Performance Evaluation of Low-Cost Smart Meter Solution for IEC 61000-4-7 Class I Harmonics Measurements in the Presence of Noise Disturbances

Giovanni Artale, *Member, IEEE*, Antonio Cataliotti, *Member, IEEE*, Valentina Cosentino, *Member, IEEE*, Dario Di Cara, *Member, IEEE*, Vito Ditta, Salvatore Guaiana, Nicola Panzavecchia, and Giovanni Tinè, *Member, IEEE*

***Abstract*—This work aims at investigating the performance of a low-cost smart meter solution for harmonics measurements in the presence of disturbances. In previous works, the authors have already shown the feasibility of the considered hardware device and signal processing metrics for harmonic analysis according to IEC 61000-4-30 Class A and IEC 61000-4-7 Class I requirements. In this work, the main focus is an analysis on the characterization issues of the developed case-study device, in the current standards framework. More in detail, standards for power system harmonic measurements do not consider any characterization tests to verify device performances in the presence of disturbances. Therefore, it is very interesting to evaluate if disturbances, normally present in real cases, can determine a loss of standard compliance and thus if such phenomena are neglectable or not. For these reasons, in this work, to test the behavior of the meter device in the presence of a real signal, it has been chosen white noise, among possible disturbances that normally occur in power systems. In this article, several experimental tests are presented and discussed that show that devices can comply with the standards accuracy requirements in the absence of disturbances, but such requirements could not be fulfilled anymore in real operating conditions of smart grids. The results obtained show that it is essential to propose and develop standard test conditions that consider real operating conditions.**

***Index Terms*—Harmonic analysis, IEC 61000-4-30, IEC 61000-4-7, noise disturbances, power quality (PQ), power system harmonics measurements.**

Received 14 May 2025; revised 27 June 2025; accepted 27 July 2025. Date of publication 8 August 2025; date of current version 20 August 2025. This work was supported in part by European Union-Next Generation EU, National Recovery and Resilience Plan, Mission 4, Component 2, Investment 1.1 "Fund for the National Research Program and for Projects of National Interest"-PRIN 2022 under Project 2022FLWXTA; in part by the "Electrical Measurements and Instrumentation for the Evaluation of E-Mobility Impact on Islands Power Systems and Microgrids (EMIslands)" under Grant CUP B53D23002600006; in part by European Union-Next Generation EU, National Recovery and Resilience Plan, Mission 4, Component 2, Investment 1.1 "Fund for the National Research Program and for Projects of National Interest"-PRIN 2022, PNRR, under Project P2022XL9NX; and in part by the Project titled "MeasurementBased Techniques for Renewable Energy Systems and Their Integration in the Case of Small Islands (MERSIS)" under Grant CUP: B53D23024160001 and Grant B53D23024140001. The Associate Editor coordinating the review process was Dr. Sara Sulis. *(Corresponding author: Vito Ditta.)*

Giovanni Artale, Antonio Cataliotti, and Valentina Cosentino are with the Department of Engineering, Università di Palermo, 90128 Palermo, Italy (e-mail: giovanni.artale@unipa.it; antonio.cataliotti@unipa.it; valentina.cosentino@unipa.it).

Dario Di Cara, Vito Ditta, Salvatore Guaiana, Nicola Panzavecchia, and Giovanni Tinè are with the Institute of Marine Engineering, National Research Council of Italy (CNR), 90146 Palermo, Italy (e-mail: dario.dicara@cnr.it; vitoditta@cnr.it; guaiana.salvatore@inwind.it; nicola.panzavecchia@cnr.it; giovanni.tine@cnr.it).

Digital Object Identifier 10.1109/TIM.2025.3596993

I. Introduction

IN RECENT decades, electrical grids have experienced significant transformations due to the increasing integration of renewable energy sources and the liberalization of electricity markets [1], [2]. Traditionally, these grids worked with unidirectional power flows from centralized generation to passive consumers. However, with the proliferation of distributed energy sources, communications and measurements distributed systems, and the electrification of transports (such as electric vehicles, trains, and underground railways), power systems have progressively faced dynamic and bidirectional energy flows, which are typical of modern smart grids [1], [2], [3]. This evolution brings new challenges to grid efficiency, stability, and power quality (PQ) requirements [4], [6]. In fact, distributed generation, storage systems, and electric vehicles charging infrastructure introduce disturbances into the grid, primarily due to power electronic converters operation, which generates noise and harmonic emissions. Moreover, a strong and increasing presence of nonlinear loads (particularly electronic devices) further contributes to noise and distortion levels. These disturbances can negatively impact not only the power system and connected loads but also measurement and control equipment, which are critical for grid operation [7], [8], [9], [10], [11], [12]. Thus, to maintain grid reliability and efficiency, accurate PQ measurements are essential [13], [14], [15]. However, achieving widespread and accurate PQ monitoring is often constrained by the high costs of instrumentation compliant with standards. In response to this, the authors have focused on developing reliable but low-cost solutions for distributed measurement systems for PQ and harmonic analysis [16], [17], [18], [19], [20], [21]. In more detail, the authors investigated the feasibility of integrating metrics for harmonic analysis into a power meter [17]; a further step consisted of exploring the use of low-cost microcontroller devices to test proper harmonic analysis algorithms for obtaining the fulfillment of standards requirements. For the measurement of PQ and harmonic analysis methods, IEC 61000-4-30 and IEC 61000-4-7 were considered. Two classes of instruments are described in such standards, based on the measurement accuracy achieved, respectively, Class A or S and Class I or II. Class A and Class I represent the highest accuracy standards [22], [23]. Despite the hard requirements of these standards, recent studies have shown that with appropriate algorithms optimization, low-cost hardware platforms can achieve the necessary accuracy and processing efficiency. In fact, the authors have demonstrated that proper metrics can enable the potential feasibility of low-cost smart meter hardware platforms for PQ monitoring. For example, focusing on harmonic analysis, the use of performant algorithms like the fast Fourier transform (FFT) and time-domain interpolation (TDI) appropriately developed for this purpose (as the Farrow interpolation algorithm) allow reaching good tradeoff between spectral analysis accuracy and signal reconstruction efficiency, thus maintaining the computational feasibility [18], [19], [20], [21], in terms of memory and processing burden. With algorithms optimization and the implementation of appropriate processing techniques, the authors have already developed a solution that allows fulfilling the requirements of the best accuracy classes according to both IEC 61000-4-30 and IEC 61000-4-7 standards.

The main issues addressed in previous work were related to two aspects: gapless acquisition and time aggregation (IEC 61000-4-30 Class A [22]) and fulfillment of accuracy requirements (IEC 61000-4-7 Class I [23]). The first aspect concerns the meter capability to continuously sample the signal, without losing information while elaborating the data. For example, for harmonic analysis, it is required to implement the DFT or FFT algorithm, grouping and smoothing while sampling the consecutive portion of the signal) (see [22, Ch. 4]). The details of these requirements have been deeply discussed in [20]. The second aspect focuses on the possibility of complying with the accuracy requirements for harmonics up to the 50th, even using a low-performance ADC [18], [21]. The results of the experimental tests have shown that the metrological performances of low-cost hardware devices can be improved by implementing efficient sampling and processing strategies; in detail, the best results, in terms of both measurement accuracy and processing time, have been obtained by implementing an oversampling technique with a moving average. The obtained results demonstrate the feasibility of spectral analysis implementation on a low-cost smart meter hardware solution, with respect to both IEC 61000-4-30 Class A and IEC 61000-4-7 class I accuracy requirements.

Other literature papers pointed out the difference between test conditions using ideal signals and the characteristics of real signals, which instruments installed in real-power systems must deal with. However, the lack of standard References in this framework does not allow to define a common framework for the evaluation of disturbances impact on PQ measurements [12], [24], [25], [26], [27]. In this work, this last issue is further investigated. More in detail, this work is an extension of [20] and it is focused on the investigation of noise impact on PQ metrics implemented in [20]. The analysis is carried out by means of an experimental measurement campaign on the case-study harmonics meter. Different tests have been carried out, consisting of a series of harmonics measurements in the absence and presence of increasing levels of white noise; the results with and without noise are compared, considering different setups for sampling frequency and signal processing metrics. The final aim of the presented study is to show and underline that, due to the lack of current standards, the proper characterization of metering devices is not ensured. In fact, standards on power system harmonics measurements do not contain any requirements for testing measuring devices in the presence of disturbances, for example, noise or other quantity variations (different from the voltage amplitude), which can occur in real-operating conditions. Consequently, as further explained in this article, a device that meets the standard requirements in "ideal" test conditions can be negatively affected by the presence of disturbances other than harmonics, such as noise. The lack of references in the standards is a problem to be evaluated, to ensure compliance with minimum requirements under nonideal conditions, instead.

