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A comparative analysis of reactive power/energy measuring algorithms in non-sinusoidal conditions by using the fundamental reactive power as a reference

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ABSTRACT
The measurement of reactive power and energy in harmonically distorted conditions is accompanied with multiple challenges. In the first place, there is the ambiguous definition of these quantities, when the systems' signals lack sinusoidal waveforms. The international standard IEEE 1459 addresses this by emphasizing the need to measure fundamental frequency power components only, even in harmonically polluted environments. Another complication arises because of different measuring algorithms implemented in the modern meters. Although these algorithms provide consistent results for ideal sinusoidal waveforms, the instruments' recordings may diverge significantly when distortion is present. In this work, the readings of different, commercially available, reactive power/energy instruments in harmonically distorted conditions will be experimentally verified. In the primary experiment, the meters' outputs are going to be analyzed against the fundamental reactive power as a reference quantity, in accordance with IEEE 1459. Later on, a mutual inter-comparison between different algorithm-based instruments will be conducted, as a contribution to the perspective of an unbroken traceability chain establishment in the domain of reactive power and energy in non-sinusoidal conditions. In order to ensure a high metrological accuracy, reference standards of the highest accuracy class available, traceable to BIPM intrinsic standards, are implemented.

Section: RESEARCH PAPER

Keywords: reactive power/energy; measuring algorithms; high-order harmonics; reference standards; fundamental reactive power

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1. INTRODUCTION

The examination of active power and active energy electricity meters in harmonically distorted conditions is a topic which is covered in different international standards [1]–[3], international recommendations [4], and plenty of scientific works [5]–[12]. The active power is an electrical quantity that is unambiguously defined in the case of distorted signals, therefore, standardized test procedures and accuracy requirements are available for different accuracy class meters [3]–[4]. The scientific community has provided research results regarding the examination of meters for active power/energy by using the standardized test protocols [5]–[8], as well as by proposing innovative examination concepts [7], [9]–[12].

In the case of reactive power and energy instrumentation, no standardized general test protocols or accuracy requirements are available for non-sinusoidal conditions. The main reason is the fact that the aforementioned quantities are ambiguously defined in the case of harmonically polluted test signals. Nowadays, multiple power theories exist, each one demonstrating certain advantages and flaws [13]–[16]. The two most notable definitions, dating from almost a century ago, are the power theory proposed by Budeanu [13], referred to as the base frequency-domain approach, and the power theory proposed by Fryze [14], regarded as the base time-domain concept for the illustration of reactive power. The main shortcoming of Budeanu's concept [13] is the fact that by compensating for the reactive power in harmonically distorted conditions, one is not able to achieve a power factor of unity, due to the existence of the distortion power [17]. Complementary, the reactive power, evaluated according to the definition of Fryze [14], cannot be fully compensated by using passive components, as it contains power fractions that are the result of mutual interrelation between signals' components at different frequencies [17].

A further issue in terms of reactive power/energy measurements in non-sinusoidal conditions is the different measuring algorithms implemented in the commercially available instrumentation. These measuring algorithms provide almost identical meter output in the case of pure sinusoidal waveforms, but the readings may vary significantly in the case of high-order harmonics. In the international standards IEC 62053 [18]–[19], the accuracy requirements for static reactive electricity meters of different accuracy classes are provided, but they are limited to measurements of 50 Hz signals.

A significant breakthrough for overcoming the aforementioned issues was made with the publication of international standard IEEE 1459, the current version being from 2025 [20]. In this standard, it is highlighted that power components that correspond to voltage and current fractions at fundamental frequency are of particular interest when it comes down to measurement, even in distorted conditions. However, the requirement for fundamental power monitoring may require the alteration of the existing measuring solutions, i.e. the application of filtering of the 50 Hz signal components [21]–[22]. Additionally, from the perspective of legal metrology, measuring only fundamental power/energy provides inequity in terms of penalizing harmonic distortion producers and, consequently, compensating distorted energy consumers [22].

In this work, an analysis of the readings of different measuring algorithm-based instruments in relation to fundamental reactive power will be conducted. In Section 2, the harmonic distortion of the signals will be mathematically presented, alongside the output of instruments based on different measuring algorithms by theoretical means. The analysed meters' output for different distortions of the input signals will be mathematically evaluated and experimentally validated, by using equipment of the highest accuracy class available. The measuring equipment and the implemented test protocols are presented in Section 3, while the experimental results are shown in Section 4. In the second part of the experiment, covered in Section 5, the deviation magnitude between different algorithm-based instruments' readings will be analytically and experimentally verified. This is performed as a contribution to the perspective of an unbroken traceability chain establishment, in the domain of reactive power and energy in non-sinusoidal conditions. Section 6 will encompass the discussion and presentation of measurement uncertainty propagation, attributed to both the sourced and the measured reactive power/energy in the introduced experimental configuration. In the end, the conclusions of the work will be presented.

2. PRESENTATION OF HARMONIC COMPONENTS AND REACTIVE POWER/ENERGY MEASURING ALGORITHMS

A harmonically distorted voltage or current signal may be mathematically evaluated in time-domain by using Fourier series [17], [23]–[26]:

$$x(t) = X_{\mathrm{DC}} + \sum_{h=1}^{n} \sqrt{2}\, X_h \sin(h\, \omega\, t + \alpha_{\mathrm{x}h})\,, \tag{1}$$

where $x(t)$ is the time-domain representation of the voltage or current signals $u(t)$ or $i(t)$; h is the harmonic order; ω is the angular frequency; X_{DC} is the DC component in the signals U_{DC} or I_{DC}; X_h is the RMS value of the voltage or current harmonic of order h, U_h or I_h; and $\alpha_{\mathrm{x}h}$ is the initial phase shift of the component with a frequency h times the fundamental, $\alpha_{\mathrm{u}h}$ or $\alpha_{\mathrm{i}h}$. In equation (1), n is the maximal harmonic order, which is taken into consideration.

Single high-order harmonics in % are more commonly presented in the form of their relative share in relation to the signals' components at fundamental frequency [3]–[4]:

$$x_{h,\%} = \frac{X_h}{X_1} \cdot 100\,, \tag{2}$$

where X_1 is the RMS of the voltage or current signal component at 50 Hz, U_1 or I_1. The relative share presented in equation (2) is also referred to as Individual Harmonic Distortion, IHD [17]. The phase shift of the harmonic component of order h is usually given in relation to the initial phase shift of the voltage or current fundamental, at positive zero crossing, α_{u1} or α_{i1} [3]–[4]:

$$\theta_{\mathrm{x}h} = \angle(\alpha_{\mathrm{x}h}, \alpha_{\mathrm{x1}})\,, \tag{3}$$

$\theta_{\mathrm{x}h}$ referring to the voltage harmonic phase shift $\theta_{\mathrm{u}h}$, or current harmonic phase shift θ_{ih}. The phase shift between voltage and current harmonics of order h is evaluated as follows [6]:

$$\varphi_h = h\, \varphi_1 - (\theta_{\mathrm{i}h} - \theta_{\mathrm{u}h})\,, \tag{4}$$

where φ_1 is the phase shift between fundamental voltage and current.

