ACTIVE POWER MEASUREMENT UNCERTAINTY BUDGET MODELLING IN CASE OF HARMONICALLY DISTORTED VOLTAGES AND CURRENTS

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Abstract:
Harmonic distortion of electrical waveforms results in a need for instrumentation performance evaluation in non-sinusoidal conditions. This is especially challenging in case of power and/or energy measuring devices, because of their place in the regulated trade of electrical energy. The measurement uncertainty evaluation procedure commences with determination of influence factors, which are correlated to harmonic components' magnitude and phase shift recording. For overall uncertainty budget modelling, a GUM based approach is implemented. The model validation and the uncertainty propagation, due to alteration of different signals' parameters, is illustrated via real time measurements, conducted with high accuracy class measuring equipment.

Keywords: high order harmonics, measurement uncertainty, reference standard.

1. INTRODUCTION

The performance of power and electricity meters, in case of harmonically distorted signals, has been regarded in many scientific contributions [1-6]. Measurement errors have been analyzed in relation to different input influence quantities, such as:

- the distortion magnitude [1, 2],
- the share of single harmonics in signals and their phase shifts [3],
- the load balance [1],
- the disturbances duration [4], etc.

Analysis have been conducted by using both test waveforms proposed in standards [7-10], as well as randomly distorted voltages and currents [1, 3].

In [1], evaluation of measurement uncertainty, in active electricity meter examination procedure, is presented. The uncertainty budget comprises of 2 components, related to the statistical scattering of single readings and reference standard's performance. By adoption of such uncertainty budget modelling methodology, insufficient data about the single harmonics' influence on the measurements is provided. In [6], the overall uncertainty related to the measured harmonic power is calculated as combined uncertainty [11], of 3 components, related to the voltage, current and phase shift of the same harmonic order. The concrete perspective details no information about the influence factors that affect the recording of the fore mentioned quantities.

In the following contribution, an original model for uncertainty propagation in active power/energy measurements is presented. In the model, influence factors, that affect the measurement of different harmonic parameters, are analytically determined. Its experimental verification is conducted in an accredited calibration laboratory, according to standard MKC EN ISO/IEC 17025:2018 [12], by using high accuracy class measurement equipment.

2. BASIC HARMONIC RELATIONS

The share of a single harmonic, in voltage or current signals, is usually expressed in relation to the fundamental component, in relative form [13]:

$$x_h = \frac{X_h}{X_1} \cdot 100\,, \tag{1}$$

where X_h and X_1 are the RMS values of the h^{th} order harmonic and fundamental voltage or current respectfully. The phase shift of a high order harmonic, θ_{xh}, is usually presented in relation to the initial phase shift of the voltage or current fundamental, at positive zero crossing. The phase shift between the h^{th} order voltage and current harmonics, φ_h, is then calculated as follows [14]:

$$\varphi_h = h\varphi_1 + (\theta_{ih} - \theta_{vh})\,, \tag{2}$$

where φ_1 is the phase shift between fundamentals and θ_{ih} and θ_{vh} are the initial phase shifts of current and voltage harmonics of order h.

The RMS of the harmonically distorted waveform equals [15]:

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

where n is the maximal harmonic order regarded for practical evaluation. For distortion quantification, the parameter named Total Harmonic Distortion (*THD*) is used [1, 2, 13, 15] and, if equation (1) is regarded, it may be expressed as follows:

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

From equations (3) and (4), fundamental voltage or current may be evaluated as follows:

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

Finally, single phase active power equals:

$$P = \sum_{h=1}^{n} V_h I_h \cos\varphi_h\,, \tag{6}$$

where V_h and I_h are the RMS values of the h^{th} order voltage and current harmonics. These quantities are obtained, if the percentage share, equation (1), and the RMS of the signals, equation (3), are known.

