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Active power measurement uncertainty modelling and propagation analysis in case of harmonically distorted signals

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ABSTRACT
The harmonic distortion of electrical waveforms results in a need for instruments' performance evaluation in non-sinusoidal conditions. Specifications, which are valid for sine-wave input signals, are not supposed to be applied directly for uncertainty determination in case of harmonics, due to the non-linear dependence between the measured quantities and the single harmonic components' magnitudes and phase shifts. Uncertainty calculation is especially challenging in case of power and/or energy measurements, because the corresponding instruments are used for legal metrology purposes i.e. in the regulated trade of electrical energy. The starting point for the concrete evaluation is related to determination of influence factors, which affect the recording of single harmonics' magnitudes and phase shifts. For overall power and/or energy uncertainty calculation, mathematical modelling, based on analytical relations between single harmonic components and the measured quantity, will be performed. A GUM based perspective for uniting single influence factors is implemented and a simplified approach for the correlation coefficients calculation is adopted. The validation of the model, as well as, the uncertainty propagation analysis due to single harmonic components alteration, is backed up by real time measurements, conducted with high accuracy class measurement equipment.

Section: RESEARCH PAPER

Keywords: High order harmonics; reference standard; measurement uncertainty; influence factors

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1. INTRODUCTION

The examination of active power and electricity meters, in case of harmonically distorted voltages and currents, is the main topic in many scientific contributions [1]-[12]. Instruments' performance have been analysed from the perspective of measurement error determination, in relation to different input parameters alteration [1]-[6], or in relation to the measurement algorithm implemented in the Unit Under Test (UUT) [7]-[8]. Different examination protocols are established by implementing both test waveforms proposed in international standards and recommendations [13]-[16], as well as by using randomly distorted voltages and currents [1]-[6].

In [1], beside the error intensity analysis, an evaluation of measurement uncertainty, in active energy electricity meter examination protocol, is presented. The overall uncertainty is presented as combined uncertainty [17], calculated from 2 mutually uncorrelated components. The first component is evaluated as Type A uncertainty and it exists due to statistical scattering of single readings around the mean value. The second influence factor, which contributes to the overall budget, is related to the performance of the Reference Standard (RS), used for providing the reference signals in non-sinusoidal conditions. The concrete uncertainty component is evaluated as Type B uncertainty, without further details about its propagation due to different signals' parameters alteration.

Another perspective for active power measurement uncertainty calculation, in case of harmonically distorted voltages and currents, is presented in [2]. The overall uncertainty is decomposed into multiple, mutually uncorrelated, components, attributed to active power fractions, obtained from signals' components that possess different frequencies. The uncertainty attributed to active power, which corresponds to a single order voltage and current harmonics, is further decomposed into 3 components, related to the voltage, current and phase shift measurement. In the concrete approach,no additional information about the influence factors that affect the recording of the aforementioned quantities are given.

In the following contribution, an original mathematical model for active power/energy measurement uncertainty calculation, will be presented. The uncertainty attributed to the measured quantity is calculated starting from the determination of single influence factors that affect the recording of both fundamental and high order harmonic voltages and currents and their phase shifts. Single influence factors are put together, in order for the uncertainty of the concrete signal parameter to be mathematically evaluated. By using basic equations, referring to different quantities in harmonically polluted environment, sensitivity coefficients are determined, which are later used for uncertainty components transfer, up to the measured active power value.

In the end, an experimental validation of the mathematical model and an analysis of the uncertainty propagation will be presented. The validation is conducted in an accredited calibration laboratory, according to standard MKC EN ISO/IEC 17025:2018 [18], by using high accuracy class measurement equipment. An analysis of the uncertainty propagation will follow, and it is going to encompass alteration of different, both fundamental and harmonic, signals' parameters.

2. BASIC MATHS IN HARMONIC ANALYSIS

A voltage or current signal, which beside the component with a frequency of 50 Hz, possess high order harmonics, may be evaluated, in time domain, by using Fourier series, as [19]-[22]:

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

where, X_h is the RMS of the harmonic component of order h, α_{xh} is its initial phase shift, ω is the fundamental angular frequency, and n is the maximal harmonic order taken into consideration. For practical analysis, it is more convenient the signal to be decomposed in frequency domain. According to standard EN 50160 [23], the share of a single harmonic is presented in relative form, in relation to the fundamental component's magnitude, X_1:

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

while the RMS of the signal is calculated as [19], [24]:

$$X = \sqrt{\sum_{h=1}^{n} X_h^2}\,. \tag{3}$$

For quantification of the harmonic distortion, the parameter named Total Harmonic Distortion, abbreviated as *THD*, is used and if (2) is taken into account, it can be expressed as follows [19], [21], [24]:

$$THD = \sqrt{\frac{\sum_{h=2}^{n} X_h^2}{X_1^2}}\cdot 100 = \sqrt{\sum_{h=2}^{n} x_{h,\%}^2} \tag{4}$$

If the RMS of the signal, X, calculated according to (3), the shares of single components, $x_{h,\%}$, calculated according to (2), and the *THD*, calculated according to (4), are known, the RMS of the voltage or current fundamental may be expressed as:

$$X_1 = \frac{X}{\sqrt{1+\left(\frac{THD}{100}\right)^2}}\,. \tag{5}$$

The phase shift of a single harmonic is usually presented in relation to the initial phase shift of the signal's fundamental, α_{x1}, at positive zero crossing [20]:

$$\theta_{xh} = \angle(\alpha_{xh}, \alpha_{x1})\,. \tag{6}$$

In order for the active power to be calculated, the phase shifts, between any voltage and current harmonics of the same order, are supposed to be determined [25]:

$$\varphi_h = h\,\varphi_1 + (\theta_{ih} - \theta_{vh})\,, \tag{7}$$

where θ_{vh} is the initial phase shift between the voltage harmonic of order h and the voltage fundamental, θ_{ih} is the initial phase shift between the current harmonic of order h and the current fundamental and φ_1 is the phase shift between V_1 and I_1. In (7), the fundamental phase shift, φ_1, is multiplied by the harmonic order h, due to the fact that the phasors of high order harmonics rotate with angular velocity that is h times higher than the angular velocity of the 50 Hz components.

