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1 Overview

Extensive integration of renewable electrical energy sources into the distribution system is essential for the implementation of “green growth” strategies. However, as integration increases electrical power quality degradation is also increasing, and therefore power quality (PQ) monitoring holds greater importance. Currently, there are no standards related to the characterisation of the instrument transformers (ITs) used for PQ measurements, even though these can introduce significant errors in the PQ measurement chain. To fill this gap, this project defined specific performance indices for ITs in PQ measurements, proposed specific PQ accuracy classes for their qualifications and developed reference measurement systems and test procedures to quantify instrument transformer (IT) accuracy and uncertainty contributions in PQ measurements. Outputs and good practice guides were provided to the Technical Committee 38 of the International Electrotechnical Commission (IEC TC 38), which is responsible for standardisation in the field of AC and/or DC current and/or voltage ITs, in particular to its working group IEC TC38/WG47, which is focused on the evolution of ITs requirements for the modern market. The project outputs in terms of reference systems and simplified test procedures, as well as measured data made available on ITs, are supporting manufactures of IT and IT test systems, as well as test and calibration laboratories in extending their products/provided services to PQ measurement. Traceability and adoption of common and standardised IT test procedures will ensure both grid operators and IT manufacturers to operate in fairer market conditions.

2 Need

Fully decarbonising Europe’s energy supply by 2050 is one of the key points for the European strategic vision for a prosperous, modern, competitive and climate neutral economy. This will require extensive deployment of renewable energy sources, which is essential for “green growth”, but also causes additional grid-injected disturbances. Proliferation of disturbances implies degradation of the quality of the delivered power. It is estimated that poor PQ costs both industry and commerce in the EU about €150 billion annually. Henceforth, there is a need to address the unavoidable task of monitoring PQ.

Effective PQ monitoring requires accurate measurement instrumentation. When PQ measurements are performed in distribution grids, ITs have to be included in the measurement chain to reduce the grid high voltages and currents to levels compatible with the PQ measurement instrument inputs. Available international standards deal only with limits for public distribution system disturbances, measurement methods for PQ phenomena, and accuracy requirements and test methods for measurement instruments, without considering ITs. On the other hand, standards for ITs are focused on accuracy verification in the absence of PQ disturbances, i.e. at 50/60 Hz, or only provide accuracy limits for harmonic components. Up to now, none of the National Metrology Institutes (NMIs) is providing traceable calibrations of ITs for PQ; moreover, standardisation related to characterisation and tests of ITs for PQ measurement under realistic conditions, including presence of multiple influence factors, is lacking.

Furthermore, there is no shared and common method that can be adopted by the interested community, from grid operators to instrument manufacturers and test laboratories, to characterise ITs and estimate their uncertainty contribution in PQ measurements. There was then a need for undertaking pre-normative research to fill these gaps, as expressed by IEC TC 38 “Instrument Transformers”.

3 Objectives

The overall goal of the project was the development of the metrological framework to enable the traceable calibration of ITs to be employed for PQ measurements in electricity grids, which could be used by IEC TC 38 Instrument transformers as a basis for the future standardisation about the use of ITs for PQ from IEC TC 38. The specific objectives of the project were:

1. To define accuracy and uncertainty limits of ITs in PQ measurements, by proposing and experimentally verifying specific performance indices for the single PQ parameters and by defining a new “PQ Accuracy Class” for ITs, which would be the extension of the concept of classical “accuracy class”.
2. To establish suitable reference measuring systems for ITs and methods for the evaluation of the relevant uncertainty contribution of ITs to PQ indices.
3. To establish traceable test procedures for reference setups to calibrate ITs used for PQ measurements in electricity grids by covering limits for PQ disturbances in the available standards.

4. To evaluate performance of ITs in PQ measurements in presence of multiple influence factors (e.g. temperature and temperature gradients, adjacent phases, proximity effects, vibrations).
5. To contribute to a revision of technical report IEC/TR 61869-103 as well as the standards in the IEC 61869 family product (e.g. 61869-1, 61869-6, etc.) by providing the data, methods, guidelines and recommendations, which are necessary for the calibration of ITs used in PQ measurements to IEC TC 38. Outputs were in a form that can be incorporated into the standards at the earliest opportunity and communicated to the standards community and to end users (Transmission system operators, distribution system operators, customers).

4 Results

Objective 1: To define accuracy and uncertainty limits of ITs in PQ measurements, by proposing and experimentally verifying specific performance indices for the single PQ parameters and by defining a new "PQ Accuracy Class" for ITs, which would be the extension of the concept of classical "accuracy class".

Objective 1 was achieved by defining accuracy and uncertainty limits of ITs in PQ measurements through the introduction and validation of new Performance Indices (PIs) specific to individual PQ disturbances and a Synthetic Performance Index (SPI). The definition of the SPI along with its limits has led to the definition of a "PQ Accuracy Class" for ITs, extending the concept of traditional "power frequency class".

Overview of the most remarkable results and outputs for this objective

First, an extensive analysis of the in-force standard and scientific literature regarding both PQ and ITs was carried out. The review process enabled to identify significant PQ phenomena as well as their realistic range of variation under which investigating the metrological performances of ITs. The work covered various PQ disturbances, including stationary, dynamic and transient events relevant for Medium Voltage (MV) application, up to 36 kV and 2 kA, with spectral content up to 9 kHz.

Moreover, it must be considered that in power systems different PQ phenomena can occur at the same time or partially overlap, therefore it is crucial to verify the performances of ITs under combined events with a time variant waveform, more representative of the actual supply conditions. For instance, it was highlighted that subharmonics can heavily impact on inductive VT performance in the measurement of the harmonics, leading to the increase of the harmonic ratio error up to one order of magnitude. For this reason, a novel time-combined waveform was also proposed, by SUN, discussed and verified as possible test waveform to assess the impact on IT performance of PQ phenomena other than those, which are the objective of the measurement.

As a following step, PIs were defined for each selected PQ phenomenon in order to quantify the errors introduced by ITs in the measurement of the specific PQ disturbance. The PIs were identified starting from the analysis of already defined and used accuracy indices for ITs as well as for Phasor Measurement Units (PMUs) or indices used for the quantification of PQ disturbances, such as Total Harmonic Distortion (THD), interharmonic subgroup, etc.

Realistic range of variations of the defined PIs and the overall SPI were quantified based on the feedback from the experimental investigations, carried out on a significant set of ITs of different operating type in presence of the different PQ events, as well as considering data from scientific literature.

Finally, by identifying limits of the SPI and following the approach used for the definition of accuracy classes for PQ measuring instruments, new PQ accuracy classes and associate limit accuracies for the SPI were defined.

More details are briefly given in the following on the defined test waveforms and parameters, PIs and SPI evaluation and the new proposed PQ accuracy classes.

Test waveforms and parameters for the characterisation of ITs under PQ events

The descriptions of the test waveforms and the range of variations of their parameters are provided below. Moreover, the mathematical model for the assessment of the performance of ITs in presence of multiple PQ disturbances is given.

Steady-state tests

The IT performances in presence of harmonics and/or interharmonics were assessed by supplying it with a test waveform composed of the fundamental tone (Equation 1) plus a number of harmonics (Equation 2) and/or interharmonics (Equation 3):

$$s_1(t) = \sqrt{2}A_1 sin\,(2\pi f_1 t + \varphi_1) \tag{1}$$

$$s_H(t) = \sum_{h=2}^{N_H} \sqrt{2}A_h\, sin\,\,(2\pi h f_1 t + \varphi_h) \tag{2}$$

$$s_I(t) = \sum_{i\epsilon I} \sqrt{2}A_i (2\pi f_i t + \varphi_i) \tag{3}$$

where:

- A_1, f_1 and φ_1 are the fundamental amplitude, frequency and phase, respectively;
- A_h, h and φ_h are the harmonic amplitude, order and phase, respectively; N_H is the number of harmonics that compose the test signal,
- A_i, f_i and φ_i are the interharmonic amplitude, frequency, and phase; I is the set of considered interharmonic frequencies.

Dynamic tests

To evaluate the IT performances in presence of dynamic disturbances, a test waveform reproducing the amplitude and phase modulation of the fundamental tone was generated according to Equations 4 and 5, respectively:

$$s_{AM} = A_1[1 + k_x\, cos\,(2\pi f_x t)]\, cos\,(2\pi f_1 t + \varphi_1) \tag{4}$$

$$S_{PM} = A_1\, cos\,(2\pi f_1 t + \varphi_1 + k_x\, cos\,\,(2\pi f_x t)\,) \tag{5}$$

where:

- A_1, f_1 and φ_1 are the fundamental amplitude, frequency and phase, respectively.
- k_x, k_a and f_x are the amplitude modulation factor, the phase angle modulation factor and the modulation frequency, respectively.

Oscillatory transient test

Among the transient phenomena, the oscillatory transient was selected being, according to the IEEE 1159 standard, the only one with spectral content which includes part of the frequency range covered by the IT4PQ project, that is up to 9 kHz. The proposed test waveform for oscillatory transients is the fundamental tone $s_1(t)$ with a superimposed exponentially decaying sinusoid, as described by:

$$s_{OT}(t) = \sqrt{2}A_1 sin\,(2\pi f_1 t + \varphi_1)\; + \sqrt{2}\, A_{OT}\, sin\,(2\pi f_{OT} t + \varphi_{OT}) \cdot e^{-t/\tau} \tag{6}$$

where:

- $\sqrt{2}A_{OT}$, f_{OT}, φ_{OT} and τ are respectively the initial peak amplitude value, the oscillation frequency, the initial phase and the decay time of the damped sinewave.

Time combined waveform tests

A generic test waveform defined as in Equation (7) was proposed and experimented in order to assess the performance of ITs in presence of multiple PQ events:

$$s_{TC}(t) = s_1(t) + \sum_k rect\left(\frac{t-t_k}{T_k}\right) \cdot s_k(t) + \sum_d rect\left(\frac{t-t_d}{T_d}\right) \cdot s_d(t) \quad (7)$$

Where:

- $rect(t-t_k/T_k)$ is the rectangle function with time duration T_k starting from t_k-T_k/2 up to t_k+T_k/2;
- $s_1(t)$ is the fundamental component (Equation 1);
- $s_k(t)$ is the PQ phenomena under which the IT performances are assessed (Equation 2 to 6)
- $s_d(t)$ is the PQ phenomena chosen as additional disturbance (Equation 2 to 6).

An example of time combined waveform is proposed in Figure 1 where a time-scheme (a) and the associated numerical simulation (b) are reported.