3. MEASUREMENT PROCEDURE

The experimental part of the work is carried out in an accredited calibration laboratory [12], called Laboratory for Electrical Measurements (LEM). The 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 2 reference standards in domain of electrical power and energy instruments calibration. The three phase power and energy comparator, ZERA COM3003 [16] is the primary reference standard (RS) of LEM. For the purposes of this work, it will be used as measuring device, on which the uncertainty evaluation model will be validated. The laboratory's secondary (working) standard, CALMET C300 [14], will be used as a source of harmonically distorted waveforms. CALMET C300 is software controlled and it is operated by using a hardware unit that is connected via RS232/USB interface. The connection scheme for three phase active power measurements is illustrated in Figure 1.

In the measurement procedure, ZERA COM3003 [16] will be used for harmonic components' share and initial phase shifts recording. Alongside harmonics' parameters, the RMS of the voltage and current signals, as well as the phase shifts between fundamental components, will be also measured directly. The active power will later be calculated in analytical way, using equations (1)–(6). The reason for choosing such measuring principle is related to the uncertainty evaluation procedure [17]. Namely, the model is supposed to unite all influence factors that affect measurement of both harmonic components' share and phase shifts and fundamental components. The overall uncertainty accompanied to the calculated power, is going to be presented as combined uncertainty, assuming the principles presented in [11].

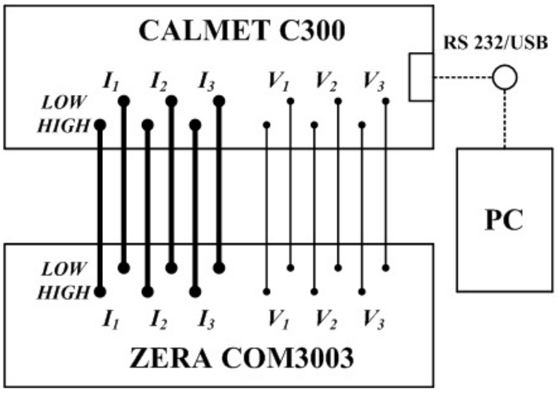

Figure 1: Connection of the LEM's reference standards in three phase active power measurement configuration

4. UNCERTAINTY BUDGET MODELLING

In the following chapter the uncertainty propagation model will be presented. The analysis commences with determination of influence factors that affect the recording of single harmonic components' share, in voltage and current signals.

4.1. Uncertainty accompanied to x_h recording

The overall uncertainty related to the recording of single harmonic's share in voltage, or current, signals is calculated as standard combined uncertainty [11] of 4 mutually uncorrelated components:

$$u_{C,xh} = \sqrt{u_{A,xh}^2 + u_{R,xh}^2 + u_{SP,xh}^2 + u_{CL,xh}^2}\,, \tag{7}$$

where $u_{A,xh}$ is uncertainty calculated according to Type A evaluation principle [11], $u_{R,xh}$ is a component related to instrument's finite resolution, $u_{SP,xh}$ is an uncertainty that derives from its specifications and $u_{CL,xh}$ is a component related to its level up calibration. Type A uncertainty is evaluated as standard deviation of the mean harmonic share recorded, if N measurements are made:

$$u_{A,xh} = \sqrt{\frac{1}{N(N-1)} \sum_{j=1}^{N} \left(x_{h,j} - x_{h,M}\right)^2}\,, \tag{8}$$

where $x_{h,j}$ and $x_{h,M}$ are single reading and mean value of the harmonic component's share respectively. The uncertainty component related to the instrument's finite resolution equals:

$$u_{R,xh} = \frac{r}{2k} = \frac{r}{2 \cdot \sqrt{3}}\,, \tag{9}$$

where r is the resolution in domain of x_h measurement. This component is obtained assuming rectangular distribution, therefore the coverage factor, k, equals √3, [11]. The specification related uncertainty is calculated as:

$$u_{SP,xh} = \left\{\left|\frac{\partial x_h}{\partial X_1} u_{SP,X1}\right| + \left|\frac{\partial x_h}{\partial X_h} u_{SP,Xh}\right|\right\}, \quad (10)$$

where $u_{SP,X1}$ and $u_{SP,Xh}$ are specification related components accompanied to fundamental and h^{th} order harmonic recording, respectively. These 2 uncertainties are treated as mutually correlated, due to the fact that single harmonic's share depends on the fundamental's value. They are calculated in a manner dictated by the instrument's datasheet provided. The sensitivity coefficients, $\partial x_h/\partial X_1$ and $\partial x_h/\partial X_h$, are calculated by using equation (1).