This article is organized as follows. Section II briefly describes the case study smart meter hardware solution for harmonics measurements according to IEC 61000-4-30 and IEC 61000-4-7 standards, already validated in previous works. Section III reports a review of current standards requirements for test conditions for PQ and power meter devices, focusing on if and how the aforesaid standards consider the presence of disturbances for accuracy evaluation tests. Section IV presents the experimental analysis of the problem of the noise presence and the importance of considering it in accuracy tests, by discussing the test results for the case-study device.

II. Smart Meter Hardware Solution for Harmonics Measurements According to IEC 61000-4-7 Class I/ IEC 61000-4-30 Class A Requirements

In previous works, the authors tested different devices, which PQ metrics were implemented on focusing the attention harmonics measurements according to standards requirements [16], [17], [18], [19], [20], [21]. Such studies allowed to find the solutions for fulfilling the requirements of both gapless acquisition and time aggregation, according to IEC 61000-4-30 Class A [22]; and accuracy, according to IEC 61000-4-7 Class I [23].

Specifically, the ad hoc developed case study measurement setup consisted of a programmable microcontroller device, the NUCLEO STM32F767ZI, by STMicroelectronics, chosen because of its flexibility in algorithm implementations and large memory buffer, capable of testing all different solutions. The case-study meter characterization has been presented in previous works [19], [20], [21]. Proper metrics have been developed and implemented on the device, to perform signal acquisition and harmonic analysis according to the IEC 61000-4-30 requirements, i.e.: observation window equal to ten cycles of the fundamental 50-Hz power system frequency,

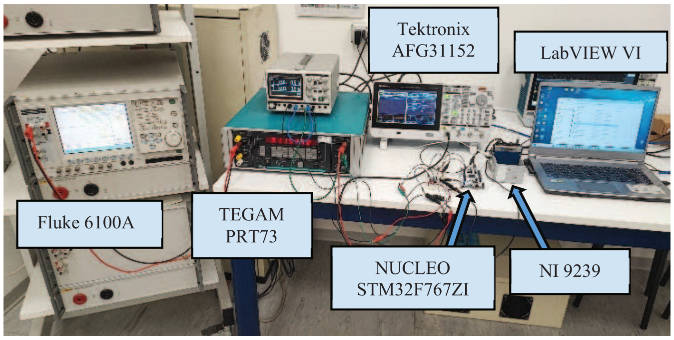

Fig. 1. Experimental setup for harmonic measurement in the presence and absence of noise.

with a synchronization error lower than 0.03%; measurements aggregation over 150 cycles; and measurements up to the 50th harmonic component. In more detail, as regards the sampling synchronization, a zero-crossing (ZC) algorithm was implemented to obtain the desired observation window of ten cycles of the power system frequency as required for Class I/A of IEC 61000-4-30 and 61000-4-7 standards.

A full description of the implemented ZC algorithm can be found in [21]. In brief, it works with the multiplication of two consecutive samples while waiting for the negative value. From that moment on, the ZC is disabled for a quarter of a period, to prevent any oscillations of the signal around 0 being exchanged for the actual passage from 0. The presence of noise may affect the zero crossings of the signal; thus, a loss of synchronization may occur. To experimentally evaluate the impact of noise on the ZC algorithm operation, the synchronization error has been evaluated, and the results are shown in the following, in both the absence and presence of noise. This aspect has been added to the comparison with Class I/A requirements according to standards (see Section IV).

The test bench used for device characterization is reported in Fig. 1. The test signal was generated by a FLUKE 6100A calibrator, and it was adapted to the NUCLEO board ADC input range (0–3.3 V) by using a high-precision voltage divider (TEGAM PRT73) and a waveform generator (Tektronix AFG31152) for the offset addition. The same signal was acquired and processed using a high-accuracy PC-based instrument, built with a 24-bit NI 9239 for data acquisition and a virtual instrument (VI) in a LabVIEW environment for signal processing, so as to have a reference instrument for the measurements' comparison. The characterization of the reference PC-based instrument was presented in earlier papers, in both sinusoidal and distorted conditions [28], [29]. As an example, in the frequency response tests, the obtained accuracies were comparable with those of the calibrator used for tests, i.e., Fluke 5720A [calibrator accuracies: (±45 ppm of output ±50 μV) in the range of 22 V, for frequencies from 40 Hz to 20 kHz; PC-based instrument measured values, tests with 5-V, 50-Hz signal: mean error over 100 measurements 16 μV/V; and a standard deviation of 6 μV/V]. More details on PC-based instrument characterization can be found in [28] and [29].

Different solutions for signal acquisition and processing were tested. In very brief, a first implementation was made

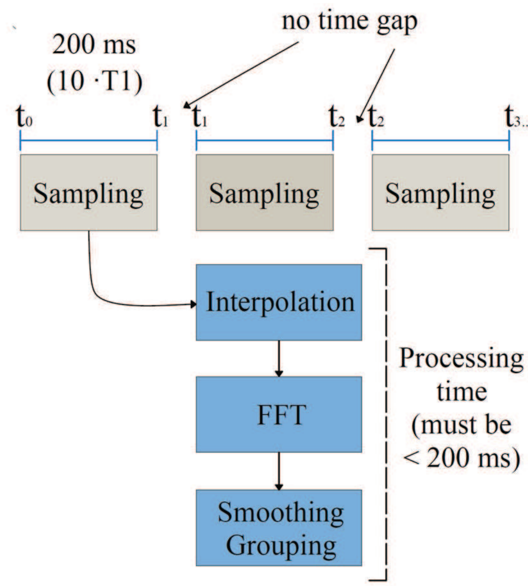

Fig. 2. Implemented gapless sampling scheme.

with a basic sampling rate f_s equal to 16, 24, or 32 kHz; in [19] and [21], it was shown that this setup allows to meet the accuracy requirements in simulation (for the processing stage) but it does not allow to suitably work with real signal acquisition, mainly because of ADC's performance.

Starting from this, several solutions have been tested to improve the behavior of the ADC.

1) Sampling rate increase, up to 48, 64, and 96 kHz, even if this requires more memory for samples storage.
2) Oversampling, with f_s between 288 and 960 kHz, and postoversampling digital decimation filter (to obtain an equivalent sampling frequency f_{s_eq} of 16, 24, or 32 kHz, respectively);
3) Oversampling, with f_s multiples of the base sampling frequencies (16, 24, or 32 kHz), and moving-average technique, over 10, 20, or 30 samples (to obtain an equivalent sampling frequency f_{s_eq} of 16, 24, or 32 kHz, respectively).

As shown in [20], these techniques allow reducing errors in the identification of individual harmonic components, so as to achieve compliance with standard requirements. However, some solutions have been later discarded because computational cost is too high and processing time is higher than the one allowed for gapless sampling (200 ms, i.e., ten fundamental periods; for a 50-Hz signal, with a period of 20 ms) [20], [22]. In fact, as shown in Fig. 2, the processing of samples acquired in a given observation window must be made before completing the subsequent 200-ms acquisition, so as to avoid data loss and overflow occurrence [23].

In order to fulfill the aforesaid processing time constraints, it was necessary to implement harmonic analysis by means of the FFT algorithm, which is much faster than the DFT algorithm suggested by the standard [23]. Thus, to have a power-of-two number of points for efficient FFT implementation, a postsampling TDI Farrow algorithm has been implemented to get back to 2048 or 4096 points, independently from the number of acquired samples and the chosen sampling frequency.

A deep explanation of the Farrow algorithm is reported in [21]. In brief, the Farrow interpolator can be seen as a particular case of the Lagrange interpolator. It can be implemented in different h order functions, and it uses the same coefficients calculation to generate a function that tries to approximate the original signal every $h + 1$ points. In Lagrange, every time a new point is considered, the entire polynomial must be recalculated. For Farrow implementation, it is assumed that the samples are equidistant, which is a reasonable assumption if a fixed sampling frequency is considered. With this assumption, the calculation time is significantly reduced even with higher order functions, because the coefficients of the polynomial remain constant. The algorithm reconstructs the sampled signal with the desired number of points for FFT, keeping the observation window unchanged.

