# Measurement of Dynamic Voltage Variation Effect on Instrument Transformers for Power Grid Applications

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***Abstract*— Within the framework of distribution and transmission grids, knowledge of Instrument Transformers (ITs) behavior in distorted conditions is a topics of great interest. Its relevance stems from the ITs wide use in metering, protection, monitoring and control applications, where their role is to reduce voltage and current to levels compatible with measuring instruments input. In force standards require that the performance of measuring instruments is assessed under realistic conditions. On the contrary, performance test of ITs are generally carried out only at rated conditions, so that their behavior under actual waveforms is not fully known. To cover this gap and starting from the hardware used for the Medium Voltage (MV) Voltage Transformer (VT) frequency characterization, a suitable setup is developed for the traceable test of VTs under a quite large set of static and time varying test waveforms. In the paper, after a short description of the setup, examples of its applications to the evaluation of the performances of ITs under different test voltage waveforms are given, including a realistic reproduction of a PQ event and focusing on the amplitude and phase modulation tests, as those suggested for the Phasor Measurement Units in IEEE Std. C37.118.1. Preliminary experimental results are shown.**

***Keywords—Instrument transformers, power grid, power quality, phasor measurement unit, uncertainty***

## I. INTRODUCTION

Power Quality (PQ) measurement instruments, Phasor Measurement Units (PMUs) and all metering and protection instruments installed in the distribution and transmission grids require the measurement of grid voltage and current [1]. Since in transmission and distribution grid amplitude these quantities span from hundreds of volt and tens of ampere up to hundreds of kilovolt and tens of kiloampere, transducers have to be introduced in the measurement chain in order to reduce the signals to be acquired to the input levels of the installed measurement instruments.

By examining the standards relating to the most common measuring instruments present on the power network, it can be observed that verification of their performance is required under different operating conditions and several measurement test points. For example, as regards the PQ instruments the IEC 62586-2 standard [2] requires tests performed in a wide amplitude range, from 5% to 150% of the nominal voltage, and additional frequency test points besides the power frequency ones are indicated. Furthermore, these instruments must be tested with several distorted waveforms, for example multi-tone signals (both harmonic and interharmonic are required), typical time-varying PQ disturbance signals (f.i. dips and swells) and also signals combining several disturbances. indications.

The IEEE C37.118.1 standard [3] and its amendment [4], focused on synchrophasor measurement methods and performance verification of PMUs, deal, among the others, with amplitude and phase modulation, frequency ramp, harmonic distortion and prescribe some tests to verify the performance of PMUs in their presence.

Even if in the power grids these measuring instruments are always coupled to Instrument Transformers (ITs), currently there is a gap in the standards about IT testing, since the accuracy verification is prescribed just at power frequency or at higher frequency but with reduced amplitudes.

Nowadays, several new kinds of voltage and current instrument transformers (active or passive, generally referred to as Low Power Instrument Transformers, LPIT) are available [5], but inductive voltage and current transformers (VTs and CTs) are still widely employed. The metrological performances of these sensors in presence of distorted signals significantly depend on their operating principles [6]-[11]. It has been highlighted that inductive ITs have, in particular, an intrinsic non-linear behaviour involving uncertainty increasing up to some percent, when they are used to measure harmonic disturbances [12][13]. However, the behavior of the inductive ITs in presence of non-sinusoidal and/or time varying disturbances is still not fully addressed and methods for the performance verification of ITs, to quantify the errors they can introduce in the measurement chain have to be identified. To this end, a set up has been developed at INRIM, which is designed to traceable characterize Voltage Instrument Transformers (VT) under a realistic set of test waveforms at rated voltage level. In particular, this setup can generate the waveforms prescribed by the IEEE C37.118.1 standard [3] for PMUs dynamic compliance verification as well as reproduce time-varying PQ disturbance. In the paper, after a short description of the setup, example of its applications to the evaluation of the performances of ITs under different test voltage waveforms are given, with focus on the amplitude and phase modulation tests, as those suggested for Phasor Measurement Units in IEEE Std. C37.118.1, and preliminary experimental results are shown.

The paper is organized as follows: signal test definitions and test procedure that can be generated by the set-up are described in Section II. Section III briefly recall the measurement setup. Preliminary experimental results of the characterization of commercial VTs are shown in Section IV. Finally, Section V draws the conclusions.

