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Evaluation of Voltage Transformers' Accuracy in Harmonic and Interharmonic Measurement

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ABSTRACT The measurement of Power Quality (PQ), generally performed at Low Voltage (LV) level, is gaining more and more importance also at the Medium Voltage (MV) level, due to the increasing presence of switching power converters (both loads or generators) directly connected to MV grids. In this case, the use of Voltage Transformers (VTs) is unavoidable to scale voltage down to amplitudes compatible with the input ranges of PQ instruments. However, the current absence of an international standard dealing with VTs used for PQ measurements leaves the manufacturers and the users in a situation of complete uncertainty, since different products can have performance specifications tested and stated in completely different ways. This paper aims at defining an integrated approach for the evaluation of VTs accuracy used for PQ measurements, focusing on harmonics and interharmonics. The paper provides experimental results of the tests performed on a MV inductive VT according to the proposed procedure. As a result, it is demonstrated that VT accuracy in the measurement of a specific phenomenon should be evaluated with complex waveforms including the contemporary presence of different PQ phenomena.

INDEX TERMS Instrument transformers, voltage transformers, harmonics, interharmonics, power system measurements, power quality, accuracy.

I. INTRODUCTION

IN MODERN energy systems, the evaluation of Power Quality (PQ) is gaining more and more importance, due to the growing presence of switching power converters, as part of distributed generation systems as well as of nonlinear loads. The PQ monitoring is traditionally carried out in Low Voltage (LV) grids. In recent years, due to the advance in the technology of switching devices, power converters can be directly connected also to Medium Voltage (MV) grids [1], [2], [3]. These devices contribute to inject several types of PQ disturbances and in particular harmonic and interharmonic components, so making PQ measurements become a key task also in MV grids.

The PQ topic is well addressed from the standard point of view; international standards [4], [5] describe characteristics, limits, measurement methods and indices for PQ phenomena. The PQ measurement methods and indices are mainly defined for PQ instruments (PQIs) which, for economic and operator safety reasons, are always installed at the LV side. Therefore, the monitoring of PQ at MV levels can be only performed using suitable Voltage and Current Transformers (VTs and CTs) to scale voltage and current to suitable levels that can be acquired by a PQIs or, more in general, by a data acquisition system or a Stand Alone Merging Unit (SAMU) and then processed by a software implementing the PQ measurement algorithms [6].

Thus, it is clear that the measurement of the PQ disturbances at MV level strongly depends on the performance of the Instrument Transformers (ITs) included in the PQ measurement chain. Very often, the ITs used for this purpose are of inductive type, as they currently are the most installed ITs for metering and protection applications. The relevant

CT and VT standards [7], [8] do not deal with the case of their employment in PQ measurements. This fact leaves the IT manufacturers the possibility to define their own procedures for the accuracy evaluation of their products. At the same time, IT users are in great difficulty when they have to choose the best IT for their application, since different products can have performance specifications tested and stated in completely different ways.

Recent literature has highlighted that inductive ITs can introduce not negligible errors in the measurement of PQ phenomena. In [9], [10], [11] the analyzed VTs and CTs introduce errors of up to some percent in harmonic measurements, due to their non-linear behavior. In [12] it is shown that inductive CTs can exceed their accuracy class if the input current is a modulated signal. In [13] the performance of VTs in presence of fast transient are investigated. Moreover, [14] shows that VT errors in harmonics measurement can increase up to tens of percent if subharmonic components are present in the input voltage.

These results highlight the need to identify proper measurement tests and performance indices to assess the errors introduced by ITs involved in the measurement of PQ disturbances [15].

In this context, this paper aims at defining an integrated approach for evaluating the IT performances in the measurement of PQ phenomena. As a first step, this entails identifying: 1) relevant PQ phenomena for IT characterization as well as their range of variation; 2) the definition of a new time-variant synthesized test waveform that enables quick and efficient testing of ITs under single and multiple PQ disturbances; 3) the identification of possible performance indices (PIs) for the quantification of IT errors in the measurement of specific PQ events; 4) finally, the design of a basic measurement setup that could be used for standardized IT performance assessment in PQ measurements.

Due to the wide variety of PQ phenomena, each one with its own specificity, in this paper we focus only on harmonics and interharmonics. Moreover, this paper examines only VTs, showing, in particular, the results of the tests performed on a commercial inductive MV VT by following the proposed integrated approach. In this way, it is experimentally verified that the VT accuracy in the measurement of a specific PQ disturbance is strongly influenced by the presence of other disturbances. In particular, different results are obtained if the test waveform includes only the fundamental and the specifically considered harmonics or interharmonics or if a more complex waveform, including also other types of phenomena, is used.

The work presented in this paper is part of the European metrology research project EMPIR 19NRM05 IT4PQ [16]. It aims at establishing the methods and procedures for assessing the errors introduced by ITs when they are used to measure PQ phenomena. Its final scope is to provide the IEC TC 38 (International Electrotechnical Commission Technical Committee) “Instrument Transformers” with the most comprehensive knowledge possible to redact an international standard on this topic.

The structure of the paper is as follows. Section II defines possible test points for harmonics and interharmonics tests. Section III introduces the possible basic measurement setup and PIs to use in the evaluation of IT accuracy. Section IV describes the synthetic test waveform. Section V and Section VI present the measurement setup and experimental results, respectively. Finally, in Section VII the conclusions are drawn.