The RMS of the voltage or current signals, U or I, which, besides fundamental components, possesses high-order harmonics as well, is calculated as [17], [26]:

$$X = \sqrt{\sum_{h=1}^{n} X_h^2}\,. \tag{5}$$

For quantitative indication of the harmonic presence in the system's signals, the parameter Total Harmonic Distortion, THD, is used [17], [23]–[26]:

$$THD = \sqrt{\frac{\sum_{h>1}^{n} X_h^2}{X_1^2}} \cdot 100\,\% = \sqrt{\sum_{h>1}^{n} x_{h,\%}^2}\,, \tag{6}$$

and it may refer to both voltage signal's distortion, THD_U, or current signal's distortion, THD_I.

As mentioned in the introduction of the paper, different measuring algorithms for reactive power/energy are implemented in commercially available instruments [27]–[31]. In this work, the two most widely used will be analysed, from the perspective of the measurement of the fundamental reactive power [20]:

$$Q_1 = U_1\, I_1 \sin \varphi_1\,, \tag{7}$$

in harmonically distorted conditions.

The first measuring solution is based on the phase shifting of the voltage (or current) input signals by 90°, before their multiplication with the instantaneous currents (or voltages). The phase shifting is done before the analogue-to-digital conversion of the signals, therefore this measuring algorithm is labelled as based on analogue (phase) displacement of input signals. The phase shifting is accomplished by means of an operation amplifier, used in an integrator configuration. When the voltage and the current signals are harmonically distorted, the measured reactive power may be analytically presented as follows [30]–[31]:

$$\begin{aligned} Q_{\mathrm{MA}} &= \frac{1}{T}\int_{0}^{T} \frac{2\,\pi}{T}\left[-\int u(t)\,\mathrm{d}t\right] i(t)\,\mathrm{d}t \\ &= \sum_{h=1}^{n} \frac{U_h\, I_h \sin\varphi_h}{h}\,, \end{aligned} \tag{8}$$

where T is the period of the signals' components at fundamental frequency, and all the other quantities have the same meaning as described before. The measured reactive power, Q_{MA}, is labelled with an index A, in order for the measuring algorithm, based on analogue displacement of input signals, to be highlighted throughout the text. According to equation (8), the instruments for reactive power/energy, based on the 90° phase displacement measuring algorithm, record the fundamental reactive power plus the high-order harmonics' power fractions, $U_h\, I_h \sin\varphi_h$, divided by the harmonic order h.

The second measuring solution is based on the multiplication of the voltage (or current) digital signal samples by the current (or voltage) digital signal samples, previously shifted by a quarter of a period, $T/4$, regarding the signals' fundamental frequency. The time displacement by $T/4$ is conducted after the digitalization of the signals, and, therefore, this measuring solution is referred to as the digital (time) displacement approach. The measured reactive power is then calculated according to the following equation [30]–[31]:

$$\begin{aligned} Q_{\mathrm{MD}} &= \frac{1}{N} \sum_{j=m}^{m+(N-1)} u_j \cdot i_{j-(T/4)} \\ &= \sum_{h=2\,k-1}^{n} \pm\, U_h\, I_h \sin\varphi_h + \sum_{h=2k}^{n} \pm\, U_h\, I_h \cos\varphi_h\,, \end{aligned} \tag{9}$$

where u_j and i_j are the voltage and current input signals' digital samples, taken for averaging in a so-called "averaging window", consisting of N samples, and k is a positive integer. The current signal samples are displaced by $T/4$, therefore, in equation (9), $i_{j-(T/4)}$ is used instead of i_j. The measured reactive power, Q_{MD}, is labelled with an index D, in order for the measuring algorithm, based on the digital displacement of input signals, to be highlighted throughout the text. According to equation (9), the even harmonics' power fractions are regarded as active power components, while the odd harmonics' power fractions are recorded as reactive power components. The different sign before each power fraction, $U_h\, I_h \sin\varphi_h$, or $U_h\, I_h \cos\varphi_h$, is a result of the actual phase shifting of each signal's harmonic component by $h \cdot 90°$, h being the harmonic order [30]–[31]. This means that the power fractions of order h = 1, 4, 5… etc. are measured with a positive sign, the way they actually flow in the system, while the power fractions of order h = 2, 3, 6, 7… etc. are recorded with a negative sign, in opposite to their actual flow in the system.

Both the fundamental reactive power, given in equation (7), and the measured reactive power, evaluated according to the two measuring algorithms given in equations (8) and (9), are presented for single-phase conditions. If a three-phase system is regarded, the overall reactive power is supposed to be calculated as a sum of the recordings in the three phases. In a special case scenario, for three-phase symmetrical conditions, the three-phase reactive power is evaluated by the multiplication of equations (7)–(9) by a factor of three. It is important to emphasize that three-phase symmetrical conditions, in the case of harmonically distorted signals, imply the same amplitudes and phase shifts for all three-phase voltages and currents, regarding both the fundamental components and the high-order harmonics.

3. TEST EQUIPMENT AND EXAMINATION PROTOCOL

In the experimental stage of the work, the mathematically obtained readings are going to be verified by experimental means. The experiments are conducted in an accredited laboratory for calibration of instruments and reference standards for electrical quantities: the Laboratory for Electrical Measurements (LEM). LEM is part of the Faculty of Electrical Engineering and Information Technologies (FEEIT) at Ss. Cyril and Methodius University in Skopje (UKIM). It is an accredited calibration laboratory in accordance with the international standard ISO/IEC 17025:2017 [32], and it maintains documented traceability to the intrinsic primary reference standards of BIPM [33].

The laboratory's secondary reference standard (RS), in the domain of electrical power and energy instruments calibrations, a three-phase power calibrator of accuracy class 0.02, CALMET C300 [34], illustrated in Figure 1, plays a central role in the experimental part of the work. This RS is, in fact, a three-phase voltage and current source, with the option of generating pre-configured, harmonically distorted signals, besides waveforms with pure sinusoidal form. The calibrator [34] is also used as a reference unit for electrical power and energy (active, reactive, and apparent), and may be set to evaluate the reference quantity according to different power theories. In the following experiment, it is implemented both as a source of distorted signals and as a reference unit for providing the fundamental reactive power.