## II. Waveform Definitions and Testing Procedure

### *A. Signal Definition*

The developed generation system is able to produce several test waveforms, compliant with standards for PMUs and PQs performance verification (multitone, frequency ramp, dips and swells, etc.). It also allows the generation of waveforms extracted from database or synthesized by the user.

As a first example of application, the reproduction of a voltage dip disturbance in a Medium Voltage (MV) grid is addressed. To this end, a fault has been simulated to reproduce those included in the QuEEN (Quality of Electric Energy) webportal, where PQ data measured by a widespread monitoring system including 400 measurement unit installed in HV/MV substations [13] distributed all over the Italian territory are reported.

To this end, a detailed model of the distribution network used (Fig. 1). The model includes a Primary Substation (PS), modelled through sinusoidal three phase 132 kV, 50 Hz generator and a 40 MVA HV/MV power transformer with 2300 MVA short circuit impedance. From the PS MV bus-bar, six feeders starts. The feeders include four underground cables and two overhead lines with 5 km to 25 km length. At the top of each line, a three-phase circuit breaker (CB) is installed and passive loads are places connected to some lines. A fault is simulated by closure of a CB on a suitable resistor.

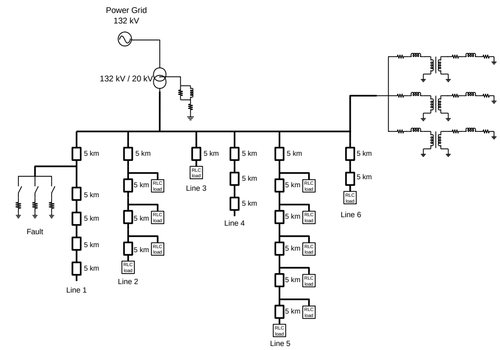


Fig. 1. Model of the considered MH/MV system.

As regards the identification of test signals under dynamic conditions, modulated signal based on [3] are considered. They consist of a fundamental tone at power frequency (i.e. the carrier), amplitude and phase modulated, according to the following expressions:

$$v(t) = \sqrt{2}X_m(1 + k_x\cos(2\pi f_m t)) \cdot \cos(2\pi f t) \qquad (1)$$

$$v(t) = \sqrt{2}X_m \cdot \cos(2\pi f t + k_a \cdot \cos(2\pi f_m t - \pi) \qquad (2)$$

where $X_m$ and $f$ are, respectively, the root mean square (rms) amplitude and the frequency of the fundamental tone, $k_x$and $k_a$ are the amplitude and phase modulation factors and $f_m$ is the modulation frequency .

An example of amplitude modulated signal is shown in Fig. 2.

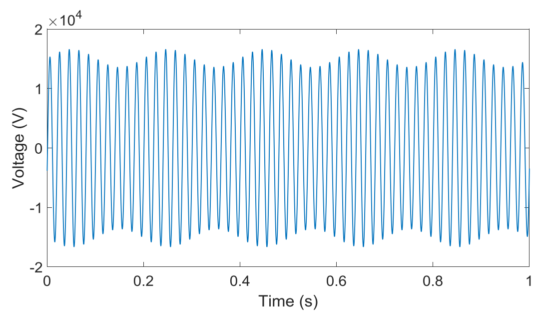


Fig. 2. Amplitude modulated signal ($k_x$=0.1, $f_m$=5 Hz)

VT accuracy is assessed according to [14], both ratio error ($\varepsilon$) and phase error ($\varphi$) are evaluated as:

$$\varepsilon = \frac{k_r V_s - V_p}{V_p} \qquad \varphi = \varphi_s - \varphi_p \qquad (3)$$

where:

- $k_r = {V_{p,r}}/{V_{s,r}}$ is the rated transformation ratio ($V_{p,r}$ and $V_{s,r}$ are the rated primary and secondary voltages);
- $V_p$ and $V_s$ are the root mean square (rms) values of the primary and secondary voltage;
- $\varphi_p$ and $\varphi_s$ are phase angles of the primary and secondary voltage.

