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How Undesired Non-Idealities of the Input Signal Affect the Accuracy Evaluation of Instrument Transformers at Power Frequency

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***Abstract*—This paper explores the calibration of Instrument Transformers (ITs) used in power grids metering. It highlights the lack of information in in-force standards regarding the non-idealities of the current and voltage generated for ITs calibration. Existing literature has proposed innovative calibration systems based on commercial ADC acquisition boards or digital multimeters. However, no studies have analyzed the impact of undesired non-idealities of the test signal on the measurement of power frequency ratio and phase errors. The paper aims to investigate and quantify the influence of Total Harmonic Distortion and frequency variation of the input voltage and current on IT accuracy assessment. The study is carried out through numerical simulations generating various THD levels and frequency variations and evaluating ratio and phase error through common algorithms. The simulation results show that especially for industrial laboratories in which uncertainty targets are more relaxed, THD levels higher than 2% can be tolerated by choosing proper measurement algorithms.**

Keywords—Instrument Transformers, Calibration, Power System Measurement, Power Frequency, Total Harmonic Distortion, Frequency Variation

I. Introduction

Instrument Transformers (ITs) are widely used in power grids to reduce the voltage and current amplitudes to levels fitting with the input stage of meters. The calibration of ITs is traditionally performed by comparison with reference transducers; they are supplied with the same test voltages or currents and their output are compared using proper instrument transformers test set. The power frequency accuracy class evaluation is covered by the IEC 61869 series [1] and IEEE C57.13 [2] standards. These standards specify the test voltage and current amplitudes and define the ratio and phase errors indexes. However, they do not provide indications about how "ideal" the test waveform should be. For instance, no indications on the spectral purity or on the amplitude and frequency accuracy are given. Furthermore, neither [1] nor [2] provide algorithms, preferred procedures, or recommended measurement systems for evaluating the electrical quantities required to calculate the ratio and phase errors of ITs.

As regard the scientific literature, a number of papers have faced the problem of calibration of ITs at power frequency [3]-[5], proposing innovative calibration system based on the use of commercial ADC acquisition boards [6] or digital multimeters [7]. For sake of brevity, here only some papers are cited.

Other papers deal with the characterization of frequency behaviour of ITs, using test waveforms with a desired predefined distortion [8]-[12]. Other information in this sense can be found in the technical report IEC 61869-103 TR [13]. However, to the best of the authors' knowledge, no papers deal with the deep analysis of the impact of possible undesired non idealities of the voltage and current test waveforms, that make them deviate from an ideal sinusoid, on the evaluation of ratio and phase errors at power frequency.

As regards the public electricity networks, the EN 50160 [14] defines the limit values for the parameters that make the supply voltage waveform deviate from an ideal sinusoid, in order to guarantee normal operating conditions to the grids. In particular, the limits for the Total Harmonic Distortion (THD) and for the power frequency variations are specified.

Similar considerations are not present in the standards about the accuracy evaluation of ITs [1], [2]. It must be noted that, differently from the public electricity grids, the accuracy evaluation of the ITs is carried out in specialized laboratories, with dedicated instrumentation and in a controlled environment. However, even in this conditions, it is impossible to have ideal sine waves with amplitude and frequency chosen with null uncertainty. In this scenario, the lack of information, regarding the potential limits of some non-idealities in the test waveforms, very often lead calibration laboratories to face significant efforts, with a consequent increase of costs, to minimize as much as possible these values. However, especially for non-primary metrological laboratories, these efforts may be excessive compared to the target uncertainty of the calibration process. For these reason, the work presented in this paper aims to study the impact of two undesired non-idealities, the THD and the frequency variations, of the input voltage and current on the accuracy evaluation of ITs. The paper also provides a practical ratio and phase errors measurement model that simplifies the estimation of the uncertainty contribution.

