Publishable Summary for 19NRM05 IT4PQ
Measurement methods and test procedures for assessing accuracy of Instrument Transformers for Power Quality Measurements

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.

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”.

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).

Progress beyond the state of the art

This project developed a complete metrological framework, to be exploited by NMIs as well as calibration and test laboratories. This will foster the adoption of common procedures for the characterisation under realistic conditions of ITs, which can be employed for PQ measurements in Medium Voltage (MV) electricity grids. The developed knowledge has been provided firstly to IEC TC 38, in a usable form that can be easily incorporated into standardisation documents to contribute to newly developed or revised standards or a technical report on ITs for PQ measurements.

With a view to the definition of accuracy and uncertainty limits, the project has proposed and validated new performance indices, which quantify the IT errors in the measurement of the single PQ parameter. Additionally, the classical concept of IT accuracy class, which defines the IT rated performances at 50/60 Hz, has been extended to IT application to PQ measurements, by defining an overall performance index and its associated limit values. Starting from knowledge and hardware from past projects concerning measurement systems for frequency characterisation of inductive voltage transformers (EMRP ENG52 Smart Grid II), calibration at 50 /60 Hz of low power output ITs (LPITs) with analogue and digital output (EMRP ENG61 Future Grid project) and characterisation of LPITs with digital output (EMPIR 17IND06 Future II), the developed set-ups were adapted, integrated and extended to build reference measuring systems allowing traceable calibration of all types of ITs under realistic PQ phenomena at distribution grid voltages (i.e up to 36 kV). Methods for the estimate of their uncertainty contributions to PQ indices were also proposed.

An architecture for traceable calibration setups and test procedures for the IT characterisation under PQ phenomena was conceived, suitable to be implemented in test and calibration laboratories. Simplified test procedures were also established, to be adopted in industrial laboratories.

By adapting and integrating the IT reference characterisation facilities, the traceable measurement of the IT performances under stationary PQ events have been extended to the assessment of the IT behaviour under more realistic conditions, by reproducing in laboratory the presence of separate and multiple influence factors and evaluating their effect on different types of ITs both separately and combined.

Results

Objective 1 - Definition of accuracy and uncertainty limits of ITs in PQ measurements and PQ accuracy class definition

Accuracy and uncertainty limits of ITs in PQ measurements were defined starting from the introduction of new Performance Indices (PIs), specific to individual PQ disturbances and of an overall Synthetic Performance Index (SPI). By the definition of the SPI along with its accuracy limits, a "PQ Accuracy Class" for ITs was proposed, which extends, by complementing it, the present concept of IT power frequency accuracy class, which refers the IT rated performances at 50/60 Hz.

As a preliminary step, significant PQ phenomena were selected, under which assessing the metrological performances of ITs, as well as their realistic range of variation. The investigated PQ disturbances included stationary, dynamic and transient events relevant for MV application (up to 36 kV and 2 kA), with spectral content up to 9 kHz. A subset of PQ parameters that are expected to be critical for ITs was identified, which included power frequency variations, harmonics, subharmonics, interharmonics, and modulated and transient signals.

Tests waveforms for each considered PQ event were defined, as well as a novel time-combined waveform to account for subsequent or partially overlapping phenomena.

Specific PIs were identified for each selected PQ phenomenon in order to quantify the errors introduced by ITs. Realistic range of variations of the defined PIs and the overall SPI were quantified based on the feedback from extended experimental investigations, carried out on a significant set of ITs covering the different operating type, in presence of the considered PQ test waveforms. Finally, by identifying accuracy limits of the SPI over three frequency subranges and adopting the same 2-level approach classification used for the definition of accuracy classes for PQ measuring instruments, two new PQ accuracy classes which correspond to different associated limit accuracies for the SPI were proposed. Overall, by defining and validating PIs and SPI for the selected PQ parameters, as well as their accuracy limits, and introducing relevant PQ accuracy classes, Objective 1 was fully achieved.

