IT4PQ Final Workshop

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

Definition of framework test conditions and metrics

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Instrument Transformers for Power Quality

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Main objective

Acuracy specifications of PQ instruments (or PMUs)

They should be consistent!

Accuracy specification of ITs used for PQ Measurements

Content

- Basic time frame for the evaluation of Performance Indexes

Basic test waveforms

IEC 61000-4-30
IEC 61000-4-7
IEC 61869

Sinusoidal waveform

$$s_1(t) = A_1\sqrt{2}\sin(2\pi f_1 t)$$

FFT over 10 – cycles of fundamental

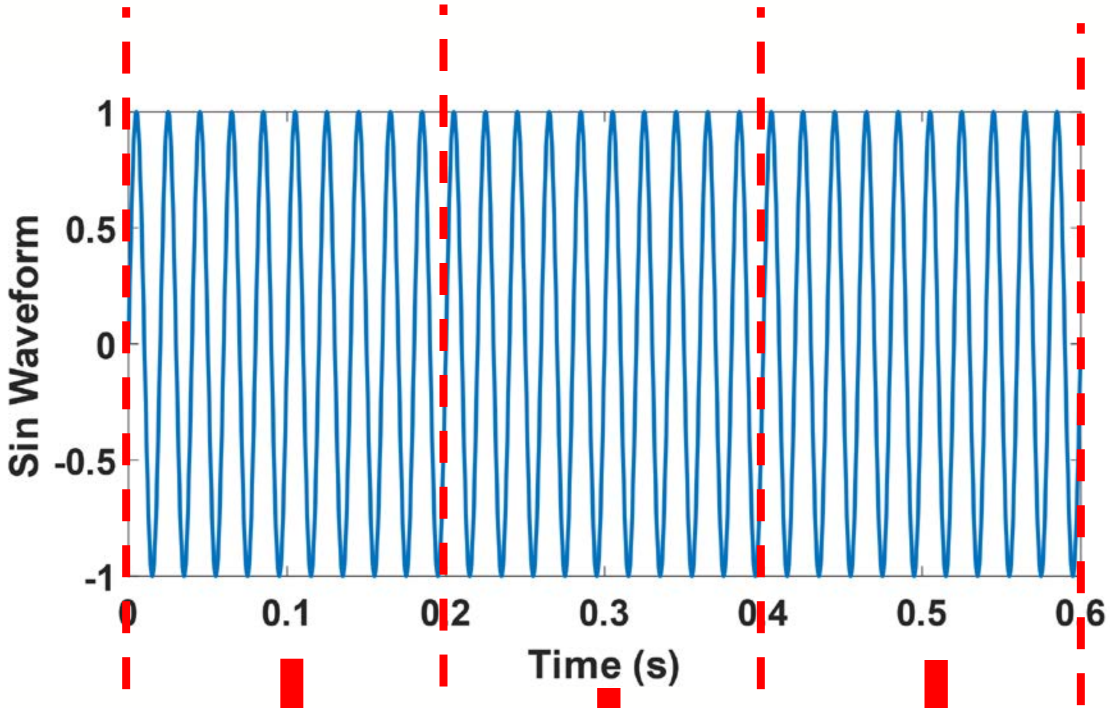
200 ms for 50Hz Power System

$$\varepsilon_{50Hz} = \frac{k_r V_s - V_p}{V_p}$$

Ratio Error

$$\Delta\varphi_{50Hz} = \varphi_s - \varphi_p$$

Phase Error



$\varepsilon_{1,50Hz}$
$\Delta\varphi_{1,50Hz}$

$\varepsilon_{2,50Hz}$
$\Delta\varphi_{2,50Hz}$

$\varepsilon_{3,50Hz}$
$\Delta\varphi_{3,50Hz}$

Accuracy Class of ITs

Possible choice of Basic Time Frame

- In the PQ Accuracy Tests of ITs, the basic time frame for the evaluation of Performance Indexes can be

200 ms

or

10 cycles of the fundamental component

Content

- Basic time frame for the evaluation of Performance Indexes
- Selected PQ phenomena and related ranges