The study is carried out through numerical simulations. Signals affected by various levels of THD and variable frequency are considered. The reference and under-test transducers are simulated basing on information provided by the IEC 61869-6 standard [16]. Three different common measurement algorithms are considered: Discrete Fourier Transform (DFT), Sinusoidal Fit (SINFIT) and Root Mean Square (RMS) calculation. The simulations output represents as an initial tool to determine the maximum tolerable level of THD for calibration laboratories aiming to perform ITs calibrations with a specific target uncertainty. Considering this target uncertainty and the contributions from other sources (such as the reference transducer, acquisition system, temperature, etc.), it is possible to determine the maximum THD value that, if not exceeded, allows staying within the declared uncertainty.

The paper is organized as follows. Section II briefly summarizes possible sources of non-idealities in common industrial laboratory generation setups. Section III introduces a measurement model for the evaluation of ITs ratio and phase errors, highlighting the main quantities to account. Section IV discusses the numerical simulations results and Section V draws the conclusions.

II. Possible Non Idealities Of Input Signal In ITs Calibration

The purpose of this Section is to outline some issues and reasons that lead to the presence of undesired harmonic components and frequency variation in IT test systems.

The most common generation system in calibration laboratories as well as in National Metrology Institutes (NMIs) is based on the use of a low voltage generator coupled with a step-up transformer. The step-up transformer is based on ferromagnetic iron core and produces spurious harmonic tone, typically up to the 9th order, at its output even when it is supplied with a virtually pure sinusoidal signal [15]. These spurious harmonics further increase if the input waveform includes a small Direct Current (DC) component, that is an undesired disturbance introduced by the low voltage generator.

In other generation systems, which also rely on step-up transformers, the low voltage signal is obtained by using a low voltage transformer, with variable transformation ratio, connected to the public power grid. In these setups, if filtering and control elements are not included, the non-idealities of the power grid supply voltage, specified by the standard [14] may be directly provided to the input of the step-up transformer.

High levels of distortion can also occur in generation systems, that inherently have low THD, when they are used to calibrate nearly-saturated inductive ITs. In this case, the Device Under Test (DUT) absorbs a highly distorted current from the generation system, which, in turn, induces distortion in the generated voltage.

III. Practical Model of the Ratio and Phase Error Measurement

The general approach for the ITs calibration is based on the logical scheme presented in Fig. 1 and the characterization outputs are the ratio error ε_{DUT} and phase error ϕ_{DUT}. The DUT is calibrated by comparison with a reference device (REF), two additional Signal Conditioning transducers (SC1 and SC2) can be included in the measurement setup to ensure that the DUT and REF output signals (U_{do1} and U_{ro1}) fit with the acquisition system/comparator voltage and current levels. The measurement and comparison component can be an analog or digital comparators specifically designed for this application, or it can be an acquisition system with post-processing algorithms [6].

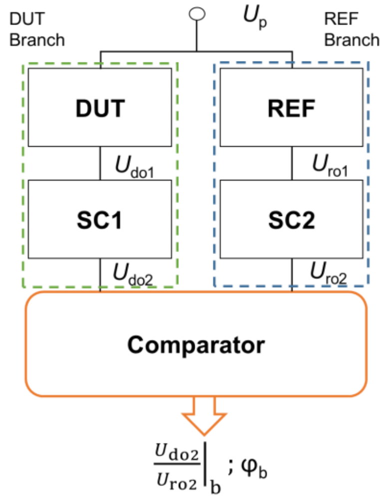

Fig. 1. Scheme of a generic calibration setup of the ITs

Considering the scheme of Fig. 1, it is possible to identify a practical measurement model for ε_{DUT} and ϕ_{DUT}. The definition of the measurement model starts from the readings provided by the comparator: the ratio ($U_{do2}/U_{ro2}|_b$) and the phase difference (ϕ_b) between the signals provided by the DUT and the REF (Reference) branch. All the scale factors of the transducers involved in the measurement must be considered, and the measurement models can be expressed as follows:

$$\varepsilon_{DUT} = \left.\frac{U_{do2}}{U_{ro2}}\right|_b h \frac{K_{DUT} \cdot K_{SC1}}{K_{REF} \cdot K_{SC2}} \cdot \frac{(\varepsilon_{REF}+1)(\varepsilon_{SC2}+1)}{(\varepsilon_{SC1}+1)} - 1 \quad (1)$$

$$\varphi_{DUT} = \varphi_b - \mu - \varphi_{SC1} + \varphi_{SC2} + \varphi_{REF} \quad (2)$$

where:

- $\left.\frac{U_{do2}}{U_{ro2}}\right|_b$ is the ratio between the voltage of the DUT and the REF branch provided by the comparator,
- h is the comparator correction factor (provided by the comparator calibration certificate) defined as $h = \frac{U_{do2}/U_{ro2}|_{cal}}{U_{do2}/U_{ro2}|_b}$, where $U_{do2}/U_{ro2}|_{cal}$ is the reference ratio applied during the calibration stage of the calibrator
- K_{DUT} , K_{REF} , K_{SC1} and K_{SC2} are the rated scale factors of the DUT and REF IT and of the signal conditioning circuit of DUT and REF branch respectively,
- ε_{REF} , ε_{SC1} and ε_{SC2} are the REF IT and signal conditioning circuit ratio errors,
- φ_b is the reading of the phase difference, provided by the comparator, between its input signals,
- φ_{REF} is the phase error of the reference IT (provide by the calibration certificate),
- μ is the phase error introduced by the comparator (provided by the comparator calibration certificate), defined as $\mu = \varphi_b - \varphi_{cal}$ where φ_{cal} is the reference phase difference applied to the comparator during the comparator calibration stage.

Introducing the quantity K_{tot} defined as:

$$K_{tot} = \frac{K_{DUT} \cdot K_{SC1}}{K_{REF} \cdot K_{SC2}} \quad (3)$$

The Equation (1) can be synthetized as:

$$\varepsilon_{DUT} = \left.\frac{U_{do2}}{U_{ro2}}\right|_b \cdot h \cdot K_{tot} \cdot \frac{(\varepsilon_{REF}+1)(\varepsilon_{SC2}+1)}{(\varepsilon_{SC1}+1)} - 1 \quad (4)$$

Thus, the measurement model for the ratio error consists of one constant quantity, K_{TOT}, and five independent variables: $\left.\frac{U_{do2}}{U_{ro2}}\right|_b$, h, ε_{REF}, ε_{SC1} and ε_{SC2}. Consequently, the evaluation of the uncertainty only requires the calculation of five propagation coefficients.

The proposed measurement model can easily incorporate the impact of influence factors on the ε_{DUT} and ϕ_{DUT}. In particular, the scope of the paper is to analyze the impact of THD and frequency variations on the calibration setup output. The presented analysis focuses on the comparator, as it is the component that may be strongly be influenced by the presence of such non-idealities in the test signal.

IV. Case Studies

This section provides preliminary results of numerical simulations performed to quantify the impact of THD and frequency variations on the ratio error ε_{DUT} and phase error ϕ_{DUT}. Considering the logical scheme depicted in Fig. 1, four elements are numerically simulated: the primary signal U_p, the reference transducer REF, the DUT and the comparator. For sake of simplicity, the two transducers SC1 and SC2 are not included in the analysis.

The input signal U_p is simulated as a multitone signal as in (5):

$$u_p(t) = A_1 \sin(2\pi f_0 t + \phi_1) + \sum_{h=2}^{9} A_h \sin(2\pi h f_0 t + \phi_h) \quad (5)$$

Fig. 2 shows an example of harmonic amplitudes, up to the 9th order, that can be contained in the signal defined in (5), namely the harmonic amplitude pattern. In this example, the amplitudes are normalized to the fundamental amplitude. In all the simulations, what remain constant are the ratio among the amplitudes of the single harmonic components, as shown in Fig. 2. Instead, the absolute value of each amplitude is set to obtain a desired THD. Specifically, the pattern is selected considering that the effects of the iron core nonlinearity in the step-up transformer are mostly evident at the third harmonic and, in general, at the odd harmonics up to the 9th order. As regards the spurious components resulting from the presence of the DC, the second and fourth harmonics are the most relevant.

