XXI IMEKO World Congress "Measurement in Research and Industry"
August 30 – September 4, 2015, Prague, Czech Republic

A SHORT DISCUSSION ABOUT IMPACT OF TIME WINDOW SYNCHRONIZATION ERROR ON ACCURACY OF HARMONIC SUBGROUPS MEASUREMENT – EXPERIMENTAL RESEARCH

Tomasz Tarasiuk [1], *Andrzej Pilat* [2]

[1] Department of Marine Electrical Power Engineering, Gdynia Maritime University, Gdynia, Poland, t.tarasiuk@we.am.gdynia.pl
[2] Department of Marine Electrical Power Engineering, Gdynia Maritime University, Gdynia, Poland, a.pilat@am.gdynia.pl

Abstract – The paper is focused on the problem of insufficient synchronization of measurement time window with actual duration of integer number of cycles of input signal and its impact on accuracy of harmonic subgroups measurement. It is analyzed in the wake of chief provisions of IEC Standard 61000-4-7. Particularly, the harmonics order, their phases and the synchronization accuracy have been considered. Numerous simulations has been carried out and their results are graphically presented. The results have been confirmed by experimental research of chosen testing signals, generated by arbitrary waveform generator.

Keywords: harmonic subgroups, fast Fourier transform, IEC Standard 61000-4-7

1. INTRODUCTION

The assessment of actual power quality is arguably one of the most frequently discussed topics in the field of metrology of electrical quantities. It requires determining of quite a number of various parameters including: r.m.s. values of voltages (sometimes currents), frequency, voltage unbalance and waveform distortions under various operation conditions of power systems. The basic framework regarding the phenomena description is laid in IEEE and IEC standards. In this context especially IEEE Standard 1159-2009 [1] has to be mentioned, whereas the commonly agreed recommendations regarding methods of their measurement and required uncertainty are laid in IEC Standard 61000-4-7 [2], IEC Standard 62586-1 [3], IEC Standard 62586-2 [4] and IEC Standard 61000-4-30 [5]. The latter standards are usually related to by manufacturers of measuring instruments dedicated to power quality analysis.

It has been above mentioned that the assessment of power quality requires measurement of numerous parameters. For this paper aim, the problem of waveform assessment has been selected, particularly determining harmonics content of voltages or currents. Arguably, the waveform distortions becomes more and more notorious in nowadays power systems, consisting of numerous non-linear loads and renewable energy resources, like e.g. solar panels. The problem of harmonics assessment has been considered in the wake of IEC Standard 61000-4-7 chief provisions [2]. This standard determines the basic structure of measuring device as follow [2]:

- input circuit with anti-aliasing filters (mandatory for Class A measurements and optional for Class S measurements [5]),
- sample-and-hold and A/D converter,
- synchronization and window-shaping unit if necessary,
- DFT processor providing the Fourier coefficients.

According to the standard, the measurement time window should be synchronized with duration of 10 periods of input signal for 50 Hz systems or with duration of 12 periods for 60 Hz systems with maximum permissible error ±0.03%. In order to perform on-line calculation of discrete Fourier transform (DFT), algorithm of fast Fourier transform (FFT) is usually implemented, at least since eighties of last century [6]. So, typical solution of measurement time window adjustment is synchronisation of sampling frequency with actual input signal frequency. The disadvantage of the method is obvious, namely it would be heavily affected by input signal frequency changes. However, another solution is currently feasible. Namely, the progress in the field of digital signal processors enables application of asynchronous sampling and adjustment of number of considered signal samples to actual duration of integer number of cycles of input signal. Subsequent calculation of Fourier coefficients can be carried out for arbitrary number of samples by, e.g. chirp z-transform CZT [7], which is less computationally efficient than FFT but still more efficient then traditional DFT.

According to IEC Standard 61000-4-30 [5], the basic measurement of harmonics for Class A measurements should be performed in accordance with IEC Standard 61000-4-7 [2] provisions for class I accuracy requirements. Particularly, harmonics subgroups are to be determined up to at least 50^{th} order harmonic [5]. The class I determines accuracy requirements for current, voltage and power measurements [2]. For example, if measured value of voltage harmonic is equal to or greater than 1% of nominal voltage, the maximum error should be not greater than ±5% of the value of considered harmonic. If the measured value is less than 1% of nominal voltage, the maximum error should be not greater than ±0.05% of nominal voltage [2]. The errors refer to single frequency and steady-state signals [2].