For the practical validation of the different measuring algorithms' readings in non-sinusoidal conditions, two measuring instruments are introduced. The first one is a reactive energy electricity meter of accuracy class 1, Landys+Gyr ZMD405CT44.2407 [35], illustrated in Figure 2. The meter is intended for instrument transformer connection, i.e. its base voltage and current equal 58 V and 5 A, respectively. According to its accuracy class, it is clear that this particular unit is compliant to the standard IEC 62053-24 [19], which refers to fundamental component reactive energy meters. The standard IEC 62053-23

Figure 1. Power calibrator, a secondary RS of LEM, used as a source of harmonically distorted signals and as a reference fundamental reactive power unit.

Figure 2. A reactive energy electricity meter with a measuring algorithm based on phase displacement of input voltages by 90° .

[18] covers only electricity meters of the lower accuracy classes of 2 and 3. According to the manufacturer's datasheet [35], its measuring principle is based on phase displacement of the input voltages by 90°. This Unit Under Test (UUT) will be further used for the experimental verification of equation (8), as well as for the error magnitude examination of a meter based on analogue displacement of input signals in distorted conditions, against the reference fundamental reactive power.

The primary RS of LEM, in the domain of electrical power and energy instrument calibrations, a three-phase energy comparator of accuracy class 0.01, ZERA COM 3003 [36], illustrated in Figure 3, is also implemented in the practical evaluation. According to the manufacturer's specification [36], it may be set to record the reactive power/energy according to different measuring principles, one of which is based on the digital (time) displacement of the input currents, by a quarter of a period. The experiments conducted with the energy comparator [36] will be used for the practical verification of equation (9), as well as for the analysis of the error magnitudes between the measured quantity and the reference fundamental reactive power. This unit is not compliant to the requirements of the standards IEC 62053 [18]–[19], due to the fact that it is a reference standard, with an accuracy class far better than those of the referred electricity meters.

The experiments will be conducted by using test signals based on those provided in the standards [3]–[4] and [19]. The first test signal set encompasses voltages and currents which possess only 5th order harmonics, beside fundamental components, with a relative share of $u_{5,\%}$ = 10 % and $i_{5,\%}$ = 40 %, respectively. The 5th order voltage harmonic is in phase with the voltage fundamental, at positive zero crossing, i.e. θ_{u5} = 0°. The 5th order current harmonic is phase shifted in relation to the current fundamental by θ_{i5} = 60°. Because this set of test waveforms comprises of 5th order harmonics only, it will be denoted as 5H test.

Another set of test signals is used, and it comprises of multiple odd harmonics, up 11th order, with random share and random phase shift in relation to fundamental voltages and currents. There is no limitation on the harmonic share of single harmonics, but there is limitation on the THD of the test signals. Namely, in this set of test signals, THD_{U} is limited to 10 %, while THD_{I} is limited to 40 %, in such a way a correlation to the 5H test is established. Because multiple harmonic components with random share and random phase shifts are present in the test voltages and currents, the examination of the meters with this set of test waveforms will be labelled as RANDOM test.

Figure 3. Energy comparator, the primary RS of LEM, with a measuring algorithm based on time displacement of input currents by T/4.

The chosen distortion level in both test signal sets is determined by the proposed waveforms in [3], [4], and [19]. In the real power grids, the voltage THD is limited to 8 % (for low and medium voltage networks) in accordance with EN 50160 [37]. In such a way, the introduction of test signals with THD_{U} of approximately 10 % may be regarded as a slight overestimation of the real in-situ conditions. Regarding the THD_{I}, in real-time conditions, different levels of distortion may be detected. In some points of the system, the recorded THD_{I} may even surpass 100 %, depending on how far from the harmonics' source the metering is performed.

Both tests are conducted in three-phase symmetrical conditions, by using single RMS value voltages and currents, equal to the base parameters of the electricity meter [35], 58 V and 5 A. For both tests, recordings in twelve measurement points are conducted, referring to a different fundamental phase shift value, φ_1, ranging between -90° and -15°, in steps of 15°, and between 15° and 90°, in steps of 15°. The selected measurement points resemble different shares of fundamental reactive power in the system. No measurements are conducted for φ_1=0°, due to the fact that the reference fundamental reactive power in such a case is equal to zero. Even if the instruments [35]–[36] are able to record some fraction of harmonic reactive power, no relevant error magnitudes may be obtained.

4. DEVIATION MAGNITUDES OF THE METERS' READINGS IN RELATION TO THE FUNDAMENTAL REACTIVE POWER

In the following section, the measuring algorithms of both the electricity meter [35] and the energy comparator [36] will be experimentally verified, by analysing the analytically obtained and the measured deviations between their readings and the sourced reference fundamental reactive power, for both sets of test signals.

4.1. Case study – electricity meter

According to equations (7) and (8), when the introduced electricity meter [35] is subjected to harmonically distorted voltages and currents, the relative deviation between its readings and the reference fundamental reactive power may be calculated as follows:

$$\begin{aligned}\varepsilon_1 &= \frac{Q_{\mathrm{MA,3P}} - Q_{\mathrm{1,3P}}}{Q_{\mathrm{1,3P}}} \cdot 100\ \% \\ &= \frac{\sum_{h>1}^{n} \frac{3\ U_h\ I_h \sin\varphi_h}{h}}{3\ U_1\ I_1 \sin\varphi_1} \cdot 100\ \% \\ &= \sum_{h>1}^{n} \frac{1}{h} \cdot \frac{u_{h,\%}}{100} \cdot \frac{i_{h,\%}}{100} \cdot \frac{\sin\varphi_h}{\sin\varphi_1} \cdot 100\ \% \,.\end{aligned} \tag{10}$$

The index 3P in both the measured power and the reference fundamental reactive power indicates that the measurements are conducted in a three-phase conditions configuration. As can be seen from equation (10), the overall deviation's fractions, related to different high-order harmonics, are directly proportional to their relative shares, $u_{h,\%}$ and $i_{h,\%}$, and inversely proportional to the harmonic order, h. The difference between the measured power and the reference power is dependent on the phase shift between the voltage and the current harmonic components of order h, φ_h, and it is inversely proportional to the share of fundamental reactive power in the system, via $\sin\varphi_1$.