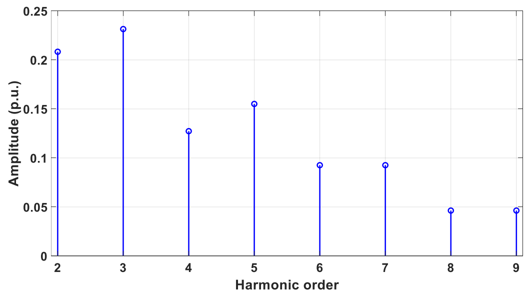

Fig. 2. Simulated

As regards the initial fundamental (ϕ_1) and harmonic phases (ϕ_h), they are randomly (uniform distribution) variable in the range $[-\pi, \pi]$.

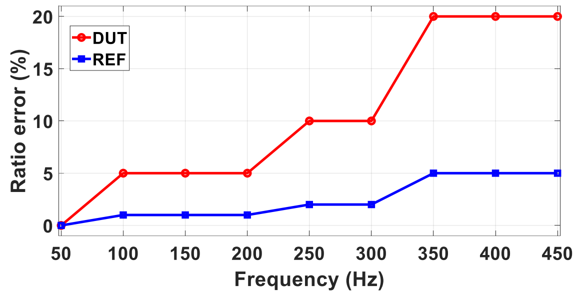

Fig. 3. Examples of simulated DUT and REF ratio error responses at harmonic frequencies meeting the limit set by the IEC 61869-6 standard.

Two sets of simulations were performed. In the first set, the fundamental frequency is fixed to 50 Hz, whereas in the second set it varies in the range [49.9, 50.1] Hz. In particular, in the first set, it is assumed that the sampling is coherent, that is there is a perfect synchronization between generation and acquisition. Instead, in the second set, sampling is chosen coherent with the rated fundamental frequency, i.e. 50 Hz, whereas the actual frequency value is different. Moreover, in this case three different signal to noise ratio levels are numerically generated and added to the $u_p(t)$ test signal.

As regards the DUT and REF devices, they are modelled starting from the information provided by the IEC 61869-6 [16] standard, which specifies the limits extension of the Low Power Instrument Transformers (LPIT) accuracy class for harmonics measurements. The DUT is simulated assuming the limits the standard [16] sets for class 0.5 transducers.

In a first step, the REF is assumed as an ideal linear device with a flat frequency response equal to zero. In a second step, the frequency response of the REF is computed, taking into account the limits specified by [16] for the 0.1 accuracy class LPIT. The harmonic ratio and phase errors for the REF (class 0.1) and DUT (class 0.5) taken from the IEC 61869-6 standard, are summarized in Table I. For sake of simplicity, the DUT and the REF are simulated with 0 % and 0 mrad errors at fundamental frequency. Worth highlighting that this modelling approach remains generic and does not represent any particular IT model. Moreover it offers the advantage of meeting the error limits specified in IEC 61869-6 [16]. Fig. 3 shows the ratio error responses of the simulated DUT and REF at the considered harmonic frequencies.

TABLE I. Accuracy classes extension for quality metering for class 0.1 (REF) and class 0.5 (DUT) LPITs according to IEC 61869-6 Standard

Harmonic order	***Accuracy class***	***Ratio error (%)***	***Phase error (degrees)***
2nd to 4th	0.1	1	1
	0.5	5	5
5th to 6th	0.1	2	2
	0.5	10	10
7th to 9th	0.2	4	4
	0.5	20	20

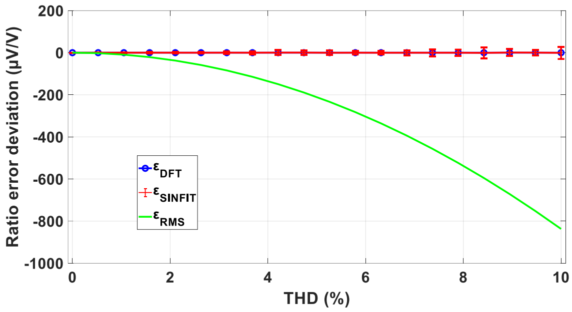

Fig. 4. Ratio error deviations as function of the input signal THD in [0,10] % range, f_0=50 Hz and REF simulated as an ideal IT.