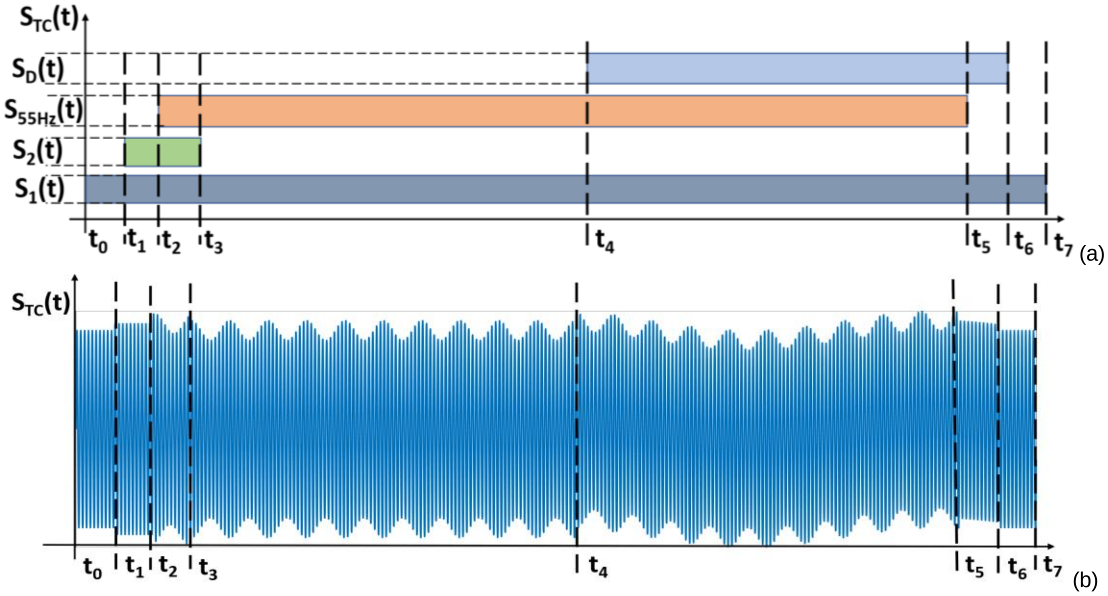


Figure.1 Example of time combined waveform: a) time combined waveform scheme and b) time domain numerically simulated signal with *h*=2, *i*=55 Hz and subharmonic at 1 Hz**.**

Range of variation of the PQ parameters.

Considering all the possible PQ test waveforms, Table I summarises the range of variation of PQ parameters from analysis of literature and standards.

Table I – Range of variation of PQ phenomena from the literature and standards review

PQ phenomena		**Inductive ITs**		**LPITs**			
				Analog output		Digital output	
		VT	CT	VT	CT	VT	CT
Voltage and current deviation		From 5 % up to 200 % of amplitude rated voltage	From 1 % up to 200 % of amplitude rated current	From 5 % up to 200% of amplitude rated voltage	From 1 % up to 200 % of amplitude rated current	From 5 % up to 200 % of amplitude rated voltage	From 1 % up to 200 % of amplitude rated current
Frequency deviation		+/- 15 % of rated frequency (isolated systems)					
Harmonic and interharmonic		At least the rated voltage/current amplitude for fundamental component See Table Ia for voltage and current amplitude from DC up to 9 kHz					
Dips (for verification)		10 % - 90 % of rated amplitude at point of wave from 0° up to 270° with 45° step and ±90° change at the beginning and the end of cycle					
Swells (for verification)		110 % - 150 % of rated amplitude at point of wave from 0° up to 270° with 45° step and ±90° change at the beginning and the end of cycle					
Interruption (for verification)		5% of rated amplitude at point of wave-interruption and restoration from 0° up to 270° with 45° step					
Transient overvoltage	Amplitude	From 5 % up to 200 % of amplitude rated voltage	From 1 % up to 200 % of amplitude rated current	From 5 % up to 200 % of amplitude rated voltage	From 1 % up to 200 % of amplitude rated current	From 5 % up to 200 % of amplitude rated voltage	From 1 % up to 200 % of amplitude rated current
	Time duration	See Table Ib					
Modulation	Amplitude	Frequency modulating from 0.1 Hz up to 5 Hz – K_x = 0.1					
	Phase	Frequency modulating from 0.1 Hz up to 5 Hz – K_a = 0.1 rad					
Frequency ramp		Ramp rate (R_f) ±1 Hz/s starting from -5 Hz up to +5 Hz of rated frequency					

Table Ia – Maximum limit of harmonic and interharmonic amplitudes

Voltage	Harmonic	Minimum harmonic order	Maximum harmonic order	Relative amplitude U_h/U_0
		2	15	10%
		16	50	5%
		51	9 kHz	2%
	Interharmonic	Minimum frequency	Maximum frequency	Relative amplitude U_h/U_0
		DC	20 Hz	5 %
		20 Hz	100 Hz	3 %
		100 Hz	9 kHz	1 %
Current	Harmonic	Minimum harmonic order	Maximum harmonic order	Relative amplitude U_h/U_0

		2	15	40 %
		16	50	12 %
		51	9 kHz	10 %
	Interharmonic	Minimum frequency	Maximum frequency	Relative amplitude U_h/U_0
		DC	20 Hz	3 %
		20 Hz	100 Hz	2 %
		100 Hz	9 kHz	8 %

Table Ib – Transient overvoltage time duration parameters

Test Type	Time specification						
	Rise Time (T_r)	Impulse duration (50 % value) (T_{id})	Relation to power supply	Duration (T_d)	Period (T)	Polarity	Max bandwidth
Single pulse	Not less than 5 ± 30 % or From 5 ns up to 1 ms	Not less than 50 µs	Asynchronous	Not applicable	Not applicable	Positive or negative	9 kHz
Multi-transient event				Single pulse	Not less than $T \geq T_r + T_{id}$		
Burst				Not less than 20 ms	Not less than T_d		

Performance Indices

In the following, the IT PIs are briefly recalled as a function of the considered PQ disturbance. Without loss of generality, the PI are reported for the voltage case, but they can be easily extended to the current case.

Steady-State

For steady-state tests (harmonics and interharmonics), two different categories of PI were defined and are reported below.

- Indices for the evaluation of the IT accuracy at specified harmonic or interharmonic frequency f i.e., the ratio error $\varepsilon(f)$ and phase error $\Delta\varphi(f)$:

$$\varepsilon(f) = \frac{k_r\, U_s(f)\ - U_p(f)}{U_p(f)} \tag{8}$$

$$\varphi(f) = \varphi_s(f) - \varphi_p(f) \tag{9}$$

where $k_r = U_{p,r}/U_{s,r}$ is the rated IT transformation ratio and $U_{p,r}$ and $U_{s,r}$ are the rated primary and secondary voltages; $U_p(f)$ and $U_s(f)$ are the RMS values of the primary and secondary voltage at the frequency f; $\varphi_p(f)$ and $\varphi_s(f)$ are phase angles of the primary and secondary *h*-order harmonic voltage.

- A synthetic index to quantify the VT performance over a specific frequency range defined from a generic f_{start} to f_{stop}, i.e., the Total Frequency Distortion (TFrD) error:

$$\Delta TFrD = TFrD_s - TFrD_p \tag{10}$$

where $TFrD_s$ and $TFrD_p$ are defined as in the following equations:

$$TFrD_p = \frac{\sqrt{\sum_{f=f_{start}}^{f_{stop}} U_p^2(f)}}{U_p(f_1)} \quad (11) \qquad TFrD_s = \frac{\sqrt{\sum_{f=f_{start}}^{f_{stop}} U_s^2(f)}}{U_s(f_1)} \quad (12)$$

In an analogous way but considering only harmonic frequencies, Equation (10) gives the error contribution of an ITs in the measurements of the Total Harmonic Distortion (THD):

$$\Delta THD = THD_s - THD_p \quad (13)$$

where the subscript p (s) refers to the quantities at the primary (secondary) side of the IT, i.e., at its input (output). These IT-PIs can be extended to other standardized indices, as subgroup, total harmonic (interharmonic) distortion THDS (TIHDS) from IEC 61000-4-7.

Frequency components f are evaluated by performing frequency domain analysis, such as Discrete Fourier Transform (DFT), over time intervals of 10 cycles of the fundamental frequency in accordance with the IEC 61000-4-7 requirements.

Dynamic tests

The test waveforms generated for the assessment of the IT performances in the presence of dynamic disturbances are defined starting from the IEC/IEEE 60255-118-1 considering the indices used for the PMU characterisation: the IT Total Vector Error (ITTVE), the IT Frequency Error (ITFE) and the IT Rate of Frequency Error (ITRFE) along with the ratio and the phase errors are provided below:

$$\varepsilon = \frac{k_r|V_s| - |V_p|}{|V_p|} \quad (14)$$

$$\Delta\varphi = \measuredangle V_s - \measuredangle V_p \quad (15)$$

$$ITTVE = \sqrt{\frac{\left(Re(k_r \boldsymbol{V}_s) - Re(\boldsymbol{V_p})\right)^2 + \left(Im(k_r \boldsymbol{V_s}) - Im(\boldsymbol{V_p})\right)^2}{Re(\boldsymbol{V_p})^2 + Im(\boldsymbol{V_p})^2}} \quad (16)$$

$$ITFE = f_{1,s} - f_{1,p} \quad (17)$$

$$ITRFE = \frac{df_{1,s}}{dt} - \frac{df_{1,p}}{dt} \quad (18)$$

where $k_r = V_{p,r}/V_{s,r}$ is the rated transformation ratio and $V_{p,r}$ and $V_{s,r}$ are the rated primary and secondary voltages; $\boldsymbol{V_p}$ and $\boldsymbol{V_s}$ are the fundamental voltage phasors at the VT primary and secondary side, respectively. The quantities $f_{1,p}$, $f_{1,s}$ are the fundamental frequencies measured at VT primary and secondary side, respectively.

The fundamental primary and secondary phasors $\boldsymbol{V_p}$ and $\boldsymbol{V_s}$ are estimated in the frequency domain, f.i. via DFT, on an observation interval of four cycles of the fundamental frequency with a reporting rate of 50 Hz in accordance with IEC/IEEE 60255-118-1.

As can be observed, the dynamic disturbances were not considered, in this specific case, as quantities to be measured, but influence factors on IT performance at rated frequency.

Oscillatory transients

Three specific performance indexes have been introduced in the measurement of an oscillatory transient as given in equation (6).

- The errors in oscillation first peak amplitude value ($U_{pk} = \sqrt{2}\, U_{OT}$):

$$\varepsilon_{pk} = \frac{k_r U_{pk,s} - U_{pk,p}}{U_{pk,p}} - 1 \quad (19)$$

where $k_r = U_{p,r}/U_{s,r}$ is the rated IT *SF* or transformation ratio, and $U_{p,r}$ and $U_{s,r}$ are the rated primary and secondary voltages; $U_{pk,p}$ and $U_{pk,s}$ are the oscillation first peak values of the primary and secondary voltage oscillation.

