The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

IT4PQ

Instrument Transformers for Power Quality

INRiM

ISTITUTO NAZIONALE DI RICERCA METROLOGICA

www.inrim.it

Inductive VTs: a comparative analysis of performances under PQ disturbances

IT4PQ - Final workshop
Torino, June 22nd, 2023, Istituto Nazionale di Ricerca Metrologica (INRIM)

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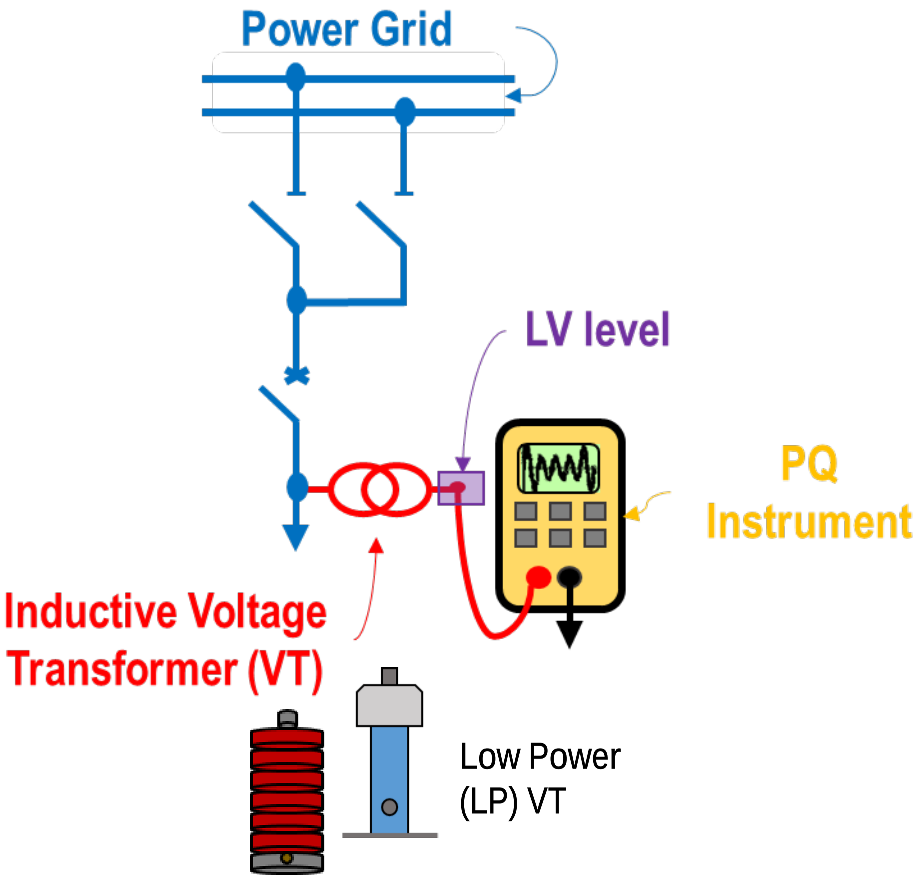
Content overview

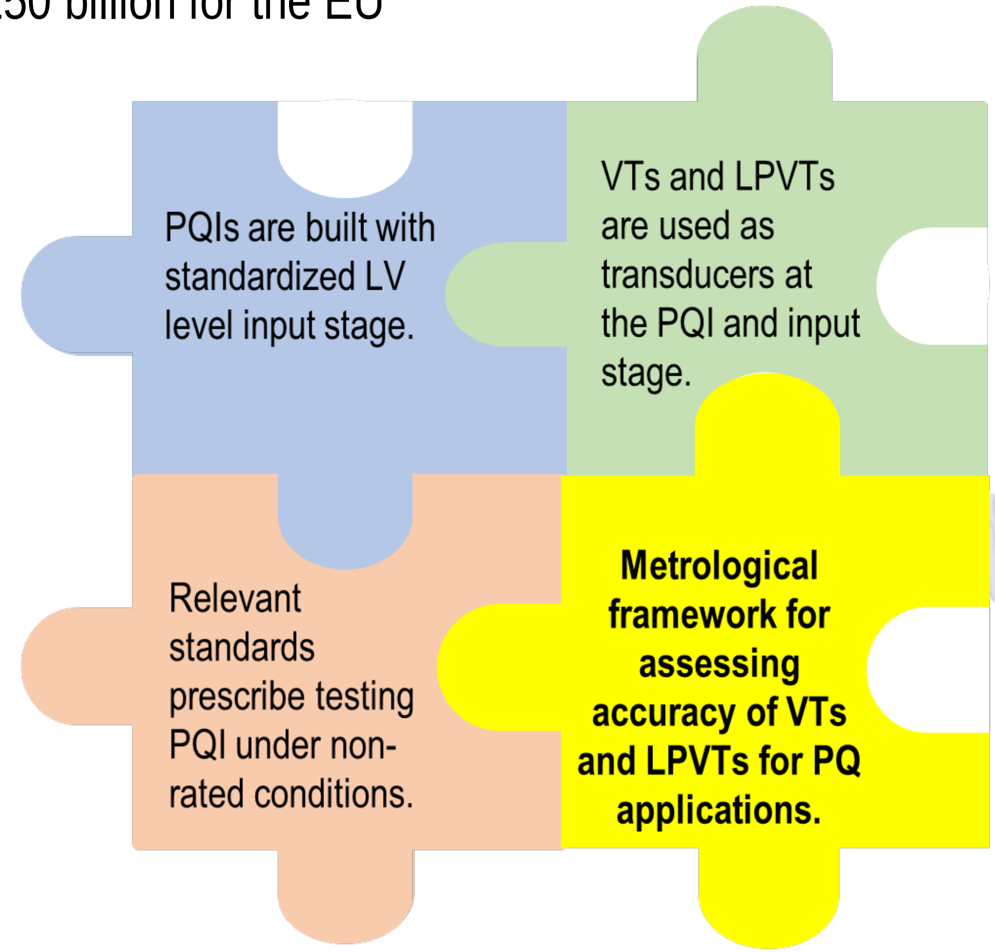
1. Background and motivation
2. Reference system for VTs laboratory calibration
3. Experimental tests - Comparative analysis
4. Discussion of results and conclusion