II. SELECTION OF PQ PHENOMENA FOR IT CHARACTERIZATION

The first step of the work is the selection of the relevant PQ phenomena for IT testing. For this purpose, a preliminary deep review of the in force standards and recent literature dealing with PQ has been carried out and presented in [17]. The information collected with the review activity has been used to identify: 1) the possible influence of IT performances in the measurement of PQ phenomena; 2) the range of variation of the characteristic parameters of PQ phenomena. By the combination of the outputs of the two points above, it is possible to select significant PQ phenomena and a combination of them to test ITs. The selected PQ phenomena are divided into three categories that are steady-state, dynamic and transient events. The steady-state phenomena are harmonics and interharmonics. Their detection and estimation strongly depend on ITs’ frequency behaviour. The dynamic phenomena are amplitude and phase modulation and frequency ramp. The transient events are voltage dips, swells, interruptions, rapid voltage variations and transient overvoltage. The detection and measurement of all these transient PQ phenomena depend on both ITs amplitude and transient performances.

As already mentioned in Section I, this work is focused on steady-state phenomena, thus Section II-A gives a brief overview of harmonics and interharmonics amplitude and frequency ranges.

A. HARMONICS AND INTERHARMONICS

The harmonic is a sinusoidal component with a frequency equal to an integer multiple of the power frequency of the supply voltage, whereas the interharmonic is a sine wave with a frequency not equal to an integer multiple of the power frequency (can be also lower than this) of the supply voltage. The measurement of harmonics and interharmonics represents a key issue for both power grid monitoring and protection applications.

According to [4], [17] and [20], in the frequency range from a few millihertz up to 9 kHz, the harmonic and interharmonic voltages can range from 0.2 % to 10 % whereas the harmonic and interharmonic currents from 0.5 % to 40 %. As previously mentioned, the frequency response of ITs can significantly affects the measurement of harmonic and interharmonic phenomena. However only standards on Low Power Instrument Transformers (LPITs) [21] and

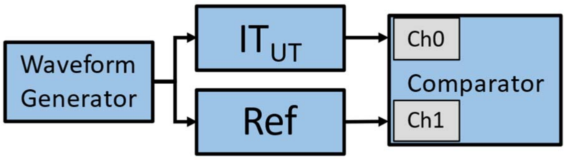


FIGURE 1. **The basic measurement setup for the evaluation of harmonic and interharmonic performance indices.**

Electronic CTs [22] prescribe tests to evaluate their accuracy at frequencies different from the fundamental. These standards define as testing points the harmonic order and the frequency ranges but do not provide information on harmonic amplitudes. Moreover, the standards [21], [22] do not define how the test waveform has to be composed but only suggest to perform the test with a signal made with the rated input signal at the rated frequency plus a percentage of the rated primary input signal at each considered harmonic frequency. However, this information can be the first guideline for ITs characterization in harmonic and interharmonic measurements.

III. PROPOSED METHOD AND PIS

This Section introduces the possible measurement setup, methods and possible IT-PIs for harmonic and interharmonic measurements.

The basic measurement setup is shown in Fig. 1. It consists of a waveform generator, able to generate arbitrary test waveforms at MV level, an IT under test (IT_{UT}), a linear reference device (Ref) and a comparator for the evaluation of the IT-PIs. In particular, the comparator is composed by a two-channel acquisition section (Ch0 and Ch1) and a post-processing section able to compute the IT-PIs for harmonic and interharmonic measurements. This measurement approach is used for the minimization of the errors introduced by the measurement chain. In fact, for instance, the use of two PQ instruments, which would have different performances (even if they are the same model of the same manufacturer) should be avoided.

For the design of the basic measurement setup, the minimum requirements should be considered on the basis of the rated features of IT_{UT}. In particular, for the voltage case, the features to take into account are the rated primary voltage A_{rated}, the rated transformation ratio k_r, the rated frequency f_0 and the accuracy class.

A possible measurement setup could include a waveform generator able to generate an arbitrary signal with a fundamental component in the range $f_0 \pm 15\ \%$ with a voltage equal to $1.5{\cdot}A_{\text{rated}}$. The generation system should allow for generating tones at frequency f, in addition to the fundamental one, with amplitude A_f according to the curve provided in Fig. 2.

As to reference device Ref, it should have a primary rated voltage at least equal to $1.5{\cdot}A_{\text{rated}}$ and a flat frequency response, f.i. up to 1/3 of the error limits required by the standard [21] for the accuracy classes extension for LPITs for quality metering and low bandwidth Direct Current (DC) applications.

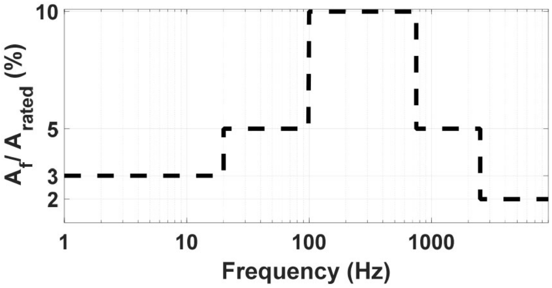


FIGURE 2. **Amplitude generation capability versus frequency of a possible waveform generator for VT testing in presence of PQ phenomena.**

The acquisition section should have input channels with a full scale input range suitable with the output of the IT_{UT} ($1.5{\cdot}A_{\text{rated}}/k_r$) and of the Ref. The sampling frequency should be adequate for the analysis of signals with spectral content up to 9 kHz, for example, 50 kHz.