- The phase displacement φ_{OT} (time shift) of the damped sine wave.
- The errors in the decay time τ of the oscillation:

$$\varepsilon_{\tau} = \frac{\tau_s - \tau_p}{\tau_p} \quad (20)$$

where τ_p,and τ_s are the decay time measured at the primary and secondary side of the IT.

These parameters are estimated in the time domain after filtering the 50 Hz component.

- The first peak amplitude value $\sqrt{2}U_{OT}$ is estimated as the maximum of the observed measurement values.
- The phase displacement is calculated as the difference in the zero-crossings following the initial peak values.
- The decay time τ can be obtained by fitting an exponential decay $e^{-t/\tau}$ to the successive peak values.

Synthetic Performance Indices and proposal for a new PQ Accuracy classes

The SPI was defined on the bases of the feedback provided by the experimental results. In particular, it was found that for the tested IT modulations did not represent critical disturbances being the PIs variations in the order of hundreds of microvolt/volt and milliradian. Moreover, a correlation was found between the PIs measured under steady state test waveforms $\varepsilon(f)$ and the transient PIs $\varepsilon_{U_{pk}}$ and ε_{τ}.

Therefore, it can be conservatively assumed that the PI $\varepsilon(f)$ provides information on the IT instrumental for both the quantification of its performance in the harmonics/interharmonics as well as in OT parameter measurement.

Based on this consideration, the proposed SPI is defined as the absolute value of the deviation between the value of the $\varepsilon(f)$ and the error at power frequency:

$$\xi(f) = | \varepsilon(f) - \varepsilon(f_1))| \quad (21)$$

As a final step of Objective 1, specific IT-PQ accuracy classes were introduced. More specifically, considering the outputs of experimental tests as well as the accuracy limits identified by the standards dealing with PQ measurements, two sets of limits were associated to $\xi(f)$, corresponding to two PQ accuracy classes (PQ1 and PQ2).

Each set of SPI limits was defined for a number of frequency subranges (FRs) from 50 Hz to 9 kHz.

Taking into account the IT4PQ frequency range investigated, the FRs are identified according to this logic:

- FR_A is defined from rated frequency (not included) up to 500 Hz for the measurement of the first 10 harmonics, which are generally the more predominant in power grids;
- FR_B is defined from rated frequency (not included) up to 2500 Hz and covers the harmonics range up to the 50th;
- FR_C is defined from rated frequency (not included) up to 5 kHz in order to cover the useful bandwidth of MV inductive VTs, that is before the first resonance frequency, which depends on their stray capacitances. From the analysis of existing literature and experimental activities carried out within the IT4PQ project, it is found that for the majority of the analysed VTs, the first resonance frequency is found for frequencies higher than 5 kHz. Starting from this consideration, the FR_C is established up to 5 kHz;
- FR_D is defined from rated frequency (not included) up to 9 kHz and covers the entire PQ frequency range considered in the IT4PQ project.

The PQ accuracy classes have been extended also to the frequency phase error, starting from the same considerations adopted for the ratio error.

Conclusions

Overall, all aspects of Objective 1 were finalised by the project consortia. In particular, new test waveforms along with realistic ranges of variation for the PQ parameters, suitable PIs to quantify the error contribution introduced by ITs in the measurement of specific PQ disturbance and a SPI and new IT PQ accuracy classes have been defined and experimented.
The achievement of Objective 1 was made possible by the collaboration of several project partners (CMI, LNE, INRIM, PTB, TUBITAK, VSL, RSE, SUN, TUD) with significant contributions in particular from SUN and VSL.

Objective 2: To establish suitable reference measuring systems for ITs and methods for the evaluation of the relevant uncertainty contribution of ITs to PQ indices.

Objective 2 was achieved by the developing and experimenting traceable reference measurement systems for ITs charcterisation under PQ events and by defining methods for evaluating the relevant uncertainty contributions of ITs to PQ indices.

Overview of the most remarkable results for this objective

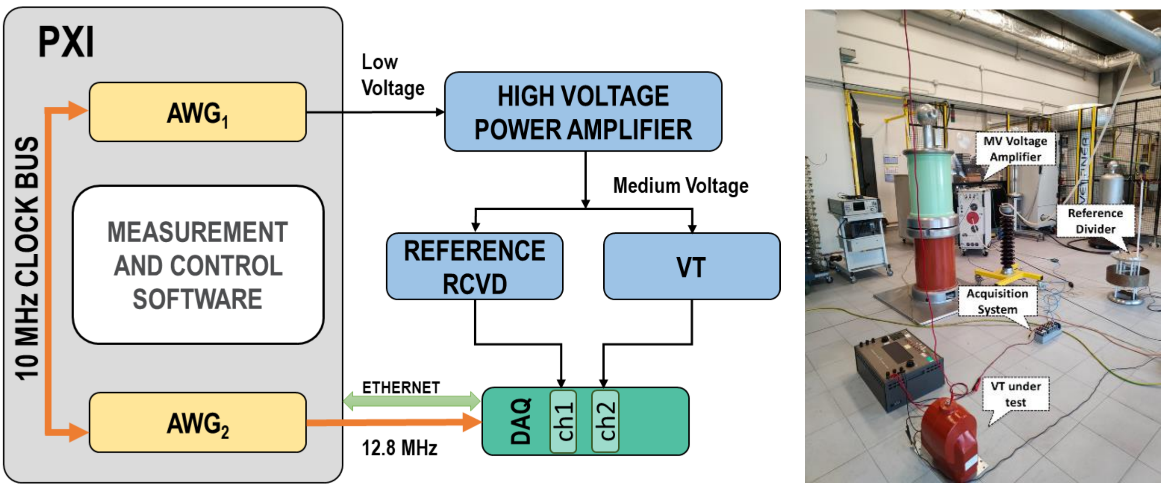
Objective 2 established reference generation and measurement systems as well as validated methods for assessing the accuracy of ITs in the measurement of PQ parameters. To this end, reference systems were developed and validated, which allow the calibration of different types of ITs (inductive VTs and CTs, LPVTs and LPCTs, combined voltage and current ITs and LPITs) for current up to 2 kA and voltage up to 36 kV and spectral content up to 9 kHz, as defined within Objective 1.

A representative set of commercial ITs was defined and collected considering different operating principles, primary voltage/current, accuracy class, manufacturer and the possibility of indoor or outdoor installations. The set of ITs was tested by the developed reference systems, and their performance was quantified in terms of the defined PIs.

Following subsections provide brief descriptions of the setups.

Generation and Measurement System for inductive VT and LPVT

The reference generation and measurement system for the characterisation of inductive VT and LPVT was developed by INRIM. A schematic representation and laboratory photos are provided in Figure 2.



(a) (b)

Figure 2: INRIM reference generation and measurement system for VT and LPVT characterisation in presence of PQ disturbances: (a) scheme and (b) laboratory set-up.

The setup can be divided into four main sections:

Generation system: The generation of MV distorted waveforms is obtained using an arbitrary waveform generator (AWG) coupled with an MV power amplifier. Specifically, the AWG module (AWG1) is used to generate user-synthetized low voltage (LV) signals. The LV signals from the AWG1 are amplified by a high-voltage power amplifier. This amplifier produces voltages of up to ±30 kV with a maximum current of ±20 mA up to 2.5 kHz, and signals with reduced voltages up to 30 kHz. For generating higher voltages, it can be substituted with a suitable step-up transformer.

Reference sensor: The reference sensor is a resistive-capacitive voltage divider (RCVD) specifically designed and built at INRIM for MV ITs wideband calibration. It has a primary rated voltage of 30 kV_{rms}, and its useful frequency range is from DC to 12 kHz.

Acquisition system: To acquire the output voltages from both the reference RCVD and the VT/LPVT under test, a digital comparator is used. This system includes a Data Acquisition system (DAQ) equipped with various acquisition modules, with analog input ±0.5 V; ±10 V; and ±425 V. All the acquisition boards have 24-bit resolution and a maximum sampling frequency of 50 kHz. The system can be reconfigured for the calibration of digital output VTs (e,g. VTs with associated stand alone merging), by introducing a reference synchronised acquisition AWG2 board as realised within the EMPIR 17IND06 Future Grid II project.

Software section: The software for data processing and instrument control is developed in LabVIEW. The generation software is able to synthetise sinusoidal waveforms (Equation 1), fundamental tone with one or multiple harmonics (Equation 2) and intherarmonics (Equation 3), amplitude and phase-modulated signals (Equation 4 and 5), oscillatory transient (Equation 6), combination of PQ disturbances (Equation 7) and also the integration of events sourced from database or user-simulated scenarios. All test waveforms are designed with a fade-in and fade-out signal to prevent rapid voltage spikes. Additionally, the software features real-time compensation for residual DC components, to prevent saturation effects in the VT iron core. The primary and secondary quantities are acquired and stored in order to perform post processing algorithms implementing the calculations of the PIs as defined from Equation 7 to 20.
All the hardware sections were properly characterised in order to quantify the uncertainty contribution associated to the measurement of PQ parameters up to 9 kHz.

Regarding the generation section, the THD of the MV generation setup was evaluated over a range of primary voltages from 2 kV to 15 kV generating virtually pure sinewave, the generated THD was determined by measuring the first 100 spurious harmonic tones. Results indicated that the measured THD remained consistently below 0.03% over the investigated voltage range.

The accuracy of the reference RC divider was assessed through several tests, including assessment the voltage dependence of the divider scale factor (SF), frequency response up to 9 kHz, and stability and proximity tests at the rated frequency. The voltage dependence of the RCVD SF was quantified for both DC and AC (50 Hz), ranging from 1 kV to 20 kV. Frequency response testing, conducted between 100 Hz and 9 kHz at reduced voltage (250 V), showed a ratio error flat within 260 µV/V and phase error within a range of 300 µrad. Stability and proximity tests had a minor impact, with variations in the few tens of ppm range, on both the RC divider ratio and phase errors.

The acquisition system was calibrated in two configurations, one for conventional VT characterisation (utilizing two channels from different modules) and another for LPVT (employing two channels from the same acquisition module). This characterisation was performed at various voltage levels, from 50 Hz to 9 kHz, using a standard calibrator and a standard inductive voltage divider as the reference system. The characterisation results show that up to 9 kHz the variations of ratio and phase errors are within tens of ppm.

