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Metrology ambiguities and constraints in establishing traceability chain for reactive power/energy instruments' calibration in non-sinusoidal conditions

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***Abstract*— The prevalence of high order harmonics in power systems results in demand for measurement equipment calibration in non-sinusoidal conditions. Establishing a routine examination procedure is challenging, when reactive power/energy instruments are regarded, for two main reasons: their role in the billing of electrical energy and the fact that the term reactive power/energy is not unambiguously defined in case of harmonically distorted signals. Additionally, the existence of multiple measurement algorithms, implemented in different measuring units, results into further complication of the concrete task. These algorithms provide the same result in case of sinusoidal voltages and currents, while in case of harmonics, the instruments' performance may vary significantly, when different power theories are adopted. In the paper, measurements conducted with a reference standard of highest accuracy class available are presented and the obtained measurement errors are further discussed. The obtained results are analyzed regarding the theoretical remarks, derived from the analytical expressions of both the standard's measuring algorithm principle and the different definitions for reactive power/ energy in non-sinusoidal conditions.**

Keywords—reference standard, high order harmonics, measurement error, reactive power theories.

I. INTRODUCTION

The presence of harmonic distortion in voltage and current signals denotes that demands for accurate measurement in power systems, at any voltage level, go beyond the instruments' specifications that refer to reference sine wave conditions. This is especially important in domain of legal metrology, i.e. when electricity meters are regarded, because of their billing role in the regulated trade of electrical energy. According to EU Directive MID 2014/32/EU [1] "all measuring instruments used for commercial transactions" are supposed to measure the quantity of particular interest with error which will not exceed the maximal permissible error, under rated operating conditions. Taking into account the harmonic distortion of both system's voltages and currents, the rated operating conditions, are no longer only pure sinusoidal, but encompass the existence of high order harmonics as well [2]. The maximal permissible error, on the other hand, is supposed to be expanded, for the influence of high order harmonics to be taken into consideration.

In domain of active power/energy meters calibration and testing, several international standards [3-5], a recommendation [2], and plenty of scientific works [6-12] exist, therefore different examination schemes are established. On the other hand, no test procedures are proposed, regarding examination of reactive power/energy meters. The main reason for that is the fact that the term reactive power/energy is not unambiguously defined in harmonically polluted conditions [13-16]. Multiple reactive power theories, in case of non-sinusoidal waveforms exist, each one possessing certain advantages and flaws. The second reason for the lack of standardized calibration procedure existence are the various measuring principles, on which different instruments are based. All of the existing measuring algorithms provide the same result in case of sinusoidal voltages and currents, but the outcome is different in case of harmonically distorted input signals [17-20]. In the standards EN 62053 [21-24] the accuracy demands for reactive electricity meters of different types are presented, but they are limited to sine wave conditions. A progress with understanding and unification of the reactive power/energy measurements was made with publication of the standard IEEE 1459 [25], in which it is stated that the quantity of particular interest for accurate measurement is the fundamental reactive power, Q_1. The main drawback of Q_1 only measurement is that it does not provide equality in terms of billing penalization of distortion producers and consequently, billing compensation of the harmonics' consumers [26].

Taking into account all previously mentioned complications, an effort for decomposing the measurement errors, obtained during calibration of a high accuracy class reference standard (RS) for electrical power and energy will be presented. The recorded errors will be compared with the theoretically calculated values regarding that both the measuring algorithm and the reactive power definition, which are implemented during the test, are known in advance. As no standardized test signals are provided in the cited standards [21-25] and scientific works [17-20], regarding examination of reactive power/energy meters, a starting point for the concrete analysis are going to be the waveforms presented in [5], used for examination of active electricity meters in non-sinusoidal conditions.