IT4PQ Project: Trigger and motivation

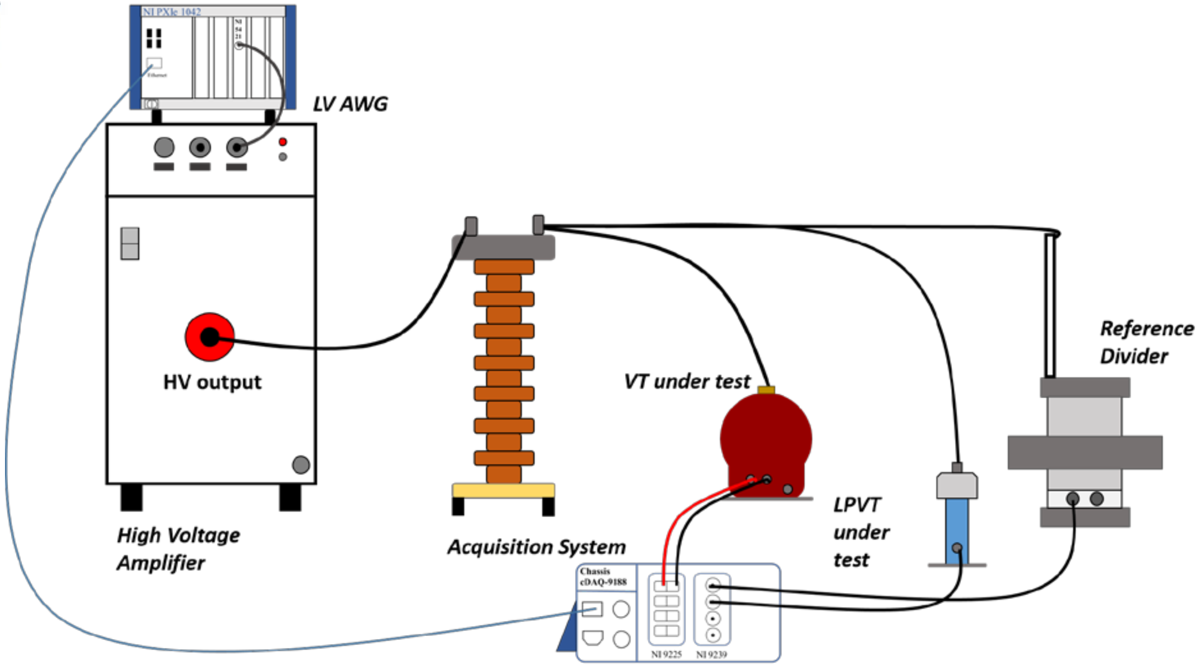
Need to monitor the **Power Quality (PQ) at Medium Voltage**

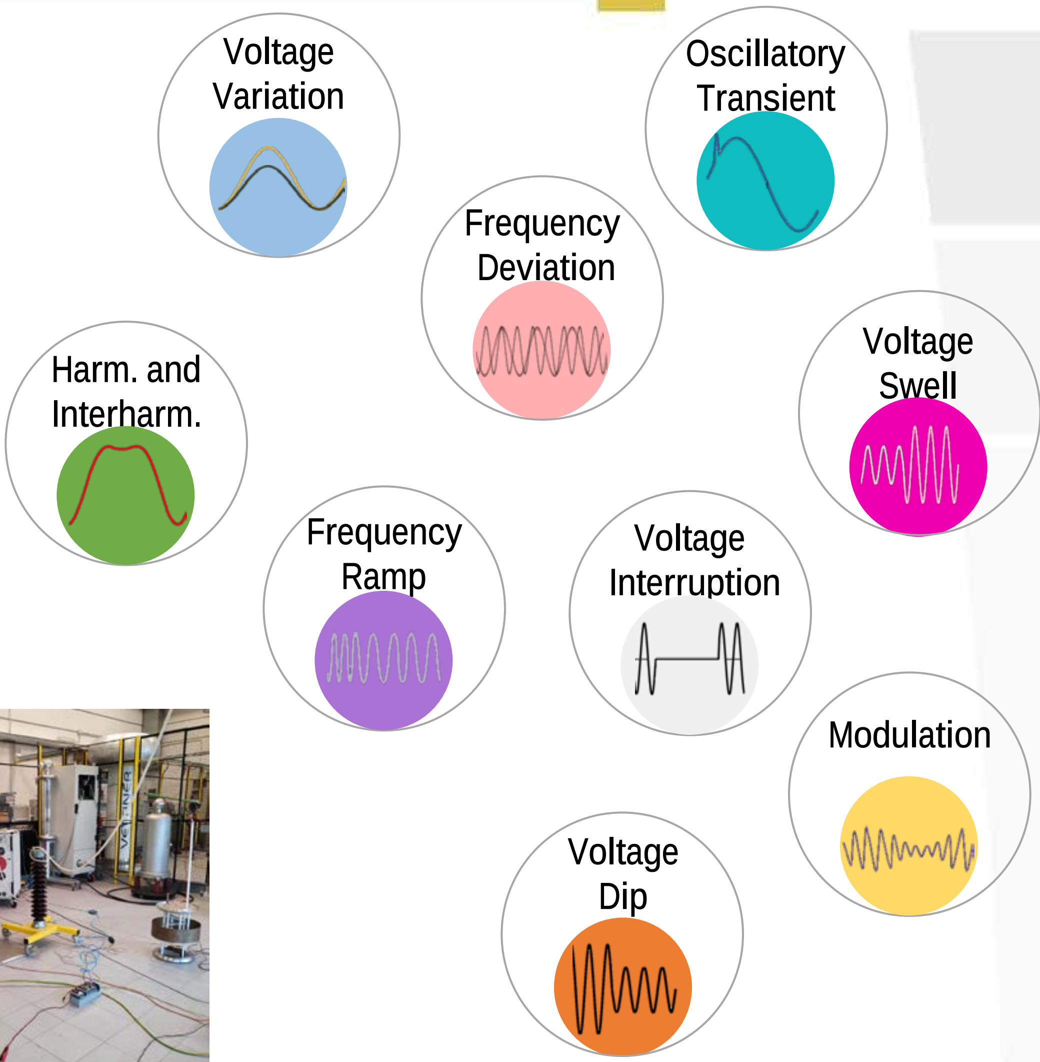
$\Rightarrow$ estimated annual cost for poor PQ equal to €150 billion for the EU





