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Assessment of Instrument Transformer Accuracy for Power Quality Measurements in Distribution Grids: Recent Activities and First Results from 19NRM05 IT4PQ Project

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ASSESSMENT OF INSTRUMENT TRANSFORMER ACCURACY FOR POWER QUALITY MEASUREMENTS IN DISTRIBUTION GRIDS: RECENT ACTIVITIES AND FIRST RESULTS FROM 19NRM05 IT4PQ PROJECT

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Abstract

Extensive integration of renewables in the electrical energy distribution system is essential for the implementation of “green growth” strategies. However, it contributes to the degradation of the quality of the electrical power, as such power quality (PQ) monitoring holds greater and greater importance. Currently, there are no standards related to the characterisation of the instrument transformers (ITs) for PQ measurements, even if ITs can introduce significant errors in the PQ measurement chain. Therefore, a project has recently funded to investigate gaps in accuracy assessment and characterisation of ITs when used in PQ measurements and to work out specific performance indices, reference measurement systems and test procedures to evaluate the ITs accuracy and uncertainty contributions in PQ measurements. Guidelines and recommendations for the calibration of ITs used in PQ measurements will be provided to the Technical Committee IEC TC 38.

1. Introduction

Extensive integration of renewables in electrical energy distribution system is essential for the implementation of “green growth” strategies, but also contributes to the increase of grid disturbance levels. Monitoring of Power Quality (PQ), namely voltage and current quality, is thus of critical importance to ensure Electromagnetic Compatibility (EMC) and will become a fundamental part of future grid operation. Given the voltage levels of the medium voltage (MV) distribution grids, instrument transformers (ITs) are required between the measurement point and the PQ measurement instrument to adapt the high primary voltages and currents to the low voltage (LV) inputs of the used instrument. However, ITs can introduce significant errors in PQ measurements (e.g. due to their frequency-dependent transfer characteristics or intrinsic non-linearities), but they are qualified and tested at power frequency only. So their contribution to the measurement uncertainty in PQ measurement is generally assumed equivalent to that estimated at 50 Hz/60 Hz or even not taken into consideration. On this subject, the research project 19NRM05 IT4PQ started in 2020 within the European Metrology Programme for Innovation and Research (EMPIR) [1]. The project aims to fill the knowledge gaps regarding accuracy assessment and definition of methods for the traceable characterisation of ITs when used in PQ measurements. It intends to develop the needed metrological framework from the national metrology institutes to the manufacturer laboratories, providing contributions to standardisation.

In the following, after a brief discussion of the background, most relevant issues and knowledge gaps, an overview of the project is given, focusing on the objectives to be achieved and the methodological approach to fulfil them. Finally, first actions implemented and preliminary results are presented.

2. Background and open issues

2.1 Use of ITs in the measurement of PQ parameters

Quality of the transmitted and distributed electrical power is defined in terms of a number of parameters, whose values quantify the deviation of the actual grid voltage and current conditions from its ideal behaviour. They are also used to define quality requirements in standards like [2]. For both the grid operators and the prosumers it is important that verification of compliance of the grid PQ parameters with relevant requirements is carried out by making use of measurement systems that can provide traceable measurement results [3] and whose characterisation is obtained following standardised and shared procedures. Measurement of grid disturbances is of great importance also for the early detection and location of disturbances, with a view to grid predictive maintenance.

As regards the PQ measuring instruments, quantities to be measured, uncertainties and instrument test methods are well defined and standardised in [4] and [5]. However, the standards explicitly exclude the accuracy requirements for external transducers. As to voltage and current transducers, PQ measurements are quite often carried out by using the already installed inductive ITs, which have to measure phenomena that can be quite different from the power frequency ones. Data reported in literature concerning voltage instrument transformer (VT) shows that systematic errors are introduced with the increase of the frequency due to the stray capacitive effects, depending on the VT primary voltage levels (Fig. 1a). In addition, magnetic core non-linearity of inductive ITs can affect its frequency response at low frequency [6], [7] and measurements can give different results, depending on the characteristic of the test, e.g. LV sweep or harmonic frequency sweep performed with the fundamental tone at rated voltage (Fig. 1b). As an alternative, a new generation of ITs, with low power output (LPIT) and better linearity, is now available. As to LPITs, literature mostly concentrates on the analysis of their frequency performance and

circuit influence quantity effects, but a quantitative and structured analysis of the errors introduced, considering their different operating principles, is missing.