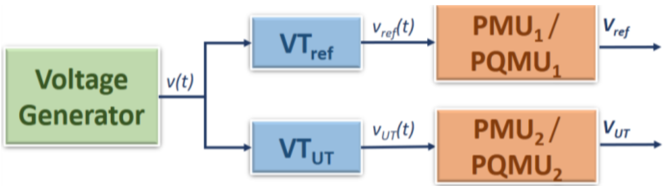


Fig. 3. Functional block diagram of the measurements

## A. VT Measurement Scenario

With the aim of investigating the possible errors introduced by the VT when it is used upstream a PMU or a PQ Measurement Unit (PQMU), the measurement system configuration shown in Fig. 3 is assumed.The reference VT ($VT_{REF}$) and the VT under test ($VT_{UT}$) are used to sense and reduce the same distorted voltage signal $v(t)$. Their outputs, $v_{REF}(t)$ and $v_{UT}(t)$, are acquired and processed by two identical, and synchronized devices, which can be PQMUs or PMUs. For the PQMUs, the output quantities $V_{REF}$ and $V_{UT}$ are the rms voltage refreshed each half-cycle ($U_{rms\ (1/2cycle)}$) at the reference and the VT chain output, from which the quantities of interest, in the considered case dip duration and residual voltage, are evaluated.

For the PMU tests, the outputs are the fundamental tone synchrophasors $\boldsymbol{V_{REF}}$ and $\boldsymbol{V_{UT}}$ from which the ratio and and phase errors are evaluated, with primary and secondary voltages phasors given by:

$$\boldsymbol{V_p} = k_{REF}\boldsymbol{V_{REF}} \qquad\qquad \boldsymbol{V_s} = \boldsymbol{V_{UT}} \tag{4}$$

where $k_{REF}$ is the transformation ratio of $VT_{REF}$, $\boldsymbol{V_p}$ is the fundamental primary voltage phasor and $\boldsymbol{V_s}$ is the fundamental secondary voltage phasor of $VT_{UT}$.

In addition, the Total Vector Error (*TVE*) is considered for the TV error analysis, as defined in [3][4]:

$$TVE=\sqrt{\frac{\left(Re(k_r\boldsymbol{V_s})-Re(\boldsymbol{V_p})\right)^2+\left(Im(k_r\boldsymbol{V_s})-Im(\boldsymbol{V_p})\right)^2}{Re(\boldsymbol{V_p})^2+Im(\boldsymbol{V_p})^2}} \tag{5}$$

If the two measuring device are assumed identical, linear and accurately synchronised, and are used to measure the same distorted voltage signal, the evaluated quantities (2), (4) and (5) can represent the errors introduced by the VT under test when it is used for syncrophasor measurement. Same consideration ca be done if the PQ event measurement is considered.

## III. Meaurement Setup

Starting from the hardware used for the MV VT frequency characterization, a suitable measurement setup is developed. The block diagram and the setup used for VT characterization at INRIM are shown Fig. 4a and Fig. 4b respectively.

The test waveform is generated by an Arbitrary Waveform Generator (the NI PXI 5422, 16 bit, variable output gain ± 12 V, 200 MHz maximum sampling rate, 256 MB onboard memory).

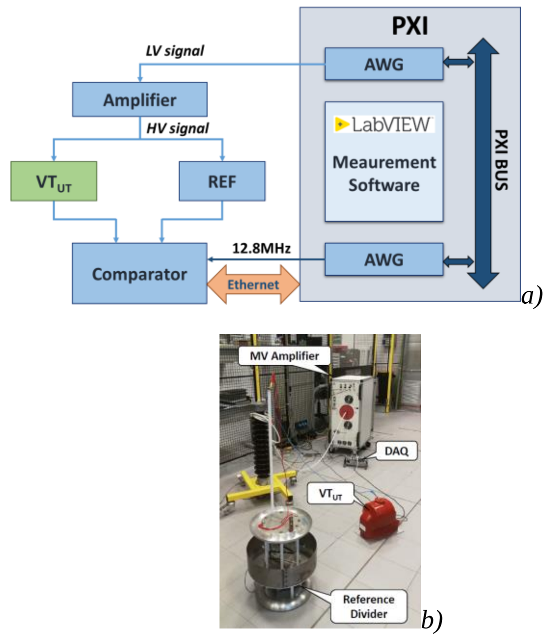


Fig. 4. Setup for the VT characterization: a) block diagram, b) experimental test bench at INRIM.