The tests carried out in [20] and [21] showed that the execution of TDI and FFT algorithms is overall much faster than the DFT one. As shown in [21], the TDI implementation allows obtaining the desired number of samples for FFT, whatever sampling frequency and number of acquired samples are.

III. Requirements for Testing Measuring Devices in the Presence of Disturbances—Power System Harmonic Measurement Standard Analysis

Standards play a key role in the evaluation of the metrological characteristics of a measurement instrument. However, a survey has been conducted on available standards for power system harmonics measurements, which have been taken as a reference for the development of the case-study PQ meter. The analysis result is that while requirements for device accuracy are covered by standards, no indications are given on how to carry out tests in the presence of disturbances. An in-depth analysis of different standards is given below.

The reference standard for PQ measurements is the IEC 61000-4-30 "Electromagnetic compatibility (EMC)—Part 4-30: Testing and measurement techniques—PQ measurement methods" [22]. In this standard, two accuracy classes are defined (Class A and Class S). The standard provides guidelines for measurement methods, uncertainty assessment, measurement evaluation, and aggregation of data for each PQ parameter, including harmonics. However, these guidelines are more focused on requirements to be met, rather than on actual procedures for conducting tests. For example, in the case of harmonics measurement, the standard indicates that harmonic analysis must be carried out at least up to the 50th harmonic for Class A and up to the 40th for Class S. For all other requirements, the IEC 61000-4-30 refers to other standards of the 61000 series, particularly IEC 61000-4-7 for harmonic measurement [23]. In Annexure A of the standard IEC 61000-4-30, some indications are given under the name "test leads," but they just indicate installation precautions, safety requirements, and the connection mode of the device to be tested to the power sources, with all the associated characteristics.

TABLE I
Harmonics Amplitudes (in Percentage of Fundamental) According to IEC 50160

Even order harmonics		**Odd order harmonics**			
Harm. order h	Relative ampl. uh	Harm. order (multiple of three, up to 21st)	Relative ampl. uh	Harm. order (other, up to 49th)	Relative ampl. uh
2	2,00%	3	5,00%	5	6,00%
4	1,00%	9	1,50%	7	5,00%
6 ÷ 24	0,50%	15, 21	0,50%	11	3,50%
				13	3,00%
				17	2,00%
				19 ÷ 23	1,50%
uh is the amplitude of the h-order harmonic (percentage of fundamental component)					

In the standard IEC 61000-4-7 "EMC—Part 4-7: Testing and measurement techniques—General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto" [23], the two accuracy classes are indicated as Class I and Class II. Even in this case, the accuracy requirements are detailed for current, voltage (and power) measurements; however, for testing purposes, only maximum values of harmonic components are given, while test conditions are not well defined. From this viewpoint, the standard provides more detailed guidance for the evaluation of components with frequencies higher than 2 kHz up to 9 kHz than for those in the range 100 Hz–2.5 kHz (50th harmonic).

The IEC 50160 "Voltage characteristics of electricity supplied by public electricity networks" [30] gives some indications on maximum values of harmonic distortion for each component up to the 25th (see Table I); in previous works and in the experimental tests herein presented, such values have been used as a reference for the amplitude of the test signal harmonics. However, in [30], there is no reference to any specific test condition for the evaluation of the harmonic content; only maximum values are provided that harmonics should assume in power systems. There is also no reference to harmonic components beyond 25th.

The aforesaid standards do not provide comprehensive information on measurements in the presence of disturbances, so other standards on power system harmonic measurement are analyzed in the following. In detail, to address the aspects related to EMC and related disturbances, the IEC standards series 61000 were considered. Moreover, to analyze the issues from the meter device viewpoint (both new PQ meter and classic energy meters), standards IEC 62057, CEI EN 62052-31, IEC 32053-21, and IEC 32053-XX series have been studied.

The IEC 61000-3-2 "EMC—Part 3-2: Limits—Limits for harmonic current emissions (equipment input current = 16 A/phase)" refers to user devices, and it does not provide indications for the measurement instruments [31]. It provides indications on maximum values of test voltage harmonics for the case of equipment under test connected directly to the source. The standard also provides indications for harmonics up to 40th and not up to 50th.

The IEC 61000-4-6 "EMC—Part 4-6: Testing and measurement techniques—Immunity to conducted disturbances, induced by radio frequency (RF) fields" [32], only considers a range of disturbance that is above the operative range of this work. The IEC 61000-4-16 "EMC—Part 4-16: Testing and measurement techniques—Test for immunity to conducted, common mode disturbances in the frequency range 0 Hz–150 kHz" [33] refers to the behavior of the EUT in the presence of conducted disturbances; for the tests, the standard provides the voltage distortion levels and harmonic amplitude in the range 15–150 kHz for the generation system, but it does not specify anything on measuring instruments, referring to the standard IEC 61000-4-7. The IEC 61000-4-19 "EMC—Part 4-19: Testing and measurement techniques—Test for immunity to conducted, differential mode disturbances and signaling in the frequency range 2–150 kHz at ac power ports" [34] provides a consistent and repeatable framework for testing electrical and electronic equipment under the influence of disturbances and signaling applied to ac power ports. This standard covers different aspects (range of test levels, test equipment, test setup, test procedures, and verification procedures). These tests aim to assess the immunity of electrical and electronic devices operating at mains supply voltages and frequencies of 50 or 60 Hz. The disturbances tested included those generated by power electronics and power line communication (PLC) systems. However, no indications are provided for the measurement setup. The main limit remains the range considered for the disturbance (starting from 2 kHz).

The IEC 62052-11 "Electricity metering equipment—general requirements, test and test conditions—Part 11—Metering equipment" [35] specifies the requirements and associated tests for ac and dc power meters. Chapter 7 is devoted to requirements and metrological performance tests; different specifications are provided for both voltage and current test conditions, but the only indications given on disturbances are the presence of a total waveform distortion of less than 2%. For low-frequency signal disturbances, the standard refers to IEC 61000-4-19, which does not provide specific information on waveforms or test conditions as specified above. It refers to IEC 61000-4-6, but only from 15 kHz onward, while for high frequency disturbances it refers to IEC 61000-4-3, where the specifications refer to a frequency range which goes beyond that considered in this work (megahertz range).

The IEC 62057-1 "Electrical energy meters—test equipment, techniques and procedures—Part 1: Stationary meter testing units (MTUs)" [36] specifies the accuracy and stability of the test voltage of the device. It is interesting to report that for distortion or disturbances, in this case, the only indication is the possibility, not the obligation, of using a signal distorted with indications for the harmonics up to 21st (chapter 6.2.5, Table VI).

The CEI EN 62052-31 "Electricity metering equipment—general requirements, test and test conditions—Part 31—Product safety requirements and tests" [37] refers to the test conditions of the devices, but only regarding the safety part, and no indication on the test bench or test signals. The IEC 32053-21 and all the other standards of the series IEC 32053-XX [38], [39], [40], [41] do not provide any indication of the meter's test conditions, and they also refer to the standard IEC 62052-11.

IV. Accuracy Evaluation in the Absence and Presence of Noise

Based on the aforesaid survey, it can be concluded that power system harmonics measurement standards do not suitably cover tests in the presence of disturbances. Measurements of voltage and current generally start from the assumption of an ideal condition, but the presence of disturbances, as noise, as well as that of harmonics and interharmonics and the dc component, contributes to making the signal waveform nonsinusoidal. Since the presence of disturbances is widespread at every level of the electrical grid, it is not possible to assume that waveforms are ideal in real systems. Therefore, it is very interesting to evaluate if disturbances, such as noise normally present in real cases, can determine a loss of standard compliance or not. For these reasons, the tests presented in this work have been carried out to characterize the metering device behavior in the presence of noise. In detail, white noise has been added to the test signal. Electrical noise refers to high-frequency interference typically occurring within the frequency range of hundreds of hertz to over gigahertz. This type of noise can be transmitted through the air and picked up by a power cord acting like an antenna, or it can travel along the power lines themselves. Sources of disturbances include devices like radios, televisions, cell phones, microwave transmitters, radar systems, arc welding equipment, and even distant lightning strikes. Also, some common electronic devices can be sources of electric noise. It typically originates from a variety of sources, and it can disrupt or degrade the performance of electrical and electronic equipment. Some common types and sources of noise are as follows.