Considering all the characterisation tests and the related results the uncertainty (level of confidence 95%) associated with the ratio (phase) error measurements from 5 kV to 20 kV are*:*

- *70 µV/V (µrad) at power frequency*
- *210 µV/V (330 µrad) from 100 Hz to 9 kHz*

Generation and Measurement System for inductive CT and LPCT

The setup for current transformers calibration under PQ phenomena (Figure 3) was designed and developed at PTB. Similar to the voltage, also the setup developed by PTB includes four main sections, described in the following:

Generation system: the distorted current generation is achieved using a programmable AWG coupled with an analogue transconductance power amplifier (up to 270 V_{rms} / 70 A_{rms}, DC to 15 kHz). The medium current level is then reached using a step up current transformer.

Reference sensors: a collection of reference Current-to-Voltage transformers with associated precision measuring resistors are used. Four reference current transformers are used (CT50, CT200, CT600 and CT1500) which allow to cover the input current range from 8 A 8RMS) to 1500 A (RMS).

Acquisition system: the acquisition system is a high-precision 2-channel measuring system (MS).

Software section: a LabVIEW program incorporating the algorithms for PQ generation was self-developed. This program is able to control and expand the generation capability of the AWG implementing the PQ phenomena identified within Objective 1.

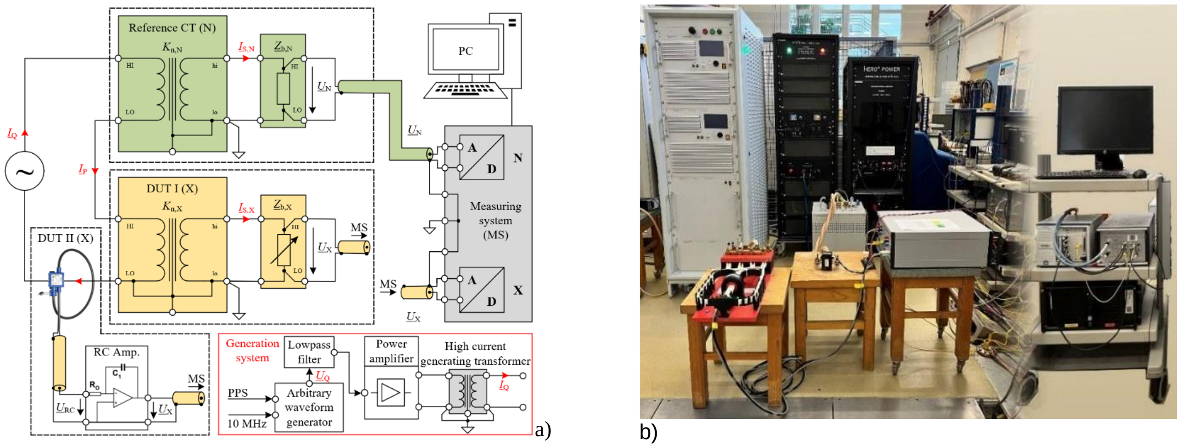


Figure 3: PTB reference generation and measurement system for CT and LPCT characterisation in presence of PQ disturbances: (a) scheme and (b) laboratory set-up.

Each hardware section was characterised to assess its contribution to the measurement uncertainty of PQ parameters up to 9 kHz.

The characterisation of the 2-channel voltage ratio measuring system under PQ phenomena was performed by means of a proper low-pass filter (LP filter) designed and developed for this application. The self-developed LP filter was designed with a cut off frequency of 12 kHz, with a stable frequency response similar to a reference CT and with a linear behaviour. The LP filter frequency response was pre-characterised by supplying it with single sinusoidal signals with amplitudes from 100 mV to 5 V up to 9 kHz and its response was found flat within ±35 µV/V. As a second step, the LP filter was used as reference for the characterisation of the 2-channel voltage ratio measuring system. In particular, the LP filter was supplied with bi-tone signals and multitoned signals with harmonics at 1 %. As a result, the measured uncertainties were within ± 6 µV/V and ± 5 µrad (k = 1) at power frequency and within ± 155 µV/V and ± 275 µrad (k = 1) up to 9 kHz.

The reference current sensors, e.g., CT200, were characterised by comparison with a precision and wideband shunt. The measurements uncertainties of CT200 under harmonics or interharmonics are estimated to be within ± 30 µA/A and ± 50 µrad (k = 1).

Based on the experimental results, the uncertainties (level of confidence 95%) for the reference measurement system under PQ phenomena are:

- *20 µA/A (10 µrad) for the ratio (phase) error at power frequency*
- *100 µA/A (400 µrad) for the ratio (phase) error from 100 Hz to 9 kHz*

Compensated current comparator for inductive CT calibration in a wider frequency range

A compensated current comparator (CCC) built at CMI was characterised in a wideband range (Figure 4). It was demonstrated that the CCC allows CT characterisation up to 9 kHz with standard uncertainties up to

400 µA/A and 400 µrad for the ratio and phase error respectively. A preliminary characterisation of a 100 A/5 A inductive CT was performed proving the feasibility of the proposed setup.

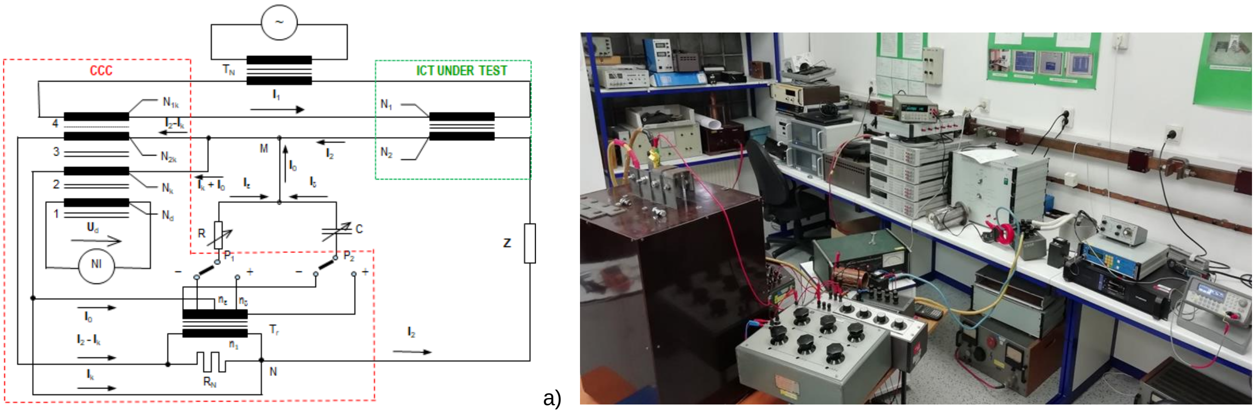


Figure 4: CMI alternative reference generation and measurement system for CT characterisation in presence of PQ disturbances, based on the use of a home developed CCC; a) scheme; b) laboratory reference set-up.

Generation and Measurement System for combined ITs

The generation and measurement systems for the characterisation of MV combined ITs and LPITs under PQ phenomena was developed by TUBITAK (see Figure 5).

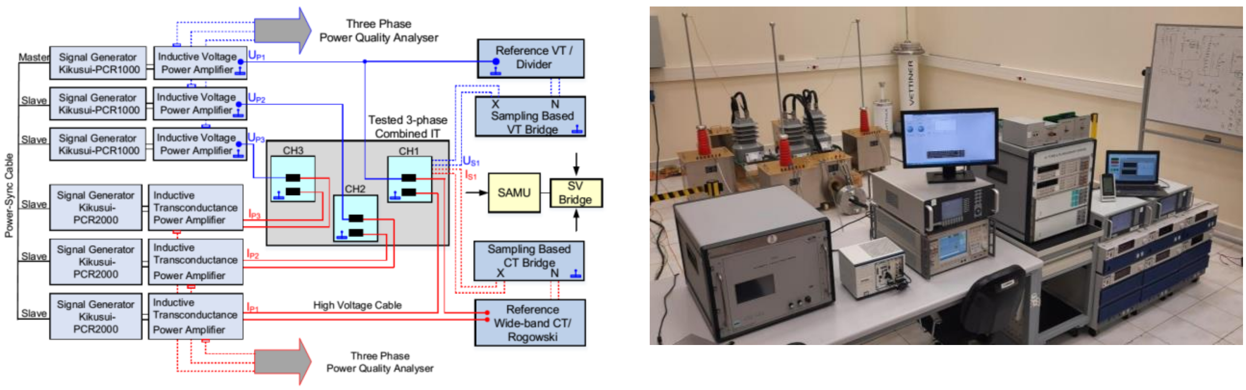


Figure 5: TUBITAK reference generation and measurement system for combined IT characterisation in presence of PQ disturbances: (a) scheme and (b) laboratory set-up.

The generation of the three-phase (6-channels) setup involves several stages, including signal conditioning, power generation, high voltage and current amplification, all controlled by feedback mechanisms. Power generation is achieved using 6 synchronised programmable linear power sources with configurable power output ranges from 1 kW up to 6 kW. The power source voltage outputs (up to 300 V) are directly applied to the primary windings of 3 high voltage power amplifiers and 3 high transconductance power amplifiers. This arrangement enables the generation of 3 voltages up to 36 kV and 3 currents up to 2 kA.

The reference measurement system includes two commercial bridges, one for VT and one for CT comparisons, to ensure accuracy measurements for each channel. Moreover, a wideband reference current and a voltage sensor are used for PQ measurements and to analyse influence factors such as proximity effects.

Several performance tests were performed in order to quantify the performances of all the setup sections such as: signal generation and conditioning, bandwidth and power limits of each source, synchronisation criteria, amplifier types and their behaviour in long-term operation (stability and losses), isolation in cabling up to 36 kV, verification of bridges for sinusoidal and non-sinusoidal waveforms.

Initially, the voltage and current ITs of each phase of the combined IT were calibrated with the reference ITs by using commercial bridges and standard burdens. Secondly, each phase of the three-phase combined IT was re-calibrated simultaneously to see any deviations in their ratio and phase errors. Finally, simultaneous calibration of each phase was performed again while the other two phases were in operation mode with a typically 120° phase difference between each other. Each test stage could be performed in high resolution with the steps of 0.01% of nominal value for both voltage and current amplitudes while the phase resolution is 0.001° for setting the phase difference between them and between each phase. The same approach was followed while performing PQ tests by using wide-band reference measurement units.

The ratio (phase) error standard uncertainties for the reference measurement system for characterisation of combined under PQ phenomena are:

- *25 µV/V/25 µrad at power frequency*
- *200 µV/V (200 µrad) from 100 Hz to 2500 kHz.*
- *More relaxed uncertainties were found at higher frequencies*

Conclusions

The combined expertise from 4 NMI partners allowed to develop new reference measurement systems and experiment evaluation methods for various types of ITs such as current transformers, voltage transformers, and combined transformers. These systems aim to assess the impact of ITs on the measurement of PQ phenomena. The uncertainties in the measurements of ITs ratio and phase errors with a confidence level of 95%, are quite low, within tens of part per million and microradian at power frequency and a few hundreds of part per million and microradian up to 9 kHz.
Overall, these achievements represent the finalisation of all aspects of Objective 2 by the project consortium.

