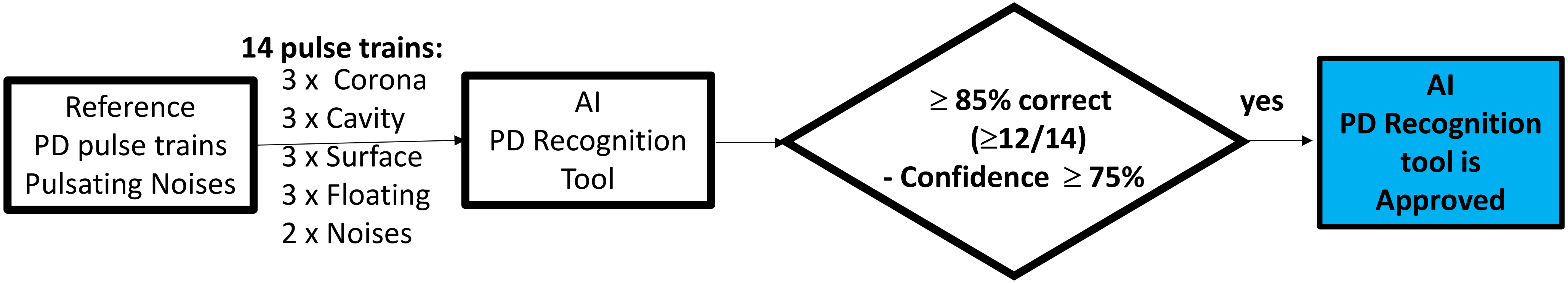


AC:
- -Corona in air,
- -Surface in air,
- Floating Potential in air,
- Cavity in solid,
- Mobile Particles SF6,
- Protussion in SF6,
- Surface in SF6.

DC:
- Corona in air,
- Surface in air,
- Floating Potential in air,
- Cavity
- Mobile Particles SF6
- Protussion in SF6,
- Surface in SF6

4.1.8. Round Robin (Aug-22 to Jan-23)

A- Qualification of PD recognition tools.



Proposed requirement to approve an AI PD Recognition tool

An AI PD recognition tool is considered approved if at least the 85% of reference PD pulse or noise trains are correctly recognised with a confidence level not less than 75%.

4.1.8. Round Robin (Aug-22 to Jan-23)

A- Qualification of PD recognition tools.

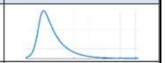
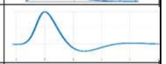
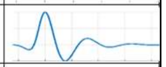
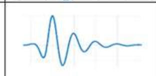
Case	AC			DC (+)			DC (-)		
	Real	AC-R1	AC-R2	Real	DC-R1	DC-R2	Real	DC-R1	DC-R2
1	Cavity	Cavity (98%)	Cavity (91%)	Surface	Cavity (48%)	Surface (100%)	Floating	Floating (84%)	Floating (93%)
2	Corona	Corona(99%)	Corona (99%)	Cavity	Cavity (67%)	Cavity (93%)	Surface	Noise	Surface (94%)
3	Floating	Floating (99%)	Floating (98%)	Corona	Corona (82%)	Noise (89%)	Noise	Noise	Noise (100%)
4	Noise	Floating (46%)	Noise (100%)	Floating	Floating (83%)	Floating (88%)	Corona	Corona (91%)	Corona(100%)
5	Surface	Surface (90%)	Surface (100%)	Cavity	Cavity (83%)	Cavity (86%)	Floating	Floating (84%)	Floating (94%)
6	Floating	Floating (97%)	Floating (84%)	Noise	Noise	Noise (98%)	Cavity	Cavity (65%)	Cavity (99%)
7	Corona	Surface(61%)	Corona(100%)	Surface	Surface (57%)	Surface (80%)	Surface	Noise	Surface (99%)
8	Cavity	Cavity (99%)	Cavity (100%)	Floating	Floating (87%)	Floating (95%)	Cavity	Cavity (83%)	Cavity (99%)
9	Surface	Surface (96%)	Surface (100%)	Corona	Corona (82%)	Corona(88%)	Corona	Corona (78%)	Corona(100%)
10	Cavity	Cavity (99%)	Cavity (100%)	Surface	Cavity (63%)	Surface (100%)	Floating	Floating (78%)	Floating (77%)
11	Noise	Noise (49%)	Noise (100%)	Noise	Noise	Noise (100%)	Cavity	Cavity (67%)	Cavity (99%)
12	Corona	Corona(98%)	Corona(97%)	Cavity	Cavity (68%)	Cavity (96%)	Noise	Noise	Noise (100%)
13	Surface	Cavity (54%)	Surface (100%)	Corona	Corona (78%)	Corona(77%)	Corona	Corona (86%)	Corona(100%)
14	Floating	Floating (100%)	Floating (99%)	Floating	Floating (100%)	Floating (94%)	Surface	Noise	Surface (97%)