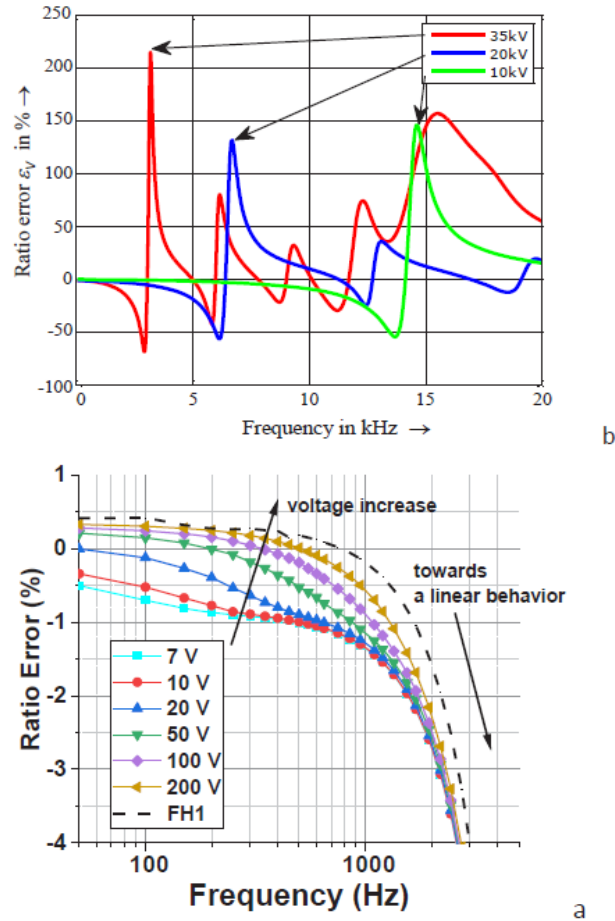


Fig. 1 (a) Ratio error measured frequency behaviour for different primary voltage VTs (10 kV to 30 kV); (b) 20 kV VT ratio error vs frequency measured at various LV amplitudes and at rated voltage plus single harmonic sweep (FH1).

Despite these considerations, no standard has been presently issued giving specific indication on tests to be performed to qualify ITs for power quality measurements. Accuracy class for harmonics measurements are only given in [8] and [9]. The technical report IEC TR 61869-103 [10] is the only document that summarises the main PQ parameters and gives an overview of the main IT types and expected impact on the accuracy of measuring the PQ parameters. The report underlines that for most IT type there are not enough data available in literature and suggests schemes of possible setups for test execution as well as proposes the introduction of PQ accuracy classes. Nevertheless, all the potential effects of ITs on the measurements of PQ parameters have not been addressed and data for a structured knowledge and classification of their behaviour is missing.

2.2 Simultaneous presence of influence quantities

Performance of ITs can be significantly affected by several influence quantities. This is considered by present international standards of the IEC 61869-X series about IT testing, which take the effect of influence quantities such as burden, temperature, vibration and electric field produced by adjacent phases on the IT performance into account, but only individual and only at power frequency.

They do not consider that under practical operating conditions more than one of the above quantities can be present at the same time.

As to literature, attention is generally focused on the analysis of one parameter at a time [11], with focus on the relatively new generation of LPITs. This aspect is critical as some analysis shows that their effects cannot always be simply linearly combined. Evaluating whether and how the combination of more than one influence quantity affects the PQ indices measurement is therefore a further open problem.

3. Project Overview

3.1 Objectives

The project IT4PQ aims to fill the knowledge gaps on the impact of PQ phenomena on ITs behaviour and to set up a complete metrological framework, to foster the adoption of common and shared procedures for the characterisation of ITs for PQ measurements in distribution grids. This is represented by four specific technical objectives that are:

1. the definition of accuracy and uncertainty limits of ITs in PQ measurements, extending the concept of IT accuracy class, now adopted at power frequency only, to the measurement of PQ parameters;
2. the development of suitable reference measurement systems, for the accurate characterisation of ITs;
3. the development of suitable test procedures to calibrate ITs used for PQ measurements in electricity grids by at least covering limits given for PQ disturbances;
4. the determination of the ITs performance in PQ measurements under multiple influence quantities.