Objective 3: To establish traceable test procedures for reference setups to calibrate ITs used for PQ measurements in electricity grids by covering limits for PQ disturbances in the available standards.

Objective 3 of the project was the set-up and validation of new traceable test procedures for reference setups to calibrate ITs utilised in PQ measurements within electricity grids, encompassing limits for PQ disturbances outlined in existing standards. Focus was on simplified and low cost calibration set-ups and traceable methods to be used in industrial enviroment.

Overview of the most remarkable results for this objective

As a first output, a generic test procedure was defined by SUN, and it is here recalled. The test procedure requires the generation of time combined waveforms according to Equation 7 and it can be adopted to measure the performance of IT in the measurement of a specific PQ parameter in terms of the proper PI, also considering the case of other PQ disturbances included into the test waveforms. The reference procedure always requires the presence of the fundamental component. The main steps of the procedure are given below with specific reference to assessing the IT performance in the measurement of harmonics and interharmonics.

1. *Select fundamental frequency and amplitude according to Table I.*
2. *Select frequency and amplitude of harmonics and/or interharmonics according to Table Ia.*
3. *Select the superimposed PQ disturbance and its parameters according to Table Ia or Ib.*
4. *Define different time frames (time durations and starting point for each waveforms).*
5. *Generate at least 10 repetitions of the time combined waveform.*
6. *Acquire the primary and secondary quantities and evaluate the steady-state PI for each time frame.*
7. *Evaluate mean value and standard deviation of the PI or each time frame.*
8. *Compare the indices for each time frame to assess the impact of the PQ disturbance.*

The reference procedure requires high level facilities since it involves the generation and measurement of distorted waveforms at MV level. For this reason, many efforts were put by the partners in the study and identification of architectures and procedures for simplified, but accurate calibration to be used for the characterisation of ITs in industrial laboratories. Four different simplified approaches within those proposed in the project are briefly recalled below.

Simplified Procedures and circuits

SINDICOMP-LV

This simplified method, developed by INRIM in collaboration with SUN, is intended to accurately approximate the frequency response (both ratio and phase errors) of MV inductive VTs.

The procedure requires two sets of data. The first set of data is obtained by supplying the VT at rated voltage and rated frequency and measuring the ratio and phase errors at rated frequency and the first 10-15 spurious harmonic tones at primary and secondary side of the VT. The second step is the measurement of the harmonic ratio and phase errors by supplying the VT at low voltage (LV) level and carry out a sinusoidal frequency sweep (SFS).

The method is based on the use of two suitable fit functions, one for the ratio error and one for the phase error, which are provided in the following:

$$\varepsilon_{FIT}(f) = \frac{\sqrt{(2\pi f a)^2 + b^2}}{\sqrt{\left(1-\left(\frac{f}{f_R}\right)^2\right)^2 + \left(\frac{f}{2\pi {f_R}^2}\cdot\frac{b}{a}\right)^2}} \quad (22)$$

$$\varphi_{FIT}(f) = artctan\left(2\pi f \cdot \frac{a}{b}\right) - arctan\left(\frac{\frac{f}{2\pi f_R^2}\cdot\frac{b}{a}}{\left(1-\left(\frac{f}{f_R}\right)^2\right)^2}\right) + 2\pi f \cdot \frac{a}{b} \quad (23)$$

Where f_R is the first resonance frequency and *a* and *b* are the fit parameters.

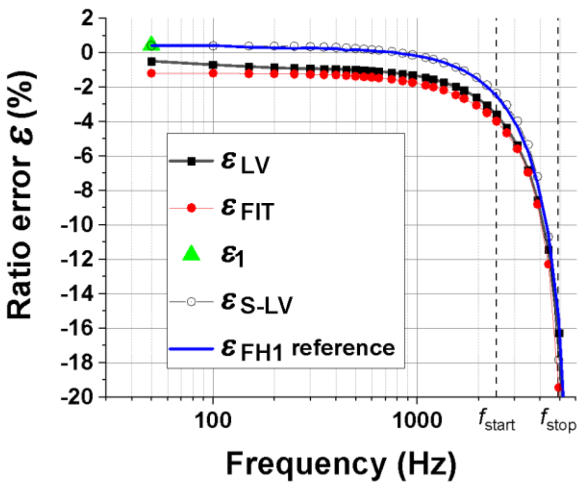


Figure 6: Representation of the SINDICOMP-LV steps for the identification of the VT ratio error frequency response compared with a reference MV frequency response.

A graphical representation of the technique is provided in Figure 6 for the ratio error. In the fitting region, that is from f_{start} to f_{stop}, the fitting function (Equation 22) is fitted to the response measured at LV (ε_{LV}). Then an offset ($\varepsilon_{OFS,a}$) is computed in order to shift the fit response ε_{FIT} to the ratio error measured at rated voltage and rated amplitude (ε_1). As final step a second offset ($\varepsilon_{OFS,b}$) is computed in order to avoid the discontinuity in the f_{start} point. At this point it is possible to obtain the approximated $\varepsilon_{S\text{-}LV}$ as given by expression (23):

$$\varepsilon_{S-LV}(f) = \begin{cases} \varepsilon_{FIT}(f) + \varepsilon_{OFS,a} & f_1 \le f < f_{start} \\ \varepsilon_{LV}(f) + \varepsilon_{OFS,b} & f_{start} \le f < f_{stop} \end{cases} \quad (23)$$

The technique was validated by comparison with the reference method adopted by INRIM for the characterisation of MV VTs (FH1 test: Frequency Sweep with fundamental tone at rated voltage with 1 harmonic tone). As a result, for all the investigated VTs, the estimate of the SINDICOMP-LV accuracy performance in the VT ratio error evaluation is found within 0.4 % up to 20th harmonic, and within 1 % up to almost the resonance frequency; as to the phase, it is always lower than 1 mrad.

Additonal Simplified Procedure for VTs

The simplified approach proposed by TUD for the frequency characterisation of MV inductive VT is again a two-steps procedure. The first generation and measurement step requires the use of a LV power amplifier in order to supply the VT under test with a bi-tone signal composed by a fundamental tone at reduced amplitude (~250 V) at rated frequency (f_R) and a superimposed tone with amplitude fixed at 5 % of the fundamental (~12.5 V) and variable frequency. Under this reduced supply conditions, the ratio errors at each frequency and other generated frequencies are measured ($\varepsilon_{U,red}(f)$).

As second step, the VT is supplied with a sinusoidal waveform at rated voltage and frequency and the ratio error is measured $\varepsilon_{ref}(f_R)$.

The approximated frequency response $\varepsilon_U(f)$ is then obtained according to Equation 24.

$$\varepsilon_U(f) = \varepsilon_{U,red}(f) - \left(\varepsilon_{U,red}(f_r) - \varepsilon_{U,ref}(f_r)\right) \quad (24)$$

Simplified procedure for characterisation of CTs for PQ by Wideband Comparator

A wideband comparator, based on the use of a precision power analyser, was developed by VSL with the scope of using it for the characterisation of CT for PQ in industrial environment. The characterisation procedure involves the generation of a distorted current signal to be applied to both the CT under test and the reference one. The two outputs of the CTs are then measured by wideband current modules of a precision power analyser. A scheme is provided in Figure 7.

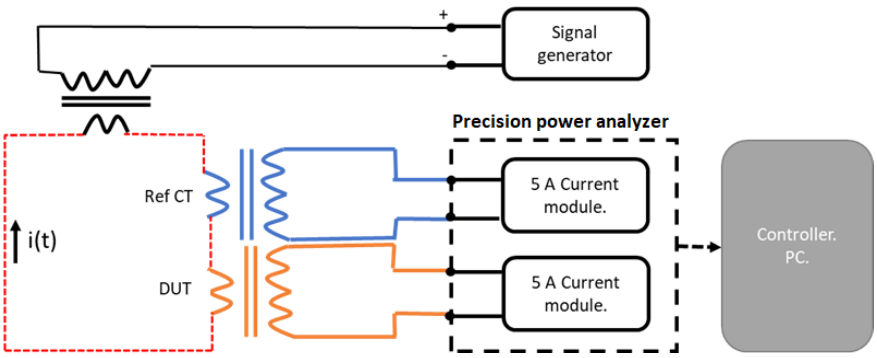


Figure 7: Schematic overview of the CT characterisation system. Generation of the high primary current, the CT-under-test (DUT) and the reference CT (which is, in fact, an electronically compensated current transformer), a precision power analyser, and the host computer.

The precision power analyser is able to acquire raw current waveforms up to 5 A, so no external transducers are needed. The raw data are then processed by the host computer, which implement the measurement in terms of PIs. The resulting wideband comparator uncertainty is within 35 μV/V and 0.2 mrad up to 5 kHz for the ratio and phase error respectively.

SINC procedure

The simplified method studied and proposed by UNIBO for the measurement of frequency response of LPCT is based on the generation of a sinc-function combined with a proper window. In fact, the sinc-function in the frequency domain can be considered a rectangular portion of the spectrum, with zero frequency components outside this window. The properties of the basic sinc function can be improved in terms of the amplitude stability of the frequency components by applying a Blackman window to it, which is described by:

$$w(n) = 0.42 - 0.5cos\left(\frac{2\pi n}{N}\right) + 0.08\ cos\left(\frac{4\pi n}{N}\right) \quad (24)$$

The impact of the use of this window is shown in Figure 8, where the time domain and frequency domain representations of the windowed sinc (blue) superimposed on the basic sinc (red) are represented.