The chassis 10 MHz PXI clock is used as reference clock for its high resolution Phase Locked Loop circuitry. The generation frequency of the AWG is therefore chosen to be an integer multiple of the generated fundamental frequency. A second AWG is used to generate a 12.8 MHz clock, which is used as a time base clock for the signal comparator. As described in [12], The low voltage waveform from the AWG is amplified by a Trek high-voltage power amplifier (30 $kV_{peak}$, 20 $mA_{peak}$) with wide bandwidth (from DC to 2.5 kHz at full voltage and 30 kHz at reduced voltages), high slew rate (<550 V/µs) and low noise. Applied voltage reference values are obtained by means of a 30 kV wideband reference divider ($VT_{REF}$ in Fig. 3) designed, built and characterized at INRIM.

The acquisition system is a NI cDAQ chassis with four acquisition modules: NI 9225 (± 425 V, 24 bit, 50 kHz), NI 9227 (± 14 A, 24 bit, 50 kHz), NI 9239 (± 10 V, 24 bit, 50 kHz), NI 9238 (± 500 mV, 24 bit, 50 kHz). Expanded uncertainty (confidence level 95%) is 0.007% for the ratio error and 0.07 mrad for the phase up to 1 kHz 0. The sampling clock of the digital comparator is derived from the 12.8 MHz time base clock so that generation and acquisition are synchronized. The software for data processing and instrument control is developed in LabVIEW. A large variety of signals can be generated, such as sinusoidal, fundamental plus a harmonic tone, fundamental with *N* harmonics, fundamental with an inter-harmonic, modulated signal, frequency ramp, transient, typical PQ events etc. The VT primary and secondary voltage are acquired with $f_s$=50 kHz sampling frequency and 20 s acquisition time.

As to the PQ event test, a second comparator device (Fig. 4a) has been used. The outputs of both the reference and under test sensor are acquired by an acquisition unit that is designed by RSE to serve also as a part of a Stand-Alone Merging Unit provided with additional functions as well. This acquisition unit has two voltage channels (100 $V_{peaks}$ or 3 $V_{peaks}$ for each channel) and one current channel (5 $A_{peaks}$) with 24 bit ΔΣ ADC and variable sampling frequency. The clock can be provided both internally by an on-board oscillator or by an external clock and an external TTL signal can trigger the sampling. The communication is made through an SPI / USB 2.0 Bridge interface and control and measurement software is C++ software. The prototype was characterize at RSE and INRIM and it is possible to attribute to the prototype a 110 dB Spurious-Free Dynamic Range (SFDR) [16].

Both PMUs and PQ algorithms are implemented through a MATLAB script. In the case of the PMU tests, because of the synchronization between generation and acquisition, the Discrete Fourier Transform (DFT) of the acquired samples is used to evaluate the voltage fundamental phasors; the observation interval is chosen equal to four cycles of the fundamental frequency and a reporting rate of 50 Hz is assumed.

## IV. Expertimal REsults

### A. Devices under test

The behaviour of two different resin insulated VTs for MV phase-to-ground 50 Hz measurements whose rated characteristics are summarised in Table I are tested. All tests described in the following were carried out with zero burden.

Table I - VT rated characteristics

| VT | $V_{pr}$ (kV) | $V_{sr}$ (V) | Burden (VA) | Accuracy class |
|---|---|---|---|---|
| **A** | 20/√3 | 100/√3 | 50 | 0.5 |
| **B** | 11/√3 | 110/√3 | 50 | 0.5 |

### B. Modulated signal test

The VTs have been tested using an amplitude (phase) modulated voltage signal with fundamental component at 50 Hz and rated amplitude, assuming an amplitude modulating factor of 0.1 (0.1 rad for the phase), with modulating frequencies 0.1 Hz, 0.2 Hz, 0.5 Hz, 1 Hz, 2 Hz, 5 Hz, in accordance with [3], [4].
Figs. 5 to 7, show the measured ratio and phase errors, expressed in percent and milliradians respectively, and the TVEs, in percent, as a function of the analyzed frames, corresponding to a time window of 20 s, when an amplitude modulation is applied. Fig. 8 and Fig. 9 show the ratio error in percent and the phase error in milliradians when a phase modulation test is performed. The obtained behaviours show the presence of oscillations in the evaluated quantities, whose amplitude is quite constant with respect to the modulating being about 0.02% for the ratio error and 0.2 mrad for the phase for amplitude modulated test. On the other hand, the number proportionally increase with the value of $f_m$. Same behaviours, but with lower oscillation amplitudes can be observed for VT B in case of phase modulated test. These phenomena can be explained considering that the VT introduces a 50 Hz phase delay with respect to the reference one, which can be determined by carrying out a calibration under sinusoidal conditions, and that DFT over a 50 Hz cycles Under the assumption of negligible phase error of the reference sensor, no deviation will be found if the VT does not introduce any phase displacement.

