Istituto Nazionale di Ricerca Metrologica, Italy
LNE, Laboratoire national de métrologie et d'essais - France
Technische Universität Dresden — TU Dresden– Germany
VSL, National Metrology Institute, Netherland
Physikalisch-Technische Bundesanstalt (PTB), Germany
TUBITAK, The Scientific and Technological Research Council of Turkey, Tukey
Dept. of Electrical, Electronic and Information Engineering, University of Bologna, Italy
Dept. of Industrial and Information Engineering, Università della Campania, Italy

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Gabriella CROTTI, P. Sara LETIZIA, Jan MEYER, Robert STIEGLER, Mohamed AGAZAR, Daniela ISTRATE, Yeying CHEN, Enrico MOHNS, Huseyin CAYCI, Burak AYHAN, Helko van den BROM, Fabio MUÑOZ, Paolo MAZZA, Daniele Palladini, Mario LUISO, Carmine LANDI, Roberto TINARELLI, Alessandro MINGOTTI

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Performance Evaluation of Instrument Transformers in Power Quality Measurements: Activities and Results from 19NRM05 IT4PQ Project

Gabriella CROTTI, P. Sara LETIZIA
INRIM – Italy
g.crotti@inrim.it

Jan MEYER, Robert STIEGLER
TU-Dresden – Germany
jan.meyer@tu-dresden.de

Mohamed AGAZAR, Daniela ISTRATE
LNE - France
mohamed.agazar@lne.fr

Yeying CHEN, Enrico MOHNS
PTB – Germany
yeying.chen@ptb.de

Huseyin CAYCI, Burak AYHAN
TUBITAK – Turkey
huseyin.cayci@tubitak.gov.tr

Helko van den BROM, Fabio MUÑOZ
VSL – The Netherlands
hvdbrom@vsl.nl

Paolo MAZZA, Daniele Palladini
RSE S.p.A – Italy
paolo.mazza@rse-web.it

Mario LUISO, Carmine LANDI
University of Campania – Italy
mario.luiso@unicampania.it

Roberto TINARELLI, Alessandro MINGOTTI
University of Bologna – Italy
roberto.tinarelli3@unibo.it

ABSTRACT

The accuracy of power quality measurements relies on the use of common measurement procedures and traceable measurement systems, which necessarily include instrument transformers. The paper provides an overview of the progress achieved within the EU project 19NRM05 IT4PQ in developing the needed metrological framework, in terms of performance indexes to qualify the instrument transformers for PQ measurements, simplified testing procedures and set-ups, and quantification of their behaviour under multiple influence factors.

INTRODUCTION

In the framework of the ongoing transition towards a net-zero emissions energy system, the infrastructure for electrical energy distribution is experiencing unprecedented challenges in terms of increased electricity demand, integration of generation from renewables and connection of variable electronics loads and storage systems. In this context, accurate monitoring of grid power quality (PQ) plays a crucial role. Accuracy of measurements, and their equivalence when performed by different operators, rely on the use of common measurement procedures and traceable measurement systems, characterised according to standardized methods. This approach is well established for low voltage power quality measurement instruments [1], but when PQ evaluation is performed at high voltage, inductive or low-power instrument transformers (ITs) are necessary to reduce the high voltage and current. There is increasing interest [2] in understanding and quantifying the wideband behaviour of ITs, which are generally characterized at rated power frequency, and in adopting suitable test procedures not covered by present standards on ITs [3].

On this subject, the EU research project 19NRM05 IT4PQ [4] is developing the needed metrological framework as well as the missing common methods and procedures for the characterization of ITs in distribution grids under realistic PQ phenomena with voltages up to 30 kV, currents up to 2 kA, and frequency spectrum up to 9 kHz. This is being accomplished by pursuing four objectives:

i) definition of parameters and metrics to qualify ITs for PQ measurement;
ii) set up of generation and reference measurement systems for the metrological characterization of the different types of ITs (inductive, low power output and combined voltage and current ITs, with analog or digital output) and quantification of their performances;
iii) development of simplified test circuits and procedures to be adopted at industrial level;
iv) quantification of IT performance dependence on the presence of multiple influence factors.