4.1.8. Round Robin (Aug-22 to Jan-23)

B) PD Clustering capability (HVAC and HVDC).

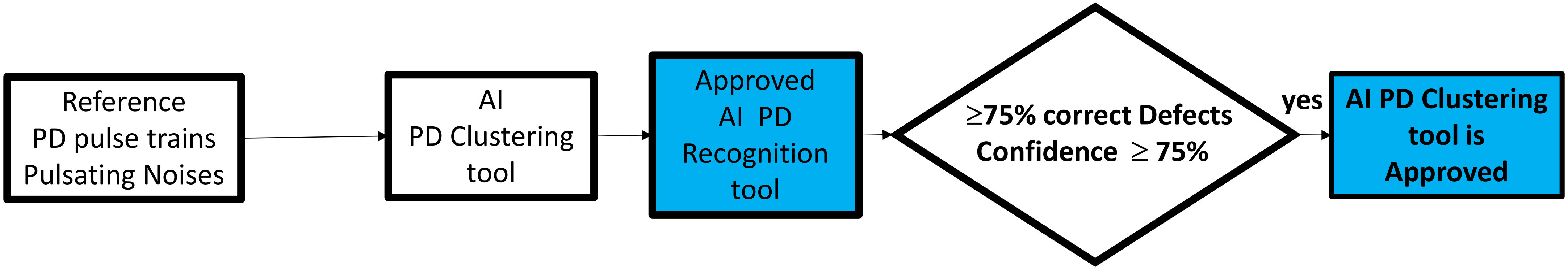
Case#	Corona	Surface	Floating	Cavity	Pulsating Noise #1	Pulsating Noise #2
Case #1 AC	25% Pulse #1	50% Pulse #2			75% Pulse #3	100% Pulse #4
Case #2 AC	25% Pulse #4		50% Pulse #1		100% Pulse #2	75% Pulse #3
Case #3 AC	25% Pulse #3			50% Pulse #4	75% Pulse #1	100% Pulse #2
Case #4 AC	50% Pulse #2	25% Pulse #3			100% Pulse #4	75% Pulse #1
Case #5 AC	50% Pulse #1		25% Pulse #2		75% Pulse #3	100% Pulse #4
Case #6 AC	50% Pulse #4			25% Pulse #1	100% Pulse #2	75% Pulse #3
Case #7 AC		50% Pulse #4	25% Pulse #3		75% Pulse #1	100% Pulse #2
Case #8 AC		50% Pulse #2		25% Pulse #3	100% Pulse #4	75% Pulse #1
Case #9 AC		25% Pulse #1	50% Pulse #2		75% Pulse #3	100% Pulse #4
Case #10 AC		25% Pulse #4		50% Pulse #1	100% Pulse #2	75% Pulse #3
Case #11 AC			50% Pulse #4	25% Pulse #3	75% Pulse #1	100% Pulse #2
Case #12 AC			25% Pulse #3	50% Pulse #2	100% Pulse #4	75% Pulse #1
Case #1 DC +	50% Pulse #1	25% Pulse #2			75% Pulse #3	100% Pulse #4
Case #2 DC -			50% Pulse #1	25% Pulse #2	75% Pulse #3	100% Pulse #4

Qualification Test to separate different PD trains related to different insulation defects or pulsating noises consists of superimposing two trains of PD pulses associated with different insulation defects mixed with two different pulsating noises.
A different dampened sinusoidal waveform is used for each PD pulse train or impulsive noise to emulate each specific traveling wave condition from each PD pulse train or noise signal.