The single phase active power is calculated as mean power during the period T, *[21]*, [24]:

$$P_{\mathrm{L}} = \frac{1}{T}\int_0^T v(t)\,i(t)\,dt = \sum_{h=1}^{n} V_h\,I_h\,\cos\varphi_h = \sum_{h=1}^{n} P_h\,. \tag{8}$$

It equals the algebraic sum of active power components, P_h, obtained from voltages and currents at different frequencies. In (8), V_h and I_h are the RMS values of the voltage and current harmonics of order h and they may be evaluated if the percentage shares, $v_{h,\%}$ and $i_{h,\%}$, and the fundamentals, V_1 and I_1, are known. The three phase active power, in a general case, is calculated as:

$$P = P_{\mathrm{L1}} + P_{\mathrm{L2}} + P_{\mathrm{L3}}\,, \tag{9}$$

where P_{L1}, P_{L2} and P_{L3} are single phase active powers calculated according to (8). If the system is symmetrical, the three phase active power is obtained by multiplying (8) with a factor of 3 [19]. It is important to be emphasized however, that a symmetrical system in harmonically polluted environment implies the presence of exactly the same harmonic components in every line voltage and current and that these components possess equal share and phase shift in relation to fundamentals.

3. MEASUREMENT EQUIPMENT AND PROCEDURE

The practical part of the analysis is conducted in an accredited calibration laboratory [18], called Laboratory for Electrical Measurements (LEM). The concrete laboratory is part of the Faculty of Electrical Engineering and Information Technologies (FEEIT), at Ss. Cyril and Methodius University in Skopje (UKIM). In its possession there are two reference standards, traceable to intrinsic standards of BIPM [26], in domain of electrical power and energy instruments calibration. The three phase power and energy comparator of accuracy class 0.01, ZERA COM3003 [27], is the primary RS of the laboratory. In the concrete evaluation, the primary RS of LEM will be used as a measuring instrument on which, the mathematical model for active power uncertainty propagation in non-sinusoidal

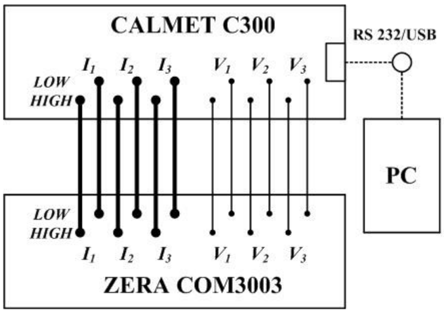

Figure 1. Connection of the LEM's reference standards in three phase active power measurement configuration

condition, will be validated. The concrete measuring unit, apart from the regime for direct measurement of the three phase active power, possess options for power quality recording as well, i.e. for measurement of single harmonics' share and phase shift. Laboratory's secondary standard, CALMET C300 [25], which is three phase voltage and current generator of accuracy class 0.02, will be used as a source of harmonically distorted voltages and currents. This RS is software controlled and it is operated by a hardware unit that is connected to the standard itself via RS232/USB interface. The connection scheme for three phase active power measurements is illustrated in Figure 1.

During the measurements, the primary RS, ZERA COM3003 [27], will be set for recording in both three phase actual values measurement mode and harmonic measurement mode, simultaneously. By using the actual values measurement regime, the RMS values of the three phase voltage and current signals, as well as the fundamental phase shifts, will be recorded. By using the harmonic measurement regime, the share and the phase shift of every single harmonic will be obtained, for the same distorted signals, generated by the secondary RS [25]. The active power is not going to be measured directly, yet it will be calculated analytically, by using (2)-(9), because of two main reasons. The first one is related to the measuring algorithm of the primary RS [27] for active power recording, according to which the high order harmonics are regarded as components that rotate in opposite direction in respect to fundamental components. The concrete statement is documented in [3]. The second reason for not measuring the active power directly is related to the main subject of the concrete work, namely the mathematical modelling of the measurement uncertainty. As stated in the introduction, the overall uncertainty attributed to the measured power, will be calculated by determination of single influence factors related to the recording of different, both fundamental and harmonic, signals' parameters. From equations (2)-(9) sensitivity coefficients are obtained as well, which are used for uncertainty transfer between different signals' parameters. The overall uncertainty, attributed to the indirectly measured active power, will be presented as expanded combined uncertainty, assuming the principles presented in [17].

4. MEASUREMENT UNCERTAINTY MODELLING

4.1. Combined uncertainty of directly measured quantities

The first step in the mathematical modelling of the measurement uncertainty is determination of all influence factors that affect the measurement process. These influence factors are supposed to be analytically expressed as standard uncertainty components, attributed to the signals' parameters or quantities that are measured directly.

According to the proposed measurement protocol, the following quantities are going to be recorded directly:

1) RMS values of the three phase voltage and current signals, V and I;
2) Phase shift between fundamental components, φ_1;
3) Single voltage harmonics' share and phase shift, $v_{h,\%}$ and θ_{vh};
4) Single current harmonics' share and phase shift, $i_{h,\%}$ and θ_{ih}.

The uncertainty attributed to any of the directly measured quantities comprises of 4 mutually uncorrelated components, and it may be calculated as follows:

$$u_{\mathrm{C,Y}} = \sqrt{u_{A,Y}^2 + u_{R,Y}^2 + u_{SP,Y}^2 + u_{CL,Y}^2} \tag{10}$$

where the single components will be addressed in the discussion that follows, while the index Y denotes the quantity to which the concrete uncertainty component is attributed. The first two uncertainty components presented in (10), $u_{\mathrm{A,Y}}$ and $u_{\mathrm{R,Y}}$, are mathematically evaluated in a unique manner, no matter the signals' parameter regarded. The uncertainty component $u_{\mathrm{A,Y}}$ is calculated according to Type A evaluation principle [17] and it is a result of the statistical scattering of measurement data, if multiple, N, recordings for any signal parameter are conducted:

$$u_{A,Y} = \sqrt{\frac{1}{N(N-1)}\sum_{i=1}^{N}(Y_i - Y_M)^2}\,, \tag{11}$$

where Y_i are the single readings of the quantity Y and Y_M is the mean value obtained from N recordings. The Type A related uncertainty is calculated by adopting Gaussian or t-distribution, assuming that every single recording may possess random value around the mean, with a specific degree of probability.

The second uncertainty component presented in (10) is related to the instrument's finite resolution, R, in domain of concrete quantity recoding. The resolution related standard uncertainty component is calculated as follows:

$$u_{\mathrm{R,Y}} = \frac{R}{2 \cdot k_{\mathrm{R}}} \tag{12}$$

and it is obtained by adopting rectangular (uniform) distribution, therefore the coefficient k_{R}, is taken as $\sqrt{3}$, [17]. The rectangular distribution is adopted because it is assumed that a single reading, Y_i, may actually possess any value within the interval of a plus/minus half resolution around the measured value, with the same degree of probability. For the primary RS of LEM [27], the resolution when voltage and current RMS values are recorded varies with the alteration of the measurement ranges. On the other hand, when harmonic components' share and phase shift are recorded, R is constant and it equals 0.01 % and 0.01°, respectively.

The remaining two uncertainty components, $u_{\mathrm{SP,Y}}$ and $u_{\mathrm{CL,Y}}$, refer to the specification of the instrument and its level up calibration. These two components are calculated differently, when different signal parameters are regarded.