A brief description of activities that shall allow achievement of the previous objectives and their operative implementation scheme (Fig. 2) are given.

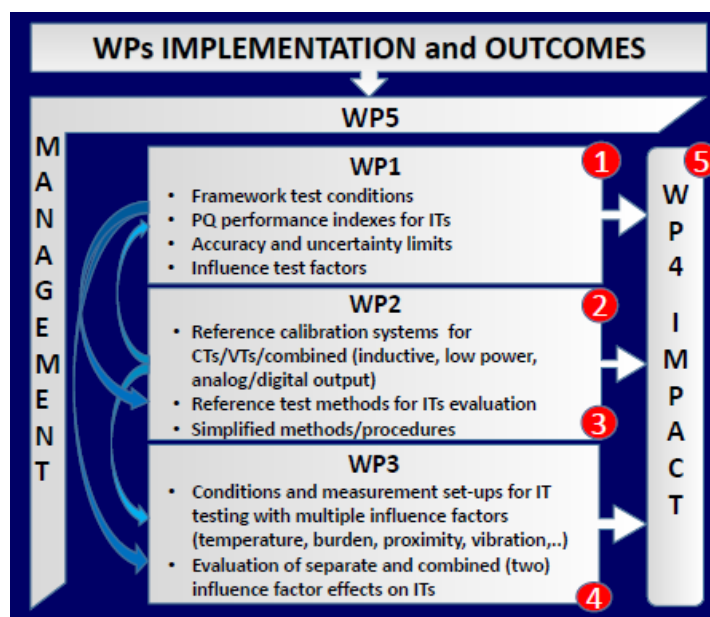


Fig. 2 Work package implementation

3.2 Activities and implementation

The first step leading to the definition of uncertainty and accuracy limits (objective one) is the identification of a suitable “performance index” that can quantify the error introduced by the IT in the measurement of the single PQ parameter for each considered power quality phenomena (e.g. the total harmonic distortion). An “aggregated” performance index that can directly qualify the overall ITs PQ performance is derived afterwards. Next, different classes of limits for this synthetic index are introduced based on a deep knowledge and classification of the errors introduced by the ITs when measuring the PQ parameters.

To gain such a knowledge, suitable generation and reference measurement set ups are developed based on the expertise and hardware already existing in the national metrology institutes (NMIs). Such a systems must be capable of reproducing and accurately measuring realistic PQ stationary and transient phenomena that will be used for the IT characterisation. Validated methods for the evaluation of the uncertainty contribution of ITs to the measurement of the PQ phenomena will be made available. A set of instrument transformer samples, representative of the different types, will be selected and their behaviour assessed with the realised calibration systems using the developed PQ performance indices to prove and validate the feasibility of the proposed approach.

In addition, to support IT manufacturers and calibration and test laboratories, simplified calibration methods and setups as well as IT test procedures will be studied, analysed and build up with integration of the previously developed and validated metrics for the PQ indices. To address the performance of ITs in PQ measurements in the presence of more than one influence quantity, attention is focused in the project on a selected list of influence quantities (burden, temperature, vibration, power frequency, magnetic and electric field produced by adjacent phases, proximity effect) and for selected PQ phenomena.

Superposition of two quantities at the same time is considered. To evaluate if and how the combination of more than one influence quantity affects the PQ performance indices previously defined, the effects of each of them are determined individually, according to the test conditions reported in the relevant standards. The test results are then compared with those obtained by applying both influencing quantities at the same time.

3.3 Consortium

The project consortium (Table 1) consists of six NMIs, three universities and one research centre with complementary competences.

Table 1 Consortium

Institution	Country
Istituto Nazionale di Ricerca Metrologica	Italy, Coordinator
Cesky Metrologický Institut	Czech Republic
Laboratoire National de Métrologie et d'Essais	France
Physikalisch-Technische Bundesanstalt	Germany
Türkiye Bilimsel ve Teknolojik Arastırma Kurumu	Turkey
VSL B.V.	The Netherlands
Ricerca sul Sistema Energetico–RSE S.p.A.	Italy
Università degli studi della Campania Luigi Vanvitelli	Italy
Technische Universität Dresden	Germany
Alma mater studiorum Università di Bologna	Italy

The presence of a stakeholder committee (composed by representatives of distribution and transmission system operators, regulatory authorities, instrument manufacturers, test laboratories) and a Chief stakeholder (IEC TC 38) maximizes the project impact, ensuring that activities are kept aligned with the stakeholder needs.