Pulse waveforms#	Double exponential PD pulse T_{PD} (ns)	*F (MHz)*	$f_{c\text{-}3dB}$ *(MHz)*	*Pulse Waveform*
Pulse #1	75	3	12,2	
Pulse #2	75	6	21,7	
Pulse #3	75	12	43,7	
Pulse #4	75	20	93,9	

4.1.8. Round Robin (Aug-22 to Jan-23)

B. Qualification of PD clustering tools.



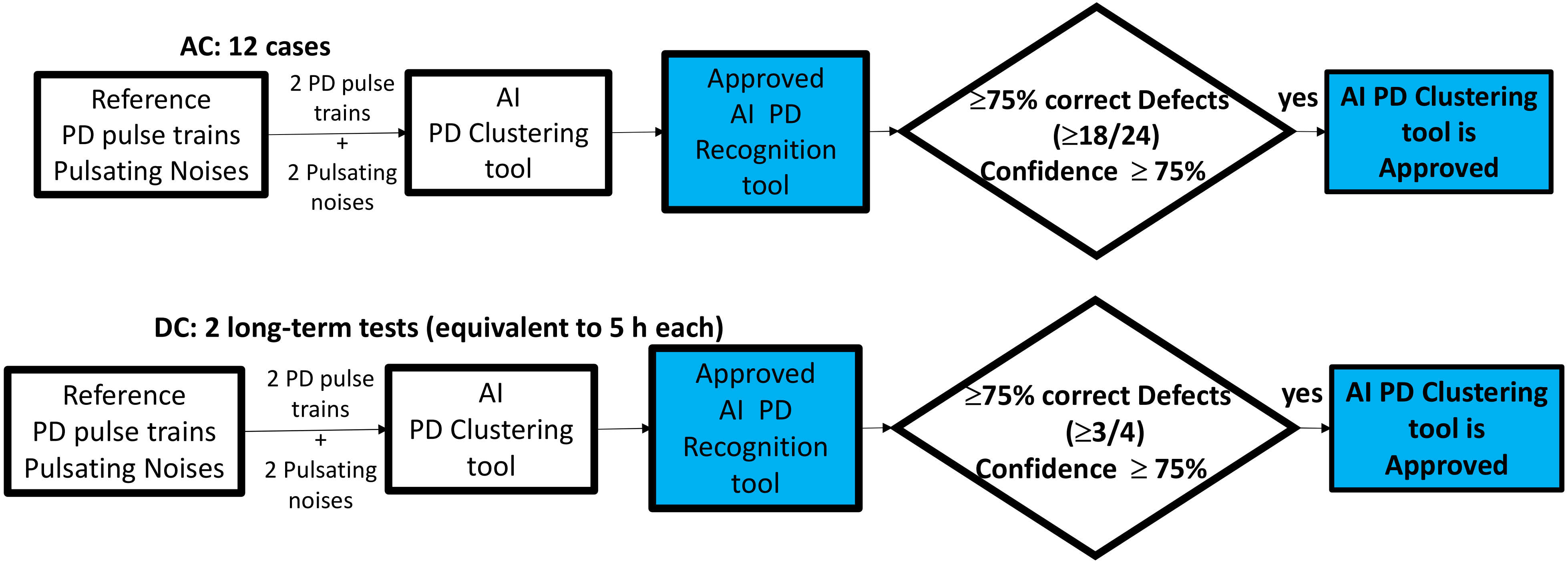
Proposed requirement to approve an AI PD Recognition tool

"A clustering tool is approved if an approved AI recognition tool recognizes at least 75% of actual PD insulation defects (corona, floating, surface and cavity) with a confidence level >75%, after applying the AI automatic clustering tool under validation."