1) *Electromagnetic Interference (EMI):* Noise caused by electromagnetic fields from electronic devices, such as motors, transformers, or RF emissions. EMI can be radiated through the air or conducted through power conductors.
2) *RF Interference (RFI):* A specific type of EMI that occurs in the RF range (typically 15 kHz–300 GHz). It can be caused by devices like mobile phones, Wi-Fi routers, or other wireless systems.
3) *Power Line Noise:* It comes from power lines, often due to switching devices, lighting dimmers, or appliances connected to the same power network. PLC systems and power electronics can introduce disturbances into ac power lines.
4) *Switching Noise: Noise* caused by the rapid switching on/off of electronic components, like transistors in power supplies or digital circuits. This can lead to high-frequency interference.
5) *Ground Loop Noise:* Occurs when multiple devices share a common electrical ground, but there is a difference in

TABLE II

STANDARD COMPLIANCE SUMMARY. TESTS IN THE ABSENCE AND PRESENCE OF DIFFERENT NOISE LEVELS

Sampling and interpolation parameters			Standard requirements in the case of a test signal according to IEC 50160 without white noise	Standard requirements in the case of a test signal according to IEC 50160 with white noise	
f_s [kHz]	f_{s_eq} (after decimation) [kHz]	Number of points after interpolation		Noise level	
				0,05%	1%
48	--	2048	Respected	Not respected	
48	--	4096	Respected	Not respected	
64	--	2048	Respected	Respected	Not respected
64	--	4096	Respected	Respected	Not respected
96	--	2048	Respected	Respected	Not respected
96	--	4096	Respected	Respected	Not respected
240	24	2048	Respected	Not respected	
240	24	4096	Respected	Respected	Not respected
320	32	2048	Respected	Not respected	
320	32	4096	Respected	Respected	

potential between the ground points, leading to circulating currents and interferences.

Among different noises, it has been selected white noise because of its characteristics. In fact, a white noise is characterized by the set of all possible tones in the spectrum. Statistically, white noise is characterized by having instantaneous values that are completely uncorrelated. If a signal of this type is sampled, each value appears completely unpredictable compared to the previous ones. In these configurations, the test refers to a disturbance that is not concentrated in a portion of the spectrum but is widespread.

Different tests have been carried out to test the behavior of the meter device. They consisted of a series of harmonic measurements both in the absence and presence of white noise. Results are compared in different conditions of sampling frequency, metrics, and algorithms for signal processing. As reported below, two different signals have been considered for the tests. The voltage signal used for the test without noise (Type 1) was built in accordance with EN 50160 standard, which provides amplitude limits for harmonics up to the 25th as reported in Table I. For higher order harmonics, amplitudes were set to values alike to those of EN 50160, i.e., 0.5% and 1.5% of the fundamental for even and odd harmonics, respectively. This is the same signal used to verify the compliance of the measurement devices in [19], [20], and [21]. To test the behavior of the device in the presence of noise, a white shape noise has been added to the voltage signal (Type-2 signal) in two different cases, one with an rms equal to 0.05% and one with a value of 1% of the fundamental component. Different voltage signals have been analyzed to evaluate the noise contribution and to find a test condition as closer as possible to the real voltage waveform of a real electric smart grid. In detail, different configurations were tested of the case study low-cost instrument, in terms of sampling frequency and TDI settings. Such configurations were first tested with a Type-1 signal to verify the compliance with the standards accuracy requirements (visibly shown in Table II, as in [19], [20], and [21]); then, they were tested again with Type-2 signal, with both low- and high-noise level (noise rms of 0.05% and 1% of the fundamental component, respectively). This was made to investigate the impact of changes in experimental conditions on the results, in terms of both sampling frequency and noise level variations. For every configuration, 1000 measurements have been acquired. The results of the harmonic analysis have been compared with the measurements of the reference PC-based instrument. For every measurement, errors (mean, maximum, and minimum values) between the device under test and the reference instrument have been evaluated, together with the standard deviations.

Table II summarizes the results obtained with different settings of sampling and TDI for the case study low-cost device. Standard compliance was considered met if the maximum error was below the limits. As visible, for the cases of a basic sampling, even with the highest f_s value, the limits are not respected in the presence of noise, while the meter was standard compliant for a Type-1 signal. However, in the other configurations, the use of more performant techniques (such as oversampling with moving average) allows reducing the noise impact and makes the device less sensitive to the noise presence and compliant with the standards even in the worst noisy test condition. However, it should be noted that this is not true for every sampling frequency but only for the case of f_s = 320 kHz and f_{s_eq} = 32 kHz (mean value over ten samples), with 4096 points after the interpolation.

In Figs. 3 and 4, mean errors, maximum errors, and standard deviations are reported for the case of f_s = 48 kHz, and f_s = 320 kHz with f_{s_eq} = 32 kHz (worst case and best case of the tests are summarized in Table II, respectively); for each sampling frequency, comparison is made among the results obtained without noise, with a noise level equal to 0.05% of the fundamental and with a noise level equal to 1% of the fundamental. It can be seen that errors and standard deviations increase with noise levels, leading to results out of standard limits in the worst case of f_s = 48 kHz. On the other hand, in the best case of moving average technique implementation, errors still increase with noise, but they remain below Class A limits.

In Fig. 5(a), focus on single harmonic components is made, with respect to mean and maximum errors behavior in different test conditions. In particular, the analysis is made for the 2nd and 44th. These two harmonics have been chosen as a case-study analysis, because they allow to evaluate what happens in

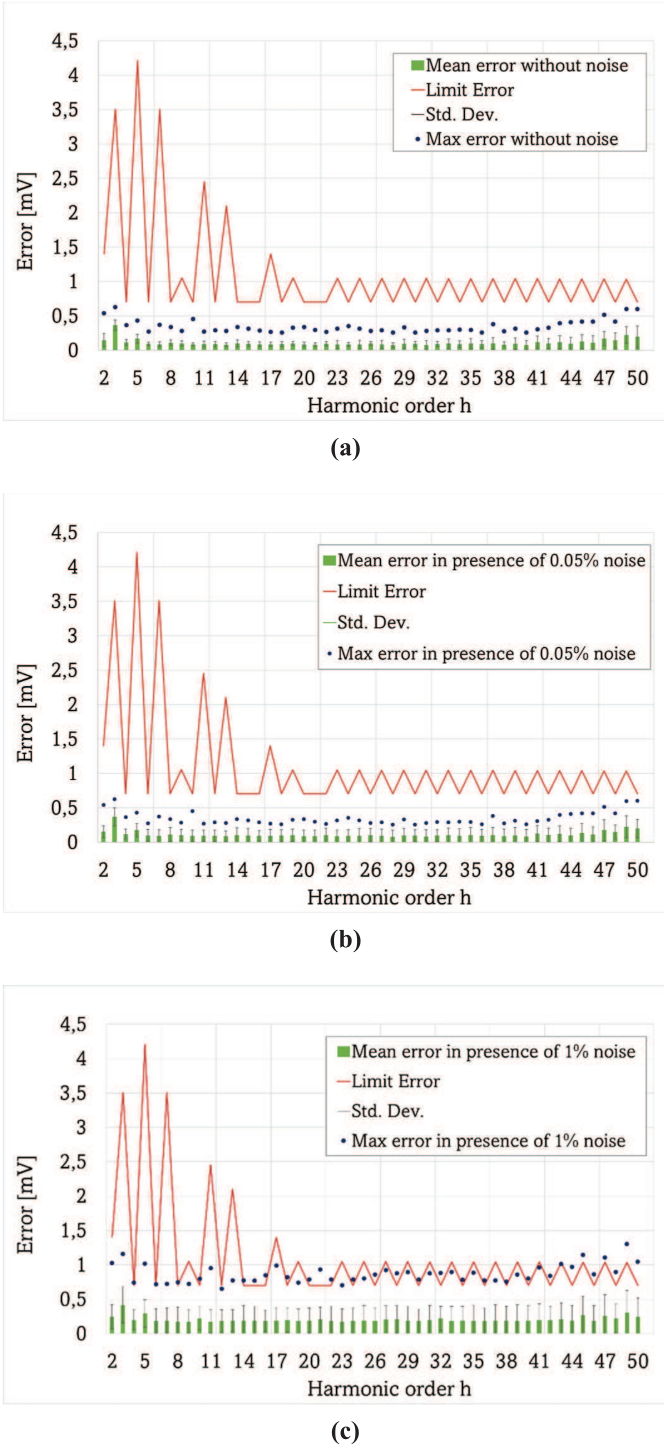

Fig. 3. Mean errors, maximum errors, and standard deviations for harmonics measurements. Case with f_s = 48 kHz, 4096 points after the interpolation. (a) Results without noise. (b) Results with 0.05% noise level. (c) Results with 1% noise level.