4.1.1. Combined uncertainty of harmonic share measurement

For single harmonic share measurement, the instrument's specification related uncertainty may be evaluated as combined uncertainty of two mutually correlated components, $u_{\mathrm{SP},X1}$ and $u_{\mathrm{SP},Xh}$:

$$u_{\mathrm{SP,Y}} = u_{\mathrm{SP},xh\%} = \left\{\left|\frac{\partial x_{h,\%}}{\partial X_1} u_{\mathrm{SP},X1}\right| + \left|\frac{\partial x_{h,\%}}{\partial X_h} u_{\mathrm{SP},Xh}\right|\right\}, \qquad (13)$$

which are attributed to the instrument's capabilities of measuring RMS values of both fundamental and h^{th} order harmonic components. The uncertainties $u_{\mathrm{SP},X1}$ and $u_{\mathrm{SP},Xh}$ are treated as mutually correlated, due to the fact that the alteration of the harmonic share will result in alteration of fundamental's value for the same RMS value of the signals. The analytical representation of the concrete components depends on the instructions provided in the instrument's datasheet.

For the primary RS of LEM [27], any of these 2 uncertainties is comprised of 3 additional mutually uncorrelated components:

$$u_{\mathrm{SP},Xh} = \sqrt{u_{\mathrm{AC},Xh}^2 + u_{\mathrm{ST},Xh}^2 + u_{\mathrm{T},Xh}^2} \qquad (14)$$

referring to the declared accuracy limits, $u_{\mathrm{AC},Xh}$, long term stability, $u_{\mathrm{ST},Xh}$, and temperature influence on meter's performance, $u_{\mathrm{T},Xh}$. The standard uncertainties in (14), are evaluated by assuming rectangular distribution:

$$u_{\mathrm{AC},Xh} = \frac{U_{\mathrm{AC},\%}}{k_{\mathrm{RS}}} \cdot \frac{X_h}{100} \cdot h\,, \qquad (15)$$

$$u_{\mathrm{ST},Xh} = \frac{U_{\mathrm{ST},\%}}{k_{\mathrm{RS}}} \cdot \frac{X_h}{100} \cdot y \cdot h\,, \qquad (16)$$

$$u_{\mathrm{T},Xh} = \frac{U_{\mathrm{T},\%}}{k_{\mathrm{RS}}} \cdot \frac{X_h}{100} \cdot \Delta t \cdot h \qquad (17)$$

and therefore the coefficient used for their calculation from the data presented in standard's specification [27], k_{RS}, equals $\sqrt{3}$, [17]. In (15)-(17) $U_{\mathrm{AC},\%}$, $U_{\mathrm{ST},\%}$ and $U_{\mathrm{T},\%}$ are accuracy, long term stability and temperature influence related data presented in percentage form, obtained from the standard's specifications [27], while h is the harmonic order. The parameter y in (16), resembles the time elapsed since the last calibration of the RS, and it is expressed on yearly basis. In (17) Δt is a parameter that depicts the temperature fluctuations at the measurement site. Equations (14)-(17) refer to $u_{\mathrm{SP},Xh}$ calculation. In order for $u_{\mathrm{SP},X1}$ to be evaluated, the same mathematical apparatus is supposed to be adopted, while X_h is substituted with X_1 and h is taken as unity. If equations (14)-(17) are expressed for both X_h and X_1 and are substituted in (13), and the sensitivity coefficients $\partial x_{h,\%}/\partial X_1$ and $\partial x_{h,\%}/\partial X_h$ are calculated from (2), the specification related uncertainty, attributed to a specific harmonic share measurement may be expressed as follows:

$$u_{\mathrm{SP},xh\%} = \frac{x_{h,\%}}{100} \cdot (1+h) \cdot C\,, \qquad (18)$$

where C is a constant dependant only on the data presented in meter's specifications. For the primary RS of LEM [27], C is presented as:

$$C = \frac{1}{k_{\mathrm{RS}}} \sqrt{\left(U_{\mathrm{AC},\%}\right)^2 + \left(U_{\mathrm{ST},\%} \cdot y\right)^2 + \left(U_{\mathrm{T},\%} \cdot \Delta t\right)^2}\,. \qquad (19)$$

For analytical expression of the uncertainty component, related to the level up calibration of the instrument, (13) is used once again, hence $u_{\mathrm{SP},X1}$ and $u_{\mathrm{SP},Xh}$ are substituted with calibration related components, $u_{\mathrm{CL},X1}$ and $u_{\mathrm{CL},Xh}$, respectively. The level up calibration uncertainty component of the voltage or current high order harmonic RMS value, X_h, is calculated as:

$$u_{\mathrm{CL},Xh} = \frac{U_{\mathrm{CL},\%}}{k_{\mathrm{CL}}} \cdot \frac{X_h}{100} \cdot h\,, \qquad (20)$$

where $U_{\mathrm{CL},\%}$ is the relative expanded uncertainty presented in calibration certificate and k_{CL} is a coverage factor which is related to the adopted distribution. In calibration certificates, the expanded uncertainty is usually presented by adopting Gaussian distribution, with declared probability of 95 % or 95.4 %. In such a scenario k_{CL}, equals either 1.96 or 2. The level up calibration uncertainty, related to fundamental voltage or current measurement, is calculated by substituting X_1 for X_h in (20) and taking the harmonic order coefficient, h, as unity. If (20) is expressed for both X_1 and X_h, and the obtained relations are substituted in (13), the calibration uncertainty in case of harmonic share measurement equals:

$$u_{\mathrm{CL},xh\%} = \frac{x_{h,\%}}{100} \cdot (1+h) \cdot \frac{U_{\mathrm{CL},\%}}{k_{\mathrm{CL}}}. \qquad (21)$$

4.1.2. Combined uncertainty of signals' RMS value measurement

The meter's specification related uncertainty, attributed to voltage or current RMS value measurement, is calculated directly from the data presented in its datasheet. In case of LEM's primary RS [27], the concrete component is evaluated as standard combined uncertainty of 3 mutually uncorrelated components, referring to its declared accuracy limits, $u_{\mathrm{AC},X}$, long term stability, $u_{\mathrm{ST},X}$, and temperature fluctuations influence, $u_{\mathrm{T},X}$:

$$u_{\mathrm{SP},X} = \sqrt{u_{\mathrm{AC},X}^2 + u_{\mathrm{ST},X}^2 + u_{\mathrm{T},X}^2}\,, \qquad (22)$$

where the single uncertainty components are calculated as depicted in (15)-(17), by substituting the measured RMS value, X, for X_h, and by taking the harmonic order coefficient, h, as unity. The level up calibration component is calculated as:

$$u_{\mathrm{CL},X} = \frac{U_{\mathrm{CL},\%}}{k_{\mathrm{CL}}} \cdot \frac{X}{100}\,, \qquad (23)$$

where the coverage factor, k_{CL}, is dependent on the adopted distribution and the confidence interval, as discussed in 4.1.1.