Making reference to these objectives, the paper provides an overview of some significant results obtained in the first two years of the project. Performance indexes are described to quantify the behaviour of ITs in the measurement of harmonic distortions. Their practical application for the accurate evaluation of IT errors is demonstrated using dedicated reference measurement systems, developed by the national metrology institutes (NMIs) involved in this project. Simplified test-circuit arrangements and procedures are then briefly described and their accuracy is demonstrated against results obtained by reference systems. Attention is finally focused on the analysis of IT performances in the measurement of PQ steady-state phenomena as a function of separate and combined external influence quantities.

QUANTIFICATION OF THE IT ERRORS

To quantify the errors introduced by the ITs in the measurement of PQ phenomena, performance indexes have been introduced as a function of the considered PQ disturbances. Examples of their applicability and quantification of the proposed indexes are provided in the following for different commercial ITs, focusing on the measurement of interharmonic and harmonic distortions by inductive ITs. IT performance indexes are measured by making use of high voltage and current reference generation and measurement systems, developed and characterised by the involved NMIs as detailed in [5].

Definition of ITs performance indexes

As a first step, performance indexes have been determined considering steady-state and dynamic PQ disturbances including harmonic and interharmonic distorted signals, frequency variations, transient and oscillatory transient with spectrum included in the considered frequency (up to 9 kHz) and amplitude (1 kV to 30 kV) ranges [5]. Indexes are worked out for voltage disturbances, but, when applicable, they are also used in the quantification of current disturbances. For sake of brevity, attention is focused in the following on the measurement of harmonic and interharmonic distorted waveforms.

The performance of voltage transformers can be evaluated in terms of ratio $\varepsilon(f)$ and phase error $\varphi(f)$ at each frequency f as:

$$\varepsilon(f) = \frac{\mathrm{k_r}\, U_\mathrm{s}(f) - U_\mathrm{p}(f)}{U_\mathrm{p}(f)} \qquad (1)$$

$$\varphi(f) = \varphi_\mathrm{s}(f) - \varphi_\mathrm{p}(f) \qquad (2)$$

where $\mathrm{k_r}=U_{\mathrm{p,r}}/U_{\mathrm{s,r}}$ is the VT rated transformation ratio ($U_{\mathrm{p,r}}$ and $U_{\mathrm{s,r}}$ are rated primary and secondary voltages); $U_\mathrm{p}(f)$ and $U_\mathrm{s}(f)$ are the root mean square (RMS) values of the primary and secondary voltage at frequency f and $\varphi_p(f)$ and $\varphi_s(f)$ are the phase angles of the primary and secondary voltages at f, all evaluated over 10 cycle of the fundamental frequency. IT performance can be also analyzed in terms of the deviation $\Delta\varepsilon$ ($\Delta\varphi$) between $\varepsilon(f)$ ($\varphi(f)$) and a defined reference error value, e.g. the one under rated frequency and amplitude conditions.

ITs performance index evaluation

Inductive VT performance evaluation under voltage distortion

Inductive VT (IVT) performance indexes are evaluated by comparison with a reference measurement system [5], under a distorted voltage supplied by an arbitrary waveform generator coupled with a power high voltage amplifier. The measurement section includes a wideband reference RC-divider, a non-commercial digital bridge and a control and measurement software developed in LabVIEW. Measurement uncertainties (coverage factor *k*=2) are within 190 μV/V and 320 μrad for ratio and phase error respectively up to 9 kHz. IVTs have been tested for harmonic ratio and phase errors (1) and (2), by applying a frequency sweep of a two-tone distorted waveform (FH1):

$$v_{\mathrm{FH1}} = \sqrt{2}U_\mathrm{n}\sin(2\pi f t) + \sqrt{2}U_h\sin(2\pi h f t) \qquad (3)$$

where U_n is the RMS value of the fundamental tone at rated frequency f and U_h is the RMS amplitude of the h order harmonic tone. A number of cast resin insulated IVTs have been tested with primary voltages from 11/√3 kV to 25 kV and from 50 Hz up to 10 kHz, evidencing, according to literature [6] a noticeable decrease of the first resonance frequency, and consequently of the useful bandwidth, with the increase of the rated primary voltage. However, Fig 1 shows the measured performance indexes of two commercial IVTs ($\mathrm{VT_1}$ and $\mathrm{VT_2}$) from two Manufactures with same primary voltage (11/√3 kV), transformation ratio (100 V/V), and class (0.5), and with different rated frequency (60 Hz and 50 Hz). Whereas $\mathrm{VT_1}$ is designed for use in railway grids, $\mathrm{VT_2}$ is intended for electrical distribution grids. Despite their almost equal rated characteristics, $\mathrm{VT_1}$ shows a much flatter frequency response with respect to VT2, but at the cost of worser errors at the lower harmonic frequencies, as evidenced in the inset. If not corrected, those errors can affect the IT behaviour in the measurement of harmonic disturbances of relatively low amplitude ($1\%\cdot U_\mathrm{n}$ in the considered case). The different frequency behaviour can be explained considering a different sizing of the iron core and number of primary and secondary windings.

