Estimation of Measurement Window Width by Interpolation Based on Wavelet Coefficients – Case Study

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Abstract **-** This paper deals with the problem of reliable width estimation of measurement window. The simple method is detection of zero-crossing moment of given signal by analysis of sample polarisation changes. But the method is sensitive to waveform distortions, especially analysed signal multiple zero-crossings. So, the idea of implementing discrete wavelet transform for risk reduction of measurement results corruption by the higher frequency phenomena has been proposed and preliminary tested [1]. In this paper, the concept has been further developed, especially the analysis of real voltage with multiple zero-crossing has been carried out.

I. Introduction

One of the basic problems in electric power quality measurement is determining the exact width of measurement window as defined in IEC 61000-4-30 standard [2]. According to the standard, the window width should be exactly 12 periods for systems with rated frequency equal to 60 Hz. The window width inaccurate estimation would affect the measurement results of all electric power quality indices but harmonics estimation would be particularly corrupted. A simple method of the period measurement is detection of zero-crossing moment of analysed signal by analysis of sample polarisation changes. For improving performance of the method, real zero-crossing moments are to estimate by means of interpolation [1]. Unfortunately, the method is sensitive to higher frequency phenomena, especially noises, transients and notching, which could cause multiple zero-crossings. These disturbances badly affect the measurement results especially if they are of unperiodic character. The example of such a phenomenon has been shown in Fig. 1. The observed notching has been caused by power converter working in isolated electric power system (naval system).

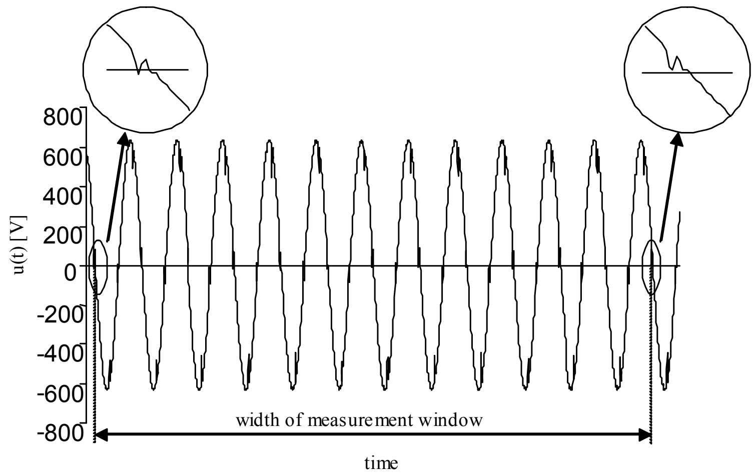

Figure 1. The three zero-crossings in the start of measurement window (a) and one zero-crossing in the end of measurement window (b)

The different number of zero-crossings at the start and end of measurement window results from different notching magnitude at these exact points. One can partially avoids of dire consequences of signal such behaviour by taking into account only first or last zero-crossing moment in previously assumed span of time. But the harmonics analysis could be still affected. The solution could be harnessing of discrete wavelet transform DWT for the window width estimation. It is viable method, if the DWT is applied to the very higher frequency phenomena estimation concurrently.

II. Fundamentals of the method

Nowadays, the discrete wavelet transform DWT is often used for transient and notching analysis [3]. DWT divides the original signal into separated frequency bands. At the same time one should remember that wavelet coefficients of low-pass filters of analysis filter bank are smoothed version of original signal. In particular, the influence of the noise or other higher frequency components is reduced [1]. Then, it is possible to apply interpolation to appropriate wavelet coefficients for efficiency improvement of measurement window width estimation.

The proposed method consists in application of wavelet coefficients *d* of low-pass filter bank for measurement window width estimation. It could be carried out by application of formula:

$$Wd = \frac{[(N-1)+\Delta N] \cdot 2^{j}}{f_s} \tag{1}$$

where: Wd – estimated measurement window width, f_s – sampling frequency, j – number of decomposition layer, N – number of wavelet coefficient calculated for integer number of analysed signal periods.