4 First selected activities and results

In the following subsections a brief description of first activities and results related to the selection of PQ parameters, reference test setups and tests with multiple influence quantities are provided.

4.1 Selection of PQ phenomena

A preliminary selection of PQ phenomena from literature and present standards such as [4] to be considered in the project is given in Table 2 including brief motivation why they are selected or not. A detailed analysis has suggested that considering harmonics, interharmonics, subharmonics, supraharmonics distortion and transients can cover most potential issues for ITs when used for PQ measurements.

Table 2 Selection of PQ parameters

Parameter	Motivation/Comments	Selected
Supply voltage variations	Test already included in present IT standards	No
Power frequency variations	Frequency variations up to 15% permitted, phase jump tests included	Yes
Harmonics, supraharmonics, interharmonics, supraharmonics	IT complex transformation ratio can vary with frequency, test conditions to be identified, THD included	Yes
Dips, swells interruptions	Not expected significant *preliminary tests on VTs to be carried out	No*
Flickers	Information from interharmonic and modulation tests	No
Modulations	Modulation of main signals	Yes
Transient signals	Transient phenomena, burst of transients	Yes

4.2 Reference Systems for IT calibration

4.2.1 Reference setup for current waveform generation: The setup of a calibration system for current transformer (CT) calibrations up to 2 kA, 9 kHz, under development at PTB, is shown in Fig. 3a. It is mainly made up of a high current generation system (red block), a set of analogue reference current transformers (green block) with associated precision resistors and a precision two-channel measuring system (purple block). The synchronization signals ("Sync.") are needed when the output of the device under test (DUT) is a sampled value data stream (SVs). The synchronization signals can be obtained by GPS receivers and be transmitted as pulse per second (PPS), IEEE 1588-2008 (PTPv2) and inter-range instrumentation group B (IRIG-B) [12]. An example of generated current waveform is shown in Fig. 3b.

4.2.2 Reference setup for voltage waveform generation: The block diagram of the setup

being developed at INRIM is shown in Fig. 4a. The system is based on a National Instruments PXI platform. Test waveforms are generated by an arbitrary waveform generator (AWG) and amplified (up to 30 kV peak, DC to 2.5 kHz, 30 kHz at reduced amplitudes). The 10 MHz PXI clock is used as reference for AWG Phase Locked Loop (PLL) and to obtain the comparator master time base. The clock is synchronized by the NI 6688H module using various sources as GPS and PTP. An example of generation capability (five harmonic tones signal with imposed 6.3% total harmonic distortion (THD)) is shown in Fig. 4b.