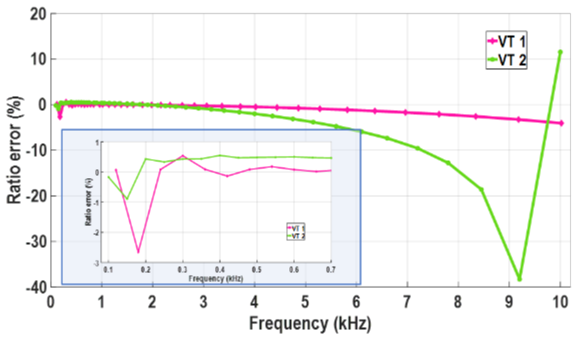

Fig 1: Comparison between the performance indexes vs frequency of two IVTs with similar rated characteristics, designed for different use.

Inductive CT performance evaluation under current distortion

The performance indexes of inductive current transformers (ICTs) are evaluated using the generation and measurement system described in [7]. The main components of the developed setup are the high current generation system, a set of analogue reference CTs with precision resistors, and a two-channel measuring system. Measurement uncertainties (coverage factor *k*=2) are within 100 μA/A and 400 μrad for ratio and phase error respectively up to 9 kHz. The generation and reference measurement system has been used to test ICTs with different primary rated currents and based on different operating principles, in presence of PQ phenomena including harmonics and interharmonics. In this respect, Fig 2 provides the frequency ratio error (1) of an ICT with primary rated current 400 A. In particular, Fig 2 shows the CT $\varepsilon(f)$ measured in the presence of a sinusoidal current (FR), a dual tone (DT) current signal composed of a fundamental tone (I_0) plus an harmonic tone (I_h), as well as a fundamental tone plus and an interharmonic tone (I_{IH}). As regard the harmonics, different harmonic amplitudes (from 1% to 10% of I_0) are tested and the highest errors (up to 1 %) are observed for the lowest amplitude of the third harmonic tone; this result is explained by the higher weight of the low order spurious harmonic tones generated by the CT iron core non-linearity.

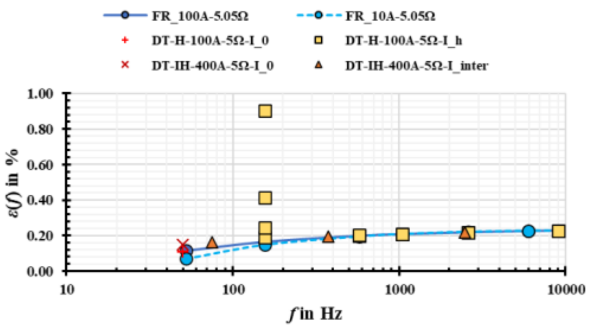

Fig 2. Obtained ratio indexes for a class 0.2 ICT with rated current 400A/1A (5VA), burden 5 Ω (resistive) with different input signals: sinusoidal (FR), dual tone with harmonics (DT-H), and interharmonics (DT-IH).

SIMPLIFIED MEASUREMENT METHODS AND PROCEDURES

Giving the complexity of the approach used in the performance evaluation of commercial ITs, simplified measurement procedures and setups for the frequency characterization of ITs are developed, to be adopted in industrial environment. These procedures have to be easy to implement, but capable of providing traceable measurement with still sufficiently low uncertainty.

Reference comparator for industrial use

A wideband comparator for industrial and/or on-site ITs characterization up to 9 kHz has been developed, including hardware and software components. The comparator digitizing part is based on a commercial precision power analyzer, with input modules up to 30 A and 1 kV and sampling rate up to 2 MHz. Preliminary tests have been performed to assess its performances. In particular, Fig 3 reports the ratio of the currents measured by the three acquisition channels of the comparator (configured for CT applications) when it is used to acquire dual-tone current waveform (3). As can be seen, the measured deviations are lower than 50 µA/A up to 10 kHz.