As regards the definition of possible IT-PIs for harmonics and interharmonics measurements, they are mainly defined starting from measurement methods and indices already given in the standards dealing with harmonic and interharmonic measurement [23], [24], [25]. This approach allows simplifying the assessment of the error associated with the measurement of harmonics and interharmonics introduced by the whole MV PQ measurement chain.

The basic measurement time interval is chosen equal to 10 cycles (12 cycles) for a 50 Hz (60 Hz) power systems, in compliance with [24]. Without loss of generality, but only for sake of simplicity and clarity, in the following reference will be made to a power system with a fixed frequency equal to 50 Hz. In this case, 10 cycles of the fundamental component will be always equal to 200 ms.

The quantities to be measured are the phasors of the voltage or current at both primary as well as secondary windings of the IT under test. These values can be obtained by performing a spectral analysis, f.i. with the Discrete Fourier Transform (DFT), provided that a coherent sampling is performed. Starting from these quantities, the IT errors can be quantified in terms of PIs at single harmonic or interharmonic tones, PIs in a delimited frequency range or PIs over the bandwidth from a few millihertz up to 9 kHz. In the Sections from III-A to III-D, the IT-PIs are presented. For sake of brevity, the IT-PIs are defined only for VTs, but the same indices easily apply to CTs.

A. SINGLE TONE INDICES

The conventional indices used for the accuracy evaluation of VTs at power frequency are the ratio and phase errors [8]. Considering the single harmonic or interharmonic tones, it is possible to extend the definitions of ratio and phase errors in frequency. The harmonic and interharmonic ratio and phase errors, as they are used for harmonics in [9], [11], [14], [15], can be defined as:

$$\varepsilon_t = \frac{\mathrm{k_r V_{s,\mathit{t}} - V_{p,\mathit{t}}}}{\mathrm{V_{p,\mathit{t}}}}, \tag{1}$$

$$\Delta\varphi_t = \varphi_{s,t} - \varphi_{p,t}, \tag{2}$$

where $\mathrm{k_r} = V_{\mathrm{p,r}}/V_{\mathrm{s,r}}$, is the rated transformation ratio ($\mathrm{V_{p,r}}$ and $\mathrm{V_{s,r}}$ are the rated primary and secondary voltages at power frequency); $V_{\mathrm{p,t}}(V_{\mathrm{s,t}})$ are the Root Mean Square (RMS) values of the primary (secondary) voltages at t-th frequency (harmonic or interharmonic); $\varphi_{\mathrm{p,t}}$ and $\varphi_{\mathrm{s,t}}$ are the phase values of the primary and secondary phasors at the t-th frequency.

Another possible PI for the evaluation of ITs errors at the single harmonic/interharmonic can be the Total Vector Error quantity (TVE) [26]. The TVE for fundamental component is already used in other works [29] and here an extension for harmonic and interharmonic frequencies is proposed:

$$TVE_t = \sqrt{\frac{\left(\Re\left(k_r\overline{V}_{s,t}\right) - \Re\left(\overline{V}_{p,t}\right)\right)^2 + \left(\Im\left(k_r\overline{V}_{s,t}\right) - \Im\left(\overline{V}_{p,t}\right)\right)^2}{\Re\left(\overline{V}_{p,t}\right)^2 + \Im\left(\overline{V}_{p,t}\right)^2}}, \tag{3}$$

where k_r is the rated transformation ratio; $\overline{V}_{\mathrm{p,t}}$ ($\overline{V}_{\mathrm{s,t}}$) is the phasor of the primary (secondary) voltage at t-th frequency (harmonic or interharmonic); the operator $\Re$ ($\Im$) refers to the real (imaginary) part of the phasor.

B. LOCAL INDICES

The amplitude of power systems' voltage can fluctuate distributing the energy of the harmonic components at adjacent interharmonic frequencies, so it may be necessary to measure the harmonic and interharmonic groups [25]. These two groupings provide a value for the interharmonic components between two discrete harmonics, which includes the effects of fluctuations of the harmonic components. The measurement indices used to quantify this phenomenon are presented in [24] and [25] and they are the gapless harmonic subgroup measurement, the gapless interharmonic group measurement and the centred interharmonic subgroup measurement, illustrated in Fig. 3 and defined as follow:

$$Y_{hsg} = \sqrt{V_{h\cdot f_1 - r}^2 + V_{h\cdot f_1}^2 + V_{h\cdot f_1 + r}^2}, \tag{4}$$

$$Y_{ig} = \sqrt{\sum_{m=1}^{8} V_{h\cdot f_1 + m\cdot r}^2}, \tag{5}$$

$$Y_{icsg} = \sqrt{\sum_{m=2}^{7} V_{h\cdot f_1 + m\cdot r}^2}, \tag{6}$$

where Y_{hsg}, Y_{ig} and Y_{icsg} are the harmonic subgroup, the interharmonic group and the interharmonic centred subgroup RMS values, respectively; $V_{h\cdot f_1}^2$ is the RMS value of voltage at h-th harmonic order frequency; f_1 is the power frequency; r is the frequency resolution equal to 5 Hz. A possible new IT-PI for the quantification of the IT error contribution over local frequency ranges can be the harmonic and interharmonic subgroup ratio error $\varepsilon_{\mathrm{sgt}}$, defined as:

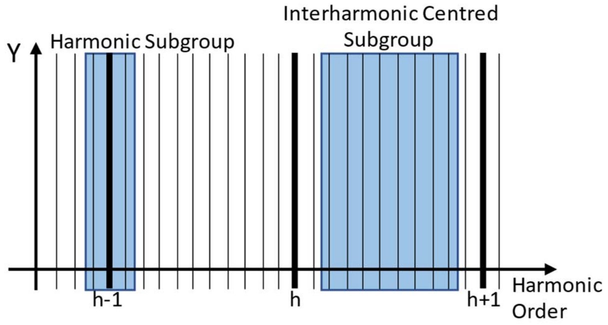


FIGURE 3. Graphical representation of harmonic subgroup and interharmonic centred subgroup.

$$\varepsilon_{sgt} = \frac{k_r Y_{s,sgt} - Y_{p,sgt}}{Y_{p,sgt}}, \tag{7}$$

where $\mathrm{k_r} = V_{\mathrm{p,r}}/V_{\mathrm{s,r}}$, is the rated transformation ratio ($V_{\mathrm{p,r}}$ and $V_{\mathrm{s,r}}$ are the rated primary and secondary voltages at power frequency); $Y_{\mathrm{p,sgt}}$ and $Y_{\mathrm{s,sgt}}$ are, respectively, the primary and secondary harmonic or interharmonic subgroup at t-th frequency.

C. GLOBAL INDICES

To globally evaluate the harmonic and interharmonic distortion, indices such as the Total Harmonic Distortion (THD) and the Total Interharmonic Distortion (TIHD) can be used [24]. The relative error contribution of the ITs on the measurement of the THD and TIHD of ITs, can be defined as follows:

$$\Delta_{THD} = THD_{\mathrm{s}} - THD_{\mathrm{p}}, \tag{8}$$

$$\Delta_{TIHD} = TIHD_{\mathrm{s}} - TIHD_{\mathrm{p}}, \tag{9}$$

where the subscript p (s) refers to the quantities at the primary (secondary) winding of IT, i.e., at its input (output). These IT-PIs can be extended to other standardized indices, as subgroup total harmonic (interharmonic) distortion THDS (TIHDS) [25].

D. TIME AGGREGATE INDICES

As it is said in Section III, according to [24] the basic measurement time interval for a 50 Hz power systems is 200 ms; it follows that the spectral resolution in frequency domain is equal to 5 Hz. The presence of interharmonics with frequency not integer multiple of 5 Hz cause a time oscillation of the IT-PIs [14]. For this reason, it could be convenient to evaluate the IT-PIs time behaviour over a wider time frame. The standard [24] suggests to use aggregation time intervals equal to 150-cycles (3 s) or 10 minutes. Considering the collected values of the IT-PIs (f.i., the harmonic ratio error), it is possible to evaluate its maximum absolute value over the aggregation time interval according to the following equation:

$$\Gamma_K = \max_{\cup\ \tau_k} |\varepsilon_{tk}|, \tag{10}$$

where: $\cup\ \tau_k$ is the union of the time frames in which the quantity ε_{tk} is evaluated. For every considered quantities, $\cup\ \tau_k$ is always equal to the aggregation time interval [24]. Each τ_k is equal to the basic measurement time interval; ε_{tk} is the ratio error at the t-th frequency component evaluated over the τ_k time frame. It is worth noting that the PI defined in (10) can be easily applied to the other IT-PIs (2), (3) and (7) - (9).

IV. A SYNTHETIC TEST WAVEFORM TO EVALUATE THE IT-PIS

A key task for the evaluation of the metrological performance of IT used for PQ measurement is the definition of new significant test waveforms.

As already mentioned in the Section I, a quite common measurement chain for the PQ monitoring at MV is composed of an IT and a PQI. For this reason, a first possible approach to characterize the IT for PQ is to use the same characterization tests required for PQIs by the proper standard [23]. The IEC 62586-2 standard [23] clearly defines the functional tests to perform for evaluating the accuracy of PQIs in the measurement of harmonics and interharmonics. In particular, it establishes: 1) how to build the test waveforms and 2) amplitudes, frequencies and phases to assign to the fundamental, harmonic and interharmonic tones. Furthermore, the standard [23] prescribes testing the PQIs in the presence of a single disturbance and both harmonics and interharmonics simultaneously.

It can be possible to consider the same functional test points and conditions for harmonic and interharmonic measurement also for the characterization of MV ITs used for PQ measurement. This approach has an important advantage. Since the procedures and methods prescribed for PQIs in [23] are well consolidated, the metrological performances of ITs can be directly compared to the accuracy requirements for PQIs.

However, the ITs, especially those of inductive type, have non-linear behavior, which means that they show different performance depending on the test characteristics. For example, in power systems with generation from hydroelectric power plants [27], low-frequency oscillations can occur. They can invalidate the IT characterization at harmonic frequencies by using test points defined by PQI standards [14] or other harmonic characterization procedures [9], [10], [11].

For this reason, the test points given in the standard [23] for PQI can be not considered sufficient to comprehensively evaluate the metrological performances of the ITs under actual working conditions. It could more be appropriate to extend the test points and introduce new test waveforms to take into account the non-linear behaviors of ITs.