II. MATHEMATICAL APPARATUS IN HARMONIC ANALYSIS

A harmonically distorted signal can be mathematically evaluated, in time domain, by using Fourier series as introduced in [27-30]:

$$x(t) = \sqrt{2}\sum_{h=1}^{n} X_h \sin(h\omega t + \alpha_{xh}), \qquad (1)$$

where h is the harmonic order, X_h and α_{xh} are the RMS value and the initial phase shift of the component with a frequency h times the fundamental and n is the maximal harmonic order regarded for practical evaluation. The share of a single harmonic component is commonly expressed as a percentage of the fundamental's RMS value, X_1 [2, 5-6, 12]:

$$x_{h,\%} = \frac{X_h}{X_1} \cdot 100, \qquad (2)$$

while its phase shift is given in relation to the initial phase shift of a 50 Hz voltage or current, at positive zero crossing, α_{x1}:

$$\theta_{xh} = \angle(\alpha_{xh}, \alpha_{x1}). \qquad (3)$$

The single phase active power, in case of harmonically distorted waveforms, is expressed as mean power in a one period time interval of the signals with fundamental frequency [6, 12]:

$$P = \frac{1}{T}\int_0^T u(t)i(t)dt = \sum_{h=1}^{n} P_h = \sum_{h=1}^{n} U_h I_h \cos\varphi_h, \qquad (4)$$

and it equals the algebraic sum of the active power components obtained from the voltages and currents at different frequencies. In (4), U_h and I_h are the RMS values of the voltage and current harmonics of order h. The phase shift between harmonic components of order h, φ_h, equals [12, 31]:

$$\varphi_h = h\varphi_1 + \theta_{ih} - \theta_{uh}, \qquad (5)$$

where φ_1 is the phase shift between current and voltage at fundamental frequency, while θ_{ih} and θ_{uh} are the phase shifts between the h^{th} order current and voltage harmonics and the corresponding components at 50 Hz, (3). In (5), the phase shift between fundamental components, φ_1, is multiplied by the harmonic's order h, because the phasors of harmonic components rotate h times faster than the phasors of U_1 and I_1.

The single phase apparent power equals the product of the voltage and current RMS values, U and I [25, 30]:

$$S = U \cdot I = \sqrt{\sum_{h=1}^{n} U_h^2} \cdot \sqrt{\sum_{h=1}^{n} I_h^2}, \qquad (6)$$

and (4) and (6) may be correlated to principles that are valid for both sinusoidal and harmonically distorted conditions. If the power triangle of P, Q and S, valid for sine wave signals, is taken as a starting point, then the reactive power equals [17-20]:

$$Q = Q_F = \sqrt{S^2 - P^2}, \qquad (7)$$

and this equation derives from the power theory proposed by *Fryze* [14], therefore it will be labeled as *Fryze's* power, Q_F. According to *Fryze* [14], the current signal, $i(t)$, is separated into two components, namely "active" current, $i_a(t)$, which is in phase with the voltage signal, $u(t)$, and possess the same waveform as it, and "non – active" or "reactive" current, $i_r(t)$, which is the remaining part of $i(t)$. The division of the current signal into two components is characterized as a time-domain approach for reactive power clarification [17]. The *Fryze's* power is referred as "non-active" power and can be further expressed as [17, 32]:

$$Q_F = U \cdot I_r, \qquad (8)$$

where I_r is the RMS of the reactive component of the current, and U is the RMS of the distorted voltage signal. Another power definition, regarded in this paper, is the one proposed by *Budeanu* [13]. This power theory is characterized as a frequency-based approach [17], in which the total reactive power is calculated as an algebraic sum of reactive power components, obtained from ideal sinusoidal waveforms at different frequencies:

$$Q = Q_B = \sum_{h=1}^{n} Q_h = \sum_{h=1}^{n} U_h I_h \sin\varphi_h, \qquad (9)$$

and it can be fully compensated by using a simple capacitor [32]. If *Budeanu's* concept [13] for reactive power is adopted, then the remaining power, which exists in the system, beside P and Q_B, is called distortion power, D:

$$D = \sqrt{S^2 - P^2 - Q_B^2}, \qquad (10)$$

and it is a result of the mutual interference of voltages and currents at different frequencies [30, 32-33].