In Figure 4, the results of the electricity meter's [35] examination, with both sets of test signals, are illustrated as two error curves. The first one represents the measured deviations, i.e. the relative difference between the recordings of the electricity meter [35] and the sourced fundamental reactive power by the calibrator [34]. The other error curve represents the simulated deviations, obtained by using equation (10). In Figure 4, for both sets of test signals, the measured error curve follows the envelope of the mathematically modelled deviations, leading to a verification of the actual measuring principle of the UUT, as presented in equation (8). In some measurement points, however, a slight mismatch between the error curves is detected. These differences are the result of two phenomena. First, there is the actual asymmetry of the sourced three-phase voltages and currents, due to the fact that the secondary RS [34] cannot reproduce the signals in the three phases with exactly the same magnitudes, phase shifts, and harmonic distortion. This issue may be covered by the uncertainty attributed to the sourced power, which will be addressed later in the paper. Further on, the meter [35] is of a lower accuracy class compared to the power calibrator [34], so the mismatch between the measured and the analytically obtained deviations is partially a result of its intrinsic errors [38]. In equation (10), the analytically obtained deviations are regarded only from the perspective of the mismatch between the measured quantity and the reference fundamental reactive power, i.e. no additional error sources are considered.

The deviation magnitudes are relatively small, below ± 1 %, when the fundamental phase shift is between -60° and -90° and between 60° and 90°. The conclusion is valid for both sets of test signals. This is in compliance with the accuracy requirements for the particular meter type, presented in [19], even though this UUT, according to equation (8), does not record the fundamental reactive power exactly as given in equation (7). For a lower share of fundamental reactive power in the system, more significant errors, up to several percent, are recorded. The maximal deviations equal approximately 2 %, for the 5H protocol, which is once again within the accuracy requirements presented in [19], i.e. errors up to ± 2 %, for $\sin\varphi_1 = 0.25$ ($\varphi_1 \approx \pm 15°$). Regarding the RANDOM test, a deviation of approximately 4 % is recorded when φ_1 = -15°, and this is the only measurement point where the meter does not fulfil the accuracy requirements of [19]. The actual error magnitudes indicate that no billing consequences will be present, if such an instrument is intended for fundamental reactive energy measurements, as long as the distortion of the signals is compliant with the selected test signals.

The measured deviations follow a sine-wave pattern of φ_1 for the 5H test, with a period 5 times smaller than the period of the signals at fundamental frequency. The sine-wave pattern of errors is present due to the alteration of $\sin\varphi_5$, according to equation (4). The RANDOM test does not result in an error curve pattern that may be solely explained by a simple mathematical law. This is a result of the partial annulment or amplification between single error fractions that correspond to harmonic components of different orders, due to the alteration of φ_h values.

4.2. Case study – energy comparator

When the laboratory's primary RS [36] is subject of analysis, equations (7) and (9) are valid for the mathematical representation of the deviation between the measured power and the sourced fundamental reactive power. When harmonic distortion of the system's voltages and currents is regarded, usually only odd harmonics are analysed, as is the case with both sets of test signals, introduced in Section 3. The presence of even harmonics indicates some malfunction in the system [24]. The relative deviation, if only odd harmonics are regarded in the test signals, equals:

$$\varepsilon_1 = \frac{Q_{\mathrm{MD,3P}} - Q_{1,\mathrm{3P}}}{Q_{1,\mathrm{3P}}} \cdot 100\ \% = \frac{\sum_{h=2k+1}^{n} \pm 3\, U_h\, I_h \sin\varphi_h}{3\, U_1\, I_1 \sin\varphi_1} \cdot 100\ \% = \sum_{h=2\,k+1}^{n} \pm \frac{u_{h,\%}}{100} \cdot \frac{i_{h,\%}}{100} \cdot \frac{\sin\varphi_h}{\sin\varphi_1} \cdot 100\ \%\,, \tag{11}$$

where k is a positive integer. Equation (11) shows that the single harmonics' error fractions are directly proportional to their relative share in the waveforms and inversely proportional only to the share of fundamental reactive power in the system. The phase shift between the voltage and the current harmonics of the same order, φ_h, influences the magnitude of the errors via $\sin\varphi_h$. Because the harmonic order, h, does not directly affect the single error fractions, as was the case in equation (10), it is expected that, in the concrete scenario, the single harmonic error fractions will be h times larger than those obtained in the analysis

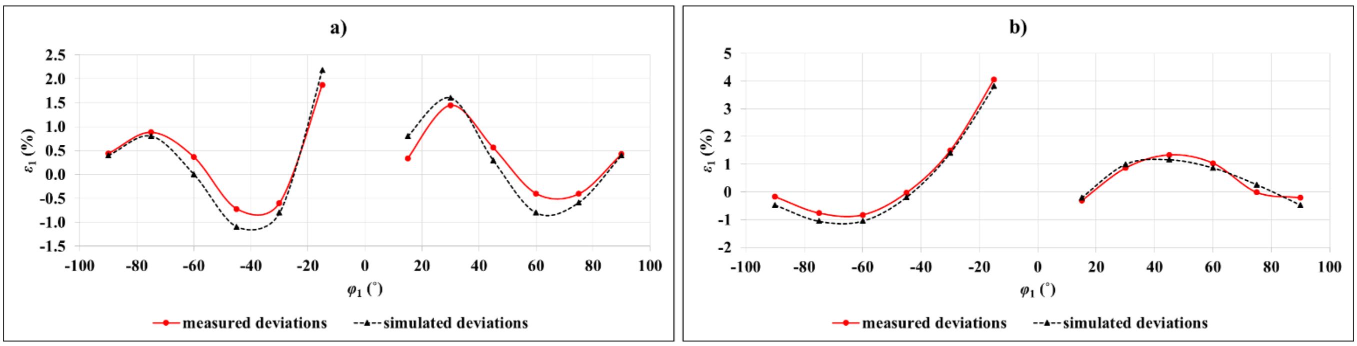

Figure 4. Relative deviations, in (%), between the electricity meter's readings and the reference fundamental reactive power/energy for a) 5H test signals, b) RANDOM test signals.