Objective 2 - Reference measuring systems and their application to the traceable calibration of current and voltage ITs under realistic PQ phenomena at distribution voltages

To determine the performances and the limits errors introduced by the ITs in the measurement of the PQ parameters, reference generation and measurement systems have to be available, which allow the calibration by comparison of the conventional as well as non-conventional analogue and digital output ITs under the different types of PQ disturbance considered, for all types of ITs, commercial or developed for experimental research purposes. So, starting from expertise and set-ups available from previous projects, reference systems were developed by the involved NMIs, for the calibration of inductive VTs and CTs, LPVTs and LPCTs, and combined voltage and current ITs.

More in details, a generation and measurement system for laboratory calibration of current transformers (CTs) was developed, including a high current generation system, a set of analogue reference wideband CTs with associated precision resistors for current to voltage conversion and a 2-channel voltage measuring system. Synchronisation signals and conversion and receiving devices were included, for testing both inductive and low power current transformers, whose output was a sampled value data stream. PQ test waveforms were generated by an arbitrary waveform generator (AWG) coupled with an analogue power amplifier (up to 30 kVA – 15 kHz). Generation capabilities presently extends to sinusoidal signals up to 5 kA at 50 Hz, sinusoidal signals with harmonics (10%, up to 50th order) up to 1 kA, square wave signals up to 1 kA and amplitude modulated signals. Expanded uncertainties (confidence level 95%) are 20 µA/A (10 µrad) for the ratio (phase) error at power frequency and 100 µA/A (400 µrad) for the ratio (phase) error up to 9 kHz A.

As a further solution, the possibility of using a compensated current comparator, commonly employed for CT calibration at power frequency, as a reference system for determining the errors of measuring current transformers in the frequency range up to 9 kHz was proved.

As to voltage transformer (VT and LPVTs), a reference system for the generation and measurement of PQ phenomena at realistic voltages up to 30 kV (phase to ground) is now available, to generate and measure all the required set of the MV voltage waveforms. Test PQ phenomena are reproduced by an AWG coupled with a High Voltage (HV) power amplifier (DC to 2.5 kHz at full voltage, up to 30 kHz at reduced voltage), and applied to the sensor under test. The errors of the device under test are determined by making use of a reference resistive-capacitive divider and a digital voltage comparator. System capabilities were extended to the generation and measurement of harmonics, subharmonics and interharmonics, amplitude and phase modulations, frequency ramps and oscillatory phenomena superimposed to the AC power frequency waveform. In addition, arbitrary test waveforms were generated reproducing actual recorded grid voltage and sequence of PQ disturbances. Expanded uncertainties are 70 µV/V (70 µrad) for the ratio (phase) error at power frequency and 210 µA/A (330 µrad) up to 9 kHz.

As to combined voltage and current ITs a three-phase generation and reference measurement system up to 36 kV and 2 kA was developed for simultaneous calibration and testing of combined ITs and sensors under sinusoidal and non-sinusoidal conditions. Power generation is obtained by six items of synchronised linear power sources with power output ranges up to 6 kW, and with inductive voltage and current amplifiers which have individual measurement sensors. Verification and performance tests on the components of the developed setup (reference sensors, wideband bridge) have been performed up to 9 kHz. Expanded uncertainties for ratio/phase erros are 25 µV/V/25 µrad at power frequency, 200 µV/V (200 µrad) from 100 Hz to 2500 kHz.

By these systems, an extended measurement campaign was carried out on a set of commercial current and voltage ITs of different operating type, size, power frequency, accuracy class, manufacturers and installation (indoor /outdoor). The ITs were measured under the selected test conditions for the considered PQ stationary, dynamic and transient oscilatory phenomena, computing the indices for their performance evaluation. The results obtained in terms of measured PIs provided both a quite extended picture of the IT performances and the input data functional to the definition of the SPI accuracy limits and the PQ specific accuracy class. Overall, all aspects relevant to Objective 2 were achieved.

Objective 3 - Traceable test procedures and setups to calibrate ITs for MV PQ measurements

Considering the complexity of the reference systems and the calibration procedures developed and applied in the NMIs, simplified and low-cost methods, suitable to be adopted in industrial test laboratories, were drawn up, focusing on the frequency characterisation tests of inductive ITs and LPITs.