There are numerous factors which impact upon error of the harmonics determining, but arguably, the most important would be insufficient synchronisation of time measurement window, which lead to notorious spectral leakage [8]. It is commonly recognised problem in the case of FFT algorithm application, but it impacts traditional DFT algorithm as well, especially if to low sampling frequency is applied. However, the resulting uncertainty of harmonics measurement would depend not only on the synchronisation accuracy of measurement time window but harmonics character as well, i.e. their r.m.s. value, order and phase shift. These problem have been investigated by authors and described in this paper.

Finally, the basic assumptions and the results of extensive simulations and experimental research have been presented in Section II of this paper. The measurements of real signals parameters has been carried out in order to confirm the validity of the simulations. Final conclusions are laid in Section III. It has to be added that the whole research has been carried out for rectangular window. It is recommended in IEC Standard 61000-4-7 [2], if synchronisation with aforementioned accuracy has been achieved.

2. RESULTS OF SIMULATIONS AND EXPERIMENTAL INVESTIGATION

It has been mentioned above that for Class A measurements, the assessment of voltage harmonic content requires determining harmonic subgroups. The concept of harmonic subgroup consists in calculation of square root of the sum of squares of harmonic component amplitude and amplitudes of two spectral components immediately adjacent to it. The result is considered as the amplitude of harmonic subgroup. In fact, “subgroup of output components of the DFT is obtained by summing the energy contents of the frequency components directly adjacent to a harmonic with that of the harmonic proper” [2]. The idea behind the concept is to account for energy of harmonic component spreading out to adjacent frequency bins that is due to signal magnitude fluctuation [2].

Therefore, the calculation of each harmonic subgroup requires calculation the magnitudes of there frequency bins. From practical point of view, it requires determining the three definite integrals over domain which should represent integer number of fundamental component cycles. The definite integral for harmonic component calculation of *h* order can be written as follow:

$$V(f_h) = \frac{2}{M \cdot T_0} \cdot \int_{\tau}^{\tau+M \cdot T_0} v(t) \cdot \exp(-j \cdot 2 \cdot \pi \cdot \frac{h}{T_0} \cdot t) \qquad (1)$$

where: T_0 – fundamental period, *h* - harmonic order, *M* – integer.

Assuming that measurement is to be carried out in 50 Hz system, the definite integral is to be calculated over 10 cycles of input signal, as required by standard [2]. It means that *M* is to be equal to 10. So, the two spectral components immediately adjacent to harmonic component are to be calculated as follow:

$$V(f_{h-0.1}) = \frac{2}{M \cdot T_0} \cdot \int_{\tau}^{\tau+M \cdot T_0} v(t) \cdot \exp(-j \cdot 2 \cdot \pi \cdot \frac{h-0.1}{T_0} \cdot t) \qquad (2)$$

$$V(f_{h+0.1}) = \frac{2}{M \cdot T_0} \cdot \int_{\tau}^{\tau+M \cdot T_0} v(t) \cdot \exp(-j \cdot 2 \cdot \pi \cdot \frac{h+0.1}{T_0} \cdot t) \qquad (3)$$

Finally, harmonic subgroup can be calculated according to the formula:

$$SGV(f_h) = \sqrt{V(f_{h-0.1})^2 + V(f_h)^2 + V(f_{h+0.1})^2} \qquad (4)$$

From practical point of view, the domain of integration would differ more or less from integer number cycles or in another words *M* value would not be integer. Chiefly, it is due to inaccuracy in fundamental period T_0 determining or it is due to impact of applied sampling frequency. In shorthand, the product of number of acquired samples and sampling period would differ from duration of assumed integer number of input signal cycles. Nevertheless, both sources of uncertainty impact upon accuracy of waveform distortion assessment, if common DFT or FFT algorithms are used for the definite integrals calculation. The resulting effect would depend on a number of factors, but some should be pointed out, like: the actual *M* value, harmonic order and magnitude as well as phase shift of considered harmonics.