As stated in IEEE 1459 standard [25], a separation principle between fundamental power and high frequency components is suggested. The fundamental reactive power equals:

$$Q_1 = U_1 I_1 \sin\varphi_1, \qquad (11)$$

where U_1 and I_1 are the RMS values of voltage and current at 50 Hz and φ_1 is the phase shift between them.

Beside the concepts proposed by *Budeanu* [13] and *Fryze* [14], which are primary frequency-based and time-based approaches for reactive power determination in harmonically distorted conditions, other power definitions exist as well [17, 32]: *Kusters – Moore*, *Page*, *Shepard – Zakikhani*, *Sharon*, etc. However an instrument's performance in relation to these power definitions is not going to be covered in the practical analysis.

III. Measurement Equipment and Test Procedure

The experimental part of the work is conducted in a laboratory for calibration of instruments and reference standards, accredited according to MKC EN ISO/IEC 17025:2018 [34]. The laboratory is designated as Laboratory for Electrical Measurements (LEM), and it is part of the Faculty of Electrical Engineering and Information Technologies (FEEIT) at Ss. Cyril and Methodius University in Skopje (UKIM). The RSs on LEM's disposal are periodically calibrated and maintain traceability to BIPM [35] intrinsic reference standards. For the purposes of this work, both the primary and the secondary RS of LEM, intended for calibration of instruments for electrical power and energy, will be implemented. The primary RS of LEM, ZERA COM3003 [36], is a three phase power and energy comparator of accuracy class 0.01, and in the concrete examination it will be used as an artefact, whose output is analyzed from the perspective of different reactive power theories. Its measuring principle, when reactive power/energy is regarded, is based on digital time displacement of the input current signals by quarter of a period, in relation to the input voltage signals. According to [17-20], when the input signals are harmonically distorted, the concrete measuring algorithm would provide the following result:

$$Q_M = \frac{1}{N} \sum_{j=m}^{m+(N-1)} u_j \cdot i_{j-(N)/4} = \sum_{h=1}^{n} \pm U_h I_h \sin(\cos)\varphi_h, \quad (12)$$

where u_j and i_j are the voltage and current input signals' samples, taken for averaging in a so called "averaging window", consisting of total N samples. According to [17-20], in (12), the even harmonics' power fractions are detected as active power components, and the odd harmonics power fractions are recorded as reactive power components with different sign, which is dependent on their order, h. If only odd harmonics are regarded, the recorded reactive power, according to the concrete measuring algorithm, is similar to the quantity calculated according to the concept of *Budeanu* [13], while the existence of eventual deviations from it, will be provided along with the presented measurement results.

Laboratory's secondary RS, CALMET C300 [31] is a three phase voltage and current signal source, of accuracy class 0.02, and in the concrete work it will be used as a generator of harmonically distorted test signals. Its output is software controlled, by connecting a hardware unit via USB/RS232 interface. CALMET C300 [31] possesses an option for sourcing reactive power, calculated according to different power definitions, which will be implemented in the analysis that follows. In the further examination the sourced reactive power will be evaluated according to both the concepts provided by *Budeanu* [13] and *Fryze* [14], as well as fundamental reactive power only [25]. The connection of both RSs in a three phase power measurement configuration is illustrated in Fig. 1.