Note: The cavity defect must be recognised with a confidence level ≥ 75%

4.1.8. Round Robin (Aug-22 to Jan-23)

B. Qualification of PD clustering tools.

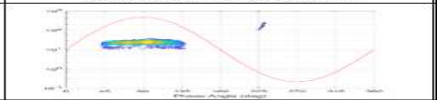
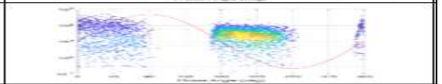
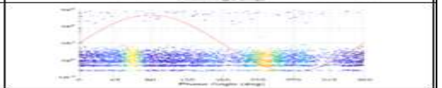
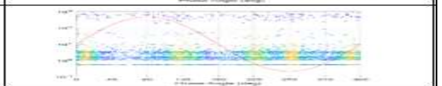
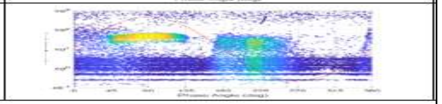


4.1 Validation of the PD procedure for qualifying PD analysers used for DC testing in the 1 - 30 MHz range

A4.1.8 Round Robin Test

B) PD clustering capability [AC]

PD Measurements in HVAC Systems: The Synthetic PD Calibrator will simultaneously generate PD pulses from all four pulse trains: two from real PD defects and the other two from impulsive noise sources. These pulse trains were recorded over a time interval of 2 seconds. This time interval will be played back continuously for an indefinite time.

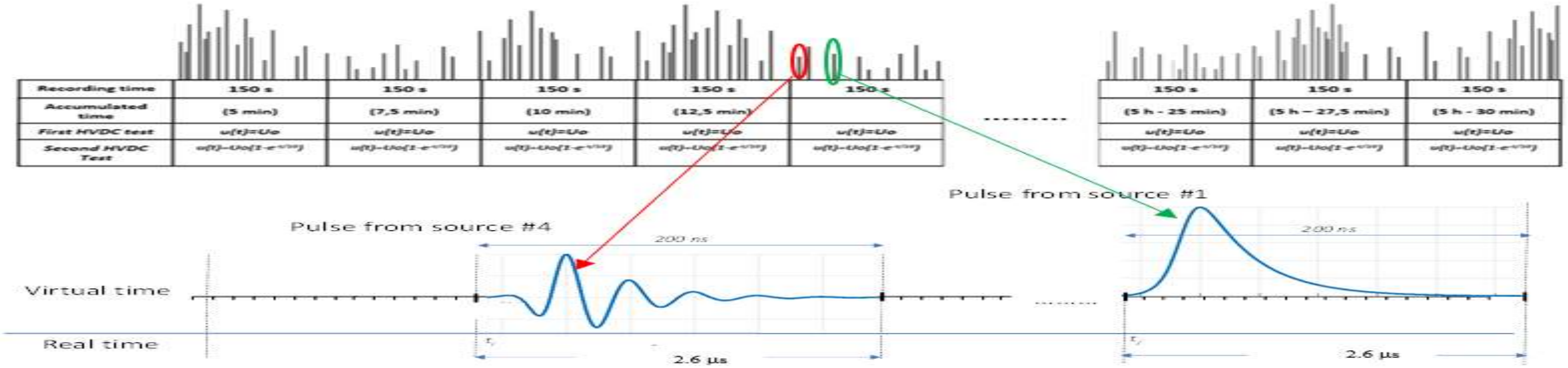
	Time interval played back = 2 seconds (100 periods) PRPD patterns recorded over the time interval of 2 seconds
Defect #1 Corona	
Defect #2 Cavity	
Impulsive Noise #1	
Impulsive Noise #2	
Acummulated pulse signals	

4.1 Validation of the PD procedure for qualifying PD analysers used for DC testing in the 1 - 30 MHz range

A4.1.8 Round Robin Test

B) PD clustering capability [AC]

PD Measurements in HVDC Systems: The Synthetic PD Calibrator simultaneously can generate PD pulses from four stored pulse trains (two from real PD effects and the other two from impulsive noise sources) that were recorded during time intervals of 150 s for 5.0 hours (at least 600 pulses of each pulse train will be generated in the 5.0 hours of high voltage test). When there are no pulse signals, the time will be played back with a time accelerator 15 times faster than the actual recording time, but no time accelerator is applied when pulse signals are present, either from a PD current pulse or from pulsating noise. In this last case, the playback time is equal to the actual recording time, without this causing an increase in the acquisition time, as shown in Figure 19. It means that if 200 ns are booked to play back a pulse (from a PD source or from a pulsating noise source) it spends 4 µs of real time.