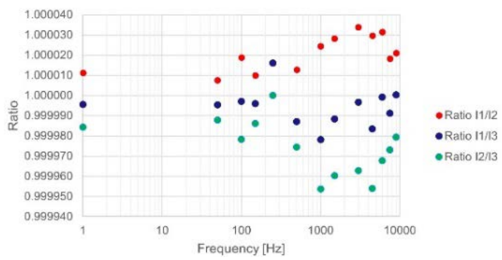

Fig 3: RMS magnitude current ratios among the three acquisition channels of the comparator from 1 Hz to 10 kHz.

Validation of simplified procedures for IVTs frequency performance evaluation

Two simplified procedures, E-SINDICOMP [8] and S-LV[9], have been studied and validated for the frequency characterization of IVTs. Both procedures can be used to approximate the IVT response before the first resonance frequency. They are based on measuring both errors at the rated frequency and amplitude, and errors vs frequency at quite reduced amplitude (down to a tens of volts). The E-SINDICOMP technique provides a method for approximating the IVT ratio error with a piecewise-defined function. The S-LV technique provides the complete IVT response errors (ratio and phase) by a fitting procedure. To quantify the accuracy of the two approaches, Fig 4 provides a comparison between the two techniques, where the same reference experimental dataset is used for the estimation of the 20/√3 kV VT performances following the two different approaches. Deviations are evaluated against "reference" errors measured under FH1 waveform by the generation and reference measurement system.

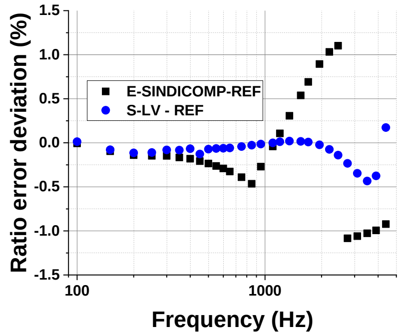

Fig 4: Comparison between E-SINDICOMP and S-LV procedures. Ratio error deviations are evaluated against "reference" errors measured under FH1 applied waveform.

As can be observed, for the first ten harmonics both the two techniques show quite good performances. Considering the entire bandwidth, the measured S-LV absolute deviations are within 0.5 %, whereas the E-SINDICOMP ones reach the 1.2 % value.

IT BEHAVIOURS IN PRESENCE OF INFLUENCE QUANTITIES

Taking into account the on-site use of ITs, preliminary investigations are addressed, mainly focused on assessing the impact of influence factors on IT performances in the measurement of PQ steady-state events. The considered influence factors are partially included in the relevant IEC 61869-X standards [3] and specifically temperature, vibration, burden.

VTs investigation under separate and combined temperature and burden

A number of cast resin MV IVTs with rated primary voltages from 10/√3 kV to 35/√3 kV from different manufacturers have been tested in the measurement of harmonics and interharmonics, in presence of separate and combined temperature and burden conditions.
As to the temperature *T*, the investigated range is from - 25°C to 55°C, whereas for the burden (*S*) the analysis is carried out from 0 % of rated burden (S_r) to 100 % of S_r.
For the burden, realistic cases are taken into account, also considering the different values of the PQ analyser input capacitance along with cables of different lengths.
Results show that the temperature has two main impacts on VTs frequency measurement performance:

1. the increase in the temperature reduces the value of the first resonance frequency;
2. with the decrease of the temperature, the non-linear

effects due to magnetic core at low-order harmonics increase.

As regards the burden condition, the resistive part of the operating burden has a significant impact on the entire frequency response (including the fundamental frequency) whereas a lower impact is observed for the capacitive part. Experimental tests for the evaluation of the combined effect of temperature and burden conditions have been carried out. Results are provided in Fig 5 in terms of $\Delta\varepsilon(f)$ (%) that is defined as:

$$\Delta\varepsilon(\%) = \varepsilon\left(f, T, \frac{S}{S_r}\right) - \varepsilon(f, T)|_{\frac{S}{S_r}=0} - \quad (4)$$

Values of $\varepsilon(f, T)|_{\frac{S}{S_r}=0}$ are given in Table I.

From Fig 5, it can be observed that the impact of burden on ratio error (1) is decreasing with rising temperature.

