Using Stationary Wavelet Transform to Evaluate the Instantaneous Components of Fundamental Frequency

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Abstract— **The capabilities related to active filtering of the Stationary Wavelet Transform - SWT were evaluated considering 3 Daubechy wavelet mothers. Firstly a study on errors was performed on synthetic waveforms. The waveforms were obtained from sinusoids polluted by single harmonics with orders from the range 3…40 and magnitudes, respectively phase differences varied in a systematic manner. The differences between the fundamental components (synthetic vs value yielded by SWT) were evaluated with 2 metrics: extreme values and RMSD. 3D representations of the metrics are provided, along with a study of instantaneous values of errors. Afterward 3 sets of signals polluted by 4 harmonics were decomposed. Low harmonics, high harmonics and respectively mixed harmonics were used. A study of errors was performed again. At the end the algorithm was applied over real data. A comparison to FFT analysis results was made. Conclusions on the usability of each of the studied wavelet mother are drawn.**

Keywords— power engineering computing; active filtering; power quality; stationary wavelet transforms.

I. Introduction

Impressive efforts have been made continuously in the recent years to obtain the reference signals (components having the fundamental frequency) from distorted waveforms. Some of the most common are:

- The sinusoidal Signal Integrators (SSI) algorithm, which extracts the sinusoidal current on the tuned frequency [1], [2];
- The positive Sequence Sinusoidal Signal Integrators ([2], [3]);
- Algorithms relying on Fast Fourier Transform (FFT) ([4…8];
- p-q IRP and d-q SRF axes theory algorithms [9] etc.

In [9] the above mentioned techniques were analyzed and it was concluded that when the overall performances were considered, the best algorithm is the one based on *d-q* axes theory because it exhibited the best ability to deal with voltage non-symmetry and distortion, low THD reference current and low computational burden for the Digital Signal Processor (DSP). Also, it has the built-in capability to compensate for reactive power as an active power filter controller.

A technique less exploited is relying on decompositions based on the Stationary Wavelet Transform (SWT) and represents the goal of this study.

II. SWT Decompositions of Synthetic Data Polluted by a Single Harmonic

Sets of pure sinusoids with the magnitude 1000, polluted by single harmonics with harmonic orders ranging from 3 to 40 and phase differences covering the range $[-\pi,\pi]$ with the step $\pi/6$ were generated synthetically. The harmonics magnitudes were varied in steps of 1% within the range [1,10]% from the magnitude of the fundamental component. This technique was successfully used in [10] and [11].

The evaluation of instantaneous values of the component at fundamental frequency (referred from this point on as the "fundamental component – FC") was made considering the "approximations" vectors from the final level of the decomposition tree implementing SWT [12]. A tree with 6 levels was built, considering one period decomposed signals with the length of 256 samples. Three wavelet mothers (wm) from the Daubechy family were employed. Considering the convention of names from MATLAB, from this point on they will be referred as 'db4', 'db14' and 'db20'. The filters lengths are: 8 for 'db4', 28 for 'db14' and 40 for 'db20'. The shorter the filter is, the smaller runtimes are involved by decomposition. On the other hand, the wm-s with longer filters provide a better selectivity of harmonics in the vectors of "details" [13].

The vectors of FC computed with SWT (denoted by CFC) were compared to the synthetically generated values of FC (denoted SFC). A study of errors was made by considering by two metrics relative to the difference (SFC-CFC):

- extreme values of the difference;
- root mean square deviation (RMSD) of the couple (SFC,CFC).

Figs. 1…3 represent the metrics for 'db4', 'db14' and 'db20'. Fig. 4 depicts the errors yielded by all studied wm-s as differences of instantaneous values for a signal polluted with

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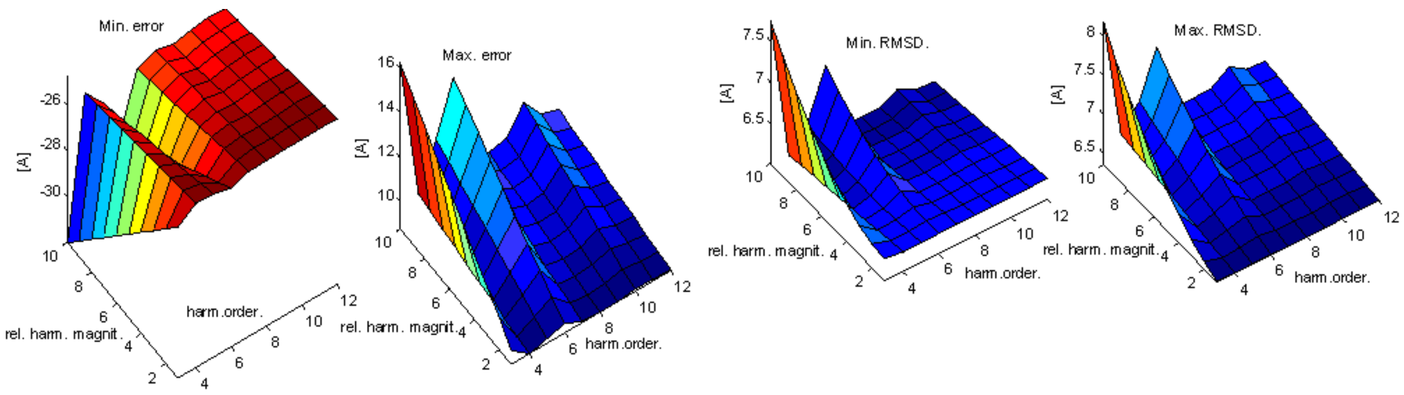