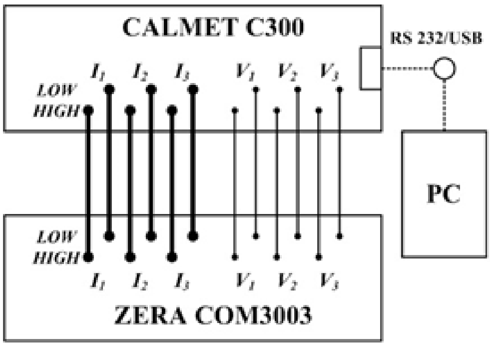

Fig. 1. Connection of ZERA COM3003 and CALMET C300 in three phase power measurement configuration

In the absence of standardized test protocols for examination of reactive power/energy instruments, the distorted voltages and currents, which will be implemented in the practical analysis, are based on the waveforms provided in [5], implemented for active energy meters examination. In the test signals, beside fundamental components, 5th order harmonics are included, with a relative share of 10 %, for the three phase voltages, and 40 %, for the three phase currents. The voltage harmonics are in phase with the voltage fundamentals, at positive zero crossing, i.e. θ_{u5}=0º. The 5th order current harmonics are phase shifted in relation to the current components at 50 Hz, for a phase angle θ_{i5}=60º. The measurements are performed for single RMS values of the test signals only, equaling 230 V and 5 A, and several different fundamental phase shifts, ranging between -90º and -15º (capacitive load) and between 15º and 90º (inductive load), with a step of 15º. Measurements for φ_1=0º are not going to be conducted, because when the generated power is regarded as fundamental reactive power only, the recorded errors will be attributed with a non-defined value. For simplification of the analysis, three phase symmetrical conditions will be regarded. Three phase symmetrical conditions, when the test voltages and currents are harmonically distorted, imply that both the fundamental components of the signals and the high order harmonics, in each phase, possess equal amplitudes and phase shifts.

IV. Test Results and Discussion

The first part of the analysis encompasses a comparison between the primary RS's readings and the fundamental reactive power, Q_1, sourced from the secondary RS, CALMET C300 [31], in the presence of the pre-defined harmonic distortion of the input signals. According to (11) and (12), the error in the recording of the fundamental reactive power with ZERA COM3003 [36], in a general case, when multiple odd harmonics exist in the test signals, equals:

$$\delta_1 = \frac{Q_M - Q_{S,1}}{Q_{S,1}} \cdot 100 = \frac{\sum_{h>1}^{n} \pm 3U_h I_h \sin\varphi'_h}{3U_1 I_1 \sin\varphi_1} \cdot 100 = \\ = \sum_{h>1}^{n} \frac{u_{h,\%}}{100} \cdot \frac{i_{h,\%}}{100} \cdot \frac{\sin\varphi'_h}{\sin\varphi_1} \cdot 100, \quad (13)$$

where, Q_M is the measured three phase reactive power, with the primary RS of LEM [36], as depicted in (12), $Q_{S,1}$ is the sourced three phase fundamental reactive power with the secondary RS of LEM [31], as depicted in (11), while $u_{h,\%}$ and $i_{h,\%}$ are the percentage shares of the harmonic components of order h in voltage and current signals, calculated according to (2). In (13) the phase shift between the measured high order harmonics' voltage and current components is denoted as φ'_h, taking into account the conclusions presented in [12]. According to [12] the phasors of the high order harmonics rotate in opposite direction in relation to the rotation direction of the phasors of fundamental voltages and currents, as recorded from the perspective of any instrument based on digital signal processing. The phase shift φ'_h is mathematically expressed as:

$$\varphi'_h = h\varphi_1 - (\theta_{ih} - \theta_{uh}), \quad (14)$$

which differs from the theoretically evaluated principle presented in (5) and in the specifications of the harmonic source [31]. According to (13) the difference between the measured and the sourced fundamental reactive power is directly proportional to the shares of both the voltage and current harmonics, $u_{h,\%}$ and $i_{h,\%}$, i.e. to their amplitudes (or RMS values), U_h and I_h. On the other hand, the error is inversely proportional to the share of fundamental reactive power in the system, according to a sinusoidal function of φ_1. These theoretical considerations may be validated by using the results from the conducted practical examination, depicted in Fig. 2, as two error curves. The error curve labelled as $\delta_{1,meas}$ represents the recorded differences between the measured and the sourced reactive power. The curve labelled as $\delta_{1,mod}$, represents the mathematically evaluated errors, by using (13). As can be seen from the illustration, the recorded error curve follows the pattern of the analytically obtained deviations. A mismatch between the error values in some measurement points exists due to the additional discrepancy between the sourced and measured signals (for example, the existence of additional measurement and sourcing errors in case of both reference standards) and the inability of the secondary RS [31] to maintain strict three phase symmetrical conditions, in harmonically polluted environment. Results presented in Fig. 2 provide justification of both the assumptions about the measuring algorithm, implemented in ZERA COM3003 [36], and the error intensity change with the alteration of the reactive power share in the system. The deviation between the measured and the sourced fundamental reactive power changes according to a sinusoidal function of φ_1. For greater fundamental phase shifts, i.e. when φ_1 is between ±45º and ±90º, maximal errors of ±6 % are recorded. For lower fundamental reactive power share in the system, an increase in the recorded deviations is detected, which for φ_1=-15º, reach maximal value of approximately 10 %.

In the further discussion, the deviations between the measured three phase reactive power and the sourced three phase reactive power, calculated according to the definition of *Budeanu* [13], will be presented. According to (12) and [17-20], when only odd harmonic components are present in the input signals' spectrums, the measured power will coincide with the reference *Budeanu's* reactive power [13]. That is not the case in practice however, due to two main reasons. The first is the fact that high order harmonics, by the digital signal processing instruments, are recorded as components whose phasors rotate in opposite direction, in relation to the rotation direction of the fundamental voltages and currents. This conclusion is elaborated in details in [12], and it is validated by using the results of the comparison between the measured reactive power and the sourced fundamental reactive power, discussed earlier in the analysis.

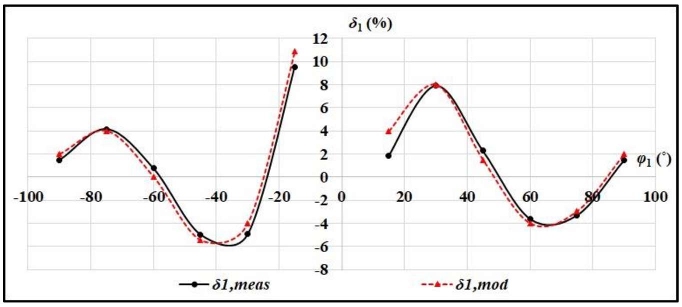

Fig. 2. Relative errors $\delta_1=f(\varphi_1)$ in reactive power measurement with ZERA COM3003, when the reference quantity is the fundamental reactive power, Q_1

Further on, the recorded reactive power components, at different frequencies, possess different sign, as depicted in (12). The sign of the measured reactive power component depends on the harmonic order, *h*. According to [17-20], reactive power components, which exist due to high order harmonics of order: 5, 9, 13, 17, etc; are recorded by the instrument with a positive sign. On the other hand, the reactive power components resulting from the high order harmonics of order: 3, 7, 11, 15, etc; are recorded with a negative sign. Taking into account the measuring algorithm of the primary RS [36], (12), and the theoretical perspective for reactive power evaluation, according to *Budeanu*'s power theory [13], (9), the expected errors may be evaluated as follows:

$$\delta_B = \frac{Q_M - Q_{S,B}}{Q_{S,B}} \cdot 100 = = \frac{\sum_{h>1}^{n} U_h I_h \left(\pm \sin \varphi'_h - \sin \varphi_h\right)}{\sum_{h=1}^{n} U_h I_h \sin \varphi_h} \cdot 100, \tag{15}$$