Since the wavelet coefficients are decimated for each consecutive decomposition layer [3], the N number decreases roughly twofold as well. It has enormous impact for method overall performance. So, the ΔN factor has been calculated for improving the method results. The ΔN can bee defined as follow:

$$\Delta N = \left| \frac{d_{j,0}}{d_{j,0} - d_{j,-1}} - \frac{d_{j,N-1}}{d_{j,N} - d_{j,N-1}} \right| \tag{2}$$

where: $d_{j,-1}$ – the last wavelet coefficient for j decomposition layer calculated in previous measurement window, $d_{j,0}$ – the first wavelet coefficient for j decomposition layer calculated in analysed measurement window, $d_{j,N-1}$ – the last the first wavelet coefficient for j decomposition layer calculated in analysed measurement window, $d_{j,N}$ – the first the first wavelet coefficient for j decomposition layer calculated in next measurement window.

II. Experimental research

The particular case of voltage registered in ship electric power system has been chosen for his research. The part of the registered voltage has been show in Fig. 1. The signal has been acquired with sampling frequency equal to 10504 Hz by Data Acquisition Board DAQ PCI703-16/A Eagle Technology. The voltage has been chosen for the research, because the multiple zero-crossings have been one of the very features of the signal.

The presented research consist of analysis of measurements results of window width by different means. In particular the method based on the first zero-crossing of original signal samples has been compared with methods based on application of wavelet coefficients from different decomposition layers. The comparison has been carried out for window width measurement as well as evaluation of the consequences for harmonic components as harmonic subgroups analysis.

The analysed voltage has been divided into quite a few frequency bands by means of Daubechies filters of length 12 (often used in electric power engineering field [3]). For comparison reasons, the method based on original voltage samples has been applied as well. Finally these methods have been designated as follow:

OVS – original voltage samples method,
WC1 – wavelet coefficients of decomposition first layer,
WC2 – wavelet coefficients of decomposition second layer,
WC3 – wavelet coefficients of decomposition third layer,
WC4 – wavelet coefficients of decomposition fourth layer,
WC5 – wavelet coefficients of decomposition fifth layer.

A. Measurement window width estimation

The first step in estimation of many electric power quality parameters is measurement of window width. The results of evaluation of 300 measurement windows width over span of approximately 60 s have been shown graphically in Fig. 2.

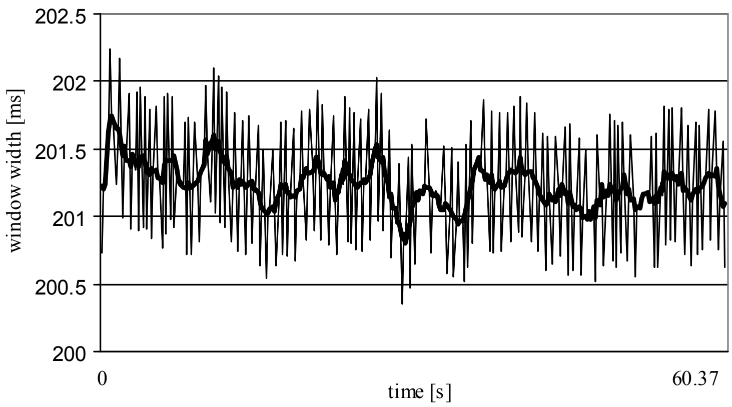

Fig. 2. Results of measurement window width estimation by WC4 method (bold line) and OSV method (thin line).

The impact of multiple zero crossing is easily discernible in the Fig. 2. E.g. for the presented in Fig. 1 sample the window width has been evaluated as equal to 201.767 ms by means OVS method and equal to 201.306 ms by means WC4 method. The Daubechies filter of length 12 has been applied. The difference seems insignificant but has discernible impact on harmonic analysis, presented in the next paragraph.

The above presented effect has resulted from the removing higher frequency components by wavelet filtering. The result of the wavelet decomposition has been shown in Fig. 3.