Investigations on the wideband response of inductive VTs showed how measurements performed by simple calibration setups, which employ AC frequency sweep at low voltage (from ten to hundreds of volts), deviate up to a few percents with respect to results obtained by the previously described reference systems, which apply MV distorted test waveforms. Simplified methods for the frequency characterisation of inductive VTs up to the first resonance frequency were developed, which are simply based on a measurement of ratio and phase errors at rated voltage and frequency, and a frequency sweep carried out with low sinusoidal signals. By this approach, only instruments and apparatus usually available in manufacturer and test laboratories are needed. Reduction of one order of magnitude of the errors introduced by pure LV sweeps with respect to MV reference tests were obtained.

As to LPITs, the feasibility of determining their frequency response by means of a low voltage/current, and hence low cost, measurement setup was confirmed, by exploiting suitably defined low voltage input signals. For combined ITs, simplified and practical test setups were studied for the manufacturer’s premises. Methods for LPCTs and VTs characterisation under dumped oscillatory waveforms were found promising.

As to the adoption of simpler, but still accurate measuring system, a wideband (up to 9 kHz) IT current comparator for industrial applications was developed, whose architecture is based on a precision power analyser with a sampling rate of 2 MS/s, 18-bit resolution, and two power modules (up to 5 A and 1000 V). The precision power analyser has been set up as a sampling and recording unit for the current and voltage signals which subsequently streams the data to a host computer for processing and computation. The uncertainty provided was typically 35 ppm up to the 50th harmonic of 1 % with a fundamental of 100 A.

Results and experience gained were summarised in a Good practice guide for stardisation bodies and end-users. Overall, by finalising all relevant activities, Objective 3 was achieved.

Objective 4 - Performance of ITs in PQ measurements in presence of multiple influence factors

Through specific set-ups and test procedures the effects of combined influence factors on the ITs behaviours were quantified. Proper reference facilities were developed, introducing sources of influence quantitites coupled with the previously realised reference measurement systems. In this way, their capabilities were extended to the testing of ITs under presence of separate and combined (two at the time) influence factors, considering the impact of:

- 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

The experimental activities have highlighted that the temperature has a significant impact on the performance of inductive VTs, particularly at low temperatures, and the resonance frequency. Mechanical vibrations have a negligible effect, even in combination with temperature variations. The VT burden significantly influences the ratio error, with its impact intensifying as the temperature decreases and frequency increases. The proximity and adjacent phase parameters have clearly no impact on VT performance, whereas for the LPVTs, the impact of the adjacent phases and proximity varies for different types of voltage LPVTs, making it challenging to draw general conclusions. For CTs and LPCTs, the centring of the primary conductor and the position of the return connectors show the strongest influence. 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 principles and construction solutions adopted. Based on experimerimental results, criteria for the significance of the effect of a combination of influence factors were drawn, based on the relationship between deviations from reference conditions due to the single influence quantity and deviation due to their combination. Tests conditions and results, as well as experience gained were summarised in a Good practice guide for standardisation bodies and end-users.

Overall, by accomplishing all relevant activities and outputs, Objective 4 was achieved.

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 (convenorship of IEC TC38 WG 47 "Development of instrument transformer for the market evolution" and 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.