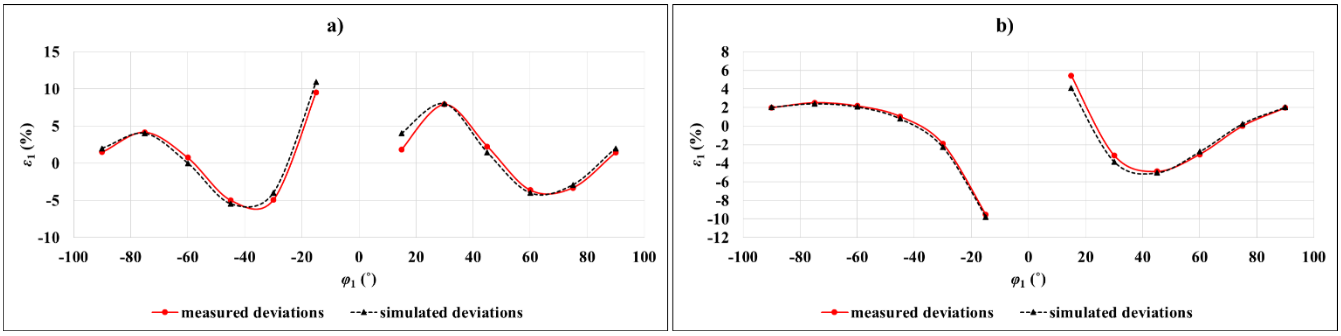

Figure 5. Relative deviations, in (%), between the energy comparator's readings and the reference fundamental reactive power/energy for a) 5H test signals, b) RANDOM test signals.

of the electricity meter [35]. This assumption is validated from both the measured and the simulated deviations, illustrated in Figure 5a), regarding the implementation of the 5H test protocol on the primary RS of LEM [36]. The deviations' magnitudes indicate that instruments based on digital displacement of input signals are not suitable for the measurement of fundamental reactive power. This conclusion is derived from the fact that errors up to several percent are recorded, even in the measurement points that correspond to a significant share of fundamental reactive power in the system, i.e. when φ_1 is between ± 45° and ± 90°. For smaller fundamental phase shifts, the difference between the measured and the reference quantity is even larger, as deviations of up to 12 % are being recorded. This implies that the implementation of a unit based on the digital displacement of input signals for fundamental reactive power/energy monitoring would have significant impact on the appropriate utility billing. The error curves follow a sine-wave pattern of φ_1, with a period 5 times that of the period of the fundamental frequency components. It is important to emphasize that a smaller mismatch between the measured and the mathematically modelled deviations is detected, in comparison to the results in subsection 4.1. This is due to the fact that the RS possesses a higher accuracy class, i.e. smaller intrinsic errors, than both the electricity meter [35] and even the harmonic signals' source [34].

In Figure 5b), the results from the implemented RANDOM test protocol are presented. By using this set of distorted voltages and currents, smaller overall errors are detected in comparison to the 5H test. This occurs because the primary RS [36], according to equation (9), measures some of the odd-harmonic reactive power fractions as they actually flow in the system (harmonic power fractions of order h = 1, 5, and 9 are measured with a positive sign), while the others are recorded opposite to their actual flow in the system (harmonic power fractions of order h = 3 and 7 are recorded with a negative sign). Since these positive and negative contributions in the overall power recorded partially cancel each other out, the total deviation appears smaller. However, the remaining harmonic power still causes a noticeable error, relative to the reference fundamental reactive power, which will eventually affect the utility billing. According to the results, illustrated in Figure 5, it is sufficient to use single harmonic component test waveforms to obtain the maximal meter deviations for a pre-defined THD of the signals.

5. DIRECT COMPARISON BETWEEN METERS BASED ON DIFFERENT MEASURING ALGORITHMS

The analysis presented in Section 4 leads to a conclusion that one must pay attention when selecting a reference unit for the calibration or verification of a meter for reactive power/energy in non-sinusoidal conditions. A direct comparison between two instruments, which are based on different measuring principles, may lead to non-usable calibration results due to the fact that both meters provide different outputs for the same input signals. In this section, the magnitude of errors, obtained from a direct comparison between the readings of the electricity meter [35] and the primary RS [36], will be analysed. The analysis will be conducted by implementing the same test waveforms introduced before. The measurements are going to be performed in the same points regarding different φ_1 values.

If the UUT's measuring principle is based on analogue (phase) displacement of input signals, $Q_{\mathrm{MA,3P}}$, and the reference unit is based on digital (time) displacement of input signals, $Q_{\mathrm{MD,3P}}$, which is an examination scenario that is available for realization in LEM, the errors due to the incompatibility of the measuring algorithms may be mathematically evaluated as follows:

$$\varepsilon_{\mathrm{A-D}} = \frac{Q_{\mathrm{MA,3P}} - Q_{\mathrm{MD,3P}}}{Q_{\mathrm{MD,3P}}} \cdot 100\ \% = \frac{\sum_{h=1}^{n} \frac{3\ U_h\ I_h \sin\varphi_h}{h} - \sum_{h=1}^{n} \pm 3\ \ U_h\ I_h \sin\varphi_h}{\sum_{h=1}^{n} \pm 3\ U_h\ I_h \sin\varphi_h} \cdot 100\ \% = \frac{\sum_{h>1}^{n} U_h\ I_h \left[\frac{\sin\varphi_h}{h} - (\pm\sin\varphi_h)\right]}{\sum_{h=1}^{n} \pm U_h\ I_h \sin\varphi_h} \cdot 100\ \%\,, \quad (12)$$

and it is valid if only odd harmonics are present in input signals. If even harmonics are also present, the harmonic active power fractions, recorded by the reference meter, are also supposed to be taken into consideration. The error is labelled as $\varepsilon_{\mathrm{A-D}}$, emphasizing the measuring algorithms of the UUT and the RS. The different sign of the harmonic power components, measured by the reference instrument, indicate that single error fractions may be modelled using different analytical forms. When odd high-order harmonics of order 3, 7, 11, 15…etc. are regarded, the error fraction will equal:

$$\varepsilon_{\mathrm{A-D},h} = \frac{\frac{h+1}{h}\ U_h\ I_h \sin\varphi_h}{\sum_{h=1}^{n} \pm U_h\ I_h \sin\varphi_h} \cdot 100\ \%\,. \quad (13)$$

When the other odd harmonics are regarded (h = 5, 9, 13, 17…etc.), the error fraction becomes:

$$\varepsilon_{A-D,h} = \frac{\frac{1-h}{h}\ U_h\ I_h \sin\varphi_h}{\sum_{h=1}^{n} \pm U_h\ I_h \sin\varphi_h} \cdot 100\ \%\,. \quad (14)$$