When the measurements are conducted with LEM's primary RS [16], the specification related uncertainties, $u_{SP,X1}$ and $u_{SP,Xh}$, comprise of 3 mutually uncorrelated components. They refer to the accuracy class of the RS, u_{AC}, its long term stability, u_{ST}, and temperature influence on its measuring performance, u_T:

$$u_{SP,Xh} = \sqrt{u_{AC,h}^2 + u_{ST,h}^2 + u_{T,h}^2}\,. \quad (11)$$

The single components in equation (11) equal:

$$u_{AC,h} = \frac{U_{AC,\%}}{k} \cdot \frac{X_h}{100} \cdot h\,, \quad (12)$$

$$u_{ST,h} = \frac{U_{ST,\%}}{k} \cdot \frac{X_h}{100} \cdot y \cdot h\,, \quad (13)$$

$$u_{T,h} = \frac{U_{T,\%}}{k} \cdot \frac{X_h}{100} \cdot \Delta t \cdot h\,, \quad (14)$$

where $U_{AC,\%}$, $U_{ST,\%}$ and $U_{T,\%}$ are specification related values, presented in a relative expanded form, k is the coverage factor, which for rectangular distribution equals √3, and h is the order of the harmonic component. In equation (13), y is the number of years that have passed since the last calibration of the RS, and Δt is data related to the temperature fluctuations in the measurement site. Equations (11)-(14) refer to $u_{SP,Xh}$ calculation, in order for $u_{SP,X1}$ value to be obtained, X_h is replaced with X_1 and h is taken as unity.

For $u_{CL,xh}$ component evaluation, the approach presented in equation (10) may also be implemented. The specification related uncertainties, $u_{SP,X1}$ and $u_{SP,Xh}$, should be replaced with level up calibration components $u_{CL,X1}$ and $u_{CL,Xh}$, respectively. These 2 components are determined according to equation (12), if the RS's accuracy limits, $U_{AC,\%}$, are replaced with data obtained from a calibration certificate, $U_{CL,\%}$., for either voltage, or current measurements.

4.2. Uncertainty of *THD* calculation

From the harmonic components' share related uncertainties, $u_{C,xh}$, the uncertainty accompanied to the calculated total harmonic distortion may be derived:

$$u_{THD} = \sqrt{\sum_{h=2}^{n} \left(\frac{\partial THD}{\partial x_h} u_{C,xh}\right)^2}\,. \quad (15)$$

The number of influence quantities present in equation (15) equals the number of high order harmonics regarded, n-1. Sensitivity coefficients $\partial THD/\partial x_h$ are calculated from equation (4). If the substitutions are made, equation (15) becomes:

$$u_{THD} = \frac{1}{THD} \sqrt{\sum_{h=2}^{n} \left(x_h \cdot u_{C,xh}\right)^2}\,. \quad (16)$$

4.3. Uncertainty in X_1 and X_h calculation

If both RMS value, X, and THD of either voltage, or current, signal are known, the waveform's fundamental component, X_1, is calculated by using equation (5). As X and THD are recorded independently, the uncertainty prescribed to X_1 will be calculated as combined uncertainty, from 2 mutually uncorrelated components:

$$u_{C,X1} = \sqrt{\left(\frac{\partial X_1}{\partial X} u_{C,X}\right)^2 + \left(\frac{\partial X_1}{\partial THD} u_{THD}\right)^2}\,, \quad (17)$$

where the partial derivatives, $\partial X_1/\partial X$ and $\partial X_1/\partial THD$, are determined from equation (5). The uncertainty related to signals' THD is obtained using equation (16). The signal's RMS related uncertainty, $u_{C,X}$, comprises of 4 mutually uncorrelated components:

$$u_{C,X} = \sqrt{u_{A,X}^2 + u_{R,X}^2 + u_{SP,X}^2 + u_{CL,X}^2}\,, \quad (18)$$

and they are result of the same influence factors as the uncertainties correlated to x_h measurement, presented in equation (7). The Type A uncertainty and the resolution based component are calculated according to equations (8) and (9), respectively. For the purpose of $u_{A,X}$ computation, single recordings and mean value of the signals' RMS, X_j and X_M, are included in equation (8). In order for $u_{SP,X}$, and $u_{CL,X}$ values to be obtained, equations (11)-(14) are used. The harmonic component's RMS, X_h, in equations (12)-(14) is substituted with X and h is taken as unity.