List of publications

1. G. Crotti, H.E. van den Brom, E. Mohns, R. Tinarelli, M. Luiso, R. Styblikova, M. Agazar, H. Cayci, P. Mazza, J. Meyer, M. Almutairi, "Measurement Methods and Procedures for Assessing Accuracy of Instrument Transformers for Power Quality Measurements," 2020 Conference on Precision Electromagnetic Measurements (CPEM), August 24-28, 2020, pp. 1-2, https://doi.org/10.5281/zenodo.5136547.
2. G. Crotti, D. Giordano, P. S. Letizia, A. Delle Femine, M. Luiso, "A simplified procedure for the Accurate Frequency Response Identification of Voltage Transformers," IMEKO TC-4 2020, 24th IMEKO TC4 International Symposium, Palermo, Italy September 14-16, 2020, https://doi.org/10.5281/zenodo.5136702.
3. G. Crotti, G. D'Avanzo, D. Giordano, P. S. Letizia, M. Luiso, "Extended SINDICOMP: Characterizing MV Voltage Transformers with Sine Waves," Energies 2021, 14(6), 1715, https://doi.org/10.3390/en14061715.
4. G. Crotti et al., "Assessment Of Instrument Transformer Accuracy For Power Quality Measurements In Distribution Grids: Recent Activities And First Results From 19NRM05 IT4PQ Project," CIRED 2021 - The 26th International Conference and Exhibition on Electricity Distribution, 2021, pp. 945-949, https://doi.org/10.5281/zenodo.6136940.
5. G. Crotti, D. Giordano, G. D'Avanzo, P.S. Letizia, M. Luiso, "A New Industry-Oriented Technique for the Wideband Characterization of Voltage Transformers", Measurement, Volume 182, 2021, 109674, ISSN 0263-2241, https://doi.org/10.1016/j.measurement.2021.109674.
6. G. Crotti, G. D'Avanzo, P. S. Letizia and M. Luiso, "Measuring Harmonics With Inductive Voltage Transformers in Presence of Subharmonics," in IEEE Transactions on Instrumentation and Measurement, vol. 70, pp. 1-13, 2021, Art no. 9005013, https://doi.org/10.1109/TIM.2021.3111995.
7. G. D'Avanzo et al., "Improving Harmonic Measurements with Instrument Transformers: a Comparison Among Two Techniques," 2021 IEEE International Instrumentation and Measurement Technology Conference (I2MTC), 2021, pp. 1-6, https://doi.org/10.5281/zenodo.6104280.
8. G. Crotti et al., "Instrument Transformers for Power Quality Measurements: a Review of Literature and Standards," 2021 IEEE 11th International Workshop on Applied Measurements for Power Systems (AMPS), 2021, pp. 1-6, https://doi.org/10.5281/zenodo.6093507.
9. Mingotti, F. Costa, L. Peretto and R. Tinarelli, "External Magnetic Fields Effect on Harmonics Measurements with Rogowski coils," 2021 IEEE 11th International Workshop on Applied Measurements for Power Systems (AMPS), 2021, pp. 1-6, https://zenodo.org/record/5946938
10. Mingotti, F. Costa, L. Peretto, R. Tinarelli, "Effect of Proximity, Burden, and Position on the Power Quality Accuracy Performance of Rogowski Coils", Sensors 2022, 22(1), 397, https://doi.org/10.3390/s22010397
11. Mingotti, F. Costa, L. Peretto, and R. Tinarelli, "Accuracy Type Test for Rogowski Coils Subjected to Distorted Signals, Temperature, Humidity, and Position Variations", Sensors 2022, 22(4), 1397, https://doi.org/10.3390/s22041397
12. F. Costa, A. Mingotti, L. Peretto L, R. Tinarelli "Combined effect of temperature and humidity on distorted current measured by Rogowski coils", 20th International Conference on Harmonics & Quality of Power, ICHQP2022, pp. 1-6, https://zenodo.org/record/6867622
13. Y. Chen; A. Dubowik; E. Mohns "Reference system for current sensor calibrations at power frequency and for wideband frequencies", 20th International Conference on Harmonics & Quality of Power, ICHQP2022, pp. 1-6, https://doi.org/10.5281/zenodo.7061846
14. R. Striegler, J. Meyer, "Impact of external influences on the frequency dependent transfer ratio of resin cast MV voltage instrument transformers", 20th International Conference on Harmonics & Quality of Power, ICHQP2022, pp. 1-6, https://doi.org/10.5281/zenodo.7442707

15. D. Giordano, P. Letizia, G. Crotti, D. Palladini; “Stray Parameter Evaluation of Voltage Transformers for PQ Measurement in MV Applications”, 20th International Conference on Harmonics & Quality of Power, ICHQP2022, pp. 1-6, https://doi.org/10.5281/zenodo.7432234

16. G. Crotti, Y. Chen, H. Caycy, G. D’Avanzo, C. Landi, P. Letizia, M. Luiso, E. Mohns, F. Muñoz, R. Styblikova, H. Van den Brom, “How Instrument Transformers Influence Power Quality Measurements: A Proposal of Accuracy Verification Tests”, Sensors 2022, *22*(15), 5847, https://doi.org/10.3390/s22155847