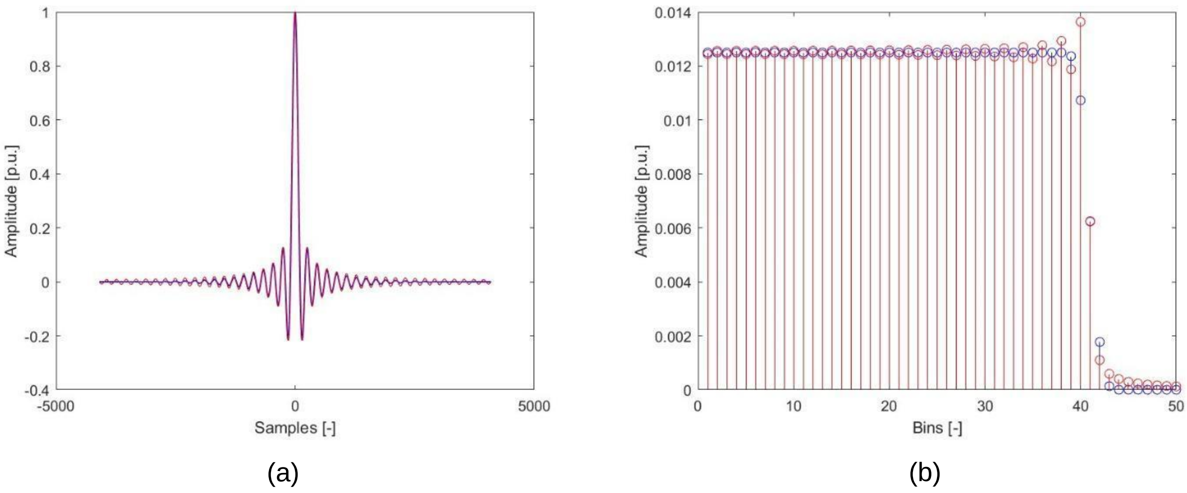


Figure 8: Time domain (a) and frequency domain (b) representation of the windowed sinc function (blue) and the basic one (red).

Conclusions

Collaboration between partners allowed the finalisation of all aspects of Objective 3. In particular, new reference circuit components as well as new simplified, but accurate methods and detailed procedures for the IT characterisation were developed and experimented. These last simplified techniques allow the test of ITs for PQ measurement in industrial laboratories using common facilities, reducing at the same time the need for expensive dedicated instrumentation. Results and experience gained were summarised in a Good practice guide for stardisation bodies and end-users, which provides detailed description of simplified calibration systems and measurement methods, as well as estimate of the accuracy limits of the considered approach.

Objective 4: To evaluate performance of ITs in PQ measurements in presence of multiple influence factors (e.g. temperature and temperature gradients, adjacent phases, proximity effects, vibrations).

Objective 4 was the analysis and the assessment of the performance of ITs and LPITs in PQ measurements when operating on-site, in presence of single and multiple influence quantities (temperature, vibrations, burden, adjacent phases and proximity effects).

Overview of the most remarkable results for this objective

Within Objective 4, the involved partners developed and experimentally validated extended methods and procedures for assessing how multiple influence factors can impact on the ITs accuracy in PQ measurements. Proper reference facilities were developed in order to perform traceable characterisation of the ITs and LPITs in the presence of PQ events and under separate and combined influence quantities. The developed set-ups and methods allowed calibration of different types of ITs (VTs, CTs, LPVTs, LPCTs and combined ITs) under the following influence quantities: temperature, vibrations, burden, adjacent phases and proximity effect. The investigated combinations of the influence quantities and ITs are:

- Vibration and temperature on VT
- Burden and temperature on VT
- Adjacent phases and proximity effect on VT and LPVT
- Frequency and burden on VT
- Adjacent phases, proximity effect, burden on LPCT
- Electric and magnetic field and proximity effect on combined ITs

Following subsections provide brief descriptions of the setups and of the main findings.

Vibration and temperature on VT

The generation and measurement setup developed by LNE for assessing the impact of vibration and temperature on VT performances in PQ measurement is shown in Figure 9.

The generation system is able to reproduce signals composed by fundamental tone at MV level with superimposed disturbances, such as harmonics and interharmonics, up to 9 kHz. The Transformer under test (TUT) was placed on a shaker inside a climatic chamber and it was tested in the presence of, single and combined influence quantities. The investigated temperature range was from -25 °C to + 55 °C whereas vibrations from 3 Hz to 150 Hz along the three directions (horizontal, longitudinal or transversal) were generated.

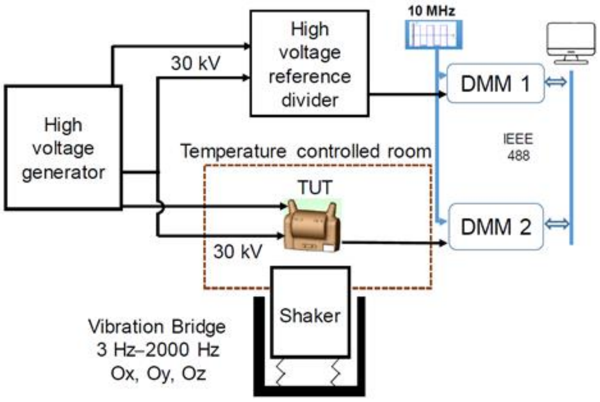


Figure 9: Schematic representation of the reference generation and measurement system for the characterisation of IT in presence of PQ disturbances under the single and combined effects of temperature and vibration

Results achieved showed that vibrations do not significantly impact on the performances of the investigated VT (rated primary voltage 30 kV and 1 % accuracy class), being the deviation measured in presence of the vibrations comparable with the measurement uncertainty (some tens of part per million). On the contrary, the temperature showed to impact on the frequency response of the tested VTs, both at low frequency (first harmonics) and more significantly close to the resonance frequency. The variations of the VT harmonic ratio errors (Equation 8) with respect to the reference value at 50 Hz and 23°C, measured under combined effects of temperature and vibration for increasing frequencies up to 900 Hz are provided in Figure 10.

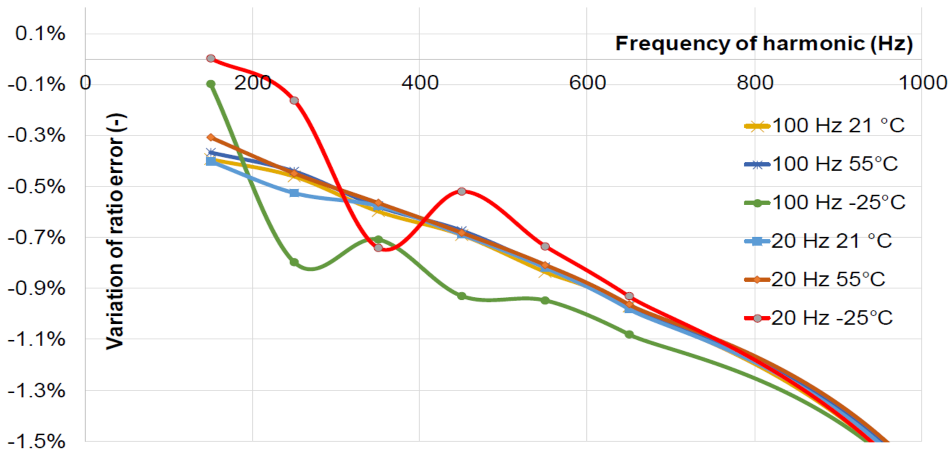


Figure 10: VT harmonic response up to 1000 Hz measured under bi-tone voltage test waveform in presence of different vibration frequency and temperatures.

The ratio error variations appear to be quite overlapped for the measurements performed at the higher temperatures (21 °C and 55 °C) independently from the vibration frequency. More significant deviations, but always below 1%), are found at the lowest temperature investigated, which can be explained considering temperature dependence of the non-linearity of the VT magnetic core.

Burden and temperature on VT

Experimental activities to quantify the effect of temperature and burden on VTs were performed by TUD. A circuital representation of the used setup and a photo of the TUT inside the thermal chamber are provided in Figure 11. The setup is able to reproduce distorted waveforms with reduced fundamental component (up to ±400 V) and it is the same setup adopted for the simplified procedure described in Objective 3 section.

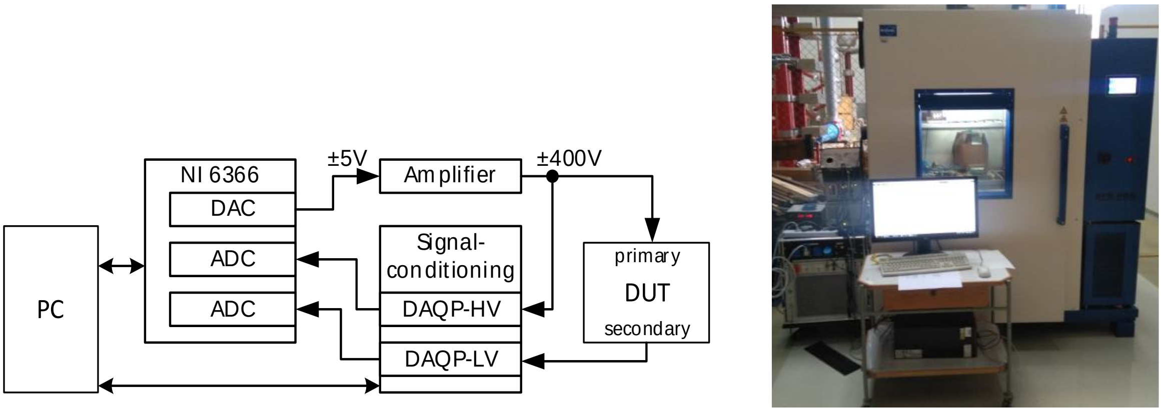


Figure 11: a) Schematic representation of DUT system for the characterisation of VT in presence of PQ disturbances under the single and combined effects of temperature and burden, b) picture of the DUT inside the climatic chamber.

A number of VTs were tested with temperature varying from -25 °C to +55 °C and resistive burden from 0 % to 100 % of the rated one. As main output it was found that the burden has a significant impact on the harmonic ratio error in the whole frequency range. Without burden, the temperature has a significant impact in the frequency range close to the resonance frequencies.

With combined influence of burden and temperature, it was found that the temperature has a nonlinear influence on the impact of burden. Figure 12 shows 3 bundles of curves vs the burden values expressed as a percentage of the rated one, measured at different interharmonics and under different temperatures:

- 55 Hz blue colour, 1205 Hz red colour and 2555 Hz yellow colour
- -25 °C circle marker, 20 °C square marker and 55 °C diamond marker

All the curves are normalized with respect to the zero burden value.

It can be observed that for all the interharmonic frequencies, the ratio error curves obtained under a temperature of 55 °C at different burden have a low deviation with respect to the same curve obtained at 20 °C. On the contrary, the curve obtained at -25°C differs significantly from the other two (up to some percents).