4.1.3. Combined uncertainty of phase shift measurements

The specification and level up calibration related uncertainty components, attributed to phase shift measurements, $u_{\mathrm{SP},\theta h}$ and $u_{\mathrm{CL},\theta h}$, are calculated in a unique manner, if the analysis is conducted on both high order harmonics' phase shifts in relation to fundamentals, θ_{vh} and θ_{ih}, or on the phase shift between fundamentals, φ_1. The concrete two components are evaluated in a way dictated by the manufacturer's manual and the instrument's calibration certificate. When calculating the measurement uncertainty of the laboratory's primary RS [27], the specification related component is presented as:

$$u_{\mathrm{SP},\theta h} = \frac{U_{\mathrm{SP},\alpha}}{k_{\mathrm{RS}}} \cdot h\,, \qquad (24)$$

where $U_{\mathrm{SP},\alpha}$ is the expanded uncertainty related to phase shift measurements, presented in absolute form, and k_{RS} possesses the same meaning and value as described above. Because the concrete instrument has not been calibrated in phase shift measurement regime, (24) is adopted for calibration uncertainty calculation as well. For $u_{\mathrm{CL},\theta h}$ expression, $U_{\mathrm{SP},\alpha}$ is substituted with the corresponding parameter from the specification of the standard, used as a reference instrument during the calibration of the concrete ZERA COM3003 unit. The coefficient k_{RS} possesses a value dictated by the distribution adopted for depicting the specification data of the used standard. Equation (24) is expressed for high order harmonics phase shift measurements, θ_{vh} and θ_{ih}. In order for the corresponding uncertainties of φ_1 to be determined, h is supposed to be regarded as unity.

4.2. Uncertainty attributed to mathematically derived signals' parameters

The combined measurement uncertainties, attributed to the quantities that are measured directly, may be further used for calculation of the uncertainties related to analytically derived signals' parameters. The uncertainties attributed to single voltage and current harmonic share measurement may be used for determination of the overall uncertainty related to signals' *THD* calculation. The *THD* related uncertainty is calculated as standard combined uncertainty from $n-1$ uncorrelated components, n being the number of high order harmonics present in the signal's waveform:

$$u_{\mathrm{THD}} = \sqrt{\sum_{h=2}^{n} \left(\frac{\partial THD}{\partial x_{h,\%}} \cdot u_{\mathrm{C},xh\%} \right)^2} \,. \tag{25}$$

The single components $u_{\mathrm{C},xh\%}$ are evaluated according to (10) and the discussion presented in 4.1.1, while the sensitivity coefficients $\partial THD/\partial x_{h,\%}$ are calculated according to (4). If the substitutions are made, (25) becomes:

$$u_{\mathrm{THD}} = \frac{1}{THD} \sqrt{\sum_{h=2}^{n} \left(x_{h,\%} \cdot u_{\mathrm{C},xh\%} \right)^2} \,. \tag{26}$$

The Total Harmonic Distortion uncertainty, together with the uncertainty attributed to voltage or current RMS value measurement may be used for determination of the uncertainty related to the fundamental's value calculation. As X and THD are measured independently, the uncertainty prescribed to X_1 is obtained as combined uncertainty from the 2 mutually uncorrelated components:

$$u_{\mathrm{C},X1} = \sqrt{\left(\frac{\partial X_1}{\partial X} u_{\mathrm{C},X} \right)^2 + \left(\frac{\partial X_1}{\partial THD} u_{\mathrm{THD}} \right)^2} \tag{27}$$

where $u_{\mathrm{C},X}$ is evaluated according to (10) and the conclusions presented in 4.1.2, u_{THD} is calculated according to (25)-(26) and the partial derivatives $\partial X_1/\partial X$ and $\partial X_1/\partial THD$ are determined from (5).

The next uncertainty component is attributed to the calculated RMS value of the harmonic component of order h. Its magnitude is obtained from the uncertainties related to both harmonic share measurement and fundamental's value calculation:

$$u_{\mathrm{C},Xh} = \left\{ \left| \frac{\partial X_h}{\partial X_1} u_{\mathrm{C},X1} \right| + \left| \frac{\partial X_h}{\partial x_{h,\%}} u_{\mathrm{C},xh\%} \right| \right\} , \tag{28}$$

where $u_{\mathrm{C},X1}$ is calculated according to (27) and $u_{\mathrm{C},xh\%}$ is mathematically evaluated by using (10) and by adopting the conclusions derived in the 4.1.1 subsection. The two components are regarded as fully correlated, as described before. The sensitivity coefficients $\partial X_h/\partial X_1$ and $\partial X_h/\partial x_{h,\%}$ are derived from (2).

From the combined uncertainties, attributed to the phase shifts that are measured directly, $u_{\mathrm{C},\varphi 1}$, $u_{\mathrm{C},\theta vh}$ and $u_{\mathrm{C},\theta ih}$, the uncertainty related to the calculated phase shift between voltage and current of harmonic order h, φ_h, may be determined. As φ_1, θ_{vh} and θ_{ih} are measured independently, the uncertainty prescribed to φ_h will be expressed as standard combined uncertainty from 3 mutually uncorrelated components:

$$u_{\mathrm{C},\varphi h} = \sqrt{\left(\frac{\partial \varphi_h}{\partial \varphi_1} u_{\mathrm{C},\varphi 1} \right)^2 + \left(\frac{\partial \varphi_h}{\partial \theta_{vh}} u_{\mathrm{C},\theta vh} \right)^2 + \left(\frac{\partial \varphi_h}{\partial \theta_{ih}} u_{\mathrm{C},\theta ih} \right)^2} \,, \tag{29}$$

where, for evaluation of $u_{\mathrm{C},\varphi 1}$, $u_{\mathrm{C},\theta vh}$ and $u_{\mathrm{C},\theta ih}$, the conclusions presented in the 4.1.3 subsection and (10) are implemented. The partial derivatives, $\partial \varphi_h/\partial \varphi_1$, $\partial \varphi_h/\partial \theta_{vh}$ and $\partial \varphi_h/\partial \theta_{ih}$, are mathematically expressed from (7). The combined standard uncertainty obtained according to (29) is further utilized for evaluation of the uncertainty related to the power factor of the h^{th} order harmonics:

$$u_{\mathrm{C},PFh} = \left| \frac{\cos\left(\varphi_h + k_{\phi h} \cdot u_{\mathrm{C},\varphi h} \right) - \cos \varphi_h}{k_{\varphi h}} \right| , \tag{30}$$

where the value of the coverage factor, $k_{\varphi h}$, is strictly related to the distribution adopted for depicting $u_{\mathrm{C},\varphi h}$. As $u_{\mathrm{C},\varphi h}$ is calculated from 3 mutually uncorrelated components, each of them obtained according to (10) and the conclusions presented in the 4.1.3 subsection, the distribution adopted for its evaluation may be regarded as Gaussian, no matter which distributions are adopted for expression of the single uncertainty components in (10) and (29). The concrete statement is backed up by the Central Limit Theorem [17], according to which the overall distribution in indirectly measured quantity tends to become Gasussian, if multiple influence factors are regarded, nevertheless which distributions are prescribed for their determination. If the concrete conclusion is adopted, and a confidence interval of 95.4 % is regarded, then the coverage factor $k_{\varphi h}$ equals 2.