The fundamental reactive power is usually much more significant than the harmonic power fractions, i.e.:

$$U_1\, I_1 \sin\varphi_1 \gg U_h\, I_h \sin\varphi_h\,. \tag{15}$$

Equation (12) then becomes:

$$\begin{aligned}\varepsilon_{\mathrm{A-D}} &\approx \frac{\sum_{h>1}^{n} U_h\, I_h \left[\frac{\sin\varphi_h}{h} - (\pm\sin\varphi_h)\right]}{U_1 I_1 \sin\varphi_1}\cdot 100\ \% \\ &= \sum_{h>1}^{n} \frac{u_{h,\%}}{100}\cdot\frac{i_{h,\%}}{100}\cdot\left[\frac{\frac{\sin\varphi_h}{h} - (\pm\sin\varphi_h)}{\sin\varphi_1}\right]\cdot 100\ \%\,,\end{aligned} \tag{16}$$

meaning that the error fractions, $\varepsilon_{\mathrm{A-D},h}$, are directly proportional to the share of single harmonics in the test signals and inversely proportional to the share of fundamental reactive power in the system. The verification of equations (12)–(16) is performed by direct comparison between the electricity meter's output and the primary RS's recordings. In Figure 6, two error curves are presented. The first is reserved for the measured deviations, while the second for the simulated deviations, by using equations (12)–(14). Both error curves follow the same pattern with a small mismatch due to the intrinsic errors [38] of the UUT [35]. When the 5H test is conducted, a maximal deviation of -8 % is recorded. If the experiment is performed with RANDOM test waveforms, even more significant errors are obtained, up to 15 %, for the lowest share of fundamental reactive power in the system. The deviation magnitudes verify that no applicable calibration or verification results may emerge from a direct comparison between two reactive power/energy instruments in harmonically distorted conditions, if they are based on alternative measuring solutions.

In an opposite situation, where the UUT is an instrument based on the digital displacement of input signals, $Q_{\mathrm{MD,3P}}$, and the reference instrument is based on their phase shifting by 90°, $Q_{\mathrm{MA,3P}}$, the measuring algorithm mismatch errors may be analytically expressed as:

$$\begin{aligned}\varepsilon_{\mathrm{D-A}} &= \frac{Q_{\mathrm{MD,3P}} - Q_{\mathrm{MA,3P}}}{Q_{\mathrm{MA,3P}}}\cdot 100\ \% \\ &= \frac{\sum_{h=1}^{n} \pm 3\, U_h\, I_h \sin\varphi_h - \sum_{h=1}^{n}\frac{3\, U_h\, I_h \sin\varphi_h}{h}}{\sum_{h=1}^{n}\frac{3\, U_h\, I_h \sin\varphi_h}{h}}\cdot 100\ \% \\ &= \frac{\sum_{h>1}^{n} U_h\, I_h\left[(\pm\sin\varphi_h) - \frac{\sin\varphi_h}{h}\right]}{\sum_{h=1}^{n}\frac{U_h\, I_h \sin\varphi_h}{h}}\cdot 100\ \%\,,\end{aligned} \tag{17}$$

an equation which is once again valid if only odd high-order harmonics are regarded. The error in equation (17) is labelled as $\varepsilon_{\mathrm{D-A}}$ to highlight the measuring algorithms of both the UUT and the reference instrument. The error fractions, corresponding to high-order harmonics of different orders, may be evaluated according to the following analytical expressions:

$$\varepsilon_{\mathrm{D-A},h} = -\frac{h+1}{h}\cdot\frac{U_h\, I_h \sin\varphi_h}{\sum_{h=1}^{n}\frac{U_h\, I_h \sin\varphi_h}{h}}\cdot 100\ \%\,, \tag{18}$$

which is valid for harmonics of order h = 3, 7, 11, 15… etc., or alternatively:

$$\varepsilon_{\mathrm{D-A},h} = \frac{h-1}{h}\cdot\frac{U_h\, I_h \sin\varphi_h}{\sum_{h=1}^{n}\frac{U_h\, I_h \sin\varphi_h}{h}}\cdot 100\ \%\,, \tag{19}$$

an expression that is used when harmonics of order h = 5, 9, 13, 17 …etc. are regarded.

If the approximation presented in equation (15) is adopted, which is even more valid in this scenario regarding the conclusions presented in Section 4 and the fact that the reference instrument records the harmonic power fractions divided by their order, equation (17) becomes:

$$\begin{aligned}\varepsilon_{\mathrm{D-A}} &\approx \frac{\sum_{h>1}^{n} U_h\, I_h\left[(\pm\sin\varphi_h) - \frac{\sin\varphi_h}{h}\right]}{U_1\, I_1 \sin\varphi_1}\cdot 100\ \% \\ &= \sum_{h>1}^{n}\frac{u_{h,\%}}{100}\cdot\frac{i_{h,\%}}{100}\cdot\left[\frac{(\pm\sin\varphi_h) - \frac{\sin\varphi_h}{h}}{\sin\varphi_1}\right]\cdot 100\ \%\,.\end{aligned} \tag{20}$$

Equation (20) once again indicates that the single harmonic error fractions are directly proportional to the relative share of the signals' components and inversely proportional to the share of fundamental reactive power in the system.

At LEM's premises, this examination configuration cannot be accomplished, as no reference instrument based on the analogue displacement of input signals with an accuracy class higher than that of the introduced energy comparator [36] is available. Hence, for experimental validation, the results from the previous comparison between the electricity meter [35] and the primary RS of LEM [36] are used, by analytically inversing their readings. The measured relative deviations are obtained as:

$$\varepsilon_{\mathrm{UUT}} = \frac{Q_{\mathrm{UUT}} - Q_{\mathrm{RS}}}{Q_{\mathrm{RS}}}\cdot 100\ \%\,, \tag{21}$$

where Q_{UUT} is the reactive power measured by the electricity meter [35] and Q_{RS} is the reactive power recorded with the energy comparator [36], which may be obtained directly from its display. The actual reactive power, recorded by the electricity meter, is then expressed as:

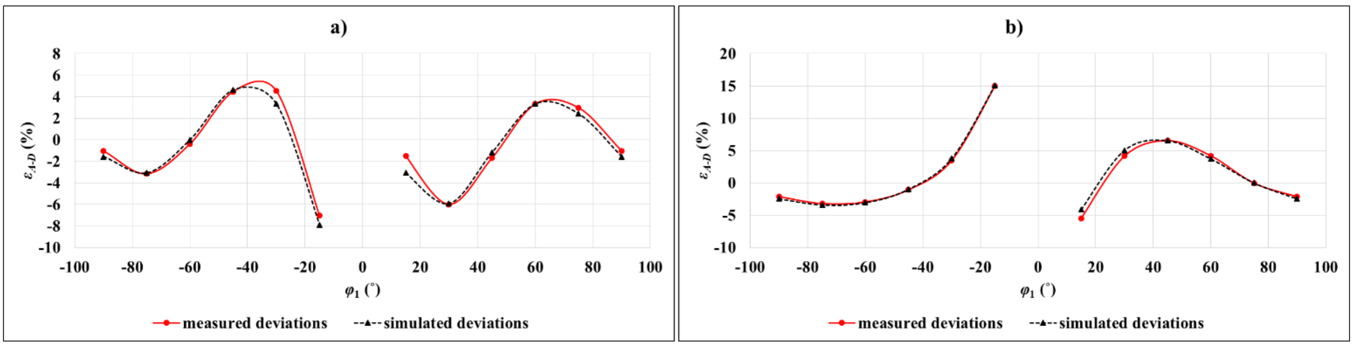

Figure 6. Relative deviations, in (%), between the readings of the electricity meter as a UUT, and the readings of the energy comparator as a reference unit for a) 5H test signals, b) RANDOM test signals.