4.1.8. Round Robin (Aug-22 to Jan-23)

B. Qualification of PD clustering tools.

Result analysis for HVAC

case	Corona	Floating	Surface	Cavity	Noise #1 / Noise #2
1	-		100,0%		100,0%
2	99,0%	100,0%			100,0%
3	100,0%			100,0%	100,0%
4	-		100,0%		100,0%
5	100,0%	100,0%			99,0%
6	99,0%			98,0%	100,0%
7		100,0%	100,0%		100,0%
8			100,0%	100,0%	100,0%
9		100,0%	100,0%		97,0%
10			100,0%	100,0%	100,0%
11		100,0%		100,0%	95,0%
12		100,0%		100,0%	99,0%

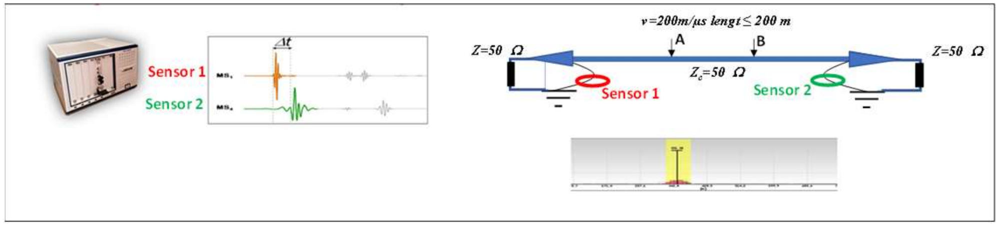
Result analysis for HVDC

Pulse trains	AICT1	AICT2
Corona (+)	93,60%	90,38%
Surface (+)	80,93%	79,33%
Cavity (-)	97,24	98,03%
Floating Potential (-)	89,82%	84,18%
Noise #1 (+)	81,27%	67,66%
Noise #2 (+)	96,48%	70,36%
Noise #1 (-)	100,00%	92,31%
Noise #2 (-)	100,00%	73,08%

4.1.8. Round Robin (Aug-22 to Jan-23)

C. PD Location along a cable

Evaluation of the ability of a PD analyser to determine the location of a PD source along a cable is carried out using the synthetic PD calibrator. A coaxial cable is used as a model of a power cable with three intermediate injections points A, B and C. Both cable ends are matched by means of an impedance with the same value as the characteristic impedance of the coaxial cable (Z_c=50Ω). The coaxial cable has a propagation velocity of 196 m/µs a nominal length of 172 m.



Location error (m)							
D(from T1) (m)		LCOE	TUDELFT	RISE	TAU	UPM
C	24	-1,0	1,0	-0,7	1,1	-1,0
A	92	-0,4	0,0	0,2	1,5	0,0
B	117	0,6	0,0	0,1	1,4	0,3

4.1 Validation of the PD procedure for qualifying PD analysers used for DC testing in the 1 - 30 MHz range

CONCLUSIONS

- **A Synthetic PD Calibrator is available for qualification of PD analysers working in the 1-30 MHz:**
  - **Metrological Tests: Noise rejection test, Linearity, PD pulse width influence test (TPD) and Resolution time.**
  - **Diagnostic Tests: PD Recognition Tests, PD clustering Test, and PD Location Test**
- **A reference database of PD event trains acquired in laboratory tests provides an experimental and traceable reference of insulation defects in HVAC and HVDC to evaluate the efficiency of PD analysers.**
- **A Procedure for qualifying PD analysers (HVDC and HVAC) has been developed.**
- **A Round Robin Test was carried out to validate the developed Procedure for qualifying PD analysers.**
- **Final Version of the Qualification procedure**
- **4 Papers are already written to submit to Open Access Journal.**


THANK YOU VERY MUCH
FFII-LCOE
EMPIR
EURAMET
The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