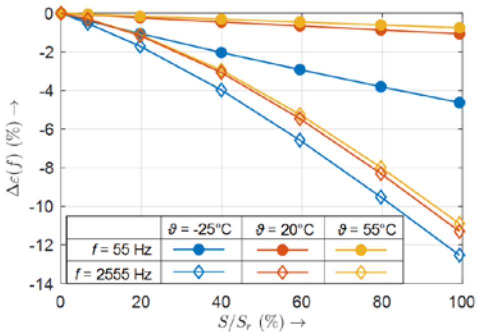

Fig 5: VT ratio error deviation as a function of burden and temperature for two different frequencies..

Table I: Measured ratio error in % at different temperatures and frequency under zero burden condition

	f=55 Hz			f=2555 Hz		
	Temperature (°C)			Temperature (°C)		
	-25	21	55	-25	21	55
$\varepsilon(f, T)\|_{\frac{S}{S_r}=0}$	-0.15	-0.16	-0.23	-18.6	-20.7	-23.8

VT investigation under combined temperature and vibrations

This subsection focuses on the assessment of IVTs performances in the harmonics measurement under combined temperature and vibrations influence factors.

The same primary voltage is applied to the standard transformer and a 30 kV IVT under test. The IVT is placed in a climatic chamber on the electromagnetic shaker while the reference measurement chain is at ambient temperature on a stable platform. Several measurements have been performed with temperature from -25°C to 55°C without applying vibrations, firstly, and then by combining vibrations and temperatures. The measurements performed at 21°C and without vibrations are assumed as the reference condition. The vibrations are applied on the vertical axis of the VT, with 0.5 g accelerations and two different frequencies: 20 Hz and 100 Hz.

The results reported in Fig 6 refer to the IVT supplied with the test signal described in (3) with U_h =5%·U_n for h varying from 3 to 40 and U_h =3%·U_n for h up to 60.

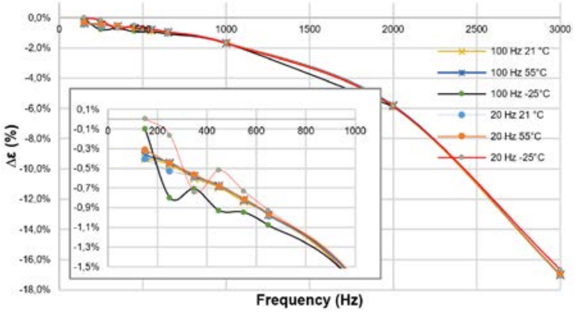

Fig. 6 Influence of combined temperature and vibration on VT performance in harmonics measurement in terms of variation of ε(f) with respect to the error at 50 Hz (reference error).

From the analysis with separate influence factors, vibrations are found to have the lower influence (some tens of µV/V) on the IVT, if compared to temperature which has the dominant effect also in the combined test.

In particular, at low harmonics (h<13) a nonlinear behavior is evidenced when the operating temperature is - 25°C in agreement with what discussed in the previous subsection. The maximum variation between the response measured at 21°C and the one measured at -25 C does not exceed 0.35 % under the considered test conditions.

LPCTs investigation under separate and combined influence factor

Commercial Rogowski coils (RCs) have been tested to assess how their accuracy is affected by burden and mutual position between the LPCT and the cable carrying the current. Five burdens have been selected: (2, 1.8, 2.2, 1, 1000) MΩ, referred to as B_R, B_1, B_2, B_3, and B_4, respectively. As to the position, the IEC 61869-10 [3] describes 4 mutual positions between the RC and the cable carrying the current to be measured. All positions have been investigated in the measurement and they are referred to as L, M, N, O. Lastly, 3 primary signals have been generated: an AC 50 Hz signal (X), and two distorted signals with THD 4.8 % (Y) and 9.2 % (Z), respectively.

The results are presented in terms the ratio error variations with respect to the ideal condition (50 Hz signal, centred position, and B_R). Fig. 7 shows the results for combination of positions and burden for all generated distorted signals. As can be seen, the burden and the distortion of the input signal have not significant effect if compared to the position of the current carrying cable.