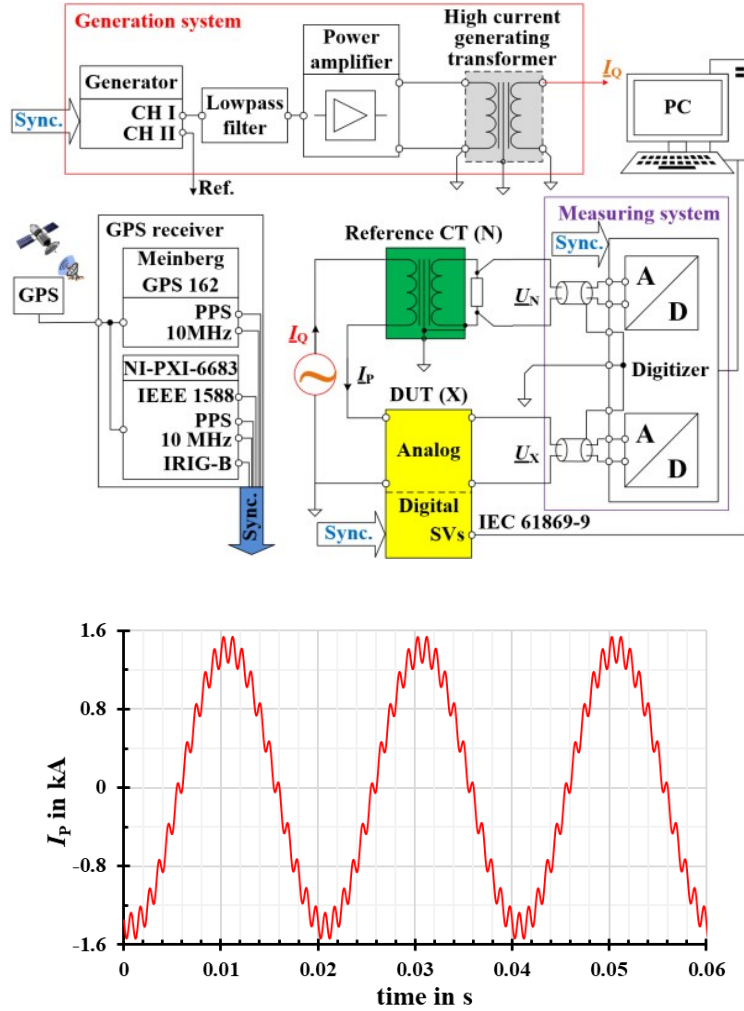


Fig. 3 (a) Distorted high current generation and measurement set up, (b) dual tone current (50 Hz, 1 kA, 21st harmonic current with 10% amplitude).

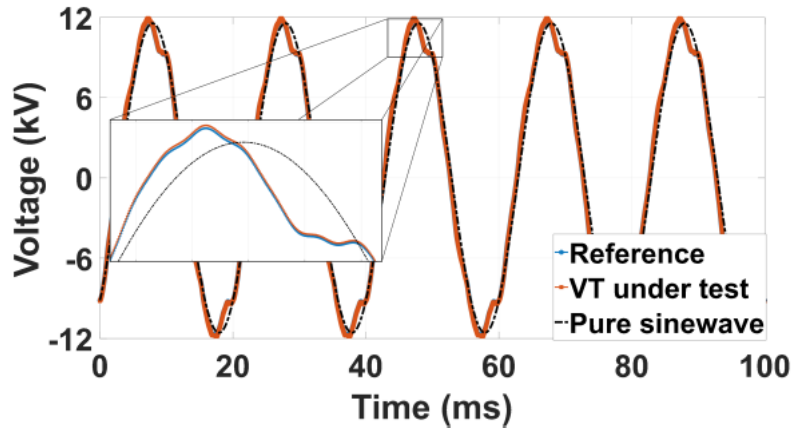
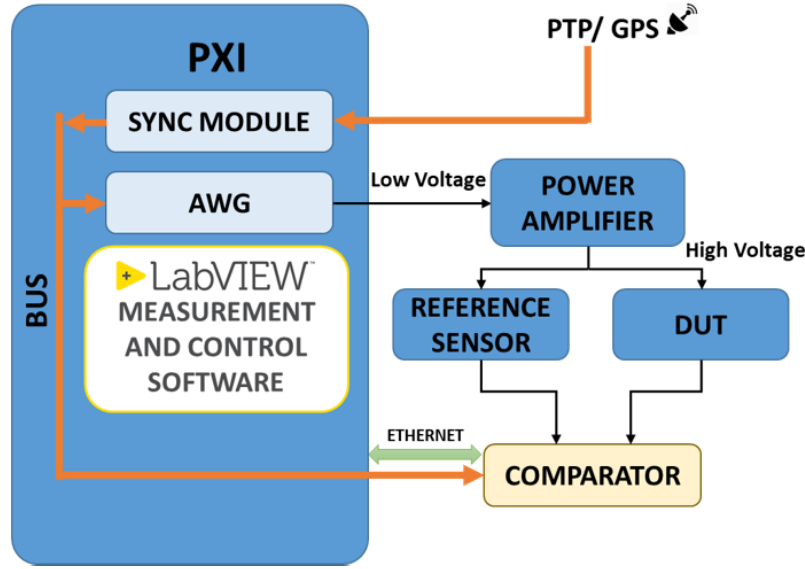


Fig. 4 (a) Block diagram of the PQ event generation and measurement circuit, (b) multitone signal with fixed THD (6.2%).