Finally, the uncertainty of the single harmonic's RMS value, is calculated as:

$$u_{C,Xh} = \left\{\left|\frac{\partial X_h}{\partial X_1} u_{C,X1}\right| + \left|\frac{\partial X_h}{\partial x_h} u_{C,xh}\right|\right\}, \quad (19)$$

assuming X_1 and x_h as mutually correlated, as described before. The sensitivity coefficients

$\partial X_h/\partial X_1$ and $\partial X_h/\partial x_h$ are determined from equation (1), while $u_{C,X1}$ and $u_{C,xh}$ are calculated according to equations (17) and (7), respectively.

4.4. Uncertainty of phase shifts measurements

The phase shift related uncertainty is calculated in an unique way, no matter if the analysis is conducted on high order harmonics' angles, θ_{vh} and θ_{ih}, or on the phase shift between fundamentals, φ_1. The overall uncertainty prescribed to either voltage, or current, harmonic phase shift is calculated as standard combined uncertainty of 4 mutually uncorrelated components:

$$u_{\theta h} = \sqrt{u_{A,\theta h}^2 + u_{R,\theta h}^2 + u_{SP,\theta h}^2 + u_{CL,\theta h}^2}\,, \qquad (20)$$

where the single components possess the same meaning as the ones determined in x_h and X measurement, equations (7) and (18) respectively. For the concrete evaluation, single phase shifts, $\theta_{vh,j}$, $\theta_{ih,j}$ and $\varphi_{1,j}$, the mean values obtained from N measurements, $\theta_{vh,M}$, $\theta_{ih,M}$ and $\varphi_{1,M}$, and the corresponding resolution of the instrument, are substituted in equations (8) and (9). The specification and level up calibration related uncertainties are calculated from corresponding documents. If the data is presented in absolute form, which is the case for ZERA COM3003 [16], $u_{SP,\theta h}$ and $u_{CL,\theta h}$ are equal to:

$$u_{SP,\theta h}\left(u_{CL,\theta h}\right) = \frac{U_{SP,\alpha}\left(U_{CL,\alpha}\right)}{k} \cdot h, \qquad (21)$$

where $U_{RS,\alpha}$ and $U_{CL,\alpha}$ are specification and calibration certificate related uncertainties presented as expanded values in ° or rad, k is the coverage factor that is dependent on the adopted distribution and h is the harmonic order. In case of φ_1 related uncertainty computation, h equals 1.

From the uncertainties prescribed to the phase shifts that are measured directly, the uncertainty accompanied to the calculated phase shift between the h^{th} order harmonics, φ_h, may be determined:

$$u_{C,\varphi h} = \\ = \sqrt{\left(\frac{\partial \varphi_h}{\partial \theta_{vh}} u_{\theta_{vh}}\right)^2 + \left(\frac{\partial \varphi_h}{\partial \theta_{ih}} u_{\theta_{ih}}\right)^2 + \left(\frac{\partial \varphi_h}{\partial \varphi_1} u_{\varphi_1}\right)^2}\,, \qquad (22)$$

where the partial derivatives are calculated from equation (2). The value obtained from equation (22) is further used for determination of the uncertainty related to the power factor of the h^{th} order harmonics:

$$u_{PF,h} = \left|\frac{\cos\left(\varphi_h + k \cdot u_{C,\varphi h}\right) - \cos\varphi_h}{k}\right|, \qquad (23)$$

where the coverage factor, k, corresponds to the adopted distribution. According to Central Limit Theorem, the overall distribution tends to become Gaussian (Normal), if multiple influence factors are regarded, no matter the distribution adopted for their determination [11]. If that conclusion is adopted and a coverage interval of 95.4 % is regarded, then k=2.