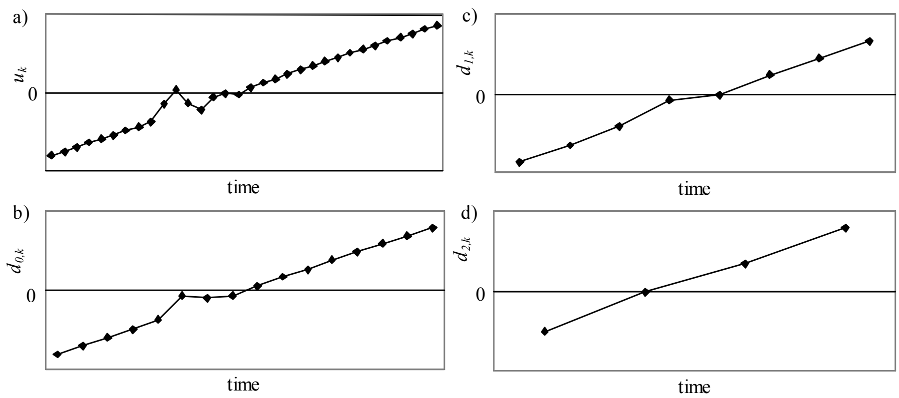

Fig. 3. Example of singular zero-crossing: a) voltage samples, b) wavelet coefficients of first layer of decomposition, c) wavelet coefficients of second layer of decomposition, b) wavelet coefficients of third layer of decomposition.

One can easily observe that there is multiple zero-crossing only for original voltage samples and there is one zero-crossing for wavelet coefficients of all decomposition layers. However, it should be assumed that probability of multiple zero-crossing decreases if used decomposition layer increases. In practical term, the number of decomposition layers should depend on higher frequency phenomena analysis requirement.

B. Harmonic components and subgroups analysis

As it has been mentioned above, the accuracy of measurement window width estimation has enormous impact on harmonic components analysis. Taking into account the widely known shape [4] of rectangular window response (window recommended in IEC standard 61000-4-7 [5]), it could be stated that apart from character of error deviation of window width measurement (plus or minus) the resulting harmonic component analysis would be damped. It can be estimated by means of formula based on the known rectangular window response [4]:

$$U_h^* = U_h \cdot \frac{sin(\pi \cdot \delta f_h)}{\pi \cdot \delta f_h} \quad (3)$$

where: U_h^* - estimated value of h-order harmonic (damped), U_h – actual value of h-order harmonic.

Whereas relative frequency shift δf_h can be calculated as follows:

$$\delta f_h = \frac{\left| f - \frac{K}{WW} \right| \cdot h}{\Delta f} \tag{4}$$

where: δf_h - relative frequency shift for harmonic component of h-order from the main lobe centre, K – number of analysed periods (10 for 50 Hz systems and 12 for 60 Hz systems), WW – measured window width, f – actual fundamental frequency, Δf – frequency resolution.

It is easy discernible that the δf_h can assume relatively great values for harmonics of higher order. Moreover, there is possibility that the value of this factor would be greater than 0.5 or even 1.5. It means shifting the harmonic component to adjacent spectrum bins which are not integer multiple of the 10 (50 Hz systems) or 12 (60 Hz systems). Eventually, in the further investigation only frequency bins with maximum values in the proximity of calculated harmonic bins have been taken into account. Obviously the problem is connected only with OVS method and sometimes WC1 or WC2 methods.

The results of the exemplary spectrum analysis in proximity of fundamental component and fifth harmonic have been depicted in Fig. 4 (the fundamental frequency component has been cut off). It represent analysis of the voltage previously presented in Fig. 1. The spectrum has been analysed by means of digital Fourier transform DFT and rectangular window.