Finally, the simulation research has been carried out using formulae (1-4) for signals containing fundamental component and single harmonic, in accordance with IEC Standard 61000-4-7 provisions [2]. It has been followed by experimental research for chosen cases of testing signals, which have corresponded to the signals assumed during simulations. These signals have been generated by Agilent 33522B arbitrary waveform generator and subsequently recorded by the controller NI PXIe-8106 equipped with two data acquisition boards NI PXIe-6124. The obtained samples has been processed by mean of FFT algorithm (2048 samples per measurement time window). Sampling frequency has been synchronised for 50 Hz and actual signal frequency slightly varied, accordingly to assumed synchronisation error, determined in relation to the duration of 10 rated cycles, i.e. 200 ms. So, the product of 2048 samples and sampling period has represented time window that has been slightly above or slightly below duration of input signal 10 cycles.

It should be added that the paper is focused solely on harmonic subgroup measurement. But similar analyses can be carried out for other power quality parameters as well. The impact of the discussed phenomenon on unbalance factor measurement has been investigated and the results described by authors in ref. [9].

The investigation has started from analysis of impact of inaccurate synchronisation on accuracy of harmonic magnitude measurement as a function of considered harmonic order, depending on harmonic relative content (in relation to assumed nominal value). The results of measurement error assessment for the synchronisation error δT equal to -0.016% are shown in Fig.1. So, it means that the actual duration of 10 cycles has been equal to product of 2048.32 and sampling period T_s.

Initial phase of each harmonic has been equal to zero and the content of analysed harmonic has been equal to 1%, 2% and 5%.

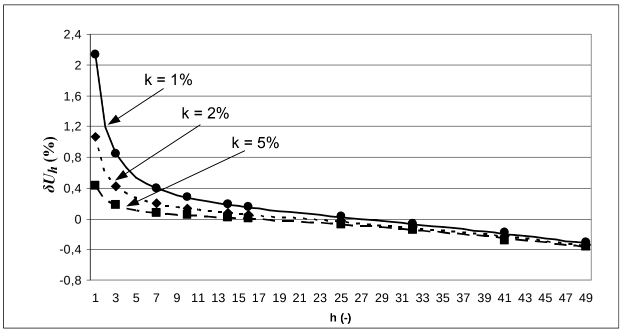

Fig. 1. Relative errors δU_h of measurement of harmonic components for three given harmonic contents: 1%, 2%, 5% and synchronisation error -0.016%, lines represent results of simulations, whereas bold points represents results of actual measurements, h- harmonic order.

Analysis of results presented in Fig. 1 lead to the conclusion that the most affected are harmonics of lower order. For these harmonics the greater relative errors are observed for the harmonics with lower harmonic content. Next, in the case of higher order harmonics the impact of considered harmonic content on relative error of its measurement becomes negligible. It can be noted that the relative error value is more or less similar for harmonics above 23rd order. Of course, the observation is valid for the assumed inaccuracy of synchronisation of measuring window with actual duration of 10 cycles. However, for higher synchronisation errors the resulting impact still will be lower for higher order harmonics in comparison with lower order ones. Moreover, the errors' sign changes depending on harmonic order. Obviously, these effects result from spectral leakage due to fundamental component, which affects chiefly the components in proximity of the fundamental one. Taking into account the above mentioned observations, the following research has been carried out chiefly for harmonics with content equal to 1%.

Subsequent research has been carried out for harmonics with content equal to 1% and synchronisation error -0.03% and +0.03%. The choice results directly from IEC Standard 61000-4-7 provision [2], which requires application of Hanning window if the error is outside range of ±0.03%. Within the range the rectangular window is to be used. The obtained results are shown in Fig. 2. Initial phase of each harmonic has been once again equal to zero.

It should be stressed that for all considered cases the absolute value of measurement error is below 5% of the considered harmonic value, i.e. the maximal permitted measurement error for harmonics with content equal to or grater than 1% of nominal voltage (according to IEC Standard 61000-4-7 [2]). However, the value of the error is above 4% for second order harmonic, which seems quite significant value, if one takes into account that the number of influence quantities is limited to only small synchronisation error.