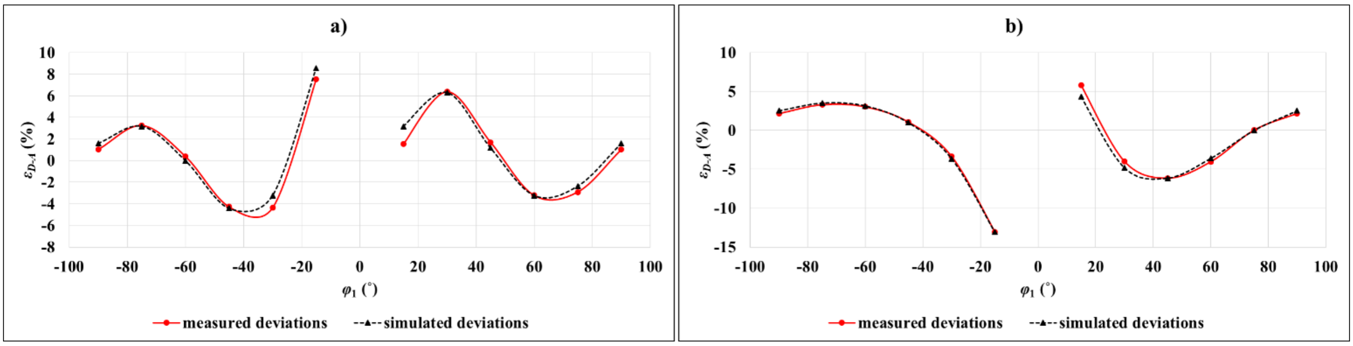

Figure 7. Relative deviations, in (%), between the readings of the energy comparator as a UUT and the readings of the electricity meter as a reference unit for a) 5H test signals, b) RANDOM test signals.

$$Q_{\mathrm{UUT}} = Q_{\mathrm{RS}}\left(1 + \frac{\varepsilon_{\mathrm{UUT}}}{100\ \%}\right). \tag{22}$$

The measuring algorithm mismatch error, obtained from real-time recordings, is then calculated as:

$$\varepsilon_{\mathrm{D-A}} = \frac{Q_{\mathrm{RS}} - Q_{\mathrm{UUT}}}{Q_{\mathrm{UUT}}} \cdot 100\ \%\,. \tag{23}$$

The results are once again presented in the form of two error curves, the first one emerging from the measurement data, transposed according to equations (21)–(23), and the other corresponding to the simulated deviations. The results for the two sets of test signals are presented in Figure 7.

As can be seen from both Figure 7a) and Figure 7b), the error curves appear inversed in comparison to those presented in Figure 6. The measuring algorithm mismatch errors between instruments based on the analogue and digital displacement of input signals have similar magnitudes, yet an opposite sign, for the same distortion of the test waveforms, no matter which instrument is regarded as a reference unit. This conclusion justifies the implementation of the introduced approximation, presented in equation (15). In other words, when THD_{U} is limited to 10 %, and THD_{I} is limited at 40 %, $\varepsilon_{\mathrm{A-D}} \approx -\varepsilon_{\mathrm{D-A}}$. For a higher distortion of the input waveforms, the harmonic power fractions may result in more significant share in relation to the fundamental reactive power. The adopted approximation may then lead to the underestimation or overestimation of the real-time measuring algorithms mismatch error magnitudes.

Both the mathematical modelling of errors and the experimental data provide an important conclusion, which may serve as a general recommendation for calibration laboratories. Namely, when considering the establishment of a calibration or verification protocol in the domain of reactive power/energy instruments in harmonically distorted conditions, a primary attention has to be paid on the determination of the measuring algorithm, implemented in both the UUT and the reference instrument. The actual performance of a meter, i.e. the existence of additional error components due to the influence of the high-order harmonics, may only be detected if both the analysed artefact and the reference standard are based on the same measuring solution.

6. MEASUREMENT UNCERTAINTY

The assessment of the deviations between different meters' readings and the sourced reference fundamental reactive power is supposed to be complemented with an uncertainty analysis. As the selected instrumentation operates according to different measuring algorithms, the measurement uncertainty cannot be evaluated in a unique way. In the discussion that follows, different perspectives will be discussed, depending on whether the evaluated uncertainty is attributed to the sourced fundamental reactive power/energy or the measured reactive power/energy. In both cases, the methodology of uncertainty propagation, presented in the Guide to the expression of uncertainty in measurements – GUM [39], will be implemented.

The uncertainty attributed to the sourced reference fundamental reactive power/energy may be evaluated as standard combined uncertainty [39], regarding two influencing factors. These influencing factors are related to the accuracy of the calibrator [34], $u_{ACC\%}$, and its traceability, i.e. level-up calibration, $u_{CAL,\%}$. The accuracy component is evaluated according to the methodology and the data presented in its specification [34]. The accuracy-related data in [34] is provided in a relative (percentage) form for the amplitude and the initial phase shift of each harmonic component of both voltage and current signals, which may be sourced by the RS. Assuming normal distribution and a coverage interval of 95 %, the standard uncertainty equals:

$$u_{\mathrm{ACC},\%} = \frac{U_{\mathrm{ACC},\%}}{1.96}\,, \tag{24}$$

where $U_{\mathrm{ACC},\%}$ is the calibrator's accuracy, evaluated as presented in [34]. Even though in the experiments, the calibrator provides the fundamental reactive power as a reference, the influence and the presence of high-order harmonics cannot be neglected.

The calibration uncertainty is taken from the certificate, regarding the last calibration performed on the calibrator [34]. In the absence of a value corresponding to non-sinusoidal conditions, as the calibration has been performed with 50 Hz test signals only, the calibration uncertainty related to non-distorted waveforms will be adopted. It is presented as expanded combined uncertainty, $U_{\mathrm{CAL},\%}$, by assuming a normal distribution and a coverage interval of approximately 95 %, hence the coverage factor $k = 2$ is utilised. The standard uncertainty equals:

$$u_{\mathrm{CAL},\%} = \frac{U_{\mathrm{CAL},\%}}{2}\,. \tag{25}$$

The overall uncertainty attributed to the sourced fundamental reactive power/energy in all the measurement points of the previous analysis regarding the two test waveforms, is presented in Table 1. It is evaluated as expanded combined uncertainty, by adopting a normal distribution and coverage interval of approximately 95 %:

Table 1. Uncertainty attributed to the sourced fundamental reactive power.