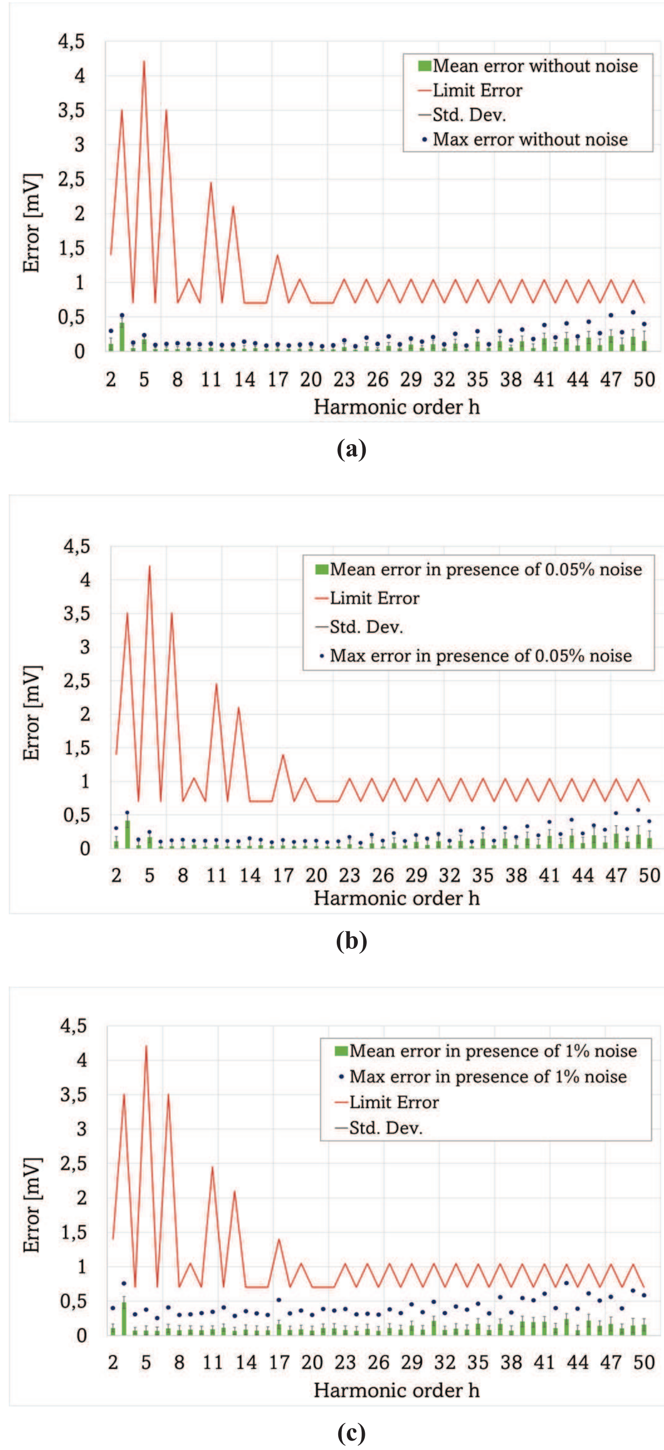

Fig. 4. Mean errors, maximum errors, and standard deviations for harmonics measurements. Case with f_s = 320 kHz, f_{s_eq} = 32 kHz, 4096 points after the interpolation. (a) Results without noise. (b) Results with 0.05% noise level. (c) Results with 1% noise level.

the case of large amplitude harmonics and in the case of low amplitude harmonics, for frequencies close to the fundamental and for higher frequencies. In Fig. 5, the errors for some of different sampling frequencies and techniques are compared (f_s = 48 kHz with 4096 points after the interpolation, f_s = 64 kHz with 4096 points after the interpolation, f_s = 96 kHz with 4096 points after the interpolation, f_s = 240 kHz with f_{s_eq} = 24 kHz; and 4096 points after the interpolation and f_s = 320 kHz with f_{s_eq} = 32 kHz and 4096 points after the interpolation), for the cases of no noise, 0.05% noise, and 1% noise level. It can be observed that, for a given sampling condition, the errors tend to increase with the noise level, and, in some cases, these errors overcome the standard limits. On the other hand, for a given noise level, the errors tend to decrease when sampling frequency increases and, even more, when averaging techniques are used. This means that, for a

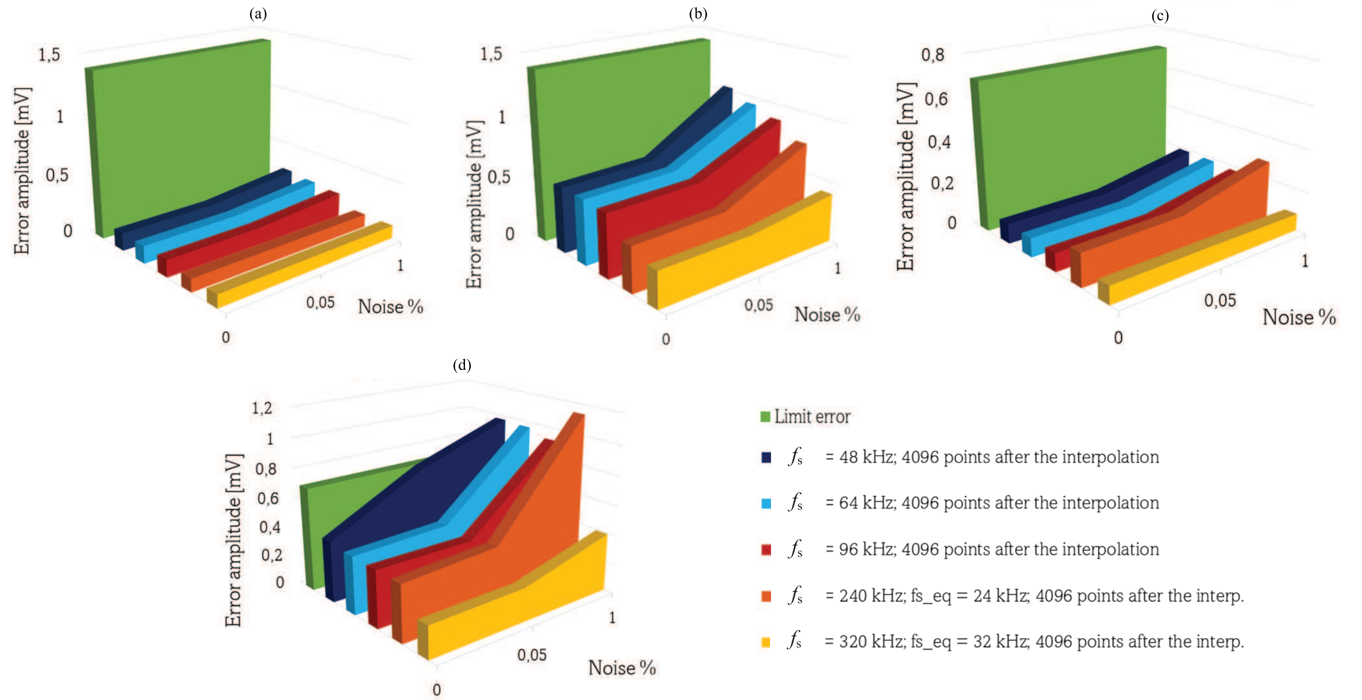

Fig. 5. Mean and maximum errors for single harmonics measurements, for cases of no noise, 0.05% noise and 1% noise level. (a) Second harmonic component, mean error. (b) Second harmonic component, maximum error. (c) 44th harmonic component, mean error. (d) 44th harmonic component, maximum error.

given sampling configuration, the instrument can be compliant with standards in the presence of low noise levels, while it can overcome the limits if the test is made with higher noise levels. On the other hand, the increase of sampling frequency and the adoption of averaging techniques make the measurement less sensitive to the presence of noise.

Also, the statistical distribution of the measured errors showed a different behavior when varying the sampling configuration and/or the noise level used for tests. For a more detailed analysis on this, the frequency distributions of the errors for the 2nd and 44th harmonics are reported in Figs. 6–9. More in detail, the frequency distribution of the error has been reported for two sampling settings in Figs. 3 and 4 (f_s = 48 kHz with 4096 points after the interpolation and f_s = 320 kHz with f_{s_eq} = 32 kHz and 4096 points after the interpolation) for the cases of no noise and 1% noise level.