where $Q_{S,B}$ is the sourced three phase reactive power, presented according to the definition of *Budeanu* [13], therefore the error is denoted as δ_B. In a general case, the error evaluated as in (15), may be decomposed into multiple components, which correspond to high order harmonics of different order, *h*. The error components which are result of high order harmonics of order: 5, 9, 13, 17, etc; may be expressed as:

$$\delta_{B,h} = \frac{-2U_h I_h \cos(h\varphi_1)\sin(\theta_{ih} - \theta_{uh})}{\sum_{h=1}^{n} U_h I_h \sin\varphi_h} \cdot 100, \tag{16}$$

while the error components emerging from the high order harmonics of order: 3, 7, 11, 15 etc; are calculated as follows:

$$\delta_{B,h} = \frac{-2U_h I_h \sin(h\varphi_1)\cos(\theta_{ih} - \theta_{uh})}{\sum_{h=1}^{n} U_h I_h \sin\varphi_h} \cdot 100. \tag{17}$$

Equations (16) and (17) are derived from (15), by using simple trigonometric identities. Considering that only 5^{th} order harmonics are included in the test signals, for mathematical modelling of the expected errors, (16) is adopted. In Fig. 3, analytically evaluated and measured deviations between the recorded and the sourced reactive power are presented, from the perspective of the *Budeanu's* power theory [13].

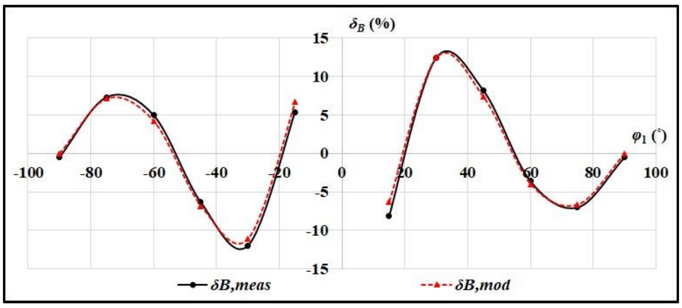

Fig. 3. Relative errors $\delta_B=f(\varphi_1)$ in reactive power measurement with ZERA COM3003, when the reference quantity is the *Budeanu's* reactive power, Q_B

In Fig.3 both the mathematically modeled and the measured deviations are illustrated in the form of error curves, labeled as $\delta_{B,mod}$ and $\delta_{B,meas}$, respectfully. The measurement results follow the pattern of the error curve that is obtained analytically, validating the aforementioned assumptions about the deviation causes, depicted mathematically via (15)-(17). From Fig. 3 it may be concluded that the deviation between the measured and sourced reactive power varies with the alteration of φ_1, according to a sinusoidal mathematical function. The error intensities are smaller, for higher reactive power share in the system, i.e. when φ_1 is greater than ±45º, errors up to 8.2 % are detected. For smaller phase shifts between fundamental components, an increased deviations are recorded, which reach a maximal value of approximately 12.5 %, for φ_1=30º.

The third and final experiment is supposed to provide the error intensities in reactive power measurement with LEM's primary RS [36], if the sourced reference power is evaluated according to the concept of *Fryze* [14]. Taking into account that the *Fryze's* reactive power [14], calculated according to (7) or (8), is referred to as total "non-active" power in the system, the most significant error values are expected, when the RS's [36] performance is compared to the sourced quantity, calculated according to the concrete power theory. The overall deviation between the measured and the sourced reactive power, in such a scenario, is a result of several phenomena, which exist due to the discrepancy between the measurement algorithm (12) and the approach for expression of the reference quantity, (7) and (8). One part of the overall measurement error, exists due to the opposite rotation direction of the high order harmonics' phasors, in relation to the rotation direction of fundamental components, as recorded from the perspective of the measuring unit, [12]. An additional error component may be present due to the opposite flow of the reactive power components, which emerge from the high order harmonics of order: 3, 7, 11, 13, etc; in relation to the way the RS [36] records these fractions of the overall power, as analyzed in the previous discussion. The total error intensity, especially for smaller fundamental phase shifts, is strongly influenced by the existence of the so-called distortion power, (10), which finds place in the total reference "non-active" power, (7).