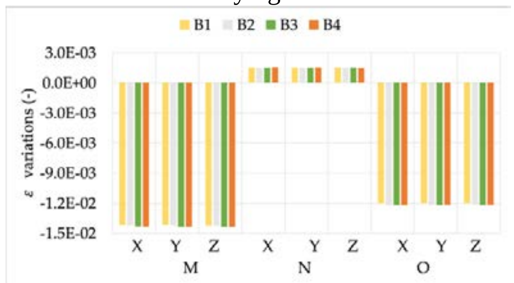

Fig 7: Impact of burden, position and signal type on the ratio error of a LPCT

Combined ITs investigation under

electromagnetic influences and burden

A number of combined ITs have been tested to analyse the ratio and phase error variations caused by the influences of current on the VT and of voltage on the CT under different burden conditions. Tests are performed according the combined IT relevant standard [3]. Preliminary analysis of the impact of the current on the VT of a 22 kV/1.2 kA combined IT for two burden values is shown in Fig. 8. According to the phase angle between the current and the voltage, the error end points lie on circles centred on the VT error without current influence. The higher impact of the currents on VT sensor is observed for higher current value. Moreover, the combination of the VT higher error with ¼ burden and the current lead the VT to exceed the 0.5 accuracy class limit.

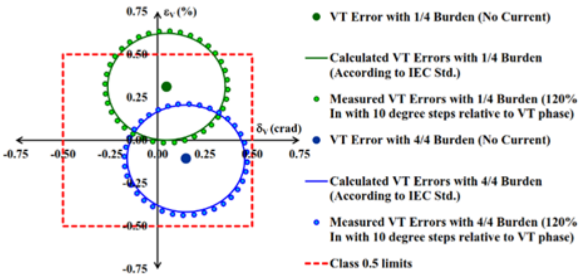

Fig 8: Influence of current transformer on voltage transformer for 22 kV/1.2 kA combined IT for two burden values.

CONCLUSIONS

The 19NRM05 IT4PQ project is developing a metrological framework for the assessment of IT error contributions in PQ disturbance measurements The framework includes performance indexes for various PQ disturbances, reference measurement setups and test waveforms for the suitable characterization of ITs in the presence of realistic PQ phenomena and under different operating conditions. Examples of the quantification of performance indexes have been provided with experimental tests on IVTs and ICTs in the measurement of stationary phenomena. Simplified measurement procedures and setups have also been developed to ensure traceable characterization of ITs vs frequency in industrial environments, showing an approximation that is ten times higher than the reference procedure uncertainty, but still sufficiently accurate (0.5%). As regard the influence factors, the more significant is the temperature that impacts on both low order harmonics and value of the first resonance frequency. An extensive measurement campaign on different types of inductive ITs and LPITs is ongoing, involving both stationary and transient PQ disturbances to collect a significant amount of data, for the IT classification on the basis of their performance indexes. We expect that the project achievements could also contribute to the issue of new or improved standards and recommendation on the use of ITs in PQ measurements.

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REFERENCES

[1] IEC 61000-4-30: 'Electromagnetic compatibility (EMC) -Part 4: Testing and measurement techniques - Power quality measurement methods', 2015.

[2] M. Kaczmarek and E. Stano, "Why should we test the wideband transformation accuracy of medium voltage inductive voltage transformers?", Energies, vol. 14, no. 15, pp. 4432, Jul. 2021.

[3] IEC 61869-X: 'Instrument transformers - Part 1, 2, 3, 4, 10.

[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, Online Conference, 2021, pp. 945-949,

[5] Crotti, G.; Chen, Y.; Çayci, H.; D'Avanzo, G.; Landi, C.; Letizia, P.S.; Luiso, M.; Mohns, E.; Muñoz, F.; Styblikova, R.; van den Brom, H. How Instrument Transformers Influence Power Quality Measurements: A Proposal of Accuracy Verification Tests. Sensors 2022, 22, 5847.

[6] R. Stiegler, J. Meyer, J. Kilter and S. Konzelmann, "Assessment of voltage instrument transformers accuracy for harmonic measurements in transmission systems," 2016 17th ICHQP, Belo Horizonte, Brazil, 2016, pp. 152-157,

[7] Y. Chen, A. Dubowik and E. Mohns, "Reference system for current sensor calibrations at power frequency and for wideband frequencies," 2022 20th ICHQP, Naples, Italy, 2022, pp. 1-6,

[8] Crotti, G.; D'Avanzo, G.; Giordano, D.; Letizia, P.S.; Luiso, M. Extended SINDICOMP: Characterizing MV Voltage Transformers with Sine Waves. Energies 2021, 14, 1715.

[9] 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.