For what concern the synchronization of the signal with the observation window and the related error, incoherence in sampling may occur in the presence of noise or other disturbances. In fact, such phenomena may determine spurious ZCs, thus affecting the ZC algorithm, which the sampling synchronization is based on. According to [23], the maximum allowed synchronization error is 0.03% of the 10-cycles observation window Tw. Thus, to verify the ZC algorithm effectiveness, different tests have been conducted to evaluate if the presence of noise could have led to a loss of synchronization beyond the aforesaid limit of 0.03% of Tw. This information have been used to declare if the setup used can fulfill Class I/A requirements or not.

The example of the cases of f_s = 48 kHz and f_s = 320 kHz with f_{s_eq} = 32 kHz (worst case and best case of the tests summarized in Table II, respectively), in the absence of noise

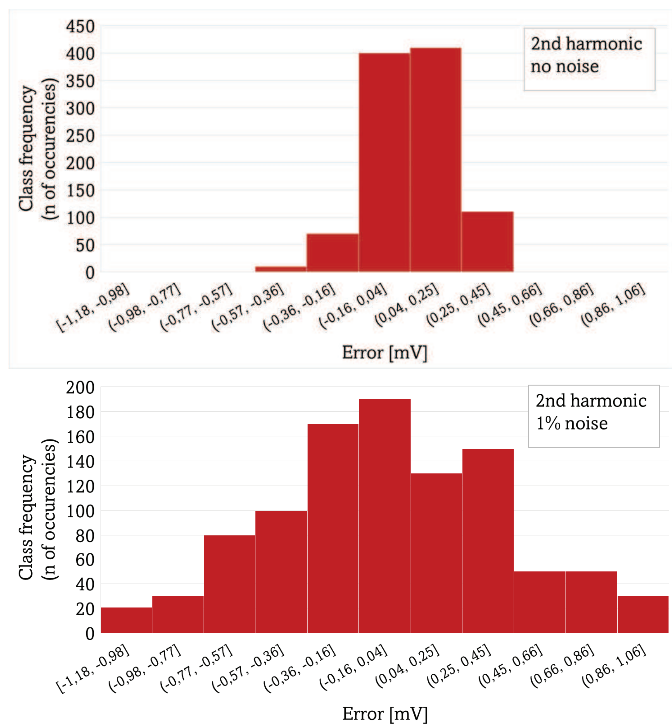

Fig. 6. Frequency distribution for the error in second harmonic measurement, for the case of f_s = 48 kHz and 4096 points after the interpolation, in the condition of no noise and 1% noise level.

and presence of noise, are discussed. The synchronization error has been calculated by acquiring 1000 observation windows of the signal (generated with the calibrator) with and without noise. Then, the number of samples acquired in ten periods (as required by the standards for Class A) and the relative time

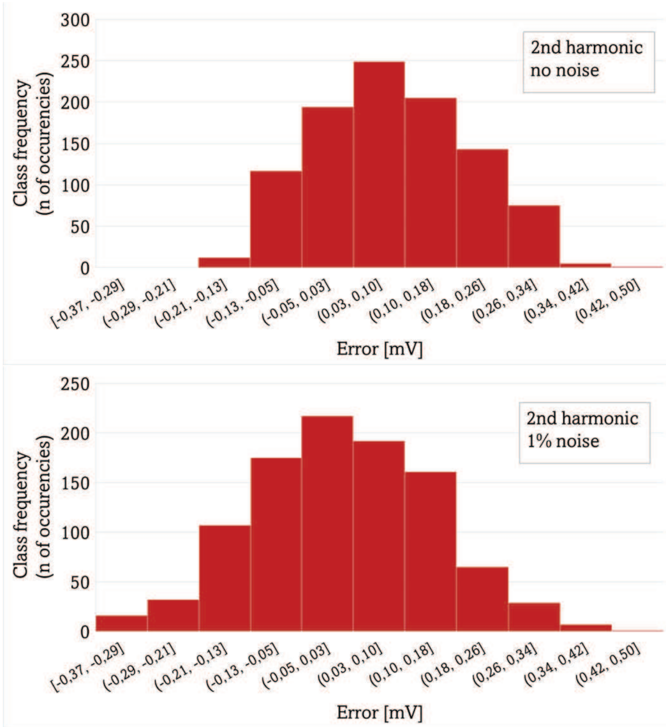

Fig. 7. Frequency distribution for the error in second harmonic measurement, for the case of f_s = 320 kHz, f_{s_eq} = 32 kHz, and 4096 points after the interpolation, in the condition of no noise and 1% noise level.

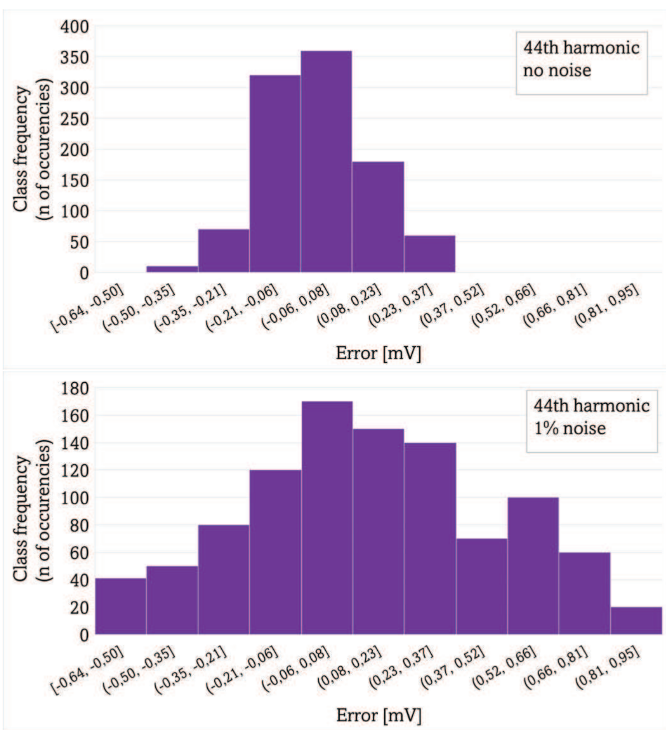

Fig. 8. Frequency distribution for the error in 44th harmonic measurement, for the case of f_s = 48 kHz and 4096 points after the interpolation, in the condition of no noise and 1% noise level.

length have been compared with the 200-ms Tw of a 50 Hz signal. In the absence of noise, the maximum synchronization error is 0.012% for the case of f_s = 48 kHz and 0.0015%

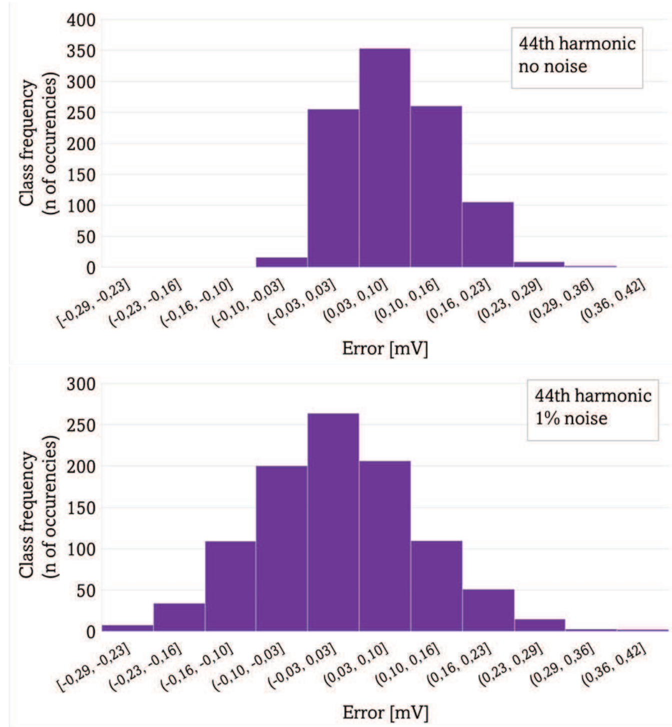

Fig. 9. Frequency distribution for the error in 44th harmonic measurement, for the case of f_s = 320 kHz, f_{s_eq} = 32 kHz, and 4096 points after the interpolation, in the condition of no noise and 1% noise level.

for the case of f_s = 320 kHz with f_{s_eq} = 32 kHz. Repeating the test with 1% noise added to the signal, the maximum synchronization error is 0.033% for the case of f_s = 48 kHz and 0.0027% for the case of f_s = 320 kHz with f_{s_eq} = 32 kHz. As expected, with the basic configuration, the presence of noise leads to a loss of synchronization, and the limit error is not respected. Using a higher sampling frequency and a mean-value technique, the error remains below the limit even if it gets worse.