TABLE 1. **Possible test points for the amplitude and frequency of the fundamental component.**

		Test Point				
Parameters	***Class***	***P1***	***P2***	***P3***	***P4***	***P5***
Frequency 50Hz	A/S	42.5	50.05	57.5	50	N.A.
Frequency 60Hz	A/S	51	59.95	69	60	N.A.
Amplitude (% of U_{rated})	A	10	45	80	115	150
	S	20	45	70	95	120

In this context, Sections from IV-A to IV-D describe how to build the components of the synthetic test waveform presented in Section IV-E. The main benefit of using the proposed test waveforms in comparison to other test waveforms suggested in the scientific literature [9], [11] is that they enable to quickly assess the performance of the IT in harmonics and interharmonics measurement and, at the same time, to account also for any additional errors that may arise from the presence of multiple disturbances.

A. FUNDAMENTAL COMPONENT

The basic waveform of the tests is a virtually pure sinusoidal waveform. This test is already prescribed by the standards [7], [8] and [21], [22] and it is used for the evaluation of the ratio and phase errors at power frequency for the ITs accuracy class verification.

The sinusoidal waveform is defined as:

$$s_1(t) = A_1\sqrt{2}\sin(2\pi f_1 t) \tag{11}$$

where A_1, f_1 are the amplitude and frequency of the voltage fundamental component, respectively.

Possible choices for fundamental amplitudes and frequencies are those in Table 3 of IEC 62586-2 [23] and here reported in Table 1. However, these test points have to be extended including also information from standards about ITs [7], [8], [21] and [22].

B. HARMONIC COMPONENTS

To evaluate the IT performances in presence of harmonic components, a test waveform composed by a number of harmonics, and defined as in (12), can be used:

$$s_H(t) = \sum_{h=2}^{N_H} A_h\sqrt{2}\sin(2\pi h f_1 t + \ \varphi_h), \tag{12}$$

where: A_h, h and φ_h are the harmonic amplitude, order and phase, respectively; $\mathrm{N_H}$ is the number of harmonics that compose the test signal.

The harmonics' amplitude and order (A_h, h) are randomly chosen with a uniform distribution to meet 1) the limits for the harmonics prescribed by Table 2 and 2) the maximum THD limit (8%) set by the standard [4]. The harmonic phase angles are independent and uniformly distributed between $-\pi$ and π.

TABLE 2. Possible test range of harmonic and interharmonic components.

Harmonic components		
Minimum harmonic order	*Maximum harmonic order*	*Maximum Relative amplitude A_h/A_1 (%)*
2	15	10
16	50	5
51	180	2
Interharmonic components		
Minimum frequency (Hz)	*Maximum frequency (Hz)*	*Maximum Relative amplitude A_h/A_1 (%)*
0	20	3
20	100	5
100	9000	1

Table 2 proposes a simplified possible test range of harmonic and interharmonic components to assess the ITs' performance according to indications found in the review of in force standards and scientific literature [17], [18], [19], [20].

C. INTERHARMONIC COMPONENTS

The IT performances in the interharmonics measurement can be assessed in presence of a test waveform composed by a number of interharmonics, defined as follow:

$$s_I(t) = \sum_{i\epsilon I} A_i\sqrt{2}\ \sin(2\pi f_i t + \ \varphi_i) \tag{13}$$

where: A_i, f_i and φ_i are the interharmonic amplitude, frequency, and phase; I is the set of considered interharmonic frequencies.

The interharmonics amplitude and frequency (A_i, f_i) are randomly chosen with a uniform distribution to meet 1) the limits on interharmonics prescribed by Table 2, 2) f_i is an integer multiple of 5 Hz and 2) a maximum TIHD equal to 4 %. The phase angles are independent and uniformly distributed between $-\pi$ and π.

D. INTERHARMONIC DISTURBANCE

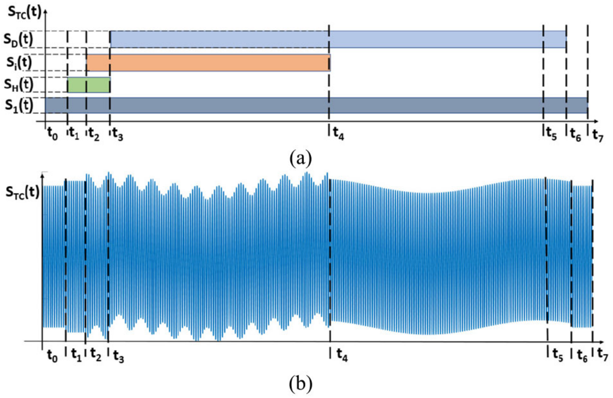
As it is said in Section III, the harmonic and interharmonic IT-PIs are evaluated over a time frame of 200 ms [24], thus the frequency resolution is equal to 5 Hz. For this reason, the interharmonics characterized by frequencies not multiple of 5 Hz cannot be measured and should be considered as disturbances. To quantify the IT errors due to these disturbances, the following test waveform is considered:

$$s_D(t) = A_D\sqrt{2}\sin(2\pi f_D t + \ \varphi_D) \tag{14}$$

where: $A_{\mathrm{D}}, f_{\mathrm{D}}$ and φ_{D} are the RMS amplitude, frequency and phase angle of the disturbance. The disturbance amplitude and frequency $(A_{\mathrm{D}}, f_{\mathrm{D}})$ are chosen to meet 1)the limits on the single interharmonic prescribed by Table 2, 2) f_{D} is not an integer multiple of 5 Hz.