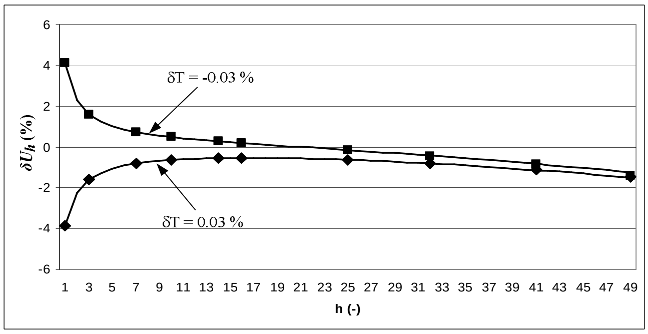

Fig. 2. Relative errors δU_h of respective harmonics content measurements for synchronisation errors δT equal to -0.03% and +0.03% and each harmonic content equal to 1%, lines represent results of simulations, whereas bold points represents results of actual measurements, h- harmonic order.

Similar research has been carried out for harmonics with content below 1% of assumed nominal voltage. For the case, the value of considered harmonic content equal to 0.5% has been chosen, since it is maximal acceptable values of voltage harmonics of 15, 21 and 6…24 orders in public distribution networks [10]. For other harmonics up to 25th order the permissible values are above 1%. It has been aforementioned that for this case the error should be not greater than ±0.05% of voltage nominal value [2]. The obtained results are presented in Fig. 3.

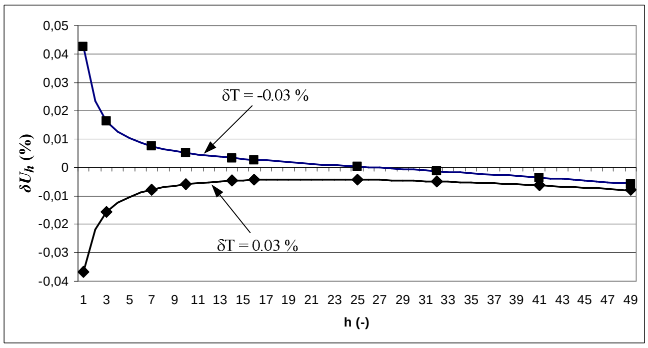

Fig. 3. Relative errors δU_h of respective harmonics content measurements (in relation to assumed nominal value) for synchronisation errors δT equal to -0.03% and +0.03% and each harmonic content equal to 0.5%, lines represent results of simulations, whereas bold points represents results of actual measurements, h- harmonic order.

The results shown in Fig. 3 confirms that for the considered cases the absolute value of measurement error is below 0.05% of the assumed nominal voltage, i.e. the below the maximal permitted measurement error for harmonics with content lower than 1% of the nominal voltage (see standard [2]).

Further, the impact of changes of the synchronisation errors on results of measurement of chosen harmonics has been analysed. They are presented in Fig. 4.

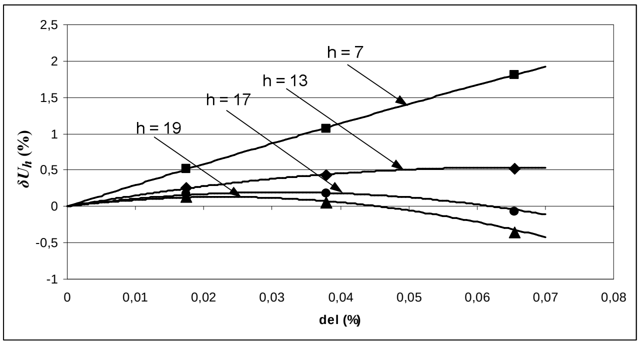

Fig. 4. Relative error of respective harmonics content measurements for various synchronisation errors (del) and each harmonic content equal to 1%, lines represent results of simulations, whereas bold points represents results of actual measurements, h- harmonic order.