The results highlight two aspects: the first is that, in the presence of noise, the dispersion of the error increases, especially for smaller amplitude harmonics and the second is that the use of higher sampling frequencies and the averaging technique allows mitigating the effects of noise, reducing errors, and their dispersion. In fact, for the best case of f_s = 320 kHz with averaging, the compliance with the standard limits is maintained even in the presence of noise; also, the results dispersion is significantly lower than that with lower sampling frequency, thus confirming the improved robustness against noise presence.

V. Conclusion

In this work, the authors have investigated the impact of disturbances, specifically noise, on the measurement of harmonics according to IEC 61000-4-30 and IEC 61000-4-7 standards. An experimental analysis has been carried out on a case-study low-cost device, where different sampling, averaging, and TDI techniques have been implemented. The presented study has shown that, starting from a configuration with a measurement setup that meets the standard requirements for a device of the highest accuracy class (Class A/I), the same configuration does not meet anymore the requirements when considering a test signal with disturbances.

In detail, the results shown in this article confirm that the problem of the test signal (and, more generally, the test condition) cannot be ignored for the evaluation of the accuracy and the behavior of a PQ meter. In fact, as shown above, standard compliance can be met if the test signal does not include noise (apart from quantization noise introduced by the ADC). On the other hand, accuracy requirements could not be fulfilled anymore when more realistic test conditions are considered, where noise can be present. The results demonstrate that it is essential to propose and develop proper test conditions that consider more realistic operating conditions of the smart grid environment. The same considerations can be made with respect to other possible disturbances that can coexist with harmonics, such as interharmonics and frequency variations. Such real-case disturbances may occur in real power systems, so that actual operating conditions can be even more severe than those normally used for tests. Moreover, different kinds of disturbances can be simultaneously present; thus, the real operating conditions of the power system and the metering equipment connected thereto can be even more challenging. In this viewpoint, future research will be devoted to the impact of different disturbances on the metering devices behavior. This should also be reflected at the standard level, so as to avoid cases, where instruments compliance with standard accuracy requirements can be ensured only under ideal or user-defined conditions. With respect to this, it can be observed that in the previous version of the standard IEC 61000-4-30 (2011), test conditions with different PQ disturbances were considered (earlier "testing states" for PQ measurements evaluation). They included a series of tests to be carried out to verify the functioning of the device in nonideal operating condition. In detail, a first series of tests was considered, defined as "testing state 1"; they should be carried out to verify the accuracy of the device when varying only one parameter (frequency, voltage amplitude, flicker, unbalance, and harmonics) with their ranges of variation. Further testing states 2 and 3 were defined, they required to repeat the tests by keeping constant one of the "testing state 1" quantities and applying given variations of the other quantities. The reintroduction of such kind of standard tests, including also the presence of noise, could be useful to properly assess the metrological features of PQ instruments in more realistic test conditions.

REFERENCES

[1] J. Zheng, D. W. Gao, and L. Lin, "Smart meters in smart grid: An overview," in *Proc. IEEE Green Technol. Conf. (GreenTech)*, Apr. 2013, pp. 57–64.

[2] A. Q. Al-Shetwi, M. A. Hannan, K. P. Jern, M. Mansur, and T. M. I. Mahlia, "Grid-connected renewable energy sources: Review of the recent integration requirements and control methods," *J. Cleaner Prod.*, vol. 253, Apr. 2020, Art. no. 119831.

[3] M. Bajaj and A. K. Singh, "Grid integrated renewable DG systems: A review of power quality challenges and state-of-the-art mitigation techniques," *Int. J. Energy Res.*, vol. 44, no. 1, pp. 26–69, Jan. 2020.

[4] A. E. Legarreta, J. H. Figueroa, and J. A. Bortolin, "An IEC 61000-4-30 class a—Power quality monitor: Development and performance analysis," in *Proc. 11th Int. Conf. Electr. Power Quality Utilisation*, Lisbon, Portugal, Oct. 2011, pp. 1–6.

[5] V. Boscaino et al., "Grid-connected photovoltaic inverters: Grid codes, topologies and control techniques," *Renew. Sustain. Energy Rev.*, vol. 189, Jan. 2024, Art. no. 113903.

[6] D. Signorino et al., "Analysis of AC oscillations in a DC smart grid," in *Proc. IEEE 14th Int. Workshop Appl. Meas. Power Syst. (AMPS)*, Caserta, Italy, Sep. 2024, pp. 1–6.

[7] A. Ujile and Z. Ding, "A dynamic approach to identification of multiple harmonic sources in power distribution systems," *Int. J. Electr. Power Energy Syst.*, vol. 81, pp. 175–183, Oct. 2016.

[8] D. Kumar and F. Zare, "Harmonic analysis of grid connected power electronic systems in low voltage distribution networks," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 4, no. 1, pp. 70–79, Mar. 2016.

[9] H. Bolcskei and F. Hlawatsch, "Noise reduction in oversampled filter banks using predictive quantization," *IEEE Trans. Inf. Theory*, vol. 47, no. 1, pp. 155–172, Jan. 2001.

[10] Ł. Michalec, M. Jasiński, T. Sikorski, Z. Leonowicz, Ł. Jasiński, and V. Suresh, "Impact of harmonic currents of nonlinear loads on power quality of a low voltage network–review and case study," *Energies*, vol. 14, no. 12, p. 3665, Jun. 2021.

[11] M. Andrejevic-Stosovic, M. Dimitrijevic, S. Bojanic, O. Nieto-Taladriz, and V. Litovski, "Characterization of nonlinear loads in power distribution grid," *Facta Universitatis-Ser., Electron. Energetics*, vol. 29, no. 2, pp. 159–175, 2016.

[12] L. Feola, R. Langella, and A. Testa, "On the effects of unbalances, harmonics and interharmonics on PLL systems," *IEEE Trans. Instrum. Meas.*, vol. 62, no. 9, pp. 2399–2409, Sep. 2013.

[13] R. Athiya and D. A. K. Sharma, "A review of experimental study of power quality monitor on harmonic measurement," *Int. J. Eng. Technol. Manage. Res.*, vol. 7, no. 6, pp. 156–159, Jul. 2020.

[14] S. T. Y. Alfalahi et al., "Supraharmonics in power grid: Identification, standards, and measurement techniques," *IEEE Access*, vol. 9, pp. 103677–103690, 2021.

[15] A. Gallarreta et al., "Comparison of measurement methods for the assessment of RMS spectra in the 9–150 kHz range," in *Proc. IEEE 14th Int. Workshop Appl. Meas. Power Syst. (AMPS)*, Caserta, Italy, Sep. 2024, pp. 1–6.

[16] G. Artale et al., "Power quality assessment with commercial microcontroller devices. Repeatability measurements of on-board harmonic analysis," in *Proc. IEEE 13th Int. Workshop Appl. Meas. Power Syst. (AMPS)*, Bern, Switzerland, Sep. 2023, pp. 1–6.

[17] G. Artale et al., "CZT-based harmonic analysis in smart grid using low-cost electronic measurement boards," *Energies*, vol. 16, no. 10, p. 4063, May 2023.

[18] G. Artale et al., "PQ and harmonic assessment issues on low-cost smart metering platforms: A case study," *Sensors*, vol. 20, no. 21, pp. 1–27, Nov. 2020.

[19] G. Artale et al., "Measurement issues on harmonic analysis according to the IEC 61000-4-7," in *Proc. 25th IMEKO TC4 Int. Symp. 23rd Int. Workshop ADC DAC Modeling Test.*, 2022, pp. 187–192.

[20] G. Artale et al., "Feasibility of IEC 61000-4-7 class I gapless implementation of harmonics measurement on low-cost microcontroller device," in *Proc. IEEE 14th Int. Workshop Appl. Meas. Power Syst. (AMPS)*, Caserta, Italy, Sep. 2024, pp. 1–6.