Reference generation and measurement system





MV test waveform generation:

- NI AWG 5422, 16 bit, ± 12 V, 200 MHz.
- High-voltage power amplifier ± 30 kV_{pk}, ± 20 mA from DC to 2.5 kHz at full voltage and to 30 kHz at reduced voltages.

Measurement system:

- Reference sensor: 30 kV wideband resistive-capacitive voltage divider designed, built, and characterized at INRIM.
- Comparator includes NI DAQ with various modules (from ± 0.5 V to ± 425 V).

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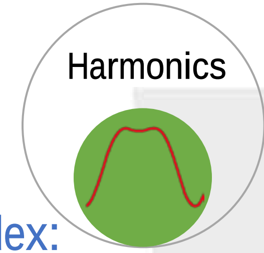
Experimental tests - PQ Phenomena



Stationary - FH1: $v_{\mathbf{FH1}}(t) = \sqrt{2}U_\mathrm{n}\sin(2\pi f t) + \sqrt{2}U_\mathrm{h}\sin(2\pi h f t + \Delta\varphi_h)$

Low order harmonics:

- U_n and f at rated amplitude and frequency
- U_h equal to 1 % of U_n
- h from 2 to 9
- $\Delta\varphi_h$ 9 point in [-π, π]

Harmonics:

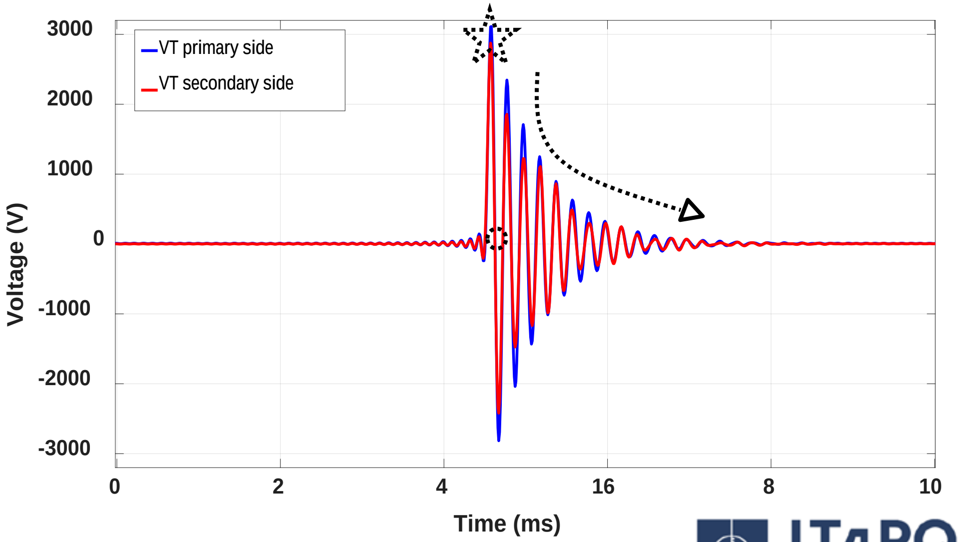
- U_n and f at rated amplitude and frequency
- U_h equal to 1 % of U_n
- h from 10 to 180 (9 kHz)
- $\Delta\varphi_h$ equal to 0 mrad

PQ performance index:

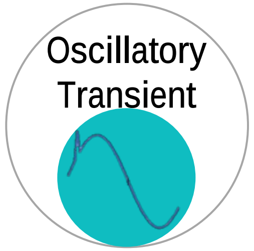
- $\varepsilon_{h,100} = 100\cdot\frac{k_\mathrm{r}\,U_{\mathrm{s},h} - U_{\mathrm{p},h}}{U_{\mathrm{p},h}}$

Transient - OT: $v_{\mathbf{OT}}(t) = \sqrt{2}U_\mathrm{n}\,sin(2\pi f t) + \sqrt{2}U_\mathrm{OT}\,sin(2\pi f_\mathrm{OT} t + \varphi_\mathrm{OT})\cdot e^{-t/\tau}$

- U_n and f at rated amplitude and frequency
- f_OT = from 500 Hz to 7 kHz, τ=600 µs, φ_OT=0 rad
- U_OT =22 % of U_n ,



PQ performance index:



- $\varepsilon_{\mathrm{pk},\%} = 100\cdot(U_{\mathrm{pk,s}} / U_{\mathrm{pk,p}} - 1)$
- $\Delta t_{\text{zero-crossing}}$
- $\varepsilon_\tau = 100\cdot(\tau_\mathrm{s} / \tau_\mathrm{p} - 1)$

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Devices under test

VT	Primary Voltage (kV)	Accuracy Class	Manufacturer	Application (indoor - outdoor)
VT1	**20/√3** kV	0.5	S	indoor
VT2	**20/√3** kV	0.2	S	indoor
VT3	**20/√3** kV	0.5	F	indoor
VT4	**20/√3** kV	0.5	S	outdoor
VT5	**30/√3** kV	0.5	S	indoor
VT6	**11/√3** kV	0.5	F	indoor
VT7	**11/√3** kV	0.5	C	indoor