E. TIME COMBINED WAVEFORM: A POSSIBLE TEST SET

Since harmonics and interharmonics in power systems can have a dynamic behavior, in order to verify the measurement performance of ITs under actual working conditions, it can be necessary to verify the effects of combined events with a time variant waveform.



(a)

(b)

FIGURE 4. Time combined waveform: a) proposed waveform scheme and b) time domain numerically simulated signal with one harmonic H = 2, one interharmonic I = 55 Hz and one subharmonic D = 0.5 Hz..

A possible test waveform for the evaluation of the IT in harmonic and interharmonic measurement is mathematically defined in (15):

$$\begin{aligned} s_{TC}(t) = s_1(t) + rect\left(\frac{t-\left(\frac{t_4-t_1}{2}\right)}{t_4-t_1}\right)\cdot s_H(t) \\ + rect\left(\frac{t-\left(\frac{t_5-t_2}{2}\right)}{t_5-t_2}\right)\cdot s_I(t) \\ + rect\left(\frac{t-\left(\frac{t_4-t_3}{2}\right)}{t_4-t_3}\right)\cdot s_D(t) \end{aligned} \tag{15}$$

where $rect(t\text{-}t_k/T_k)$ is the rectangle function with time duration T_k, from t_k-$T_k/2$ up to t_k+$T_k/2$; $s_1(t)$ is the fundamental component; $s_H(t)$ includes the harmonic components; $s_I(t)$ includes the interharmonic components and $s_D(t)$ includes the interharmonic disturbances.

The Fig. 4a and Fig. 4b show the time combined waveform scheme and its numerical simulation, respectively.

For each indicated time interval, the time combined waveform is obtained by superimposing the disturbances on the fundamental component. It is worth noting that in both the first as well as the last time frames (T_1 and T_6), the test signal $s_{\mathrm{TC}}(t)$ corresponds to the fundamental component $s_1(t)$. This choice allows evaluating if the presence of harmonics and interharmonics introduce persistent variation in the VT fundamental accuracy due to the iron-core's non-linearity. In other words, it is possible to verify if the VT returns to the starting conditions at the end of the test.

It is worth recalling that the amplitudes of each component are chosen according to the values given in Table 1 and Table 2. As the time duration T_k, the proposed values are provided in Table 3. The detail of the test is shown in Table 4, where at each time frame the occurred PQ event and some of the possible IT-PIs are associated. For sake of clarity, Fig. 5 shows the flow chart of the proposed procedure.

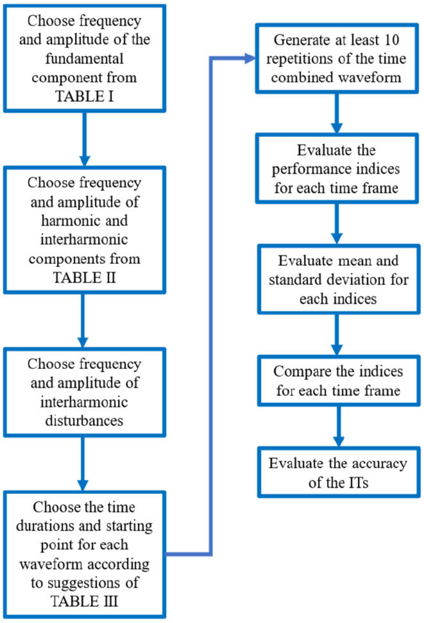


FIGURE 5. Flow chart of proposed integrated approach.

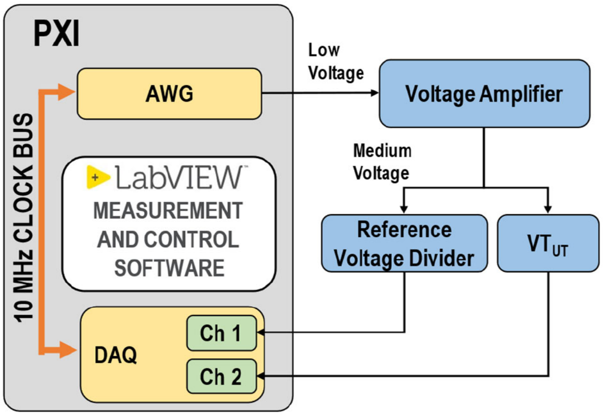


FIGURE 6. Generation and measurement setup for the laboratory characterization of VTs for PQ applications.

TABLE 3. Possible time durations of the time combined waveforms $s_{TC}(t)$.

Time frame	Time duration
$T_1(t_0$ to $t_1)$, T_2 $(t_1$ to $t_2)$, $T_3(t_2$ to $t_3)$, $T_6(t_5$ to $t_6)$, $T_7(t_6$ to $t_7)$	At least 10 frames of the basic measurement time interval.
$T_4(t_3$ to $t_4)$, T_5 $(t_4$ to $t_5)$,	At least 150-cycles of the power frequency if the frequency of the disturbance f_D is an integer number. At least one period of the $s_{TC}(t)$signal if the frequency of the disturbance f_D is not an integer number.