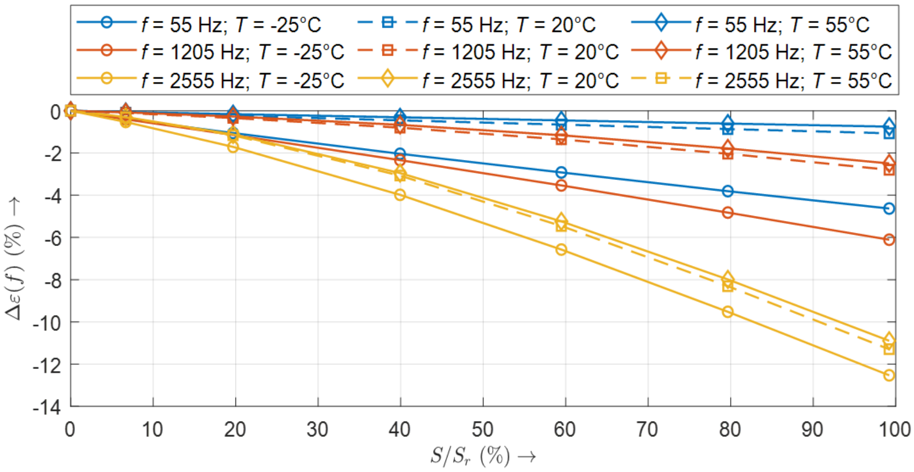


Figure 12: VT responses at three intherarmonic frequencies (55 Hz, 1205 Hz and 2555 Hz) as function of burden measured under three different temperatures (-25 °C, 20 °C and 55 °C).

Adjacent phases and proximity effect on VT and LPVT

The study of how adjacent phases and proximity impact on the performances of VT and LPVT was carried out by INRIM, making use of the developed three phase generation and measurement setup shown in Figure 13:

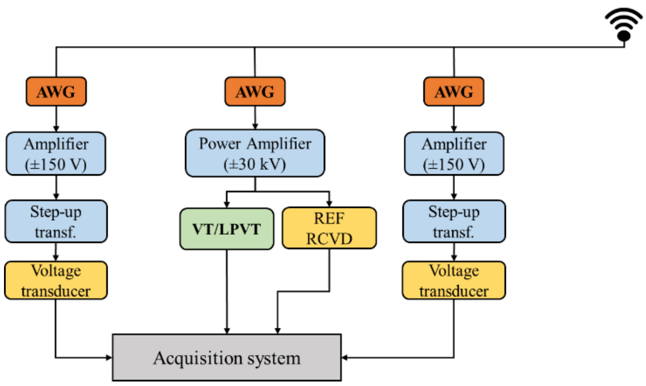
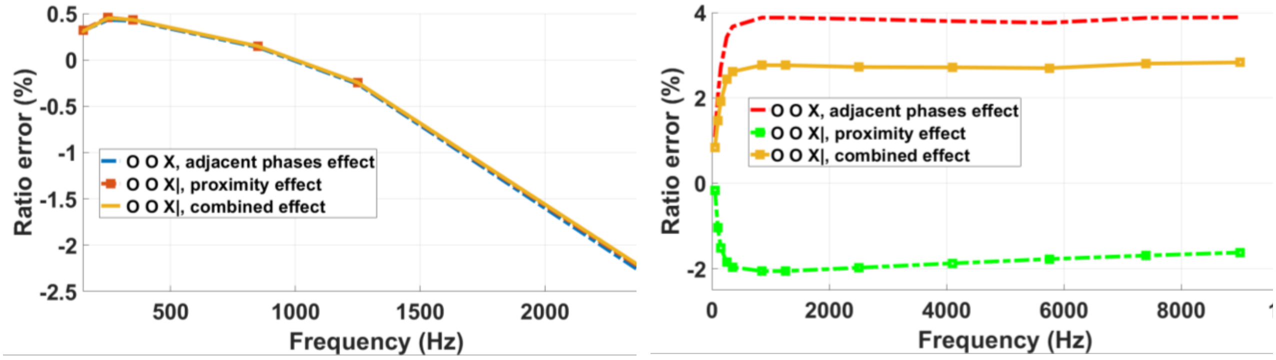


Figure 13: Schematic representation of the three phase generation and measurement system developed at INRIM for the characterisation of VT and LPVT under PQ disturbances and in presence of single and combined effects of adjacent phases and proximity effects.

Experimental activity involved testing of an inductive VT and different types of LPVT: resistive, capacitive and resistive-capacitive. The DUTs were tested in presence of signals composed by fundamental tone at MV and superimposed harmonics. The adjacent phases, cables and the metallic plate (grounded) where placed at a distance of 20 cm. Different position of the DUT (X) were investigated (the central one is represented by "OXO" and the external positions are indicated with "OOX"). The adjacent phases were supplied as in-phase voltages or three-phases voltages. In addition, measurement was performed also with the two adjacent phases grounded.

Not surprisingly, it was found that when the three-phase configuration is adopted, the measured results were comparable with the results measured under grounded adjacent phases conditions. On the contrary, the in-phase case results can differ up to some percent with respect to those obtained with grounded adjacent phases.

The two influence quantities investigated had a significantly different impact depending on the tested devices. For example, Figure 14 shows the ratio error responses of the inductive VT and the resistive-capacitive LPVT vs frequency up tp 2 kHz. It can be observed that for the inductive VT, the curves measured under single and combined quantities are well overlapped, so the impact of combined influence factors appears not significant, whereas for the resistive-capacitive LPVT, differences of several percents are observed.



(a) (b)

Figure 14: VT (a) and resistive-capacitive LPVT (b) frequency ratio error responses under single and combined effects of adjacent phases and proximity.

Note: The symbol ‘O’ refers to the adjacent phases, the symbol “X” to the DUT, the symbol “|” represents the presence of the grounded metallic plate.

Power frequency variation and burden on VT

The reference generation and measurement system developed by INRIM within Objective 2 and represented in Figure 2 was exploited to perform experimental tests to assess the impact of power frequency variation and burden on VT. The power frequency was varied in the range 50 Hz ±15 % whereas, inductive (power factor 0.8) burdens from 0 % to 100 % of the rated value were investigated.

The measured results suggested that power frequency variation has low impact (less than 0.1 % for the ratio error). As the burden, its impact on the VT harmonic response is a bias value that is quite constant over the useful frequency bandwidth.

As the combined effects, the burden effect on the harmonic ratio error remains consistent regardless of the power frequency value.

Adjacent phases, proximity effect, burden on CT and LPCT

Influence of the primary and adjacent phases on inductive CTs and a LPCT (RC) wers investigated by PTB, focusing on the current sensor accuracy performance at 50 Hz. Effects of conductor postions were estimated considering both the primay conductor, and perturbing effects effects generated by the return conductor distance, as well as sensor connector positions. Tests were performed with 100 A and rated burden. For the investigared influence parameters and sensors, the centering of the primary conductor was the dominant effect, which is particular significant for the RC, leading, for the worst case, to ratio errors up to twice the maximum errors expected according to the RC rated performances (0.5 accuracy class).

To estimate the effects of adjacent phases, the errors induced by an external conductor, with no primary current linked with the coils were measured, considering various distances of the external conductor and various CT connector positions. The highest ratio errors, of the orders of hundreds of parts per million, were founded again for the investigated RC, which are dominated by the sensor connector position.

Impact of adjacent phases, proximity and burden on the wideband performance of LPCT from different manufactures was assessed by UNIBO.

A representation of the experimental setup designed and developed for this activity is provided in Figure 15.

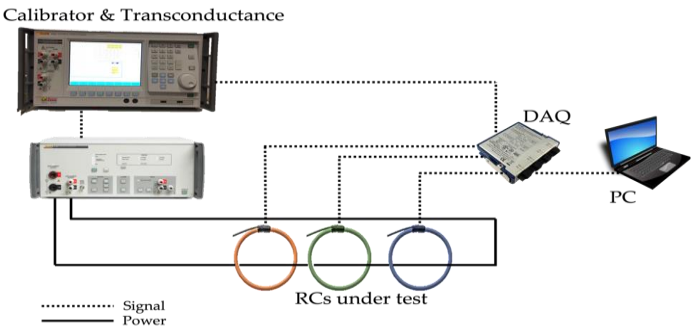


Figure 15: Schematic of the UNIBO measurement setup.

The generation and measurement setup was employed to test three off-the-shelf Rogowski Coils (RCs) from different manufacturers under sinusoidal and distorted current conditions. The RCs were tested under three different current conditions: pure sinewave, multitone signal with *THD* = 4.8% and multitone signal with *THD* = 9.2 %.

As regard the influence quantities, the impact of the resistive burden was assessed by selecting 5 values: rated burden B_R=2 MΩ, B_1=1.8 MΩ, B_2=2.2 MΩ, B_3=1 MΩ, B_4=1000 MΩ, whereas for the adjacent phases and proximity, four position of the primary conductor were investigated:

- centred conductor aligned with the RC axis, as in Figure 15;
- conductor almost perpendicular to the RC axis;
- tilted conductor at an angle of less than 90° with respect to the RC axis;
- conductor perfectly centred and with an additional parallel external conductor situated near the outer surface of the RC This last case was intended to examine the impact of external magnetic fields generated by other phases or return conductors.

As for the LPVT, also for the LPCT it was found that each investigated RC having specific manufacturing solutions responds differently when exposed to various influence quantities, so the impact of the considered single influence quantities, or superposition of the single effects, cannot be estimated a priori and the combination of two or more non-ideal conditions may result in unexpected behaviors, making tests necessary.

Electric and magnetic field and proximity effect on combined LPIT

The TUBITAK three-phases reference generation and measurement system derived form the one developed within Objective 2 (Figure 4) and shown in Figure16 was used to assess the impact of electric and magnetic fields on combined ITs.

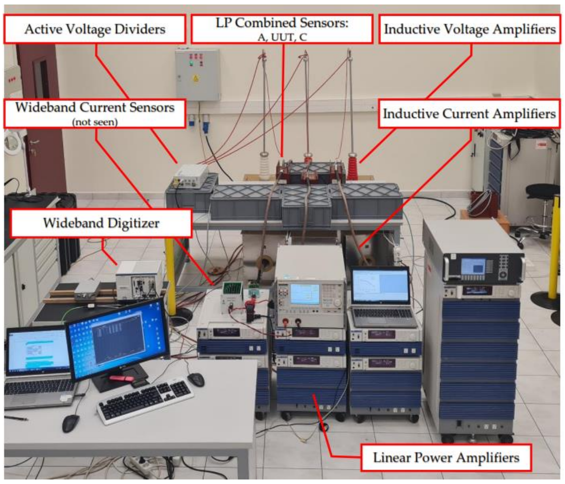


Figure16 – TUBITAK three-phase measurement set-up for the characterisation of combined ITs and LPITs in presence of influence factors

Testing was concentrated on the current measuring sensor (RC) of a LP MV combined sensor, along with two additional identical combined ITs. The 3 RCs tested have a nominal primary current range of 1600 A, a nominal output voltage of 0.150 V (at 50 Hz), and 0.5 accuracy class.