In Fig. 4 the recorded errors are depicted, regarding the examination of the primary RS [36] with the aforementioned test signals. Taking into account that the sourced power is greater than the measured quantity, the errors are negative in every measurement point. Additionally it may be concluded that the error curve cannot be evaluated in analytical form, by using any simple mathematical function, as was the case in the previous analysis.

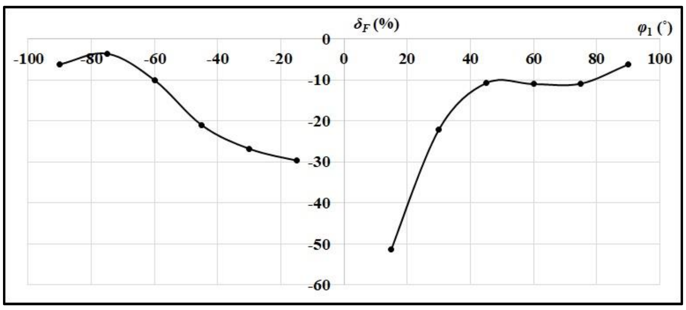

Fig. 4. Relative errors δ_F=$f(\varphi_1)$ in reactive power measurement with ZERA COM3003, when the reference quantity is the *Fryze's* reactive power, Q_F

In case of greater phase shifts between fundamental voltages and currents, i.e. when φ_1 is between ±60º and ±90º, a relatively constant errors are detected, which do not go past -12 %, for the concrete examination scheme setting. For smaller fundamental phase shifts, a significant increase in the measured deviations is recorded and the extreme values are detected in the measurement points that correspond to the lowest reactive power share in the system, for φ_1=±15º. In case of inductive load, the extreme error value exceeds -50 %, while in case of capacitive load, for the concrete setting of the test signals, the maximal error equals approximately -30 %.

V. Conclusions

In the paper a response analysis of a reference standard for electrical power and energy, of the highest accuracy class available, is conducted, when the concrete unit is subjected to harmonically distorted voltages and currents. The quantity on the basis of which RS's performance is analyzed is reactive power, taking into account the metrological ambiguities and constraints for the measurement of the concrete electrical quantity in harmonically distorted conditions. The analysis is based on determination of the perspectives for recording strictly controlled reactive power, evaluated according to different, well known, power definitions.

According to the measuring algorithm of the RS, which is known in advance, its response is tested in respect to the generated fundamental reactive power, in harmonically distorted conditions, as well as in relation to the reference quantity calculated according the principles proposed by *Budeanu* and *Fryze*. Before any examination data is provided, analytical expressions, for error change in respect to different harmonic parameters alteration, are presented. From the practical tests it is concluded that the recorded deviations follow the pattern of the analytically modelled errors, which gives a justification of the theoretical assumptions regarding the recorded quantity, according to the implemented measuring algorithm. Taking into account the intensity of the measured discrepancies and the shape of single error curves, which correspond to different reactive power theories, it may be concluded the concrete RS is neither suitable for recording the fundamental reactive power in harmonically distorted conditions, nor may it be used for direct measurement of the reactive powers, calculated according to definitions of both *Budeanu* and *Fryze*. For different power theories scenarios, the measured error causes are elaborated in detail, by correlating both the theoretical and practical consciousness, as well as the knowledge acquired on the basis of previous research.

Taking into account the results of the conducted analysis it may be concluded that the concrete RS cannot be used directly for establishing and maintaining an unbroken traceability chain, in domain of reactive power/energy measurements, in harmonically distorted conditions. What can be done, on the other hand, is using the concrete RS for measuring the amplitudes and phase shifts of single, both fundamental and high order harmonic, components and thus obtaining the reference value for the measured power, in indirect manner.

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