Moreover, the results highlight that the peak to peak value of the oscillations is quite constant increasing the modulating frequency.

Looking at the mean value, in all test conditions, the analyzed indexes have an almost equal value and the investigated VT remains in its accuracy class.

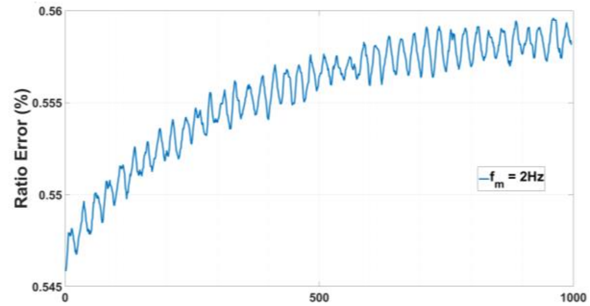


Fig. 8 TV B Ratio error for 2 Hz phase modulating frequency

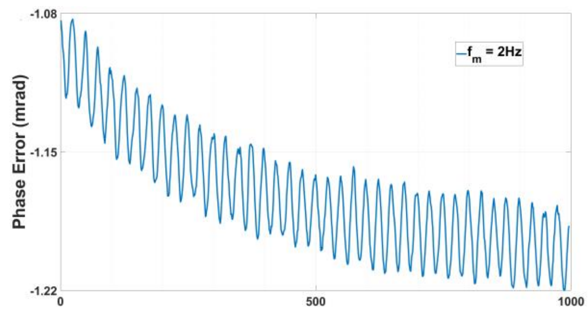


Fig. 9 TV B Phase error for 2 Hz phase modulating frequency

### A. Voltage dip test

The voltage dips measured by the reference sensor and by the VT A under application of a simulated realistic voltage dip, are shown in Fig 10, where the voltage values are normalised to the MV grid rated primary value (20 kV/√3). The evaluated quantities are the residual voltage ($U_{res}$), and the voltage dip duration $t_{dip}$; according to the IEC 50160, the selected dip threshold is set to 90% of the MV line rated primary voltage $U_r$, while the hysteresis is set to $2\%\cdot U_r$.
As regard the voltage dip duration, since the voltage time variation of the reproduced dip is very fast, no difference is measured between the duration measured by the reference divider and the VT under test (170 ms). As to the measurement of the residual voltage $U_{res}$, the deviation between the value obtained with the VT and the reference one reaches a maximum difference of 0.15%. This deviation is significantly lower than the quantity to be measured, but cannot be considered negligible, since it is of the same order of magnitude of the uncertainty required by the standards for the measuring instrument associated to the VT, when measuring the dip residual voltage [2].