Selected PQ phenomena and related ranges

PQ Phenomenon	Limits
Frequency deviation	±15% of rated frequency
Supply voltage and current deviation	From 5% up to 200% of amplitude rated voltage From 1% up to 200% of amplitude rated current
Harmonic voltage	10% from 2nd up to 15th—5% from 16th up to 50th 2% from 51th up to 9 kHz
Interharmonic voltage	3% from DC up to 20 Hz—5% from 20 Hz up to 100 Hz 1% from 100 Hz up to 9 kHz
Amplitude and phase modulation	Frequency modulating from 0.1 Hz up to 5 Hz—K_x = 0.1% Frequency modulating from 0.1 Hz up to 5 Hz—K_a = 0.1 rad
Oscillatory Transient	Up to 5 kHz, up to 22% of rated amplitude

Content

- Basic time frame for the evaluation of Performance Indexes
- Selected PQ phenomena and related ranges
- Possible choices of Performance Indices

Performance indexes for subharmonic measurements

IEC 61000-4-7 General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto

$$\varepsilon_{g} = \frac{k_r Y_{s,g} - Y_{p,g}}{Y_{p,g}}$$

Ratio Error
Of Grouping Frequency

Y_{g} the RMS of a grouping frequency

$$\varepsilon_{f\_sub} = \frac{k_r Y_{s,f\_sub} - Y_{p,f\_sub}}{Y_{p,f\_sub}}$$

Ratio Error
of subharmonic frequency

PIs for **Steady State** PQ phenomena

- Accuracy at a specific frequency **tone**

$$\varepsilon(\bar{f}) = \frac{k_r\, U_s(\bar{f}) - U_p(\bar{f})}{U_p(\bar{f})}$$

$$\Delta\varphi(\bar{f}) = \varphi_s(\bar{f}) - \varphi_p(\bar{f})$$

- Accuracy in a specific frequency **range**

$$TFrD_p = \frac{\sqrt{\sum_{f=f_1}^{f_N} U_p^2(f)}}{U_p(f_{rated})}$$

$$TFrD_s = \frac{\sqrt{\sum_{f=f_1}^{f_N} U_s^2(f)}}{U_s(f_{rated})}$$

$$\varepsilon_{TFrD} = \frac{TFrD_s - TFrD_p}{TFrD_p}$$

Accuracy for a specific **distortion index**

$$\Delta\mathrm{THD} = THD_s - THD_p$$

PIs for **Dynamic** PQ phenomena

$$\varepsilon = 100 \cdot \frac{k_r|\boldsymbol{V_s}| - |\boldsymbol{V_p}|}{|\boldsymbol{V_p}|}$$

$$\Delta\varphi = \measuredangle \boldsymbol{V_s} - \measuredangle \boldsymbol{V_p}$$

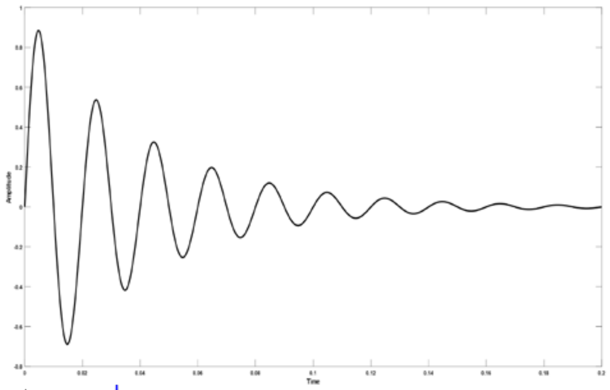
$$TVE = \sqrt{\frac{\left(Re(k_r\boldsymbol{V_s}) - Re(\boldsymbol{V_p})\right)^2 + \left(Im(k_r\boldsymbol{V_s}) - Im(\boldsymbol{V_p})\right)^2}{Re(\boldsymbol{V_p})^2 + Im(\boldsymbol{V_p})^2}}$$