Fundamental phase shift, φ_1 (°)	Expanded combined uncertainty, $U_{C,\%}$ (%)	
	5H test signals	RANDOM test signals
-90	± 0.081	± 0.068
-75	± 0.086	± 0.08
-60	± 0.1	± 0.098
-45	± 0.18	± 0.1
-30	± 0.15	± 0.24
-15	± 0.57	± 0.52
15	± 0.47	± 0.37
30	± 0.29	± 0.22
45	± 0.13	± 0.17
60	± 0.14	± 0.095
75	± 0.052	± 0.055
90	± 0.081	± 0.068

$$U_{C,\%} = 2 \cdot \sqrt{u_{ACC,\%}^2 + u_{CAL,\%}^2}\,, \tag{26}$$

hence the coverage factor of $k = 2$ is used.

Results presented in Table 1 indicate that the overall uncertainty is strongly dependant on the magnitudes and on the phase shifts of individual harmonics, as well as on the share of fundamental reactive power in the system. More significant overall uncertainties are obtained when the 5H test is applied. This is due to the fact that the harmonic distortion is a result solely on the 5th order harmonics, in contrast to the RANDOM test, where 3rd order harmonics contribute with significant share in the test waveforms. According to [34], the calibrator's accuracy margin expands proportionally to the harmonic order. Exceptions of this pattern are detected, and they may be prescribed to the harmonics' phase shifts alterations. In general, the overall uncertainty increases as the share of reactive power in the system decreases; exceptions are present due to the alteration of harmonics' phase shifts, once again.

The uncertainty attributed to the measured reactive power/energy with the laboratory's primary RS [36] may be evaluated according to the mathematical model, presented in [40]–[41]. It is developed and validated in LEM, primarily in the domain of active power/energy measurements in non-sinusoidal conditions. For the purposes of this analysis, it has been modified according to the algorithm for reactive power recording, presented in equation (9). The model is based on combining multiple influencing factors that affect the measurement of the relative share and the initial phase shift of single high-order harmonics, the RMS of voltage and current signals, and the phase shift between fundamental components. These quantities are regarded as directly measured. The uncertainty transfer toward the reactive power, as an indirectly measured quantity, is later based on the law of uncertainty propagation, covered in GUM [39]. The influencing factors that affect the measurement of the directly recorded quantities emerge from the statistical scattering of single measurements, the resolution, the accuracy specifications, and the level-up calibration of the primary RS [36]. The details regarding the analytical model are presented in [40]–[41].

Table 2. Uncertainty attributed to the measured reactive power with the energy comparator.

Fundamental phase shift, φ_1 (°)	Expanded combined uncertainty, $U_{C,\%}$ (%)	
	5H test signals	RANDOM test signals
-90	± 0.031	± 0.029
-75	± 0.034	± 0.029
-60	± 0.037	± 0.031
-45	± 0.04	± 0.037
-30	± 0.05	± 0.048
-15	± 0.093	± 0.091
15	± 0.088	± 0.084
30	± 0.055	± 0.048
45	± 0.043	± 0.036
60	± 0.035	± 0.033
75	± 0.032	± 0.031
90	± 0.031	± 0.029

In Table 2, the expanded combined uncertainties are presented for the introduced test waveforms and the different fundamental phase shifts. The expanded uncertainties are presented for a coverage interval of approximately 95 %, assuming normal distribution, as there are multiple influencing factors taken into consideration [39]. The overall uncertainty alterations follow a similar pattern to the one already discussed when the calibrator's performance was analyzed. The expanded combined uncertainties attributed to the energy comparator's recordings [36] are however smaller than those attributed to the performance of the calibrator [34]. This is due to the lower base accuracy; the energy comparator [36] is the primary RS of LEM.

The mathematical model presented in [40]–[41] cannot be implemented directly for the uncertainty evaluation of the electricity meter's performance, even if adjustments regarding its measuring algorithm, see equation (8), are applied. This is due to the fact that the electricity meter [35] does not record the harmonics' share and phase shifts as individual signal components. The measurement uncertainty, attributed to its readings, may be adopted to equal $\pm$ 1 % for fundamental phase shifts between $\pm$ 60°and $\pm$ 90°, and up to $\pm$ 4 % for lower fundamental reactive power share in the system. These uncertainty magnitudes are adopted according to the recorded deviations, presented in Section 4. As the meter [35] is compliant to the requirements of the standard IEC 62053-24 [19], the prescribed uncertainty values will be adequate for depicting its performance in relation to the fundamental reactive energy. If the uncertainty budget is about to be complemented with additional influencing factors, a repetition of the experiment with the same or alternative distorted waveforms may be considered. In such a way, the statistical variations of the meter's recordings, as well as contributions regarding the presence of specific harmonic components, may be included in the overall budget.

7. CONCLUSIONS

In the paper, an analysis of the performance of reactive power/energy instruments in non-sinusoidal conditions was performed, with a focus on their suitability for measuring fundamental reactive power in accordance with IEEE 1459. Two instruments, an electricity meter and an energy comparator, based on different measuring algorithms, were regarded.

The analysis was performed by doing mathematical modelling of the instruments' recordings, followed by an experimental verification with test waveforms consisting of both single high-order harmonics and random distortion. The results showed that both instruments follow the predicted deviation pattern, thus confirming their behaviour in non-sinusoidal conditions. The electricity meter, based on the phase displacement of input signals, despite its lower accuracy, provides better results in terms of fundamental power/energy monitoring. In such a way, a compliance with the requirements of the standard IEC 62053-24 has been demonstrated. The energy comparator, based on the time displacement of input signals, is found to be unsuitable for fundamental reactive power measurements, as deviations of up to more than ± 10 % are detected.

According to the later experiment in which the two meters were directly compared, it was found that no calibration procedure may be conducted in the case of distorted waveforms if the UUT and the RS are based on different measuring algorithms. Measuring algorithm mismatch errors of up to ± 15 % were recorded and they were found to be approximately equal, no matter which instrument was regarded as a reference.

From the perspective of uncertainty propagation analysis, it was found that the overall uncertainty attributed to either the sourced power/energy or the measured quantity is strongly correlated with the share and the phase shift of the high-order harmonics. The measurement uncertainty, evaluated according to the proposed mathematical models, generally increases as the share of fundamental reactive power in the system decreases.

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