The uncertainty attributed to the calculated active power, which corresponds to voltage and current harmonics of order h, P_h, is evaluated as standard combined uncertainty from 3 mutually uncorrelated components. These components are related to the calculated RMS values of the high order voltage and current harmonics and the corresponding power factor:

$$u_{\mathrm{C},Ph} = \sqrt{\left(\frac{\partial P_h}{\partial V_h} u_{\mathrm{C},Vh} \right)^2 + \left(\frac{\partial P_h}{\partial I_h} u_{\mathrm{C},Ih} \right)^2 + \left(\frac{\partial P_h}{\partial \cos \varphi_h} u_{\mathrm{C},PFh} \right)^2} \,, \tag{31}$$

where $u_{\mathrm{C},Vh}$ and $u_{\mathrm{C},Ih}$ are evaluated according to (28) and $u_{\mathrm{C},PFh}$ is obtained by using (30). The sensitivity coefficients $\partial P_h/\partial V_h$, $\partial P_h/\partial I_h$ and $\partial P_h/\partial \cos \varphi_h$ are calculated according to (8). For calculation of the uncertainty attributed to the fundamental active power, P_1, the uncertainty components related to voltage and current fundamentals, $u_{\mathrm{C},V1}$ and $u_{\mathrm{C},I1}$, are evaluated by using (27).

The overall single phase active power measurement uncertainty is computed by superposition of single harmonic active power uncertainty components. The single components $u_{\mathrm{C},Ph}$ are treated as mutually correlated due to the fact that the voltages and currents at different frequencies are bound via the fundamentals' magnitudes and the RMS of the signals. Additionally, the phase shifts between voltage and current harmonics of the same order are related via the fundamental phase shift, φ_1, (7). Taking the concrete conclusions into account the overall, expanded, active power measurement uncertainty is evaluated as:

$$U_{\mathrm{C},PL} = k_{\mathrm{P}} \cdot \sum_{h=1}^{n} \left| u_{\mathrm{C},Ph} \right| \qquad (32)$$

and its value is obtained by assuming Gaussian distribution and a confidence interval of approximately 95.4 %, therefore the coverage factor k_{P} is taken as 2. The three phase active power expanded uncertainty, $U_{\mathrm{C},P}$, is calculated as an algebraic sum of the $U_{\mathrm{C},PL}$ values for all three phases:

$$U_{\mathrm{C},P} = \left\{ \left| U_{\mathrm{C},PL1} \right| + \left| U_{\mathrm{C},PL2} \right| + \left| U_{\mathrm{C},PL3} \right| \right\}. \qquad (33)$$

5. PRACTICAL VALIDATION OF THE MATHEMATICAL MODEL

In the practical part of the work, the presented analytical model will be validated, by real time measurements conducted with laboratory's primary RS [27]. The tests are performed in three phase symmetrical conditions. The test voltages and currents possess only odd harmonics up to 11th order, their share and phase shift are presented in Table 1. A limitation of the *THD* is applied [15], equalling 10 % for voltage signals and 40 % for current signals. Measurements are conducted in multiple measurement points, each one corresponding to a different φ_1 value, ranging between -60° and 60°, with a step of 15°. The RMS of the test signals equal 230 V and 5 A.

In Table 2, the magnitudes of different uncertainty components, in voltage and current harmonic share recording, are presented. The concrete measurement point, for which the propagation of single influence factors is illustrated, refers to a scenario, where the voltage and current fundamentals are mutually in phase, i.e. $\varphi_1 = 0°$. As can be seen from Table 2, in case of voltage harmonic share measurement, the highest uncertainty component is related to the RS's finite resolution. The resolution as an influence factor dominantly shape the overall budget, especially for higher order harmonics, due to their low share in the voltage waveform. For lower frequency components, i.e. in case of 3rd and 5th order harmonics measurement, the level up calibration possesses an equal order of magnitude value as $u_{\mathrm{R},vh\%}$. In the concrete measurement point, no fluctuations in the readings, i.e. no Type A uncertainty, is recorded for any high order voltage harmonic. The situation is slightly different in case of current harmonic share measurements. From Table 2, it may be concluded that the resolution, the specification and the level up calibration components possess an equal order of magnitude values, the last one contributes with a highest share in the overall budget. This assumption is valid especially for single harmonics of lower frequencies. In case of 9th and 11th order harmonic components measurements, the resolution is the dominant component, taking into account that $u_{\mathrm{SP},ih\%}$ and $u_{\mathrm{CL},ih\%}$ are proportional to $i_{h,\%}$ and the share of the concrete harmonics in the current waveform is low. Type A uncertainty is recorded only during the measurement of the 5th order harmonic, which implies that the single readings fluctuations in the concrete measurement setup, may be neglected. In Table 2, the single influence quantities' values are presented for only one measurement point, however the conducted propagation analysis is valid for different φ_1 values as well.

Table 1. Test signals harmonics' share and phase shifts.

h	$v_{h,\%}$ (%)	ϑ_{vh} (°)	$i_{h,\%}$ (%)	ϑ_{ih} (°)
3	8.2	65	34.9	119
5	4.4	247	15.1	194
7	1.15	174	8.5	48
9	0.78	12	2.45	7
11	0.12	325	0.87	204
THD **(%)**	9.41		39.05	

The uncertainty propagation, in the measurement of voltage and current initial phase shifts in relation to fundamentals, is illustrated in Table 3. For the following discussion, the results in the measurement point that corresponds to the highest fundamental phase shift are presented, i.e. $\varphi_1 = 60°$, because in it the extreme harmonic phase shift related uncertainties are expected. As may be concluded from the results, illustrated in Table 3, the specification and the level up calibration related components, dominantly shape the overall budget in both voltage and current harmonics' phase shifts measurement. These 2 influence factors possess equal values for both θ_{vh} and θ_{ih} recording, in case of same order harmonics, taking into account the fact that their intensity is affected only by the data presented in RS's datasheet or calibration certificate, and the order of the harmonics, (24). Additionally, for any voltage or current harmonic phase shift, the values of $u_{\mathrm{SP},\theta h}$ and $u_{\mathrm{CL},\theta h}$ are equal. This situation is present due to the fact that the calibration of the concrete ZERA COM3003 was conducted with a RS that possess similar measurement characteristics as the primary RS of LEM. When θ_{vh} and θ_{ih} are measured, a significant dispersion of single readings, i.e. a not negligible Type A uncertainty, is