[21] G. Artale et al., "Processing techniques for metrological improvement of low-cost smart meter hardware solution for IEC 61000-4-7 class I harmonics measurements," *Measurement*, vol. 242, Jan. 2025, Art. no. 115898.

[22] Electromagnetic Compatibility (EMC) Part 4–30: Testing and Measurement Techniques—Power Quality Measurement Methods, Standard IEC 61000-4-30/2015-12, 2015.

[23] Electromagnetic Compatibility (EMC)—Part 4–7: Testing and Measurement Techniques—General Guide on Harmonics and Interharmonics Measurements and Instrumentation, for Power Supply Systems and Equipment Connected Thereto, Standard IEC 61000-4-7, 1993.

[24] D. Brnobić, S. Vlahinić, and N. Stojković, "The effect of IEC grouping algorithms on frequency domain noise," *Measurement*, vol. 43, no. 3, pp. 426–433, Apr. 2010.

[25] M. Karimi, H. Mokhlis, K. Naidu, S. Uddin, and A. H. A. Bakar, "Photovoltaic penetration issues and impacts in distribution network—A review," *Renew. Sustain. Energy Rev.*, vol. 53, pp. 594–605, Jan. 2016.

[26] G. Frigo, A. Derviškadic, A. Bach, and M. Paolone, "Statistical model of measurement noise in real-world PMU-based acquisitions," in *Proc. Int. Conf. Smart Grid Synchronized Meas. Analytics (SGSMA)*, College Station, TX, USA, May 2019, pp. 1–8.

[27] G. Frigo, "Measurement of conducted supraharmonic emissions: Quasi-peak detection and filter bandwidth," *Metrology*, vol. 2, no. 2, pp. 161–179, Mar. 2022.
[28] A. Cataliotti, V. Cosentino, A. Lipari, S. Nuccio, and D. Serazio, "DAQs-based wattmeters for high accuracy measurements. Comparison with the Italian power primary standard," *Measurement*, vol. 46, no. 9, pp. 3460–3468, Nov. 2013.
[29] A. Cataliotti, V. Cosentino, D. Di Cara, A. Lipari, S. Nuccio, and C. Spataro, "A PC-based wattmeter for accurate measurements in sinusoidal and distorted conditions: Setup and experimental characterization," *IEEE Trans. Instrum. Meas.*, vol. 61, no. 5, pp. 1426–1434, May 2012.
[30] Voltage Characteristics of Electricity Supplied by Public Electricity Networks, Standard IEC 50160, May 2023.
[31] Electromagnetic Compatibility (EMC)—Part 3–2: Limits—Limits for Harmonic Current Emissions (equipment Input Current = 16 A Per Phase), Standard IEC 61000-3-2, Dec. 2021.
[32] Electromagnetic Compatibility (EMC)—Part 4–6: Testing and Measurement Techniques—Immunity to Conducted Disturbances, Induced by Radio-Frequency Fields, Standard IEC 61000-4-6, Sep. 2014.
[33] Electromagnetic Compatibility (EMC)—Part 4–16: Testing and Measurement Techniques—Test for Immunity to Conducted, Common Mode Disturbances in the Frequency Range 0 Hz to 150 kHz, Standard IEC 61000-4-16, Sep. 2018.
[34] Electromagnetic Compatibility (EMC)—Part 4–19: Testing and Measurement Techniques—Test for Immunity to Conducted, Differential Mode Disturbances and Signalling in the Frequency Range 2 KHz to 150 KHz at A.C. Power Ports, Standard IEC 61000-4-19, May 2015.
[35] *Electricity Metering Equipment—General Requirements, test and Test Conditions—Part 11—Metering Equipment*. IEC 62052-11, Mar. 2022.
[36] Electrical Energy Meters—Test Equipment, Techniques and Procedures—Part 1: Stationary Meter Testing Units (MTUs), Standard IEC 62057-1, Sep. 2023.
[37] Electricity Metering Equipment—General Requirements, Test and Test Conditions—Part 31—Product Safety Requirements and Tests, Standard CEI EN 62052-31, Apr. 2018.
[38] Electricity Metering Equipment—Particular Requirements—Part 21: Static Meter for AC Active Energy (Classes 0, 5, 1 and 2), Standard IEC 32053-21, Jan. 2020.
[39] Electricity Metering Equipment—Particular Requirements—Part 22: Static Meter for AC Active Energy (Classes 0.1S, 0.2S, and 0.5S), Standard IEC 32053-22, Feb. 2022.
[40] Electricity Metering Equipment—Particular Requirements—Part 23: Static Meter for Reactive Energy (Classes 2 and 3), Standard IEC 32053-23, Jan. 2020.
[41] Electricity Metering Equipment—Particular Requirements—Part 24: Static Meter for Fundamental Component Reactive Energy (Classes 0.5 S, 1 S, 1, 2 and 3), Standard IEC 32053-24, Dec. 2021.

Giovanni Artale (Member, IEEE) received the M.S. degree in electronic engineering and the Ph.D. degree in electronic and telecommunication engineering from the University of Palermo, Palermo, Italy, in 2010 and 2014, respectively.

He is currently an Associate Professor with the Department of Engineering, University of Palermo. His current research interests include low-frequency harmonic analysis algorithms, power line communications, and smart grids.

Antonio Cataliotti (Member, IEEE) received the M.S. and Ph.D. degrees in electrical engineering from the University of Palermo, Palermo, Italy, in 1992 and 1998, respectively.

He is currently a Full Professor of electrical and electronic measurements with the Department of Engineering, University of Palermo. His current research interests include power quality measurements, power line communications, and smart grids.

Valentina Cosentino (Member, IEEE) received the M.S. and Ph.D. degrees in electrical engineering from the University of Palermo, Palermo, Italy, in 2001 and 2005, respectively.

She is currently a Full Professor of electrical and electronic measurements with the Department of Engineering, University of Palermo. Her current research interests include energy and power quality measurements, virtual instrumentation, and measurement and communications systems for smart grids.

Dr. Cosentino is currently an Associate Editor of IEEE TRANSACTIONS ON POWER DELIVERY and IEEE TRANSACTIONS ON INSTRUMENTATION AND MEASUREMENT.

Dario Di Cara (Member, IEEE) received the M.S. and Ph.D. degrees in electrical engineering from the University of Palermo, Palermo, Italy, in 2005 and 2009, respectively.

Since 2012, he has worked as a Researcher with the National Research Council of Italy, Palermo. His current research interests include power quality measurements, current transducers characterization in nonsinusoidal conditions, power line communications, and smart grids.

Vito Ditta received the M.S. degree in electrical engineering and the Ph.D. degree in energy from the University of Palermo, Palermo, Italy, in 2020 and 2024, respectively.

He is currently working as a Research Fellow with the Institute of Marine Engineering (INM), National Research Council of Italy (CNR), Palermo. His current research interests include power quality measurements, harmonics, virtual instrumentation, microcontroller systems, and smart grids.

Salvatore Guaiana received the M.S. degree in electronics and photonics engineering and the Ph.D. degree in energy and information technologies from the University of Palermo, Palermo, Italy, in 2012 and 2019, respectively.

He is currently a Research Fellow with the Institute of Marine Engineering, National Research Council of Italy, Palermo. His current research interests include power line communications, the development of microcontroller systems, and communications protocols for smart grid applications.

Nicola Panzavecchia received the M.S. degree in computer science, the master's degree in domotics and building automation, and the Ph.D. degree in information and communication technologies from the University of Palermo, Palermo, Italy, in 2007, 2011, and 2022, respectively.

Since 2007, he has been working as a Consultant, a Developer, a System Administrator, and a Cloud Architect. Since 2013, he has been with the Institute of Marine Engineering (INM), National Research Council of Italy (CNR), Palermo, first as a Research Fellow, and a Researcher since 2020. He has developed software and hardware solutions in the framework of several research projects. His current research interests include software development for energy management and embedded systems, smart grids, and power line communications.

Giovanni Tinè (Member, IEEE) received the M.S. degree in electronic engineering and the Ph.D. degree in electronics, computer science, and telecommunications engineering from the University of Palermo, Palermo, Italy, in 1990 and 1994, respectively.

Since 2000, he has worked as a Researcher with the National Research Council of Italy, Palermo. His main scientific interests are distributed measurement system for smart grids, power-line communication in medium- and low-voltage systems, electromagnetic compatibility (EMC), and intelligent electronic devices for smart grids.