17. Mingotti, C. Belli, L. Peretto, R. Tinarelli, “Simplified and Low-Cost Characterization of Medium-Voltage Low-Power Voltage Transformers in the Power Quality Frequency Range”, *Sensors* 2022, *22*(6), 2274; https://doi.org/10.3390/s22062274

18. P.S. Letizia, D. Signorino, Impact of DC Transient Disturbances on Harmonic Performance of Voltage Transformers for AC Railway Applications”, Sensors, 2022, *22*(6), 2270; https://doi.org/10.3390/s22062270

19. G. Crotti, M. Luiso, G. D’avanzo, P.S., Letizia “The Use of Voltage Transformers for the Measurement of Power System Subharmonics in Compliance with International Standards” in IEEE Transactions on Instrumentation and Measurement, vol. 71, pp. 1-12, 2022, https://doi.org/10.1109/TIM.2022.3204318.

20. G. D’Avanzo, M. Faifer, C, Landi, C. Laurano, P. S., Letizia, “Theory and Experimental Validation of Two Techniques for Compensating VT Nonlinearities”, in IEEE Transactions on Instrumentation and Measurement, vol. 71, pp. 1-12, 2022, https://doi.org/10.1109/TIM.2022.3147883

21. G. Crotti, G. D’Avanzo, C. Landi, P. S. Letizia and M. Luiso, "Evaluation of Voltage Transformers’ Accuracy in Harmonic and Interharmonic Measurement," in *IEEE Open Journal of Instrumentation and Measurement*, vol. 1, pp. 1-10, 2022, Art no. 9000310, https://doi.org/10.1109/OJIM.2022.3198473

22. P.S., Letizia, “Development and Experimentation of Traceable Characterization Methods for Medium Voltage Instrument Transformers for PQ and PMU Applications”, 2022, https://hdl.handle.net/11583/2972563

23. G. Crotti, P.S. Letiza J. Meyer, R. Stiegler, M. Agazar, D. Istrate, Y. Chen, E. Mohns, H. Cayci, B. Ayhan, H. van den Brom P. Mazza, D. Palladini, M. Luiso, C. landi, R. Tinarelli, A. Mingotti,” Performance Evaluation of instrument transformers in power quality measurements: activities and results form 19NRM05 IT4PQ Project”, 27th International Conference and Exhibition on Electricity Distribution, CIRED 2023 - 2023, https://doi.org/10.5281/zenodo.8378930

24. M. Agazar, D. Istrate, “Evaluation of the Accuracy and the Frequency Response of Medium Voltage Instrument Transformers under Combined Influence Factors of Temperature and Vibration*”,* Energies 2023, 16(13), 5012 ; https://doi.org/10.3390/en16135012

25. P.S. Letiza G. Crotti, A. Mingotti, R. Tinarelli, Y. Chen, E. Mohns, M. Agazar, D. Istrate, B. Ayhan, H. Cayci, R. Stiegler, “Characterization of Instrument Transformers under Realistic Conditions: Impact of Single and Combined Influence Quantities on Their Wideband Behavior”, Sensors 2023, *23*(18), 7833; https://doi.org/10.3390/s23187833

26. Y. Chen, E. Mohns, A. Mingotti, G. Crotti. P.S: Letizia, R. Stiegler, H. Cayci, B. Hayan, F. Munoz, “Reference Measurement Systems for the Calibration of Instrument Transformers under Power Quality Phenomena and their Uncertainties”, *2*023 IEEE 13th International Workshop on Applied Measurements for Power Systems (AMPS), Bern, Switzerland, 2023, pp.01-06; https://zenodo.org/records/10068876

27. G. Crotti, , D. Giordano, P.S. Letizia, C. Iodice, C. Landi, M. Luiso, P. Mazza, D. Palladini, “How Undesired Non-Idealities of the Input Signal Affect the Accuracy Evaluation of Instrument Transformers at Power Frequency”, 2023 IEEE 13th International Workshop on Applied Measurements for Power Systems (AMPS), Bern, Switzerland, 2023, pp. 1-6, https://zenodo.org/records/10068934

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Project start date and duration:	01 August 2020 - 36 months	
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RMG: -		