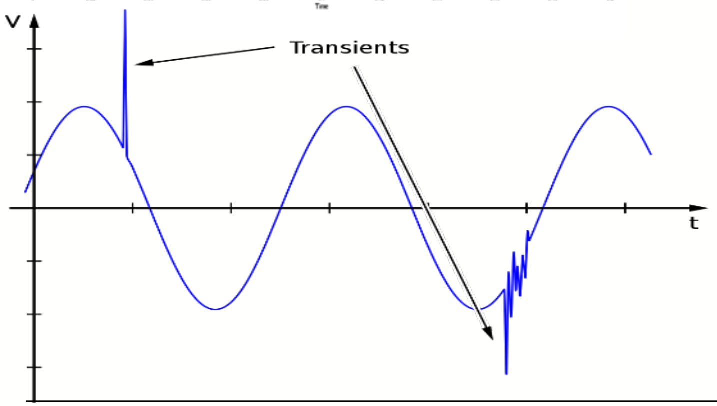
$$FE = f_{0,s} - f_{0,p}$$

$$RFE = \frac{df_{0,s}}{dt} - \frac{df_{0,m}}{dt} = ROCOF_s - ROCOF_p$$

PIs for **Transient** PQ phenomena

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





- The change in first peak magnitude value $U_{pk} = \sqrt{2} U_{OT}$

$$\varepsilon_{Upk} = 100 \cdot \left(\frac{U_{pk,s} - U_{pk,p}}{U_{pk,p}} - 1 \right)$$

- Oscillation frequency f_{OT} of the damped sine wave.
- Phase displacement (or time shift) of the damped sine wave.
- Decay time τ of the oscillation.

These parameters can be analyzed in the time domain after filtering the 50 Hz component by fitting the damped sinusoid

Summary of possible PIs

Test Category	Test Type	Quantity to Measure	Performance Index
Steady State	Amplitude and Frequency Variation	Amplitude	Ration error $\varepsilon\left(\overline{f}\right)$
		Phase	Phase error $\Delta\varphi\left(\overline{f}\right)$
	Harmonics and Interarmonics	Amplitude	Ratio error $\varepsilon\left(\overline{f}\right)$
		Phase	Phase error $\Delta\varphi\left(\overline{f}\right)$
		Total Distortion	Total frequency error ε_{TFrD}
Dynamic	Amplitude modulation Phase modulation Frequency Ramp	Amplitude Phase Combination of amplitude and phase Frequency	Ratio error ε Phase error $\Delta\varphi$ Total Vector Error *TVE* Frequency Error *FE* Rate of change of Frequency Error *RFE*
Transient	Oscillatory Transient	Peak magnitude Time shift Decay time	Error peak magnitude $\varepsilon_{\mathrm{Upk}}$ Time shift error $\Delta t_{\mathrm{zero-crossing}}$ Devay time error ε_{τ}

Content

- Basic time frame for the evaluation of Performance Indexes
- Selected PQ phenomena and related ranges
- Possible choices of Performance Indices
- Possible waveforms to use in the PQ accuracy tests

Waveforms for PQ accuracy tests

- Fundamental component $$s_1(t) = A_1\sqrt{2}\,sin(2\pi f_1 t)$$
- Harmonic components $$s_H(t) = \sum_{h=2}^{N_H} A_h\sqrt{2}\,sin(2\pi h f_1 t + \varphi_h)$$
- Interharmonic components $$s_I(t) = \sum_{i\epsilon I} A_i\sqrt{2}\,sin(2\pi f_i t + \varphi_i)$$
- Modulation tests $$X_a = X_m[1 + k_x\,cos(2\pi f_x t)]\,cos(2\pi f_0 t + \varphi)$$ $$X_a = X_m\cos(2\pi f_0 t + \varphi + k_x\cos(2\pi f_x t))$$
- Oscillatory transients $$v_{OT}(t) = \sqrt{2}\,U_{OT}\sin(2\pi f_{OT} t + \varphi_{OT})\cdot e^{-t/\tau}$$

Single Phenomenon or Multiple Phenomena?

- In general, ITs can be non linear
- Waveforms should be realistic, representative of real situations that can be encountered in power system
- Fundamental should always be present
- But the presence a specific phenomenon can influence the accuracy of the IT in the measurement of another phenomenon

Time combined waveforms

$$s_{TC}(t) = s_1(t) + \sum_k rect\left(\frac{t - t_k}{T_k}\right) \cdot s_k(t) + \sum_d rect\left(\frac{t - t_d}{T_d}\right) \cdot s_d(t)$$

- s_1 is the fundamental component
- $rect$ is the rectangular function, centered in $\mathrm{t} = t_k$ and duration T_k
- s_k is the $k - th$ PQ phenomenon, against which evaluate IT accuracy
- s_d is the $d - th$ disturbance (another PQ phenomenon not included in the accuracy evaluation or, extending the concept, an influence factor)