Table 2. Uncertainty budget in $v_{h,\%}$ and $i_{h,\%}$ measurement for φ_1=0°

	$v_{h,\%}$				$i_{h,\%}$			
h	$u_{\mathrm{A},vh\%}$ (%)	$u_{\mathrm{R},vh\%}$ (%)	$u_{\mathrm{SP},vh\%}$ (%)	$u_{\mathrm{CL},vh\%}$ (%)	$u_{\mathrm{A},ih\%}$ (%)	$u_{\mathrm{R},ih\%}$ (%)	$u_{\mathrm{SP},ih\%}$ (%)	$u_{\mathrm{CL},ih\%}$ (%)
3	0	0.0029	0.00063	0.002	0	0.0029	0.0045	0.0085
5	0	0.0029	0.00051	0.0016	0.002	0.0029	0.0029	0.0055
7	0	0.0029	0.00018	0.00057	0	0.0029	0.0022	0.0042
9	0	0.0029	0.00015	0.00048	0	0.0029	0.00079	0.0015
11	0	0.0029	0.000028	0.000088	0	0.0029	0.00034	0.00064

Table 3. Uncertainty budget in θ_{vh} and θ_{ih} measurement for φ_1 = 60°

	θ_{vh}				θ_{ih}			
h	$u_{A,\theta vh}$ (°)	$u_{R,\theta vh}$ (°)	$u_{SP,\theta vh}$ (°)	$u_{CL,\theta vh}$ (°)	$u_{A,\theta ih}$ (°)	$u_{R,\theta ih}$ (°)	$u_{SP,\theta ih}$ (°)	$u_{CL,\theta ih}$ (°)
3	0.0024	0.0029	0.0087	0.0087	0.002	0.0029	0.0087	0.0087
5	0.0024	0.0029	0.014	0.014	0.0049	0.0029	0.014	0.014
7	0.0068	0.0029	0.02	0.02	0.0063	0.0029	0.02	0.02
9	0.0068	0.0029	0.026	0.026	0.0051	0.0029	0.026	0.026
11	0.021	0.0029	0.032	0.032	0.013	0.0029	0.032	0.032

recorded. As can be seen from Table 3, the statistical uncertainty rises with the increase of the harmonic order. For lower frequency components, $u_{\mathrm{A},\theta h}$ and $u_{\mathrm{R},\theta h}$ possess an equal order of magnitude value. For higher order harmonics, the resolution related uncertainty is almost negligible in comparison to other components.

The expanded uncertainty, attributed to the three phase active power, for different φ_1 values in the interval between -60° and 60°, with a step of 15°, is illustrated in Figure 2. Its value, for different measurement points, is presented in relative form, in relation to the analytically obtained three phase active power, *P*:

$$U_{\mathrm{C},P\%} = \frac{U_{\mathrm{C},P}}{P} \cdot 100\,, \tag{34}$$

where $U_{\mathrm{C},P}$ is calculated according to (33).

In Figure 2, two data sets are presented. The first one, depicted as square points, resemble the overall measurement uncertainty, if the concrete quantity is measured directly with the primary RS. The standard combined uncertainty is calculated according to (10) and it comprises of 4 mutually uncorrelated components. Type A and resolution related uncertainties are calculated as presented in (11) and (12) respectively, where the corresponding active power recordings and resolution are supposed to be substituted. The specification related uncertainty is obtained from 3 mutually uncorrelated components, according to (14)-(17), where X_h is replaced with the measured three phase active power, P, and h is taken as unity. Level up calibration related uncertainty is calculated as presented in (20), once again by substituting P for X_h, and by taking h as a unity. The expanded uncertainty is obtained according to the conclusions of the Central Limit Theorem [17], by adopting Gaussian distribution and confidence interval of 95.4 %. This implies that the expanded uncertainty is calculated by multiplying the standard uncertainty evaluated according to (10) with a coverage factor, k_P, which, for Normal distribution and confidence interval of

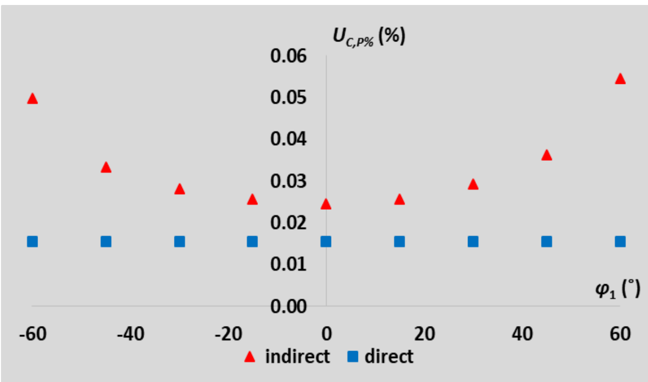

Figure 2. Uncertainty propagation in direct and indirect measurement of three phase active power with ZERA COM3003

95.4 %, equals 2. The concrete approach is valid for active power measurements in sinusoidal conditions [28]. The appropriateness for its implementation in case of harmonically distorted waveforms is questionable, due to the fact that the overall uncertainty, in such scenario, would not be dependent on the degree of harmonic distortion, or on the presence of specific components with different frequencies. As can be seen from Figure 2, the uncertainty curve for direct measurement of three phase active power is flat, eventual variations in different measurement points are result of the statistical scattering of recorded data.

The triangular points in Figure 2 resemble the calculated uncertainty according to the proposed mathematical model in the concrete contribution. As may be noticed, the overall uncertainty is higher than the value obtained in case of direct active power measurement, even when fundamental voltages and currents are mutually in phase, i.e. when $\varphi_1 = 0°$. As the active power share in the system decreases, the overall uncertainty increases significantly. In the measurement points where $\varphi_1 = \pm 60°$, the overall uncertainty is approximately 3 times higher than the value related to the measured active power in a direct manner. The results depicted in Figure 2 provide a conclusion that the concrete approach, although quite complex and time consuming, represents detailed and more realistic measurement performance illustration.