V. MEASUREMENT SETUP AND DEVICE UNDER TEST

The measurement setup used for the inductive MV VT characterization is shown in Fig. 6. The signal generation is obtained by the NI PXI 5422 (Arbitrary Waveform Generator, AWG, board, with 16 bit, variable output gain, output range of ± 12 V, maximum sampling rate of 200 MHz, onboard memory of 256 MB). The 10 MHz PXI clock is used as reference clock for both the AWG boards. Acquisition of the primary and secondary waveforms of the VT under test has been performed through the data acquisition board PXIe-6124 (±10 V, 16-bit, maximum sampling rate of 4 MHz). Waveforms have been sampled with 100 kHz rate obtained through oversampling in order to reduce the impact of noise. The output of the AWG is connected to a high-voltage power amplifier (NF HVA4321, up to 10 kV, from DC up to 30 kHz) feeding the VT under test. Primary voltages are scaled by a Ohm-Labs KV-10A High Voltage Divider with rated ratio of 1000 V/V and accuracy below 0.1 %.

TABLE 4. Numerical values of the times T_k.

T_1	0.2 s
T_2	0.4 s
T_3	0.6 s
T_4	2.6 s
T_5	4.6 s
T_6	4.8 s

The VT tested is an inductive resin insulated voltage transformer with 3 kV rated primary voltage, 30 V/V rated transformation ratio and 0.5 accuracy class. It is tested with null burden, that is with only the input impedance of the acquisition system greater than 100 GΩ in parallel with 10 pF. In fact, the burden effect on VT performance does not represent a significant influence parameter (please see also [14]), compared to the variations of the PIs induced by the other quantities involved in the tests. For this reason and for sake of simplicity, the VT is not tested under different burden conditions.

VI. MEASUREMENT RESULTS

This section provides preliminary experimental results related to the characterization of a commercial VT following the approach described in Sections III and IV.

Considering the equation (15), the generated test waveform is composed by: 1) the fundamental component $s_1(t)$ at 50 Hz; 2) the $s_H(t)$ harmonic components that, for sake of simplicity, include only the second harmonic; 3) the $s_I(t)$ interharmonic components with one tone at 55 Hz and 4) the $s_D(t)$ disturbances composed by one subharmonic at 0.5 Hz. The amplitude of the fundamental component is chosen equal to 80 %, 100 % and 120 % of the rated VT amplitude. The amplitudes of the other components are equal to 1 % of the fundamental amplitude in compliance with the limits provided in Table 2.

A. ACCURACY AT FUNDAMENTAL FREQUENCY

Fig. 7 shows the ratio error, phase error and TVE at fundamental frequency versus time, with different values of the

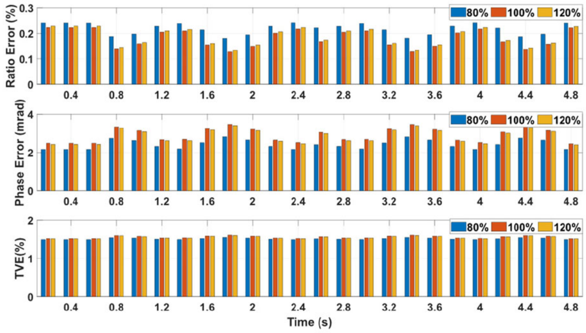


FIGURE 7. Ratio error, phase error and TVE at fundamental frequency versus time, with different values of the fundamental amplitudes.

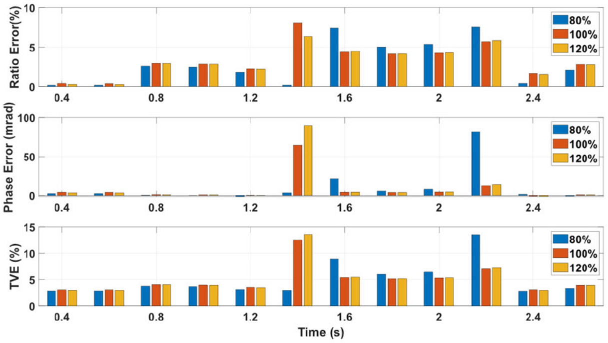


FIGURE 8. Ratio error, phase error and TVE at the second harmonic frequency versus time, with different values of the fundamental amplitudes.

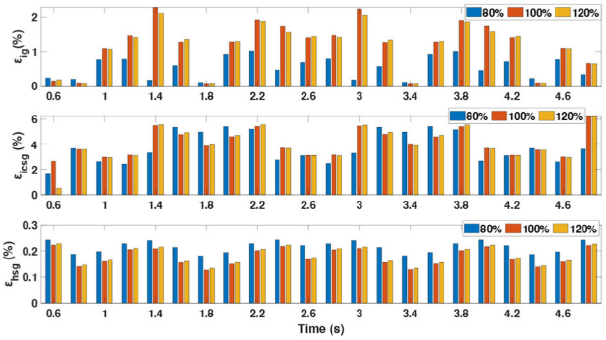


FIGURE 9. Ratio error of the second interharmonic group, second centered interharmonic subgroup and first harmonic subgroup versus time, with different values of the fundamental amplitudes.

fundamental amplitude. First of all, it can be observed that ratio and phase errors are always below the limits set by the standard [8] for the 0.5 accuracy class of VTs (0.5 %, 6 mrad). All the errors have the same values until 0.6 s. Therefore, it follows that the presence of the second harmonic and the interharmonic at 55 Hz does not affect the VT accuracy at fundamental frequency. After 0.6 s, when also the subharmonic at 0.5 Hz is present, oscillations in all the errors can be observed with maximum variations of 0.1 %, 1 mrad and 0.1 % for ratio error, phase error and TVE, respectively. The variations are equal to a certain fraction of the VT accuracy class, in particular the 20 % for the ratio error and about 16 % for the phase error. However, there can be situations, for instance when the ambient temperature makes the ratio error increase [28], in which the ratio or the phase errors, without the subharmonic can be very close to the accuracy class limits; so, if a subharmonic applies, the VT can exceed its accuracy class.