The deviation between the THD measured by a $20 \text{ kV}/\sqrt{3}$ VT (red curve), tested at 80% of its rated value, and by the reference sensor (blue curve) is found to be 0.6%. The single harmonic tone ratio errors vary from 0.51% for the 5th harmonic tone (amplitude 4% of the fundamental tone) down to -0.7% at 1.5 kHz (amplitude 0.3% of the fundamental one), due to decreasing frequency response trend (Fig.1b)

4.3 Combined effect of thermal cycles and electric fields

Off-the-shelf 0.5 class LP voltage transformers (LPVTs) based on different operating principles were tested for accuracy at power frequency under combined presence of temperature variations and stray electric field [13]. The ratio and phase errors of capacitive LPVT were first measured at rated voltage ($20/\sqrt{3} \text{ kV}$) by comparison with a reference 0.1 class VT coupled with a LV resistor divider. Ratio error measurements were performed under a thermal cycle according to [8] from 5 °C to 40 °C, inside a thermostatic chamber. Measurements were then repeated by applying both the same thermal cycle and an external electric field [14]. Fig. 5 shows the ratio error of a capacitive LPVT measured during a thermal cycle in absence (orange bar) or presence (green bar) of an external electric field, where parameter τ is the LPIT thermal constant (60 min). Also the limits of the ratio error are indicated. The IT errors measured in absence of the electric field clearly follows the thermal cycle. The simultaneous presence of temperature and electric field does not seem to significantly affect the LPVT error, except for the lowest temperature (steps #7 and #8). In this

situation, the increase of the ratio error, probably due to the long stay (2τ) at low temperature, appears to be compensated by the effect of the electric field on the LPVT, resulting in the ratio error being within the accuracy limits.

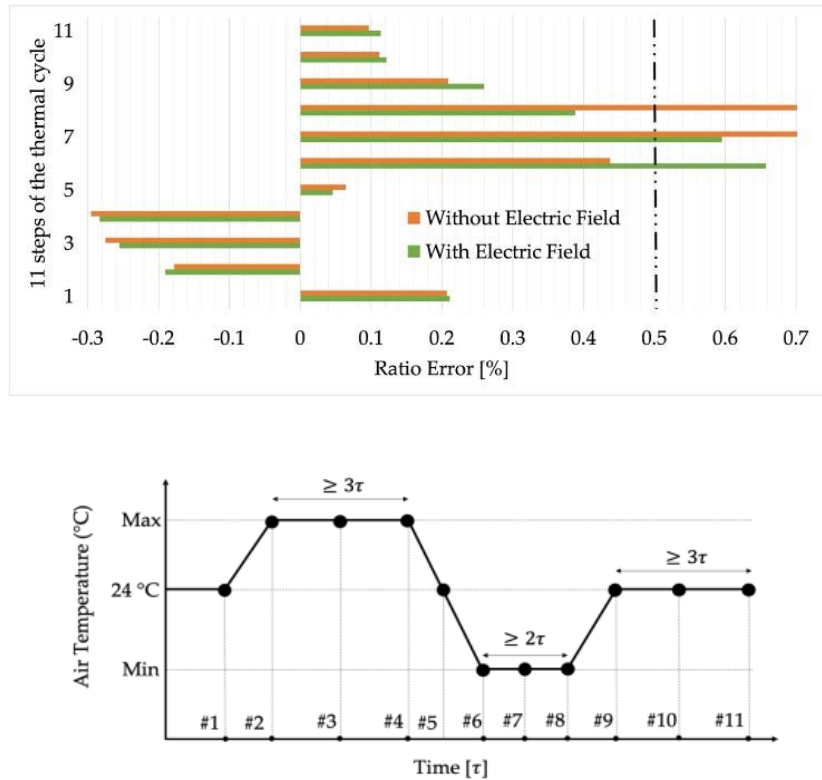


Fig. 5: (a) LPVT ratio error measured at different steps of the thermal cycle (b), in absence (orange) and in presence (green) of an external electric field.

5 Conclusions

Objectives, main activities and first results of research project EMPIR 19NRM05 IT4PQ have been presented and discussed. Starting from the definition of suitable performance indexes for the different types of ITs and their experimental validation under realistic PQ phenomena, it is expected that the present concept of IT accuracy class, now defined at power frequency only, can be extended to IT for PQ measurement. The project achievements, in terms of: *i)* classification criteria for ITs accuracy in PQ measurement; *ii)* reference set-ups for ITs calibration as well as suitable measurement methods and uncertainty evaluation; *iii)* ITs performance under PQ disturbances, are also expected to contribute to the standardisation work for the issue of new or improved guides, recommendation and standards on the use of ITs in PQ measurements.

6 Acknowledgements

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