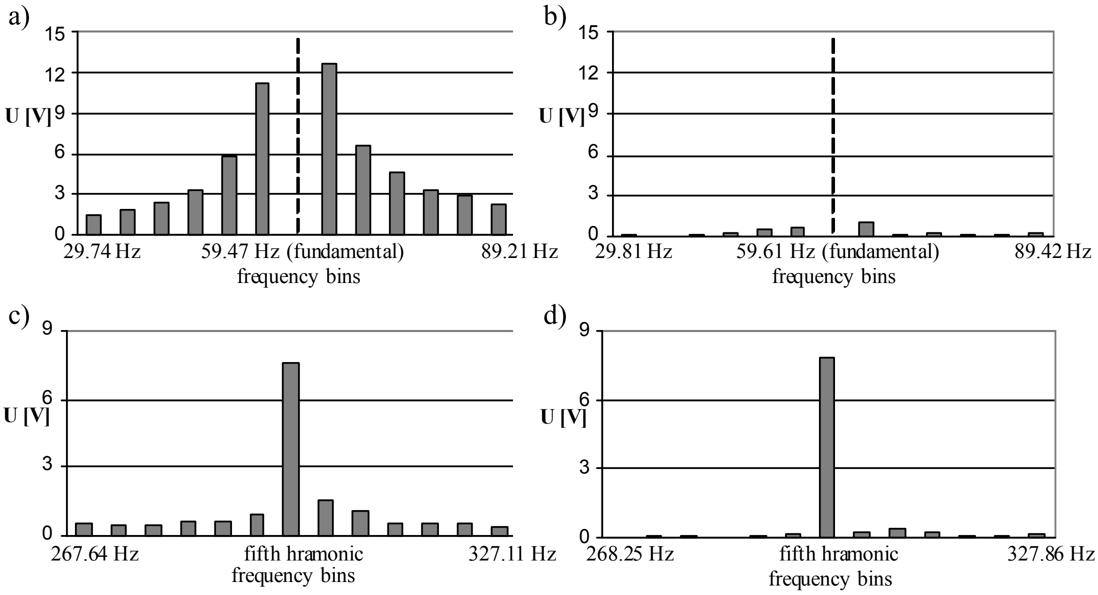

Fig. 4. Results of spectrum measurement a) frequencies adjacent to fundamental component measured by OVS method, b) frequencies adjacent to fundamental component measured by WC4 method, c) fifth harmonic and adjacent frequencies measured by OVS method, d) fifth harmonic and adjacent frequencies measured by WC4 method

The difference is easily discernible. Namely, there is visible spectrum leakage due to inaccurate measurement of window width. So, the measured value of fifth harmonic is equal to 7.59 V for OVS method and 7.88 V for WC4 method. However, if one assumes that the WC4 method yields accurate results the δf_h relative frequency shift can be calculated for fifth harmonic as equal to 0.1374. Finally, assuming that actual U_5 value is equal to 7.88 V, the result of OVS method can be calculated by means of formula (3) as equal to 7.64 V (estimated amplitude damping equal to 0.969). The result of this evaluation is roughly the same like obtained in real measurement.

It has been mentioned above that the analysis has been carried out for 300 measurement windows. The results of the whole analysis have been laid in Table 1. It consists of measurements of window width, THD and chosen harmonics (all harmonics with rms value greater than 5.5 V). The designation in this Table means: EX- mean value, DX – standard deviation, max – maximum observed value, min – minimum observed value. Obviously, there have been only min values for THD and harmonics, since the inaccurate window width estimation causes only damping of the result of the measurement.

The results in Table 1 reveal the enormous impact of chosen method of window width estimation on results of harmonics analysis. Especially, the results obtained by OVS method seem to be corrupted. Further, the quality of analysis deteriorates if harmonic order increases. The effect has been mentioned above and results from formulas (3) and (4). Moreover, there are some differences among methods based on wavelet coefficients. The methods based on wavelet coefficients of greater decomposition layers generally yields better results, albeit from some point (second decomposition layer in considered case) they are fully comparable.