By the comparison of the PIs measured in T1 and T7, it can be noticed that, after that VT is supplied with the selected PQ harmonics and interharmonics, it returns at the same values. In fact, for instance, the ratio error, phase error and TVE have the same value equal to 0.2 %, 2.5 mrad and 1.5 % at 100 % of rated amplitude. As regards the different primary amplitudes, the same PIs variations are observed for the ratio and phase error and the TVE.

As a result, the accuracy of a VT, also at fundamental frequency, should be tested with complex waveforms including PQ phenomena in order to accurately take into account the effect of disturbances on VT accuracy.

B. ACCURACY AT HARMONIC FREQUENCY

Fig. 8 shows the ratio error, phase error and TVE at the second harmonic frequency versus time, with different values of the fundamental amplitude.

The maximum values of the second harmonic ratio error, phase error and TVE, at 0.4 s and 0.6 s, are equal to about, respectively, 0.4 %, 4 mrad and 3.5 %. Therefore, the VT accuracy at second harmonic is not influenced by the presence of the interharmonic at 55 Hz. On the contrary, the PI values change dramatically, when the subharmonic at 0.5 Hz applies, i.e., starting from 0.8 s. The maximum variations are equal to about 7.7 %, 90 mrad and 10.7 %, respectively for ratio error, phase error and TVE. Differently from the case of fundamental frequency, here the variations are much higher than the limits of the 0.5 accuracy class.

Different PIs variations are observed for the various primary amplitudes. At 80 %, in the presence of the 0.5 Hz subharmonic, the maximum increment of the ratio error is 4.8 %, at 100 % is 5.1 % and at 120 % is 3.4 %. It follows that the analysis must take into account the entire range of variation of the VT primary amplitude.

Therefore, the presence of the subharmonic has a very high influence on the VT accuracy at the harmonic frequency. As it is concluded for the fundamental frequency, the VT accuracy at harmonic frequency should be tested in presence of other PQ phenomena

C. ACCURACY AT INTERHARMONIC FREQUENCY

Fig. 9 shows the ratio error of the second interharmonic group, second centred interharmonic subgroup and first harmonic subgroup versus time, with different values of the fundamental amplitudes. Differently from the previous two cases, that are the errors at fundamental frequency and those at the harmonic frequency, here the ratio errors of the second interharmonic group and of the second centred interharmonic subgroup depend on the presence of the harmonic and of the subharmonic. In fact, first of all, these errors at 0.6 s, when there are the fundamental, the harmonic and the interharmonic tones, have different values with respect to 4.8 s, when there are only fundamental and interharmonic tones. Moreover, they assume still different values in the central part of the waveform, in presence of the subharmonic and the harmonic (from 0.8 s to 2.6 s) and in presence of the subharmonic but without the harmonic (from 2.8 s to 4.6 s). The maximum variations are equal to about 2.3 % and 6.2 % respectively for ratio errors of the second interharmonic group and of the second centred interharmonic subgroup. A different consideration must be done for the ratio error of the first harmonic subgroup. In fact, this includes the tones at 45 Hz, 50 Hz and 55 Hz and its value is practically determined by the ratio error at fundamental frequency, since the amplitude of the tone at 45 Hz is zero and the amplitude of the tone at 55 Hz is only 1 % of the fundamental tone. Therefore, in practice, for the ratio error of the first harmonic subgroup the same considerations done for the ratio error at fundamental frequency (see Section VI-A) apply. It can be concluded that VT accuracy at interharmonics depends on the used test waveform and so, as stated also for fundamental and harmonic frequencies, it should be measured in presence of other PQ phenomena.

VII. CONCLUSION

This paper has proposed possible performance indices, test procedure and synthetic waveforms that could be employed for the accuracy evaluation of ITs used for harmonic and interharmonic measurements. A commercial MV VT has been tested by using the proposed approach. Experimental results show that the accuracy of the VT in the measurement of a specific PQ phenomenon is dependent on the presence of other PQ phenomena. In other words, f.i., the VT ratio error in the measurement of a specific harmonic tone, when the waveform contains only fundamental and this harmonic tone, has a different value with respect to the case in which the waveform contains also other PQ phenomena. This suggests that the accuracy of a VT in the measurement of PQ phenomena should be evaluated by using complex waveforms to allow to measure the dependence of the accuracy in the measurement of a specific phenomenon on all the other PQ phenomena.

This work represents a task of a wide range of activities aimed at the development of a comprehensive knowledge that will allow to redact a standard focused on ITs used for PQ measurements. Future works will deal with the definition of a measurement procedure for the IT performance verification in presence of other types of PQ phenomena.

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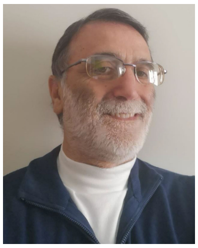

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