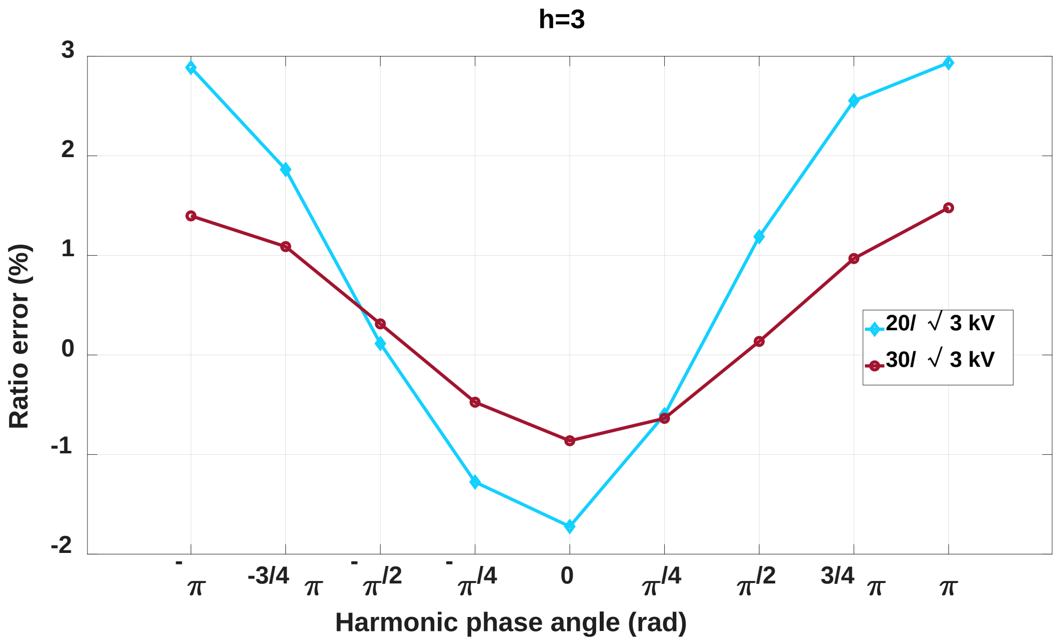
<u>Example of comparative analysis</u>

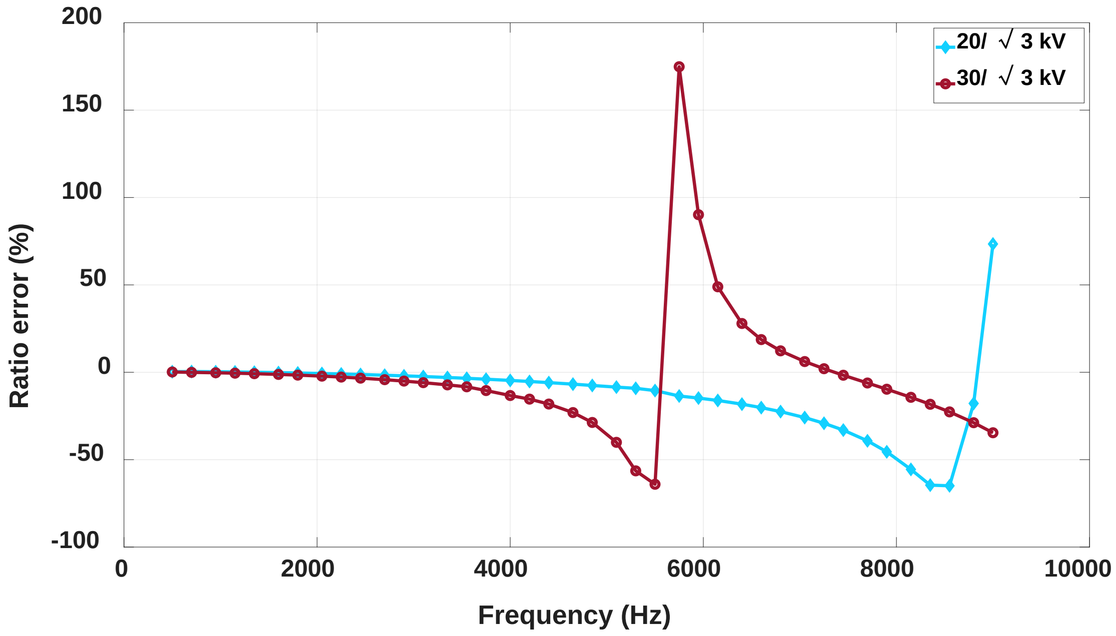
- VT1 vs VT5 and VT3 vs VT6 → Rated primary voltage
- VT1 vs VT3 and VT6 vs VT1 → Manufacturer
- VT1 vs VT2 → Accuracy class
- VT1 vs VT4 → Application

Experimental tests: FH1 ⇒ Rated primary voltage

Results

VT1	20/√3 kV	0.5	S	indoor
VT5	30/√3 kV	0.5	S	indoor





- Increasing the voltage decreases the useful bandwidth (→ known in scientific literature)
- Increasing the voltage decreases the low-order harmonic error

→ Same findings from comparison of VT3 (20/√3 kV) with VT6 (11/√3 kV) harmonic responses.