4.5. Uncertainty of active power calculation

Finally, from the previous analysis, the overall uncertainty accompanied to the measured active power may be computed. The uncertainty related to the active power of the h^{th} order harmonics equal:

$$u_{Ph} = \\ = \sqrt{\left(\frac{\partial P_h}{\partial V_h} u_{Vh}\right)^2 + \left(\frac{\partial P_h}{\partial I_h} u_{Ih}\right)^2 + \left(\frac{\partial P_h}{\partial cos\varphi_h} u_{PF,h}\right)^2}\,, \qquad (24)$$

where u_{Vh} and u_{Ih} are calculated according to equation (19) and the partial derivatives are computed by using equation (6). In case of fundamental active power uncertainty calculation, u_{P1}, single uncertainty components related to the voltage and current signals, u_{V1} and u_{I1}, are calculated as presented in equation (17).

The active power of harmonically distorted voltages and currents is computed by superposition of components at different frequencies, equation (6). Assuming the uncertainty components associated with active powers at different frequencies as fully correlated, the expanded uncertainty of the distorted voltage and current signals' active power equals:

$$U_{C,P} = k\sum_{h=1}^{n}\left|u_{Ph}\right| = 2\sum_{h=1}^{n}\left|u_{Ph}\right| \qquad (25)$$

adopting Gaussian distribution and confidence interval of approximately 95.4 %.

5. CASE STUDY

In the practical evaluation, several aspects are going to be discussed. First, the uncertainty propagation of single harmonic's share and phase shift recording will be presented and the dominant influence factors are going to be determined. Next, an analysis of the uncertainty intensity in active power measurement will be performed, regarding 2 different approaches. For the concrete performance, voltage and current signals with 230 V and 5 A RMS values and random harmonic distortion [3] are generated from CALMET C300 [14]. The single harmonics' share and phase shifts in relation to fundamentals are illustrated in Table 1.

Table 1: Test signals harmonics' share and phase shift

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	

In Table 2, the single influence factors' values, in measurement of current harmonics share, i_h, are presented. The data corresponds to measurement point in which the phase shift between fundamentals equals 0˚. As can be seen from Table 2, components related to RS's resolution, specification and level up calibration possess the same order of magnitude value, in case of high harmonic distortion of the signal. For lower i_h, i.e. in case of the 9th and 11th order harmonics recording, the overall uncertainty intensity is dominantly related to the standard's resolution. Dominant resolution related components are recorded in v_h measurements as well, due to the fact that the *THD* of voltage signal is significantly lower than the *THD* of the measured current. As the resolution is small, it equals 0.01 %, for both v_h and i_h measurements, the scattering of the measurement data is rarely recorded. That implies that Type A uncertainty is usually neglected.

Table 2: Uncertainty budget in i_h measurement, for φ_1=0˚

h	$u_{A,ih}$, %	$u_{R,ih}$, %	$u_{SP,ih}$, %	$u_{CL,ih}$, %
3	0	0.0029	0.0045	0.0085
5	0.002	0.0029	0.0029	0.0055
7	0	0.0029	0.0022	0.0042
9	0	0.0029	0.0008	0.0015
11	0	0.0029	0.0003	0.0006

Uncertainty propagation in case of θ_{vh} recording is presented in Table 3. The data corresponds to a measurement point in which φ_1 equals 60˚. The resolution in both θ_{vh} and θ_{ih} measurements is constant and it equals 0.01˚, resulting in constant $u_{R,\theta h}$ component. The reference standard's specification and calibration related uncertainties dominantly shape the overall budget and possess almost equal values. This is due to the fact that the calibration of ZERA COM3003 [16] was performed with a RS, that possess similar measurement characteristics as the concrete unit. Statistical scattering of measurement data is not recorded for lower harmonics, however from the 7th order harmonic onwards, significant Type A component is present, which possess the same order of magnitude value as the resolution related uncertainty. The discussion is valid for θ_{ih} uncertainty propagation analysis as well, in any measurement point regarding different φ_1 value.