6. OVERALL UNCERTAINTY PROPAGATION SIMULATION

In order for overall active power measurement uncertainty propagation analysis to be conducted, a simulation procedure, regarding alteration of different harmonic signals' parameters will be presented. The simulation will be based on the conclusions from the practical measurements. In the simulation, only one high order harmonic component will be regarded in the signals' waveforms, and the test signals proposed in [15], regarding only 5th order harmonics, will be taken as a reference. The limitation of *THD* for voltage and current signals equals 10 % and 40 % respectively, while the measurement points correspond to the same fundamental phase shifts, as in the practical evaluation. The RMS of the signals equal, once again, 230 V and 5 A. Taking into account that no real measurements are conducted in the following evaluation, the Type A uncertainty component, attributed to different harmonic parameters will be approximated with an expected value, obtained from the real time measurements. This implies that the scattering of single recordings around the mean will be neglected in case of $v_{h,\%}$ and $i_{h,\%}$ measurement. In case of θ_{vh} and θ_{ih} recording, the Type A uncertainties will be approximated with the results presented in Table 3, as highest values obtained for harmonics from different order.

In Figure 3 and Figure 4, the active power measurement uncertainty propagation is illustrated, with respect to the

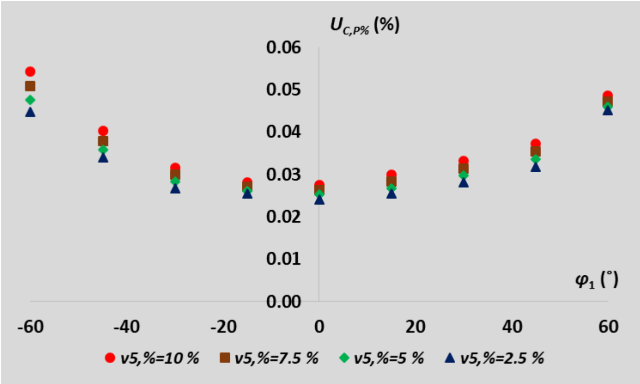

Figure 3. Active power measurement uncertainty propagation with alteration of $v_{5,\%}$, $i_{5,\%}$ = 40 %, θ_{v5} = 0° and θ_{i5} = 60°

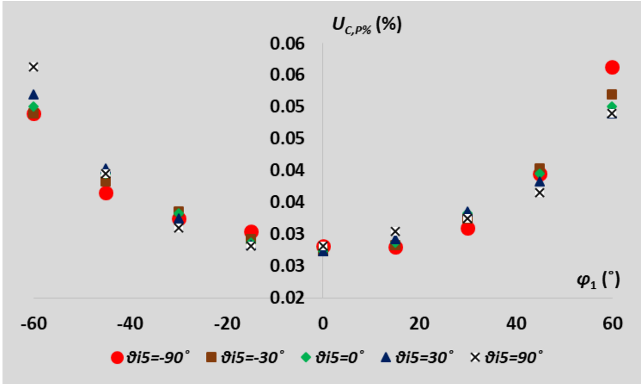

Figure 5. Active power measurement uncertainty propagation with alteration of θ_{i5}, $v_{5,\%}$ = 10 %, $i_{5,\%}$ = 40 % and θ_{v5} = 0°

alteration of voltage and current 5th order harmonics, respectively. The initial phase shifts of the voltage and current 5th order harmonics in relation to fundamentals, θ_{v5} and θ_{i5}, are held constant at 0° and 60°, respectively. As the dominant uncertainty components in harmonic share measurement, especially the one related to the instrument's calibration, are proportional to the altered parameters, the decrease in $v_{5,\%}$ and $i_{5,\%}$ results in almost linear alteration of $U_{\mathrm{C},P\%}$. The concrete alteration is more noticeable in the simulation with variable $i_{5,\%}$ value, due to the fact that the current harmonic share measurement uncertainty is dominated by both RS's specification and calibration related components. In case of voltage harmonic share measurement, a significant resolution related component maintains the combined uncertainty at relatively constant value. The overall active power measurement uncertainty change in respect to $v_{5,\%}$ and $i_{5,\%}$ alteration is more noticeable in measurement points that correspond to lower active power share in the system, i.e. the $U_{\mathrm{C},P\%}$ change is most significant for $\varphi_1 = \pm 60°$.

In Figure 5 and Figure 6 the active power measurement uncertainty propagation is presented in relation to current and voltage 5th order harmonics' initial phase shifts alteration. The overall uncertainty in harmonic phase shifts measurement is not affected by the change of both θ_{ih} and θ_{vh} values, due to the fact that the dominant components are a result of the accuracy limitations and level up calibration data, calculated according to (24). The concrete conclusion is backed up by the measurements presented in the practical validation of the mathematical model, i.e. in Table 3. However, in the overall active power measurement uncertainty, a small alteration is recorded, for different values of the 5th order harmonics' initial phase shifts, θ_{i5} and θ_{v5}. The variations of $U_{\mathrm{C},P\%}$ are present due to the influence of θ_{i5} and θ_{v5} on uncertainty attributed to $\cos(\varphi_5)$ calculation. The direct impact of different harmonic phase shifts on active power uncertainty alteration is not visible in the measurement points that correspond to small φ_1 value. However, in the measurement points that correspond to a lower active power share in the system, a mismatch between the overall uncertainties that correspond to different θ_{i5} and θ_{v5} values, may be recorded. If the difference between the initial 5th order harmonics' phase shifts, $\theta_{i5} - \theta_{v5}$, is between 0° and 180°, then the peak of the uncertainty curve is oriented toward the capacitive range of φ_1. The previous statement is backed up by the results of the simulation that correspond to θ_{i5} values of 90° and 30°, presented in Figure 5, taking into account that θ_{v5} is held constant at 0°; and the results of the simulation that correspond to θ_{v5} values of -90°, -30°, 0° and 30°, illustrated in Figure 6, taking into account that θ_{i5} is fixed at 60°. On the contrary, the peak of the uncertainty curve is oriented toward the inductive range of φ_1, when the initial harmonic phase shift difference is between 180° and 360°. The concrete conclusion is derived from the results illustrated in Figure 5, that correspond to θ_{i5} values of -90° and -30°, as well as the uncertainty curve that corresponds to θ_{v5} value of 90°, illustrated in Figure 6. When $\theta_{i5} - \theta_{v5} = 0°$, the active power uncertainty curve is symmetrical for both inductive and capacitive range of φ_1.