Content

- Basic time frame for the evaluation of Performance Indexes
- Selected PQ phenomena and related ranges
- Possible choices of Performance Indices
- Possible waveforms to use in the PQ accuracy tests
- Example of a PQ accuracy test

Example of a PQ accuracy test

Time window	Event	Possible IT-PIs
T1	Only fundamental component	ε_1, $\Delta\varphi_1$, TVE_1
T2	Fundamental component plus 2nd harmonics	ε_1, $\Delta\varphi_1$,TVE_1, ε_2 , $\Delta\varphi_2$, TVE_2
T3	Fundamental component plus 2nd harmonic and 55 Hz interharmonics	ε_1, $\Delta\varphi_1$, TVE_1,ε_2 , $\Delta\varphi_2$, TVE_2, ε_{55Hz}, $\Delta\varphi_{55Hz}$, TVE_{55Hz}
T4	Fundamental component plus 55Hz interharmonics	ε_1, $\Delta\varphi_1$, TVE_1, ε_{55Hz}, $\Delta\varphi_{55Hz}$, TVE_{55Hz}, Γ_{TVE_1}, $\Gamma_{TVE_{55Hz}}$
T5	Fundamental component with 55Hz interharmonics and low frequency disturbance	ε_1, $\Delta\varphi_1$,TVE_1, ε_{55Hz} , $\Delta\varphi_{55Hz}$, TVE_{55Hz}
T6	Fundamental component with low frequency disturbance	ε_1, $\Delta\varphi_1$, TVE_1
T7	Only fundamental component	ε_1, $\Delta\varphi_1$, TVE_1