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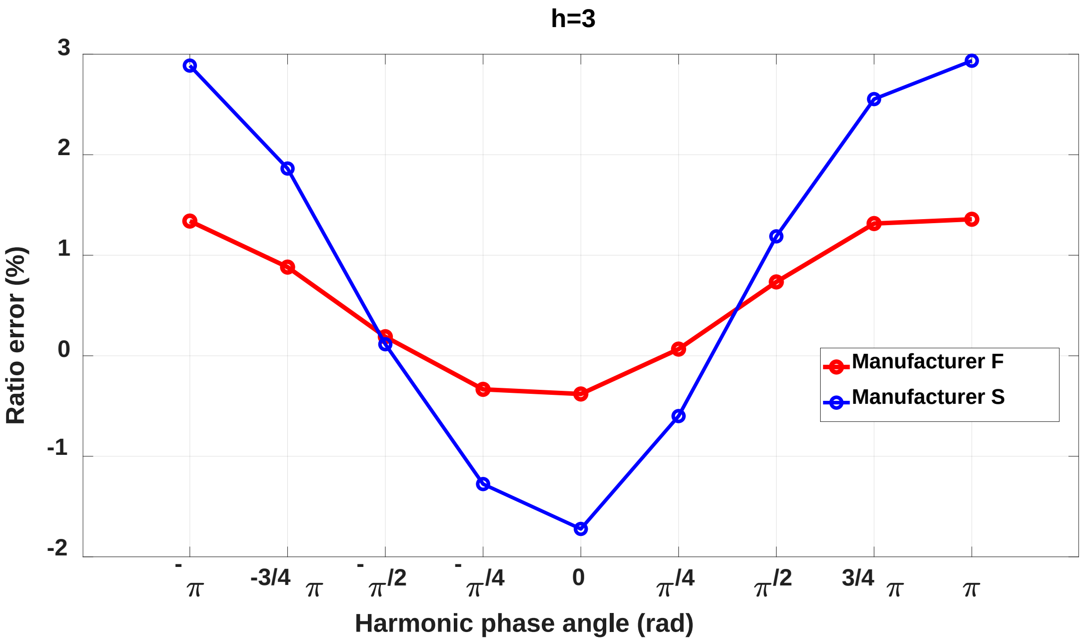
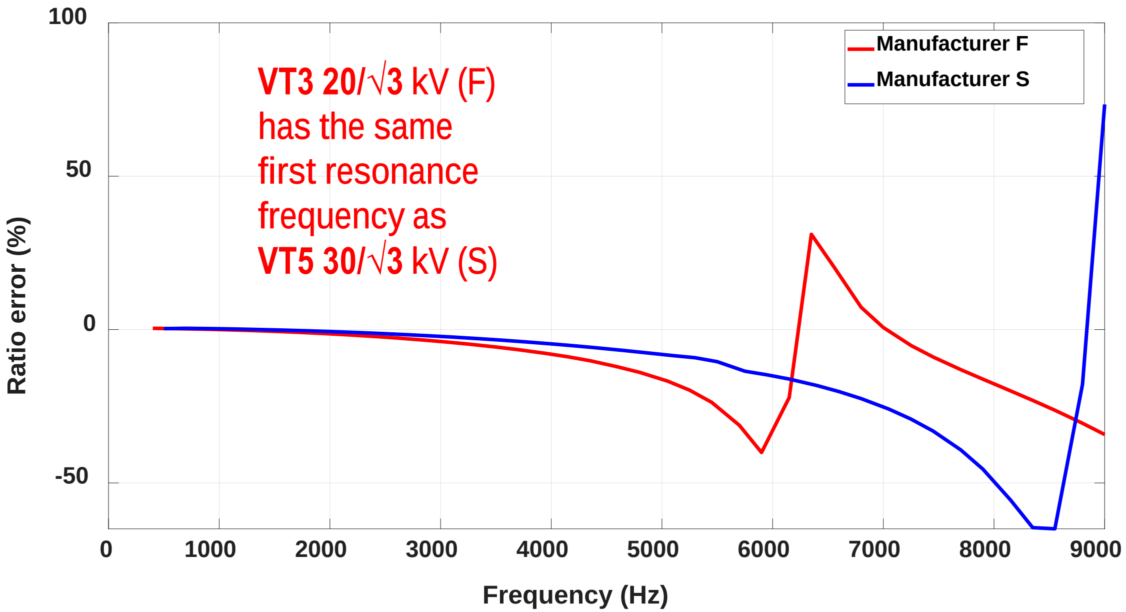
Experimental tests: FH1 ⇒ Manufacturer (1/2)

Results

VT1	**20/√3** kV	0.5	S	indoor
VT3	**20/√3** kV	0.5	F	indoor

(➡ 20 kg / 32 kg)





Events	Frequency (Hz)	
	VT1	VT3
First resonance	~8100	~6000
Ratio error >5 %	4100	3000
Ratio error >10 %	5400	4100
Ratio error >20 %	6500	4600