Table 1. Statistical results of measurement window widths, THD and chosen harmonic components

		OVS	WC1	WC2	WC3	WC4	WC5
window width [ms]	EX	201.24	201.24	201.24	201.24	201.24	201.24
	DX	0.40	0.19	0.16	0.15	0.15	0.15
	max	202.24	201.80	201.77	201.76	201.75	201.78
	min	200.35	200.68	200.80	200.78	200.80	200.85
THD [%]	EX	4.49	4.74	4.72	4.77	4.79	4.79
	DX	0.29	0.16	0.12	0.09	0.09	0.09
	min	4.01	4.2	4.28	4.45	4.39	4.36
fundamental component U_1 [V]	EX	440.13	440.44	440.47	440.48	440.48	440.48
	DX	0.59	0.28	0.20	0.20	0.19	0.19
	min	438.87	439.31	439.36	439.35	439.40	439.37
fifth harmonic U_5	EX	8.05	8.18	8.20	8.20	8.20	8.20
	DX	0.21	0.17	0.16	0.16	0.16	0.16
	min	7.62	7.83	7.83	7.83	7.83	7.82
seventh harmonic U_7 [V]	EX	6.25	6.48	6.50	6.50	6.50	6.50
	DX	0.37	0.20	0.18	0.18	0.17	0.17
	min	5.40	5.74	6.00	6.06	6.09	6.07
eleventh harmonic U_{11} [V]	EX	5.40	5.88	5.93	5.94	5.94	5.94
	DX	0.51	0.22	0.12	0.13	0.13	0.12
	min	4.50	5.05	5.53	5.55	5.55	5.55
thirteenth harmonic U_{13} [V]	EX	5.07	5.72	5.78	5.80	5.80	5.80
	DX	0.69	0.30	0.14	0.14	0.14	0.14
	min	3.78	4.48	5.36	5.36	5.36	5.36
seventeenth harmonic U_{17} [V]	EX	4.55	5.45	5.54	5.57	5.58	5.58
	DX	0.93	0.43	0.11	0.10	0.10	0.10
	min	3.45	3.63	5.19	5.28	5.28	5.29
nineteenth harmonic U_{19} [V]	EX	4.74	5.47	5.58	5.61	5.62	5.62
	DX	0.81	0.50	0.14	0.13	0.13	0.13
	min	3.55	3.53	5.09	5.18	5.16	5.09

In the IEC standard 61000-4-7 a concept of harmonic subgroups has been introduced. It is to avoiding consequences of spectrum leakage to frequency bins adjacent to harmonics. The effect is due to voltage amplitude and fundamental frequency fluctuation as well as considered insufficient synchronization (multiple zero-crossings). The idea 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 rms value of harmonic subgroup. The results of statistical analysis for the considered research have been laid in Table2.

Table 2. Statistical results of measurement of chosen harmonic subgroups

Subgroups		OVS	WC1	WC2	WC3	WC4	WC5
fundamental component U_1 [V]	EX	440.36	440.47	440.48	440.49	440.49	440.49
	DX	0.51	0.25	0.20	0.20	0.19	0.19
	min	439.27	439.41	439.39	439.36	439.41	439.38
fifth harmonic U_5	EX	8.19	8.21	8.22	8.22	8.22	8.22
	DX	0.16	0.16	0.16	0.16	0.16	0.16
	min	7.86	7.92	7.91	7.91	7.92	7.92
seventh harmonic U_7 [V]	EX	6.45	6.52	6.52	6.53	6.53	6.53
	DX	0.28	0.19	0.18	0.18	0.17	0.17
	min	5.74	5.93	6.11	6.14	6.14	6.14
eleventh harmonic U_{11} [V]	EX	5.81	5.94	5.95	5.96	5.96	5.96
	DX	0.19	0.13	0.12	0.12	0.12	0.12
	min	5.41	5.55	5.58	5.60	5.60	5.61
thirteenth harmonic U_{13} [V]	EX	5.64	5.80	5.82	5.82	5.83	5.83
	DX	0.22	0.16	0.14	0.14	0.14	0.14
	min	5.20	5.25	5.42	5.42	5.42	5.42
seventeenth harmonic U_{17} [V]	EX	5.37	5.57	5.59	5.60	5.60	5.60
	DX	0.23	0.14	0.10	0.10	0.10	0.10
	min	4.95	5.11	5.32	5.32	5.32	5.32
nineteenth harmonic U_{19} [V]	EX	5.44	5.61	5.64	5.65	5.66	5.65
	DX	0.23	0.17	0.12	0.12	0.12	0.12
	min	5.04	5.00	5.26	5.27	5.27	5.26