Example of a PQ accuracy test

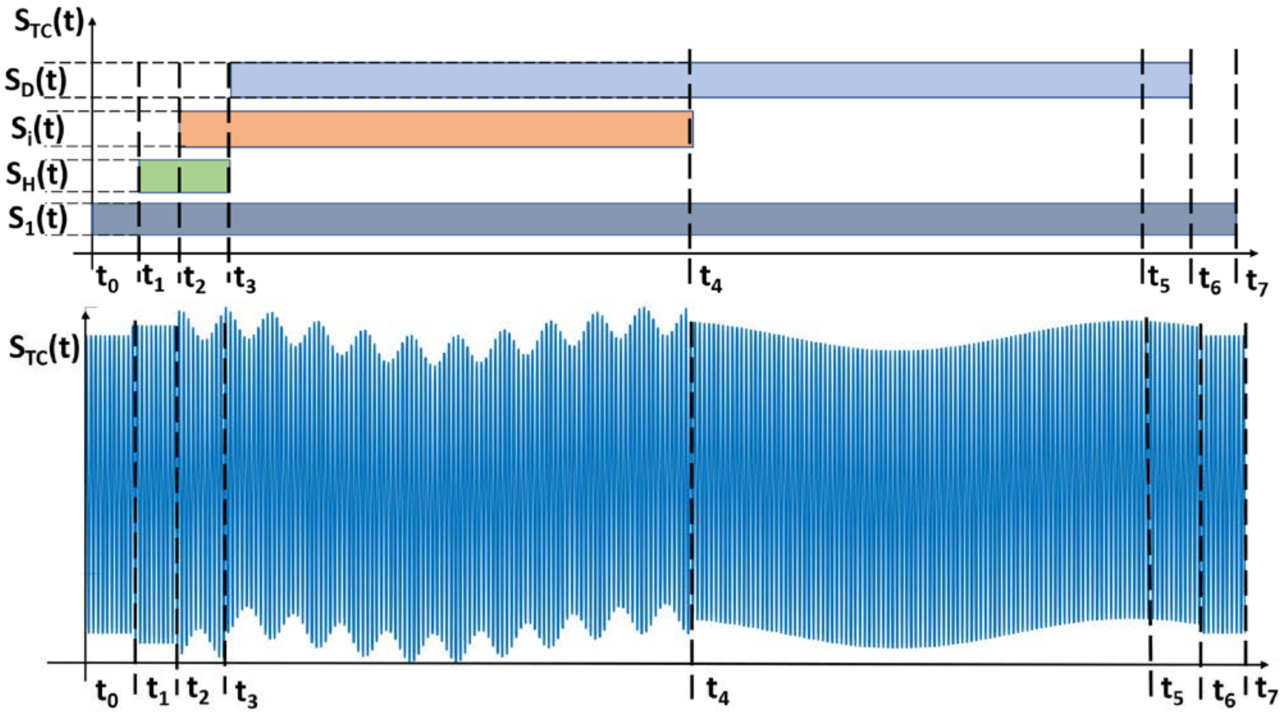


TABLE I. NUMERICAL VALUES OF THE TIMES T_K

T_1	0.2 s
T_2	0.4 s
T_3	0.6 s
T_4	2.6 s
T_5	4.6 s
T_6	4.8 s

Example of a PQ accuracy test

- Commercial VT, 3 kV / 100 V, 50/60 Hz, 0.5 accuracy class

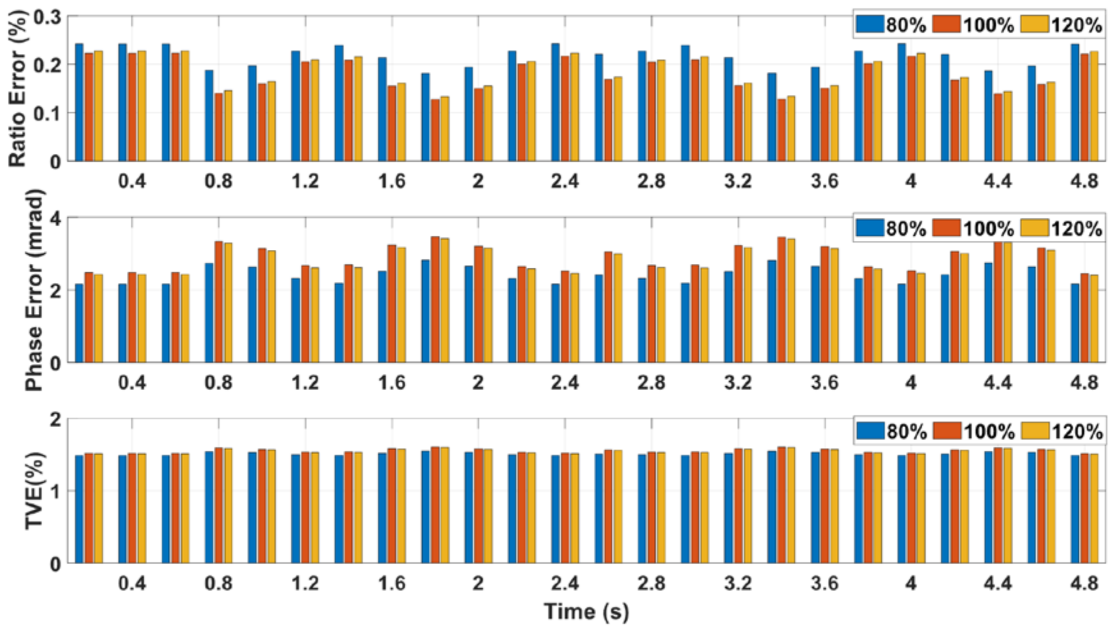


Fig. 7 Ratio error, phase error and TVE at fundamental frequency versus time, with different values of the fundamental amplitudes.