The last uncertainty simulation data set is presented, for the dependence between the order of high harmonics and the active power uncertainty propagation to be depicted. The simulation is

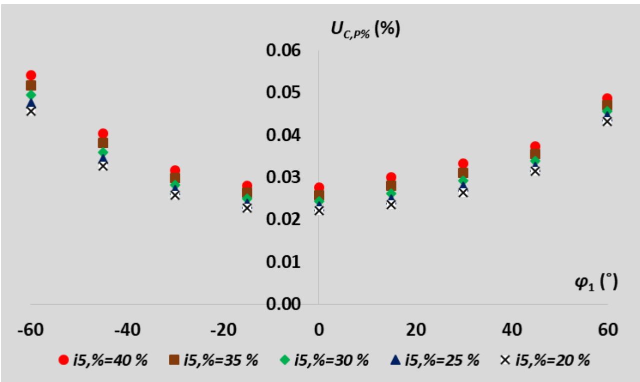

Figure 4. Active power measurement uncertainty propagation with alteration of $i_{5,\%}$, $v_{5,\%}$ = 10 %, θ_{v5} = 0° and θ_{i5} = 60°

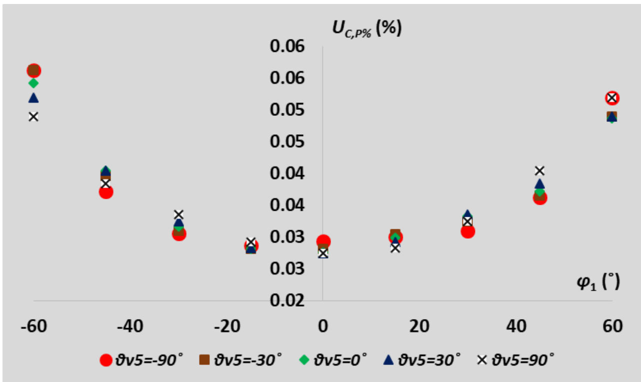

Figure 6. Active power measurement uncertainty propagation with alteration of θ_{v5}, $v_{5,\%}$ = 10 %, $i_{5,\%}$ = 40 % and θ_{i5} = 60°

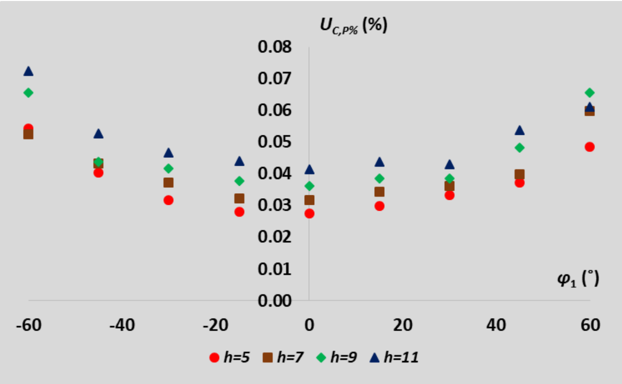

Figure 7. Active power measurement uncertainty propagation with alteration of harmonic order h, $v_{h,\%}$ = 10 %, $i_{h,\%}$ = 40 %, θ_{vh} = 0°, θ_{ih} = 60°

conducted with fixed harmonic distortion of voltage and current waveforms, equalling 10 % and 40 % respectively, while the harmonics' initial phase shifts, and θ_{vh} and θ_{ih} are fixed at 0° and 60°. The results of the simulation are illustrated in Figure 7. The order of harmonics, h, present in the signals, affects the uncertainties of almost every directly measured and analytically obtained parameter, according to the mathematical model. Taking into account the conclusions presented in the fifth chapter of the manuscript, the dominant uncertainty components in harmonic share and phase shift measurement are directly proportional to the order of harmonics. Regarding this conclusion, it is expected that the overall uncertainty, attributed to the active power, will increase with the frequency increment of the harmonic components, in case of fixed *THD* values. The concrete assumption is valid for lower fundamental phase shifts, where an almost linear overall uncertainty increase is recorded. For lower active power share in the system, that is not the case however, and in some measurement points the overall uncertainty is lower, even if higher order harmonic components are present in the waveforms. An example of such a scenario may be recorded from the data presented in Figure 7, for measurement points that correspond to a fundamental phase shift, φ_1, of ± 60°. When the fundamental power factor of the signals equals 0.5 L, the simulation that corresponds to 11th order harmonics results in lower overall uncertainty in relation to the value obtained if only 9th order harmonics are present in the three phase voltages and currents. The concrete phenomena is a result of the harmonic power factor related uncertainty, which is dependent not only on the order of the high frequency components in the signals, but on the value of the phase shift between them, φ_h, as well.

7. CONCLUSIONS

In this paper, a mathematical model for measurement uncertainty calculation in active power measurement, when voltages and currents are harmonically distorted, is presented. The model is based on direct measurement of multiple signal parameters, such as single harmonics' share and phase shift, while the active power is obtained in an analytical manner, by using a known mathematical apparatus for harmonic distortion analysis. The concrete measurement approach is implemented in order for all influence factors that affect the recording of every signal parameter, to be evaluated analytically.

The validation of the proposed mathematical model for active power uncertainty evaluation is conducted by using reference standard of high accuracy class that possesses international traceability to BIPM, as a measurement device. The practical evaluation is conducted with test signals, which possess random harmonic distortion, with certain limitation proposed in the existing standards. From the practical test, conclusions about the dominant uncertainty components in directly measured quantities are derived and the influence factors that have negligible effect on the overall uncertainty intensity are detected. Finally, an illustration of the overall active power measurement uncertainty propagation is provided, with respect to its share in the system. The results are compared with data obtained according to a sine wave adopted approach.

For deeper analysis of the uncertainty propagation, a simulation procedure is conducted, in which different harmonic parameters' values are altered. In the simulation, the findings derived from the practical evaluation, regarding the statistically obtained data, are implemented as well. It may be concluded that the overall active power measurement uncertainty changes almost linearly with the alteration of both voltage and current harmonic share in the signals. The change in overall uncertainty value is more prominent in case of low active power share in the system. The initial phase shifts of high order harmonics do not affect significantly the overall active power uncertainty, however their value dictate the peak point of the uncertainty curves, illustrated in relation to the fundamental phase shift. The order of high order harmonics present in the signals, affect the overall uncertainty value significantly, and its influence is more prominent in case of high active power share in the system.

The main disadvantage of the proposed mathematical model is the volume of calculations that are supposed to be performed and the fact that it is primary intended for instruments that have options for individual observation of high order harmonics in frequency domain. For its implementation, in case of units that measure the active power in a direct manner only, additional approximations are supposed to be applied. In such a scenario, the uncertainty attributed to single harmonics share and phase shift measurements are supposed to be evaluated in an empirical way, by observation of the previous performance of the concrete instrument in measuring harmonically distorted signals. The proposed mathematical model may be improved in future as well. Namely in the concrete work, the correlation of single influence factors is done by using a simplified approach, and for obtaining the combined uncertainties' distributions, no additional mathematical modellings is provided. Taking into account that multiple influence factors are regarded in the overall uncertainty budget, the calculations may be improved by implementation of numerical model based on Monte Carlo simulation or Bayesian statistics.

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