Taking into account results laid in Table 2, it can be stated that the in the case of harmonic subgroups analysis the influence of chosen method on measurement results is less significant than in the case of harmonic components measurement. Nevertheless, the methods based on wavelet coefficients still yields better results.

D. Histograms

Since the multiple zero-crossings have been caused by notching, it seems interesting to analyse distribution of measurement results. So, the histograms of measurement results for OVS and WC4 method and above analysed 300 measurements have been depicted in Fig. 5. The results for WC4 method have been designated by solid lines.

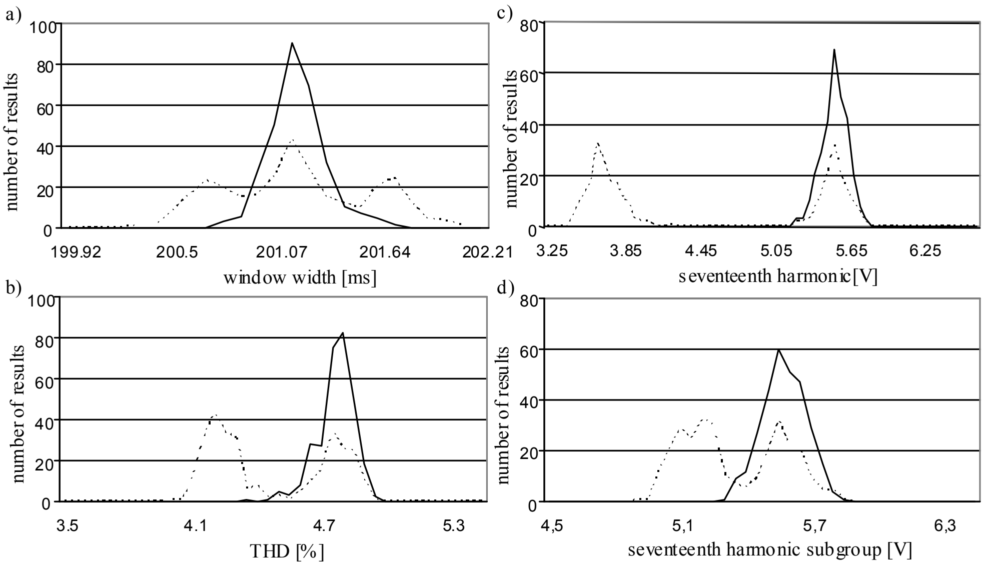

Fig. 5. Histograms of measurement results OSV and WC4 (solid lines) methods: a) window width, b) THD, c) seventeenth harmonic and d) seventeenth harmonic subgroup

Eventually, it can bee stated there are two local extremes while analysing parameters of harmonics distortions by OVS method, albeit the histogram of window width measurements has three local extremes. So, the presented in Fig. 5 results once again reveals advantages of the methods based on wavelet coefficients.

III. Final remarks

The importance of the proper evaluation of measurement window width for power quality estimation can be hardly overstated. The proposed method based on the interpolation of wavelet coefficient is simple and leads to satisfactory results. Moreover, if wavelet transform is to implement for transient analysis, this improvement could be attained virtually without any need of additional computational power of measurement device.

The choice of applied wavelet coefficients (layer of decomposition) for the particular measurement should depend on requirement of transient and notching measurement but it can has some impact on method performance, especially if first decomposition stages are implemented.

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