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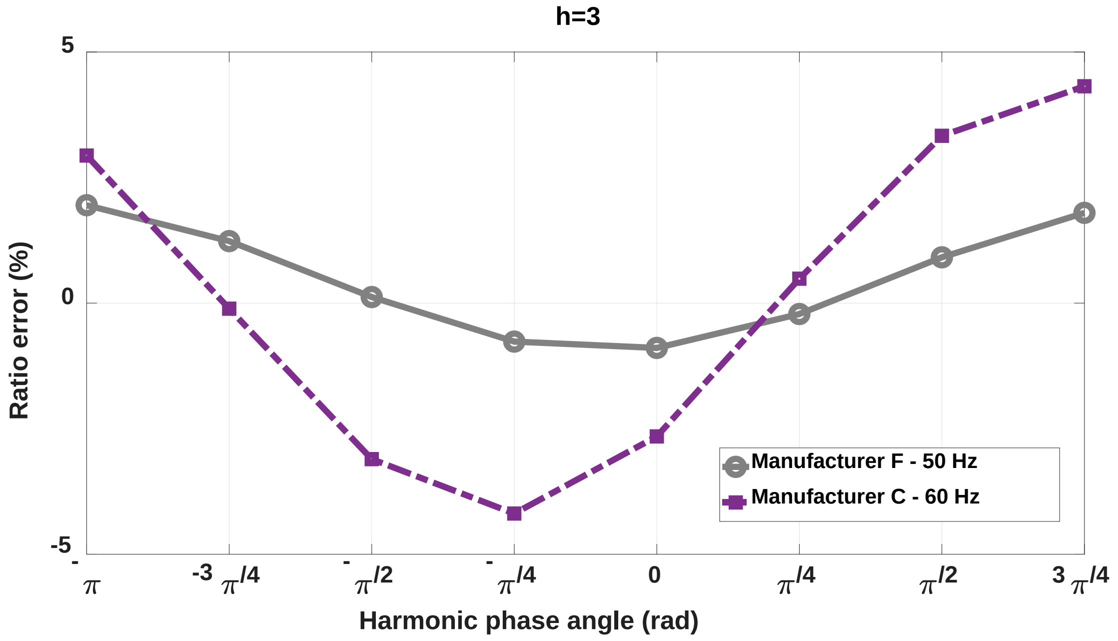
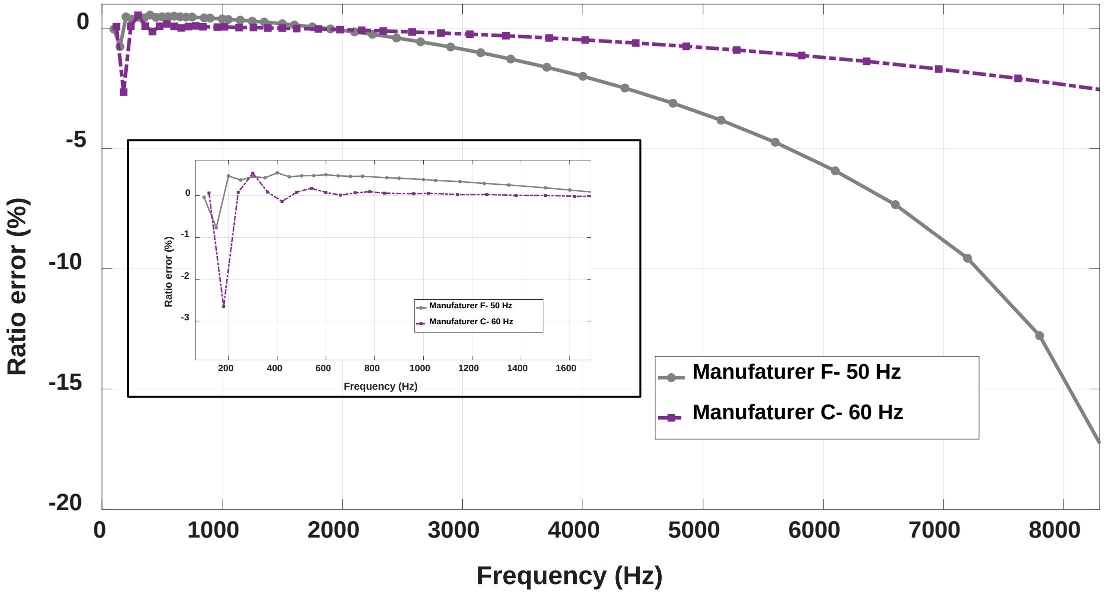
Experimental tests: FH1 ⇒ Manufacturer (2/2)

Results

VT6	**11/√3** kV	0.5	F	indoor	50 Hz
VT7	**11/√3** kV	0.5	C	indoor	60 Hz





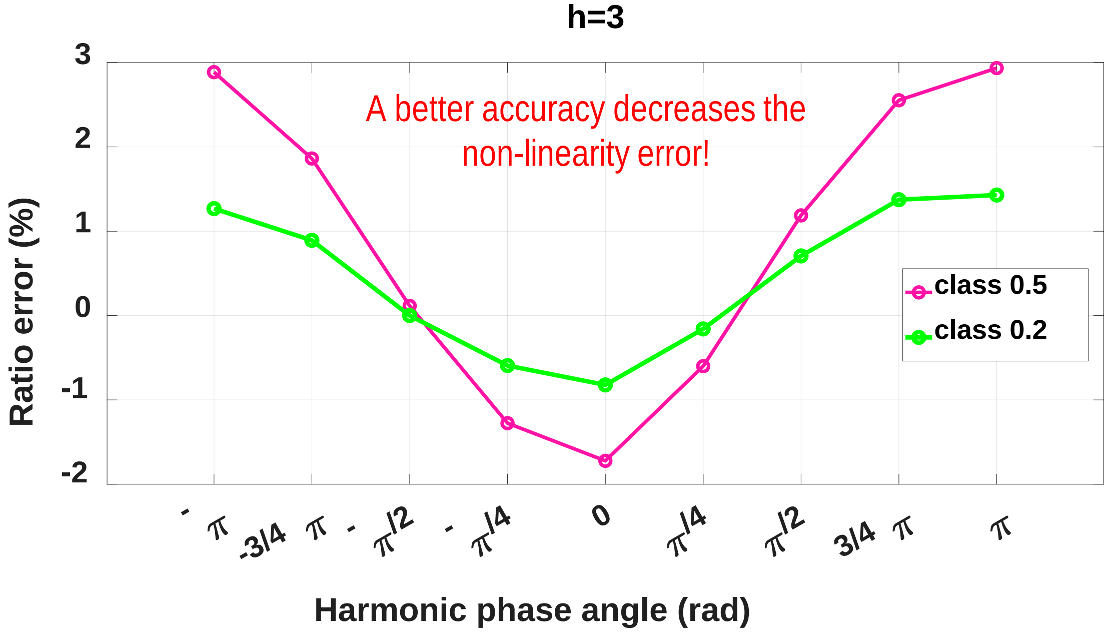
Both cases:

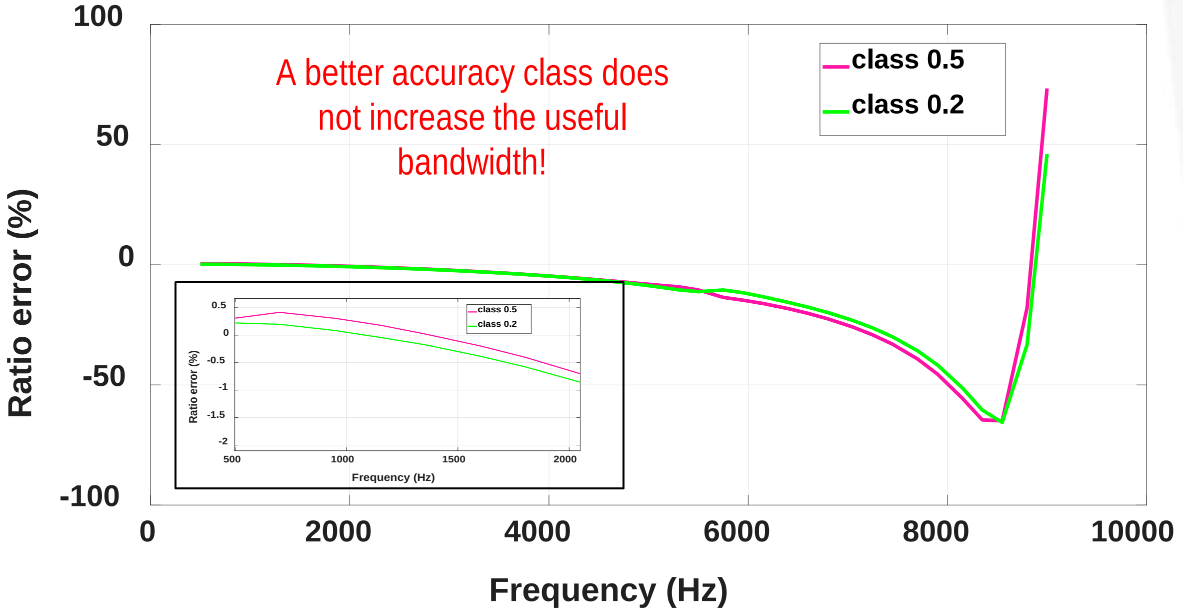
The higher the errors at low-order harmonics, the higher the first resonance frequency.

Experimental tests: FH1 ⇒ Accuracy class

Results

VT1	20/√3 kV	0.5	S	indoor
VT2	20/√3 kV	0.2	S	indoor





Events	Frequency (Hz)	
	VT1	VT2
First resonance	~8100	~8500
Ratio error >5 %	4100	4100
Ratio error >10 %	5400	5250
Ratio error >20 %	6500	6800

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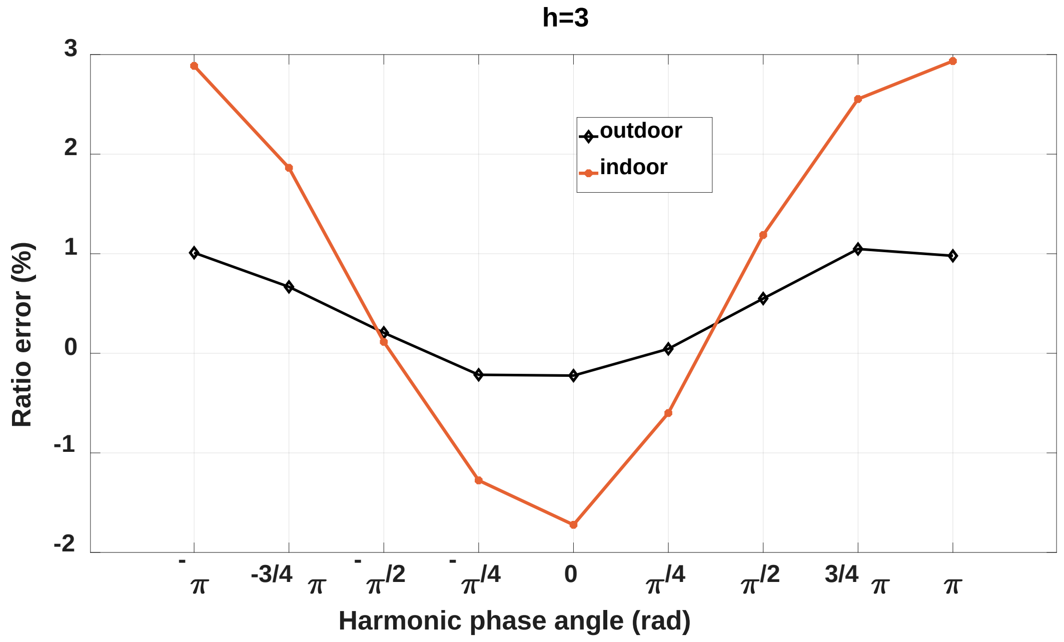
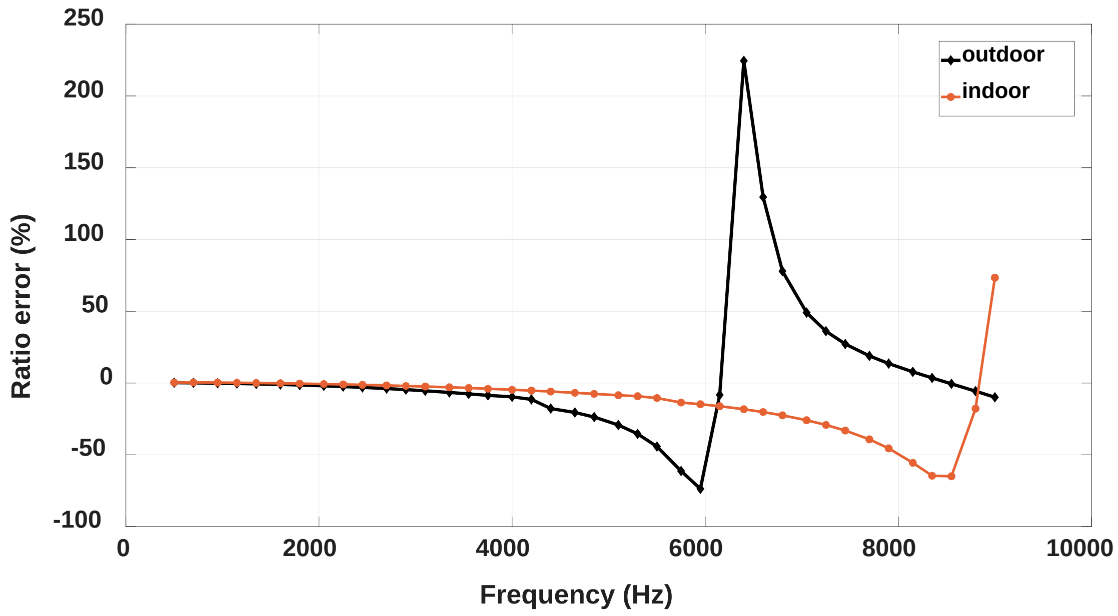
Experimental tests: FH1 ⇒ Application indoor and outdoor