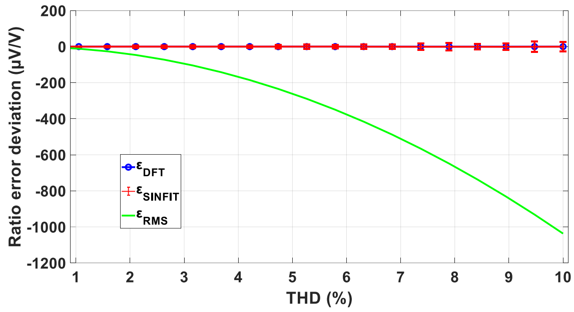

Fig. 6. Ratio error deviations as function of the input signal THD in [0,10] % range, f_0=50 Hz and REF simulated as class 0.1 IT.

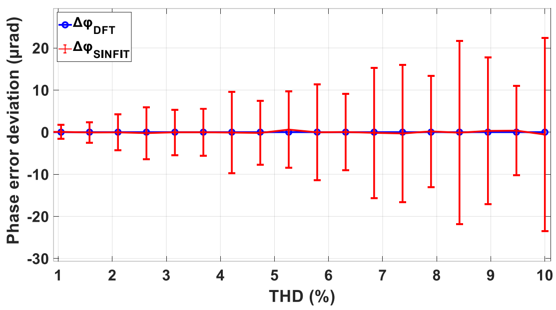

Fig. 5. Phase error deviations as function of the input signal THD in [0,10] % range, f_0=50 Hz and REF simulated as an ideal IT.

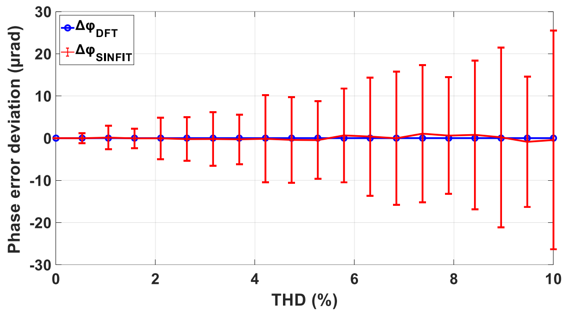

Fig. 7. Phase error deviations as function of the input signal THD in [0,10] % range, f_0=50 Hz and REF simulated as class 0.1 IT.

As regards the comparator section, three commonly used algorithms are implemented: the DFT, SINFIT and the measurement of the RMS value. The sampling frequency of the simulate comparator is set to 50 kHz and the analysis time is equal to 10-cycles of the 50 Hz. As regard the SINFIT, it consists in the fitting of the the acquired samples to the function reported in equation 6:

$$u_{FIT}(t) = \sqrt{2}a\sin(2\pi bt + c) + d \qquad (6)$$

Where *a*, *b*, *c* and *d* are the fit parameters. These parameters are determinate by solving a nonlinear least-squares problem using the optimization algorithms provided by Matlab software and by assuming as starting point for parameter "*b*" the rated power frequency, i.e. 50 Hz.

A. Impact of THD

In the first set of simulations, the fundamental frequency is set to 50 Hz and the harmonic amplitudes values are chosen to generate 20 different THD values, ranging from 0% to 10%. The signals are numerically generated for a time duration of 200 ms and 100 initial phase angles are randomly extracted.