It should be noted that the sign of relative error of respective harmonics content measurements depends on considered harmonic order and synchronisation error. For some harmonics the error changes its sign if synchronisation error increases. Once again, the impact of spectral leakage due to fundamental component is to be pointed out as a reason of the observed phenomenon. It means that for lower synchronisation errors the measurement results are affected chiefly by long-range spectral leakage due to fundamental component, whereas in for higher synchronisation errors the results are affected by short-range spectral leakage of considered component energy to adjacent frequency bins.

Furthermore, the impact of harmonics initial phase on the respective harmonic measurement accuracy has been analysed as well. The results obtained for chosen harmonics are depicted in Fig. 5.

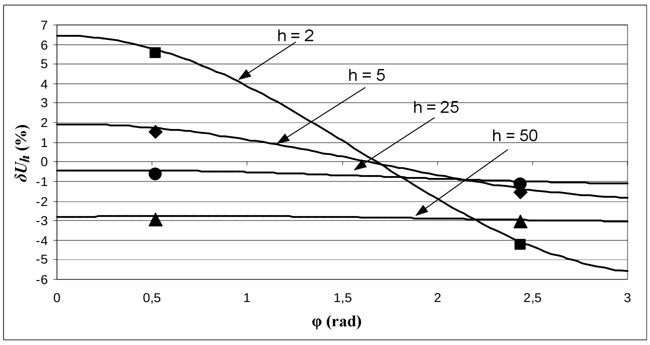

Fig. 5. Relative errors δU_h of respective harmonics content measurements for various initial phases of considered harmonics and each harmonic content equal to 1%, lines represent results of simulations, whereas bold points represents results of actual measurements, h- harmonic order.

Analysis of Fig. 5 leads to conclusion that the initial phase of considered harmonic clearly impacts the outcome of its measurement. Obviously, it is related to synchronisation error and Fourier transform of applied window (rectangular in the considered research). Nevertheless, the case of second harmonic with initial phase equal to zero still remains the worst case.

Finally, the extensive simulation research revealed that measurement errors would be above maximal permissible errors laid in IEC Standard 61000-4-7 [2] for the following cases:

- second harmonic with content 1% if synchronisation error would equal to -0.036% or +0.04%,
- second harmonic with content 0.5% if synchronisation error would equal to -0.035% or +0.044%,
- second harmonic with content below 0.14% if synchronisation error would equal to +0.03%.

4. CONCLUSIONS

The papers concerns the problem of accuracy of harmonics estimation considered in the wake of IEC Standard provisions [2]. It has been found that required accuracy of measurement time window synchronisation is sufficient to attain required uncertainty of respective harmonic estimation for class I measurements, for all possible combination of harmonic order, their initial phases and content. However, if lower uncertainty would be required the requirement of the synchronisation with maximum permissible error ±0.03% would be insufficient.

Moreover, the chief source of uncertainty in harmonics content measurement is synchronisation error of measurement time window with integer number of fundamental component cycles. It is confirmed by very good agreement of simulation results with actual measurements.

Finally, it must be firmly stated that synchronisation error below ±0.03%, does not ensure that errors of measurement of all harmonics will be below the maximal errors for class I measurements. Simply put, if more harmonics would occur concurrently there is the greater impact of long-range spectral leakage. For example, if the considered voltage would contain second order harmonic with content equal to 1% as well as third order harmonic with content equal to 11% and initial phase π, the error of measurement of second harmonic magnitude would be above permissible 5%, even if synchronisation error would be not greater than 0.03%. Similarly, the respective error of measurement of second harmonic content would be above permissible limit, if investigated signal would contain concurrently: third harmonic with content 7% and fifth harmonic with content 10%, even for synchronisation error slightly below 0.03%. Therefore, it is at least advisable to reconsider amendment of discussed IEC Standard 61000-4-7 [2]. It means that including more complex testing signals is necessary for better assessment of accuracy of measuring instruments, like e.g. high grade power quality analysers. These testing signals should be commonly agreed upon and standardised but first of all they should mimic real measurement situations.

Other problem would be estimation of accuracy of interharmonics subgroups measurement. In this case the similar influence factors should be taken into account like in the case of harmonics, completed by impact of their frequency. In fact, relation of their frequency to fundamental one.

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