Results

VT1	**20/√3** kV	0.5	S	indoor
VT4	**20/√3** kV	0.5	S	outdoor

⇒ Insulation:
- epoxy resin
- silicon





Events	Frequency (Hz)	
	VT1	VT4
First resonance	~8100	~6000
Ratio error >5 %	4100	3000
Ratio error >10 %	5400	4100
Ratio error >20 %	6500	4600

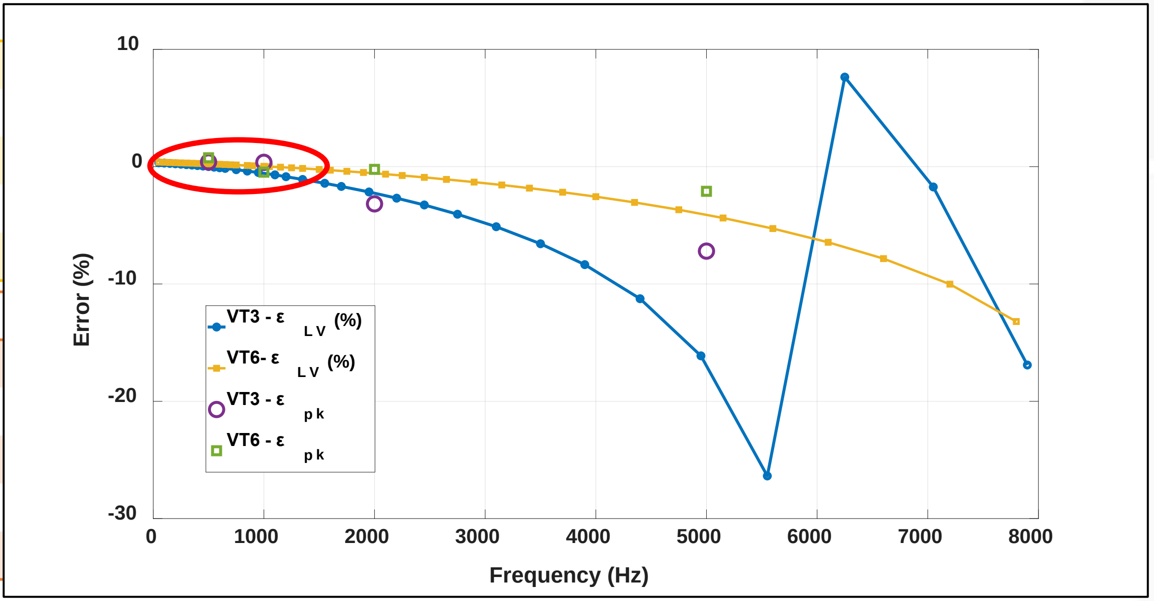
Experimental tests: Oscillatory Transient

Results

VT3	20/√3 kV	0.5	F	indoor
VT6	11/√3 kV	0.5	F	indoor

VT3			
Frequency (Hz)	ε_{pk} (%)	$\Delta t_{zero\text{-}crossing}$ (ms)	ε_T (%)
500	0.40	0.01	-0.36
1000	0.37	0	0.49
2000	-3.17	0	-1.01
5000	-7.20	-0.01	4.52

VT6			
Frequency (Hz)	ε_{pk} (%)	$\Delta t_{zero\text{-}crossing}$ (ms)	ε_T (%)
500	0.76	0	-0.29
1000	-0.47	0	0.03
2000	-0.23	0	0.02
5000	-2.1	0	2.36



Correlation between the frequency responses of the VTs and the errors they introduce in the measurement of the OTs.

→ VT3 and VT6 exhibit similar behavior in the first frequency band (up to 1 kHz) and in this range the ε_{pk} values are similar.

→ As the frequency increases, the frequency responses of VT3 and VT6 start to diverge, and consequently, the ε_{pk} values also change.

Discussion of results and conclusion

- ✓ From all the performed experimental tests, it is found that **the higher the first resonance frequency the higher the non-linearity effects.**
- ✓ Considering VTs from the same **manufacturer**, it is possible to assume the frequency response as a function of primary voltage.
- ✓ Two VTs with the same **primary voltage** from different manufacturers can exhibit a very different frequency behavior.
- ✓ Improving the **accuracy class** does not increase the useful bandwidth but reduces the error associated with the measurement of the first harmonics (reduces the non-linearity effect).
- ✓ There is a strong correlation between the errors introduced by the VT in the measurement of oscillatory transient and their frequency response.

Characteristics	*Impact on useful bandwidth (first resonance frequency)*	
	Low	*High*
Primary voltage		X
Manufacturer		X
Accuracy class	X	
Application indoor-outdoor		X

EMPIR EURAMET

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

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