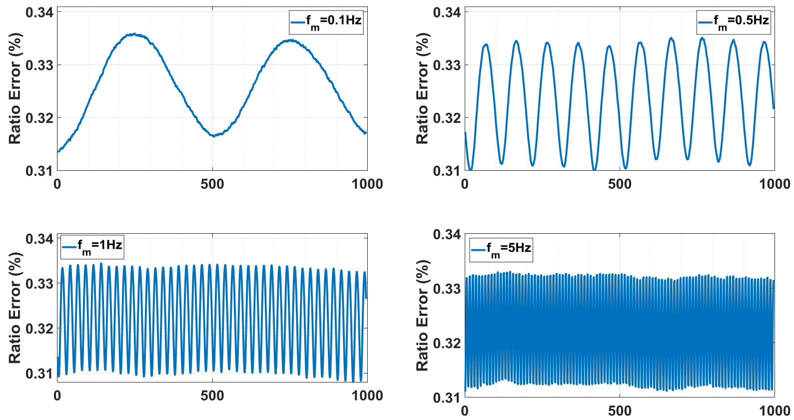


Fig. 5 TV A: Ratio error for 4 amplitude modulating frequency

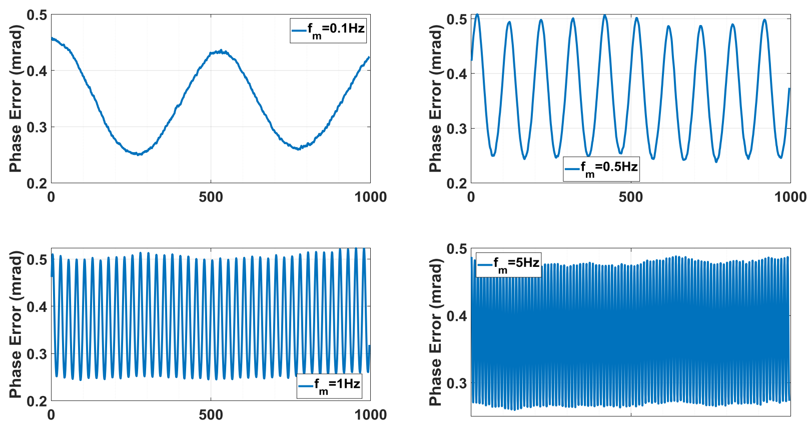


Fig. 6 TV A: Phase error for 4 amplitude modulating frequency

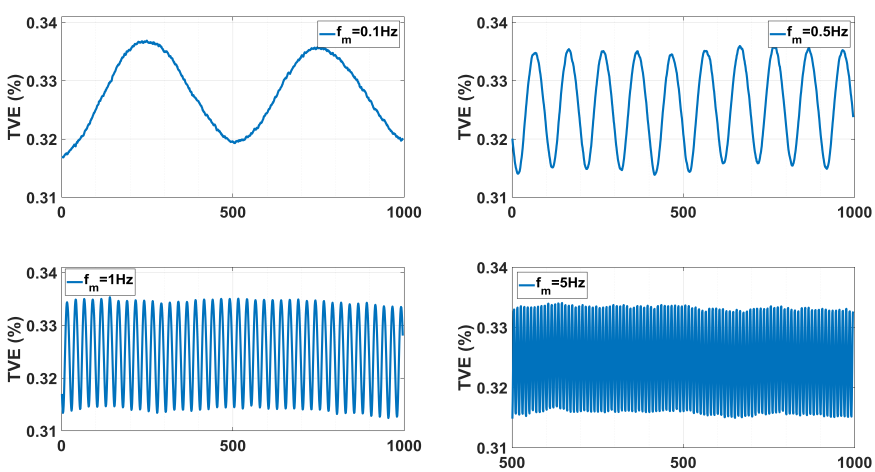


Fig. 7 TV A: Total vector errors for 4 amplitude modulating frequency

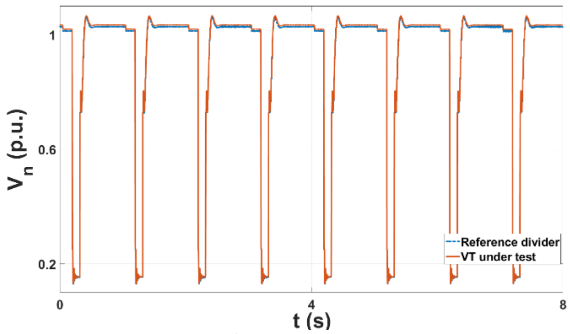


Fig.10 TV A vs Reference Divider $U_{rms\,(1/2cycle)}$ p.u.

## V. CONCLUSION

A measurement approach for the quantification of the error contribution of VTs when they are involved in PQ measurement or synchrophasor measurement performed by a PMU has been presented. The developed measurement setup is modular, so it is easily extensible to characterization of different types of sensors including current transformers LPITs with analog and digital output.

First tests performed on commercial VTs for MV applications has proved the feasibility of the proposed approach. By the developed system, investigations about the VT performance will be possible, by varying other parameters, such as fundamental amplitude, frequency and phase. VTs with different rated characteristics and of different types will be also investigated.

Thanks to the large set of implemented test waveforms, the same generation and measurement system will be used to test the sensors in presence of several phenomena including typical PQ disturbances.

## VI. ACKNOWLEDGEMENT

The work presented in this paper was funded by EMPIR, 17IND06 Future Grid II project, which is jointly funded by the EMPIR participating countries within EURAMET and the European Union.

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