Activity number	Activity description	Partners (Lead in bold)
A4.2.1 M06	TU Delft will study the electromagnetic waves propagation in their HVDC GIS including attenuation factors in different GIS components and propagation modes. Analysis of typical insulation defects producing partial discharges in GIS and analysis of the PD current pulses, their wave shapes and frequency content will be performed by TU Delft.	**TU Delft**
A4.2.2 M12	Using input from A4.2.1, TU Delft and FFII will develop at least 4 test cells with artificial defects simulating the most common insulation defects in HVDC GIS. TU Delft with support from FFII will record representative PD pulses of four aging defects in HVDC GIS systems: floating electrode, surface discharges, protrusion and jumping particle. For each defect, the amplitude, repetition rate, and pulse trains will be analysed to produce representative PD pattern evolution of typical defect as a function of time. An extensive database containing representative patterns of defects in HVDC GIS will then be created by TU Delft.	**TU Delft**, FFII

A4.2.3 M20	TU Delft will develop an inductive sensor for partial discharge measurements in HVDC GIS capable of measuring in the 30 – 300 MHz range. The sensor will be suitable for installation in existing GIS dielectric windows. The sensor will be able to measure PD pulses discharges in the order of 1 pC for representative defects in GIS.	**TU Delft**
A4.2.4 M24	TU Delft, with support from FFII, will develop a characterisation procedure for the PD sensors in a theoretical frame alongside with the development of a methodology for charge estimation.	**TU Delft**, FFII
A4.2.5 M26	TU Delft will design and develop a testing workbench for calibration of PD sensors from A4.2.3 with an embedded high frequency current probe for reference currents. The workbench will allow the injection of calibrator pulses with frequency content above 300 MHz. The testing workbench will be developed at the High Voltage Laboratory of TU Delft and will have similar dimensions and geometry to a real operational HVDC GIS.	**TU Delft**
A4.2.6 M30	Using input from A4.2.5, FFII and TU Delft will prepare a characterisation setup of a HVDC SF_6 GIS up to 100 kV to install test cells developed in A4.2.2. The validation of the characterisation procedure developed in A4.2.4 will be performed by TU Delft and FFII using at least two different methods (high voltage and low voltage). The low voltage method will use at least one commercial PD calibrator from 1 pC to 1000 pC.	**TU Delft**, FFII
A4.2.7 M33	TU Delft, with support from FFII, will perform the analysis of the two validation methods established in A4.2.6. This includes the uncertainty determination of each method and the influence of noise.	**TU Delft**, FFII
A4.2.8 M36	Using input from A4.2.1-A4.2.7, TU Delft, with support from FFII will draft a paper on a method for PD calibration in d.c. power grids for GIS and send it to the coordinator. Once agreed by the consortium, the coordinator on behalf of TU Delft and FFII will submit the paper to a peer reviewed journal and to EURAMET as **D8**: ‘*Paper on the method for PD calibration in d.c. power grids in a 100 kV HVDC GIS submitted to a peer-reviewed journal*’.	**TU Delft**, FFII

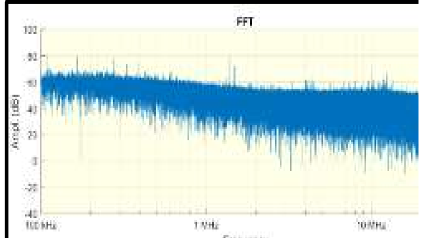
4.1.8. Round Robin (Aug-22 to Jan-23)