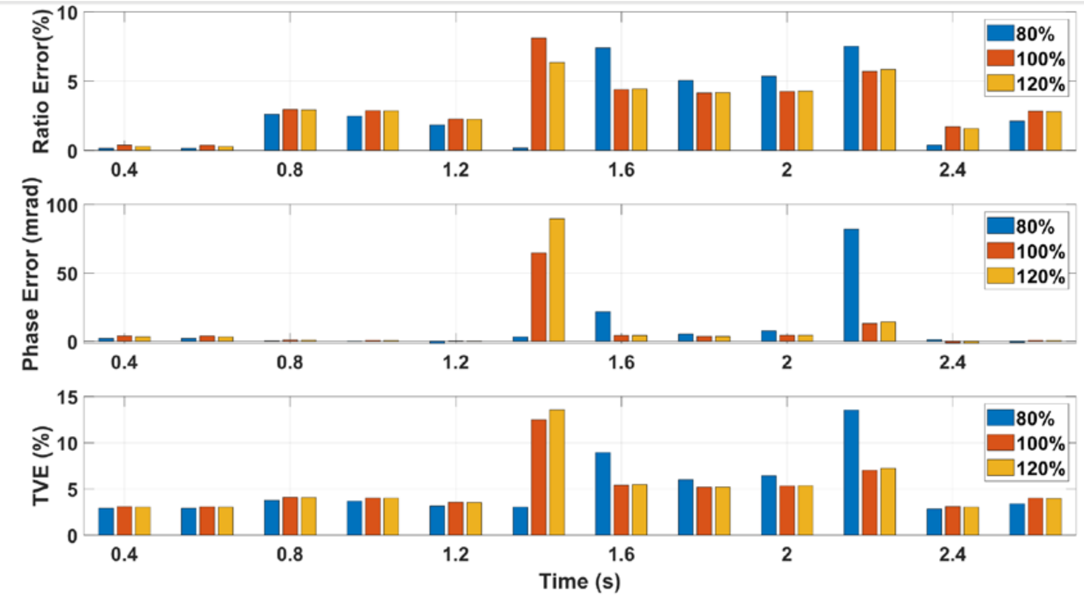


Fig. 8 Ratio error, phase error and TVE at the second harmonic frequency versus time, with different values of the fundamental amplitudes.

Example of a PQ accuracy test

- Commercial VT, 3 kV / 100 V, 50/60 Hz, 0.5 accuracy class

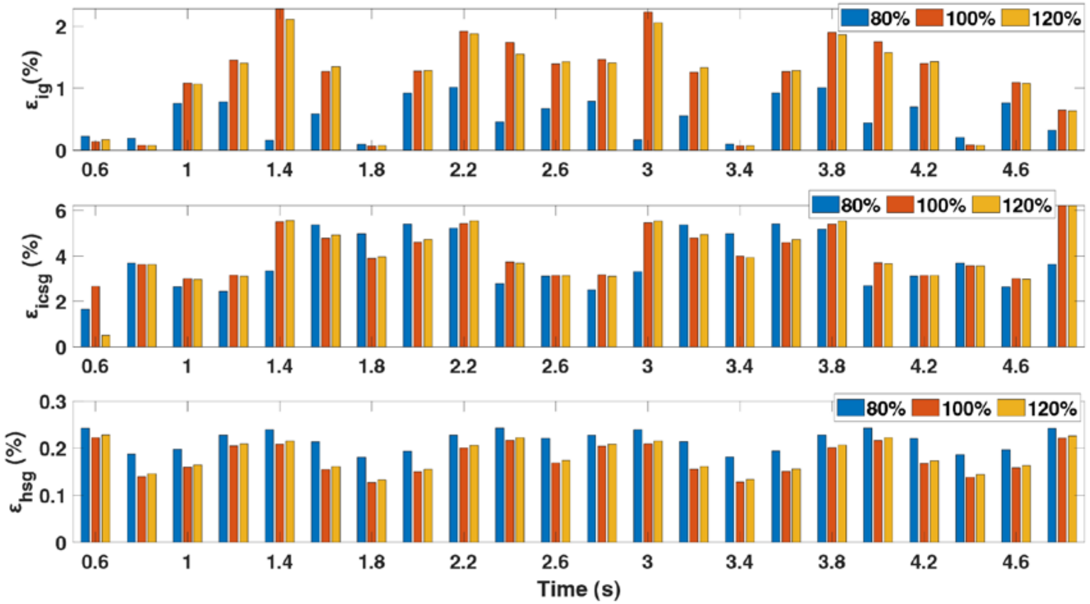


Fig. 9 Ratio error of the second interharmonic group, second centered interharmonic subgroup and first harmonic subgroup versus time, with different values of the fundamental amplitudes.

Conclusions

- Accuracy specification of PQ instruments (or PMUs) and ITs should be consistent, in order to easily select the best ITs for a PQ instrument
- A selection of PQ phenomena (already standardized) and related variation ranges to use in PQ accuracy tests for ITs was done
- A proposal of possible Performance Indexes to evaluate the accuracy of an IT versus a specific PQ phenomenon was done
- Experimental results show that complex waveforms, with combinations of different phenomena, should be used in the tests
- In this way, the influence of a specific phenomenon on the accuracy of an IT in the measurement of another phenomenon can be evaluated

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