As first result, it is found that the errors obtained using the DFT and RMS do not depend on the initial phase values for each simulated THD. On the contrary, the SINFIT is sensitive to the initial phases for THD values higher than 0%. Therefore, for the SINFIT analysis, it is important to evaluate the errors in terms of mean value and maximum variations.

The simulation results in terms of ratio and phase error deviation, assuming REF as an ideal linear device, are presented in Fig. 4 and Fig. 5, respectively.

As can be observed, the DFT algorithm is completely immune to THD as both the ratio and phase errors deviations estimated through it are equal to zero for each simulated distortion level. The evaluation of the ratio error performing the RMS measurement of primary and secondary side quantities, can be affected by errors up to hundreds of microvolt/volt depending on the test signal distortion. For THD values that are common in test laboratory (~ 2 %) the error introduced in the measurement of ε_{DUT} through the RMS is -35 μV/V and it exceeds -150 μV/V only for THD values higher than 4 %.

As the SINFIT, it provides measurement of ratio and phase errors that depends on the THD and the signal initial phases. However, for THD values lower than 2 % and for all the simulated initial phases, the ratio and phase errors variations are lower than 4 μV/V and 4 μrad, respectively. Error variations higher than 10 μV/V and 10 μrad are observed for THD higher than 4 % and the maximum deviations are lower than 25 μV/V and 25 μrad even for a THD equal to 10 %.

When the REF sensor is simulated as a 0.1 accuracy class IT with frequency response described in Table I, the errors deviations of both SINFIT and the RMS slightly increase. The simulation results are shown in Fig. 6 and Fig. 7.

As the SINFIT algorithm, the ratio and a phase errors deviations observed for a THD equal to 2 % are 6 μV/V and 5 μrad and they reach the maximum values of 28 μV/V and 25 μrad, respectively, for a THD equal to 10%.

The ratio error deviation measured through the RMS for a THD of 2 % is -47 μV/V that is about 10 μV/V higher than the previous simulation case (ideal REF). For a THD equal to 4 %, the ratio error deviation is close to -200 μV/V.

B. Impact of THD and frequency variations

In the second set of simulations, the fundamental frequency variation in the range [49.9, 50.1] Hz is included in the analysis. Twenty different harmonics amplitudes are selected to investigate THD values from 0 % to 10 % and 100 initial fundamental and harmonic phases randomly variable (uniform distribution) in the range [−π, π] are generated.

In the case under analysis, which includes fundamental frequency variation, all the three approaches provide results depending on the initial phase values and at the same level of THD, they provide higher errors if compared to f_0=50 Hz case. Considering the case of ideal REF and two fundamental frequency f_0=49.90 Hz and f_0=49.95 Hz, the ratio error deviations obtained performing FFT, SINFIT and RMS measurement are reported in Fig. 8 and Fig. 9, respectively.

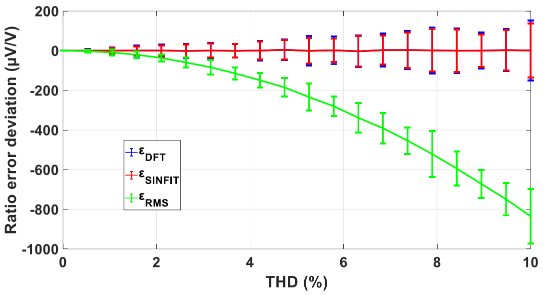

Fig. 8. Ratio error deviations as function of the input signal THD in [0,10] % range, f_0=49.90 Hz and REF simulated as an ideal IT.

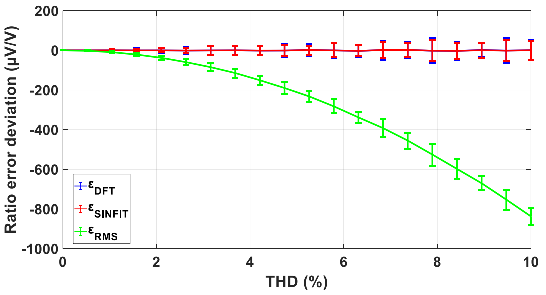

Fig. 9. Ratio error deviations as function of the input signal THD in [0,10] % range, f_0=49.95 Hz and REF simulated as an ideal IT.