Table 3: Uncertainty budget in θ_{vh} recording, for φ_1=60˚

h	$u_{A,\theta vh}$, %	$u_{R,\theta vh}$, %	$u_{SP,\theta vh}$, %	$u_{CL,\theta vh}$, %
3	0	0.0029	0.0087	0.0087
5	0	0.0029	0.014	0.015
7	0.0024	0.0029	0.02	0.019
9	0.0024	0.0029	0.026	0.028
11	0.035	0.0029	0.032	0.032

The expanded uncertainty, correlated to active power measurements, for different φ_1 in the interval between -60 ˚ and 60 ˚, is illustrated in Figure 2. It is presented in a percentage form, in relation to the measured active power, *P*. Two approaches are regarded. Rectangular points resemble the uncertainty intensity in different measurement points, obtained if the active power is recorded directly with the RS [16]. Combined uncertainty is calculated according to equation (18), if related data in domain of active power measurement is included. The expanded uncertainty is obtained, by adopting Gaussian distribution and coverage probability of 95.4 % [11]. As can be seen from Figure 2, the overall uncertainty, calculated according to the direct measurement principle, possess constant value, for every φ_1. The same value is obtained in case of sine wave signals measurement [17], eventual variations may appear due to statistical scattering of single recordings. The overall uncertainty is not dependant on the degree of harmonic distortion, or the presence of harmonics at different frequencies in the signals.

The triangular points in Figure 2 correspond to uncertainty in active power measurements, if the analysis is conducted according to the presented mathematical model. Indirect measurement of active power results in higher overall uncertainty in comparison to the values obtained by implementation of the direct method. The intensity of $U_{C,P}$ is strongly dependant on the influence factors that affect the measurement of both fundamental and harmonic phase shifts. This is especially significant in the measurement points that correspond to a low active power share in the system. When φ_1=±60˚, the overall uncertainty is approximately 3 times bigger than the value related to the measured active power in a direct manner. The concrete approach, although quite complex and time consuming, provide detailed and realistic measurement performance illustration.

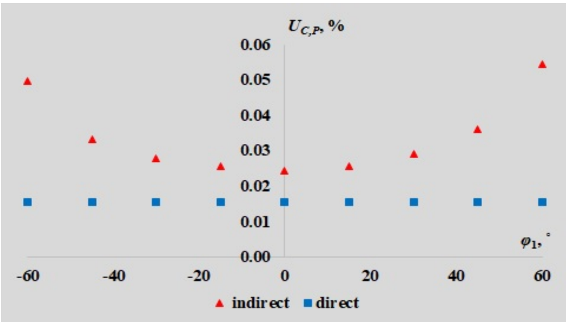

Figure 2: Uncertainty propagation in direct and indirect active power measurement with ZERA COM3003

6. SUMMARY

In the contribution, mathematical model for uncertainty propagation in active power measurements, in non-sinusoidal conditions, is presented and it is experimentally verified by using high accuracy class measuring equipment. The model is realized starting from harmonic components' magnitudes and phase shifts recording, rather than direct measurement of active power. This approach is chosen in order for all influence factors that affect measurement of both fundamental and harmonic parameters to be determined analytically. The overall uncertainty prescribed to the measured active power is further calculated as standard combined uncertainty of single components related to different signals' parameters.

The uncertainty accompanied to harmonics' magnitudes and phase shifts recording is dominantly result of the instrument's specification and level up calibration. In case of low harmonic distortion, which is more typical for voltage signals, the resolution related uncertainty dominantly shape the overall budget. If significant fluctuations in measurement results exist, an additional Type A component should also be taken into account.

For mathematical model verification, the calculated overall uncertainty is compared to a corresponding value obtained by direct power measurement. It is concluded that the overall uncertainty in direct power recording does not provide sufficient information about the individual signals' parameters influence on the measured quantity. This is especially significant for lower active power share in the system, when the phase shift related uncertainty dominantly impact the active power measurements.

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