The combined sensors are arranged and supplied under in-phase and three-phase conditions analogous to those indicated for the "*Adjacent phases and proximity effect on VT and LPVT*" section. In this case, the proximity test was carried out by modifying the path of the primary current conductor, by aligning it 90 °C downwards at a 1 distance at 20 cm from the sensor axis.

Based on the experimental results, the RC of the tested combined sensor was found to be affected both by adjacent phases and proximity effects. As to the adjacent phases tests, the in-phase and three-phase supply conditions show similar ratio error variations with respect to the stand-alone measurements at frequencies different from 50 Hz, where the error variations are up to the percent. As to the proximity effects, the effect is detectable, but not so significant.

As to the combination of both the investigated influence quantities, results showed that the combined effect is larger than their individual impacts, but lower than the summation of the single effects.

Conclusions

The analysis of the results of the extensive measurement investigation carried out to both identify and quantify the most critical influence quantities delineate their most detrimental combinations and highlighting those quantities that do not significantly impact the frequency performance of ITs. As for the interactions between two influence quantities and their combined impact on the frequency performance of ITs, they are not easily predictable a priori, being strongly dependent on the considered ITs, in terms of both the operating principle and construction solutions adopted. Results and experience gained were summarised in a Good practice guide for standardisation bodies and end-users on extended methods and procedures for the evaluation of ITs for PQ measurements in the presence of multiple influence factors. The relevant open access data set of measured data was also published.

5 Impact

To facilitate and maximise the impact of the project, outputs generated within the project have been disseminated by specific actions targeted to the standardisation, industrial and scientific community.

A Stakeholder committee was established, which included 25 members by the end of the project, from the community of manufacturers of instrument transformers and test and measuring instrument, transmission and distribution system operators, test laboratories and a national authority. 3 stakeholder workshops were held, with a significant presence from industry and several meetings and presentations were given.

To disseminate knowledge and outputs from the project, 27 peer reviewed open access publications have been produced, 13 presentations were given at international conferences including CPEM2020, I2MTC2021, CIRED2021 and 2023 and AMPS 2022 and 2023. With a specific focus on power quality measurement, a special session focused on IT4PQ project outputs has been organised at the ICHQP2022. Two papers were published in national trade journals.

Ten datasets relevant to publications, one dataset of measurement data vs test conditions relevant to IT performance characterised in the presence of separate and combined influence factors were produced and made available on the IT4PQ Community Zenodo repository. Indications and good practice guides were produced and made available to IEC TC 38 and in particular to its WG47.

Impact on industrial and other user communities

Inadequate quality of the electrical grid power at all voltage levels is a cause of malfunctioning or damage of industrial equipment such as lifetime reduction of dielectric insulations, relay tripping, over-heating in motors, etc. Voltage reductions and interruptions are often the source of outages and, consequently, can lead to significant economic losses for all the different manufacturing companies. The project outputs in terms of reference systems and procedures as well as measured data made available on ITs are supporting the quality and continuity of the electrical supply, so reducing possible damages and costs consequent to outages for the industry in particular. Manufactures of IT and IT test systems, as well as test and calibration laboratories, need calibrated reference systems and adoption of suitable tests procedures for PQ, ensuring traceability of the measurement performed, to extend their products/services to PQ measurement. Traceability and adoption of common and standardised test procedures, also ensure their operation in fairer market conditions.

As first, but significant early uptakes of project outputs, 4 wideband characterisation of commercial inductive VTs and LPITs to be used for PQ measurements have been provided to manufacturers, who are active in the electrical measurement sector, being one of them an on-site calibration. In addition, one demonstration was given in the manufacturer premises of the simplified methods developed for the accuracy tests of combined ITs, as developed within the project.

Implementation of the developed simplified procedures for ITs calibration in industrial laboratories will allow a lower costs and faster IT calibration in a hard environment with a higher, but still acceptable uncertainty with respect to the one associated with the reference systems operating at NMIs.

From the perspective of grid operators, they can dispose of accepted methods and procedures to assess the level of "quality" of their product (the electrical grid power supply), with a given level of uncertainty, to make the most effective investments to take corrective actions to improve it.

Finally, the National Regulatory Authorities will rely on trustworthy measurements of the quality of the energy at all voltage levels, in a more consolidated framework, to improve the protection of consumers' interests and promote competition and efficiency.

Impact on the metrology and scientific communities

The measurement methods, reference setups and protocols developed in this project enables extended testing of the main types of ITs (voltage/current, inductive/LPIT, analogue/digital output) to PQ conditions representative of the realistic ones, also considering simultaneous presence of more than one influencing factor, ensuring traceability of measurement results to national reference standards. This will allow, first of all, the extension of calibration and measurement capabilities (CMCs) of NMIs involved in the project, which, in the near future, will be able to support the increase of the metrology capacity of EURAMET Member States whose metrology programmes are at an early stage of development. First calibrations on an extended frequency range under a distorted sinudoidal sweep have been performed both in laboratory and on-site as regards ITs, LPITs and combined ITs and relevant CMCs are under definition.

The project will also impact on the scientific community through application of the new reference systems and measurement methods, as well as of the IT characterisation results made available, to the investigation of new systems, materials, and components under realistic and harsh PQ conditions. Application of the systems and methods developed will also allow obtaining reliable input data with defined uncertainties, for the study, the analysis, and the smart control of the electrical grids.

Impact on relevant standards

As a first early impact, this project has provided the metrological measurement framework, including the measurement methods, test procedures and instrumentation, as well as the experimental data which will facilitate and contribute to the standardisation relevant to the use of Instrument Transformers for PQ measurements, a topic that is not covered by a dedicated standard at international/national level yet. The knowledge developed has benefited in particular the IEC TC 38 “Instrument Transformers”, which was the project Chief stakeholder organisation and whose role was to keep aligned the project progress and outputs with the need of the stakeholder community, as well as the CENELEC TC 38. This was facilitated by the links of project partners both in terms of working group membership and role (RSE hast the convenorship of IEC TC38 WG 47 "Development of instrument transformer for the market evolution" and UNIBO is the convenor of JWG 55 "Uncertainty evaluation of the calibration of Instrument Transformers" and Secretariat of CENELEC TC 38, participation of partners in the mirror national committees). These strict links with IEC TC 38 ensured a continuous exchange of knowledge between the project partners and the various TC WGs making possible an effective contribution to the revision or the issue of new standards/reports focused on use of ITs for PQ or, in general, on the topics connected to ITs (standards of the 61869-X series).

Overviews of IT4PQ activity and progress have been presented at the Plenary meetings of the IEC TC 38 and the associated TC 38 Workshops as well as to the Plenary meeting of CLC TC 38. Regular contacts have been kept with the IEC TC 38 “Instrument transformer” WGs, providing information on the project objectives and outputs to the WG 49 Instrument transformers for low voltage applications. A strong liaison was established in particular with the IEC TC38/WG 47, which is in charge of preparing the evolution of the requirements contained in IEC TC 38 standards on ITs, to take into account the technological evolution and the new needs associated with emerging applications, such as power quality.
Detailed inputs were regularly provided at the 3 annual in-person and web meetings of IEC TC 38/WG47 and at two IEC TC 38 Chair advisory Groups meetings and at the monthly meeting of the IEC TC 38/WG55. One full day for presentation and discussion was dedicated to IT4PQ during the IEC TC 38/WG47 meeting in

November 2022, which was jointly organised by the IEC TC 38/WG47 and IT4PQ, as well as the Final stakeholder workshop in June 2023.

All input information presented and discussed during the TC IEC 38 and IEC TC 38/WG meetings have been provided as presentations and or documents and made available to all the IEC TC 38 WGs on the dedicated area of the IEC Collaboration platform.

Presentation and discussion of project achievements and outputs was focused in particular on the following items, which have been identified as of particular interest by IEC TC 38/WG 47:

• Literature and standards about PQ and ITs and proposed ranges of variation for ITs tests

• Test Waveform and performance indexes proposed for ITs characterisation

• Accuracy and uncertainty limits, as a PQ accuracy class definition for ITs to be used in PQ measurements in distribution grids with rated voltage up to 36 kV and currents up to 2 kA.

• Simplified Calibration setups and traceable methods to be used for the characterisation of instrument transformers in industrial premises.

• Good practice guide on extended methods and procedures for the evaluation of ITs for PQ measurements in the presence of multiple influence factors.

Advancement and achievements of interest for the Chief stakeholder organisation have been collected in an overall input document, whose draft has been provided to the IEC TC 38 WG/47 as the IT4PQ contribution to the revision work in progress of the technical report IEC/TR 61869-103 and other IEC 61869 standards dealing with the definition of methods, procedures and accuracy limits for the evaluation on ITs in PQ measurements.

Input by the project partners have been regularly provided to the IEC WG 55 during the projects meetings and a specific presentation was given in March 2023. A document dealing with the problem of assessing the uncertainty of voltage and current comparators under distorted waveforms has been provided to the IEC TC 55, whose content is the base for an IEEE AMPS 2023 paper.

Contacts and technical exchanges with IEC SC 77A “Standardization in the field of electromagnetic compatibility with regard to low frequency phenomena (ca <= 9 kHz)” and IEC TC 85 “Measuring Equipment for Electrical and Electromagnetic Quantities” were also established during the Stakeholder workshops.

Longer-term economic, social and environmental impacts

A secure and reliable electricity supply is of the utmost importance for society as whole. To guarantee a good quality of the supplied energy will increase the efficiency of the energy transmission and distribution system and, at the same time, contribute to the reliability and safety of the electrical supply in Europe.

Being that instrument transformers are a needed component for PQ evaluation in distribution grids, the evaluation of the uncertainty associated with the measured value of a PQ parameter with a defined level of confidence has to be performed by considering the contribution of the ITs. The outcomes of this project in terms of methods and procedures consent an overall estimate of the uncertainty in the quantification of PQ events with a defined level of confidence, so that more appropriate actions aimed at solving a PQ related issue, which can imply a significant financial investment, will be taken by the grid involved actors on the basis of an effective estimate of the grid conditions.

On a societal level, the adoption of standardised procedures in PQ measurements with a quantifiable level of uncertainty can contribute to the" legal certainty" in disputes, when assessing responsibilities in equipment malfunctioning and production outages.

Since the presence of PQ polluting devices is increasing more and more in the electricity grids, performing accurate PQ monitoring is essential to guarantee the reliability of our daily electricity supply. This project supported its development by providing the IT related required knowledge and calibration facilities, needed for a trustworthy design and production of future grids, to prevent outages and foster efficiency of the electrical distribution systems.

Advantages are expected also from the environmental point of view, since a better control of the grid conditions will lead to a decrease of PQ issues with a consequent increase in the useful life of equipment and a reduction in waste products in case of production outages, with a positive impact also from the economic point of view.

6 List of publications

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7 Contact details

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