The ratio errors deviations increase with the increase of the difference between the simulated frequency and the rated one (50 Hz). However, considering THD level equal to 2 % and f_0=49.90 Hz, the approach based on the RMS provides a deviation equal to -37 μV/V ±10 μV/V whereas the FFT and SINFIT deviations are 1 μV/V ±30 μV/V and 1 μV/V±26 μV/V, respectively. Simulations with THD equal to 10 % provide maximum deviations lower than 150 μV/V for both FFT and SINFIT.

Considering the case of f_0=49.95 Hz, the REF 0.1 accuracy class device and including into the simulation also the measurement noise contribution, the results obtained for the THD=10 % are provided in Fig 9.

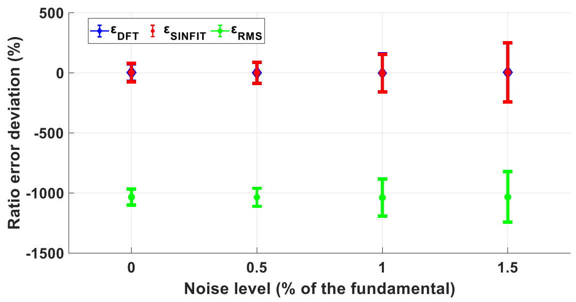

Fig. 10. Ratio error deviations as function of the noise level for THD=10%, f_0=49.95 Hz and REF simulated as a class 0.1 IT

As can be observed, for higher noise levels higher variability is measured. For the ratio error the variability goes from ±65 μV/V to ±210 μV/V increasing the noise level from 0 % of the fundamental to 1.5 %. As the mean value, the noise presence has no impact.

V. Discuss of the Results and Conclusions

The presented paper has examined the impact of THD and frequency variation in input voltage and current on the accuracy evaluation of ITs at power frequency. The study has been carried out with simulations to numerically generate different levels of THD and frequency variations. Common measurement algorithms to calculate the ratio and phase errors have been used. Preliminary analysis, indicates that the presence of harmonic distortion and frequency variations has an impact that varies depending on the algorithm implemented in the comparator section.

Specifically, when the fundamental frequency is equal to the rated frequency:

- Evaluating the ratio error by measuring the RMS amplitude can result in an error lower than 100 μV/V for THD lower than 3.5%. Generally, there is a third-order power function that relates the ε_{RMS} deviation to the input signal THD.
- The results obtained performing the SINFIT method have a deviation lower than 30 μV/V, even for THD=10%. A linear approximation can be used to relate the ε_{SINFIT} deviation to the input signal THD.
- The results provided by the DFT are unaffected by the THD.

However, when the fundamental frequency differs from the rated frequency, the overall error deviations increase. The results obtained from the DFT are comparable to those obtained with the SINFIT method, and both exhibit a linear dependence on the THD.

Table II summarizes the main results for the three adopted approaches with specific reference to their impact on the measurement of the 50 Hz ratio error in presence of the considered generation disturbances.

TABLE II. Impact of the three adopted approaches on the measurement of the ratio error in presence of the two different considered non idealities

Algorithm	Disturbances	
	THD	THD plus frequency variation
RMS	The impact increase with the increase of the THD. Error up to 0.1% for THD=10%	Impact increase with the increase of both THD and difference from 50 Hz power frequency. The maximum deviation for THD=10 % and f_0=49.9 Hz is lower than 0.15 %.
SINFIT	Impact lower than few ppm up to THD=10 %	Impact increase with the increase of both THD and difference from 50 Hz power frequency. The maximum deviation for

		THD=10 % and f_0=49.9 Hz is lower than 200 μV/V.
DFT	Unaffected	Same behavior as SINFIT

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