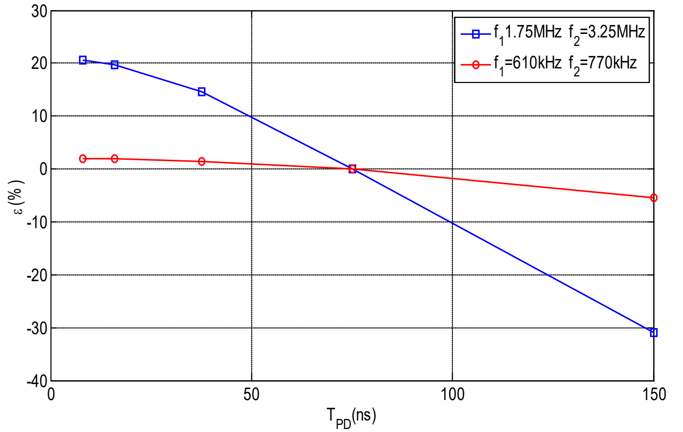
Summary for Noise #2

b) Invariable Noise #2

for On-site PD Measuremer

according to TS IEC 62478





PD Analyser for Sporadic online measurements		PD Analyser B-1	PD Analyser B-2	PD Analyser B-3	PD Analyser B-4
HFCT bandwidth f_1-f_2 (MHz)		0.2- 20	0.08 -61	0.004 – 1,112	0.2 – 20
Charge measurement Method f_1-f_2 (MHz)		Quasi-integration f_1=1.75, f_2= 3.25	Direct reading of HFCT (1)	Integration in time domain	Quasi-integration f_1=2.45, f_2=3.95
Digitizer: Bandwidth		30 MHz ...IS/s)	50 MHz (100 MS/s)	20 MHz (1.25 GS/s)	50 MHz (100 MS/s)
		...nd filter ...ual ...n of f_1, f_2 ...ger level ...f_2= 3.25	4th order Passband filter Butterworth f_1=0.05, f_2= 45 (software)	8th order lowpass filter f_2= 20 (hardware)	Passband filter Manual Selection of f_1, f_2 and trigger level f_1=2.45, f_2= 3.95
		Charge error & PD repetition rate errors v.s. noise level Requirements ...ax ABS(ε_q)≤ 30%, Max ABS(ε_n)≤ 2% under 200% noise level			
		...0 %	ε_q=-0.9 %	ε_q=-36.5%	ε_q=16.4%
		...0 %	ε_n=0.0 %	ε_n=0.7 %	ε_n=-0,0%
		...2 %	ε_q=-0.4 %	ε_q=13.0%	ε_q=8.1%
		...0 %	ε_n=0.0 %	ε_n=0.7 %	ε_n=-0,0%
		...,9%	ε_q=-0.2 %	ε_q=10.4%	ε_q=3.3%
		...0 %	ε_n=0.0 %	ε_n=0.7 %	ε_n=-0,0%
		...2 %	ε_q=-0.1 %	ε_q=1.7%	ε_q=1,0 %
		...0 %	ε_n=0.0%	ε_n=0.7%	ε_n=-0,0%
Linearity under 35% noise	**Charge range (pC)**	**Linearity error = (Max error – Min error) / 2 Requirement ≤ 5% under 35% noise level**			
	50 to 2,400	±0.3 %	±0.6%	±13,2 %	±3,6 %
	10 to 2,400	±0.6 %	±12.7%	±14,0 %	±4,1 %
T_{PD} influence under 35% noise q=200 pC	**T_{PD} range (ns)**	**T_{PD} error = (Max error – Min error) / 2 Requirement ≤ 30% under 35% noise level**			
	37.5 - 150	±25.1 %	±1.9 % (*)	±2.8 %	±25.4 %
	8 to 150	±29.1%	Not applicable (**)	±4.0 %	±29.6%
Resolution Time under 35% noise q=200 pC	**t_{res} range (µs)**	**PD repetition rate error for decreasing time interval between PD pulses Requirement ≤ 2% under 35% noise level, at least t_{res} = 20 µs**			
	2,500 – 10	10 µs, ε_n=-0.4 %	20 µs, ε_n=0.0 %	2.5 ms, ε_n=0.0 %	10 µs, ε_n=0.0 %

4.1.8. Round Robin (Aug-22 to Jan-23)

B) PD Clustering capability (DC).


LCOE

ROUND ROBIN TEST

PROCEDURE FOR THE QUALIFICATION OF PD ANALYSERS WORKING IN THE HIGH FREQUENCY RANGE (0.1- 30 MHz)

USED TO ANALYZE THE INSULATION CONDITION OF HV DC AND AC CABLE SYSTEMS.