Fig. 1. Extreme values of errors (left) and extreme values of RMSD (generated versus computed fundamental component) for ‘db4’, right.

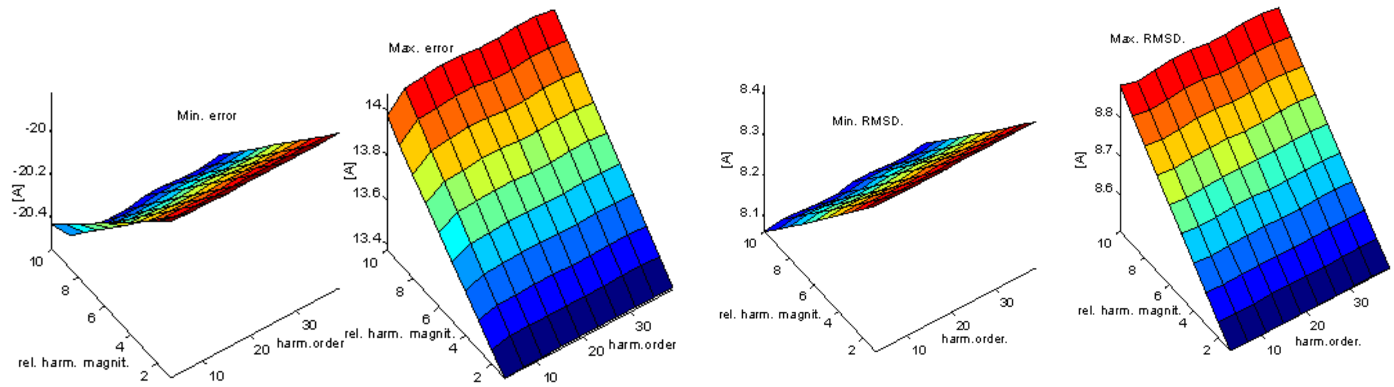

Fig. 2. Extreme values of errors (left) and extreme values of RMSD (generated versus computed fundamental component) for ‘db14’, right.

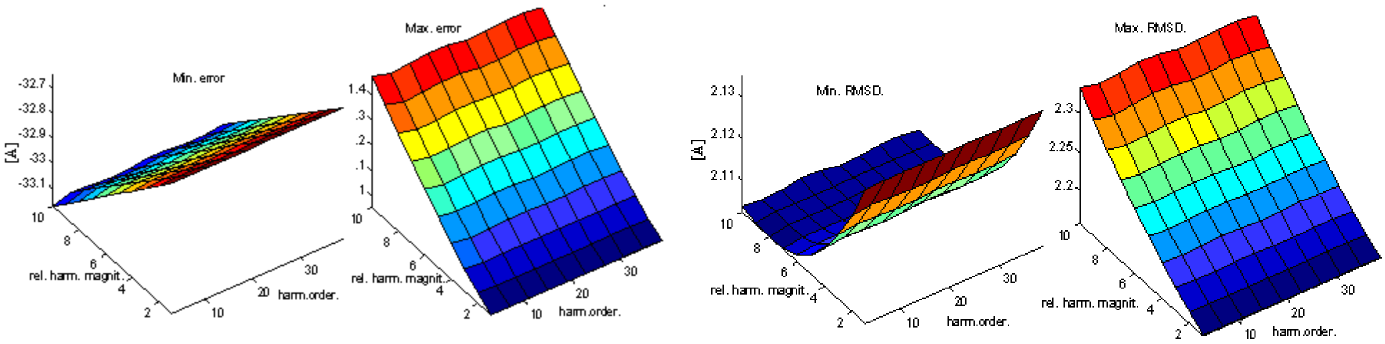

Fig. 3. Extreme values of errors (left) and extreme values of RMSD (generated versus computed fundamental component) for ‘d20’, right.

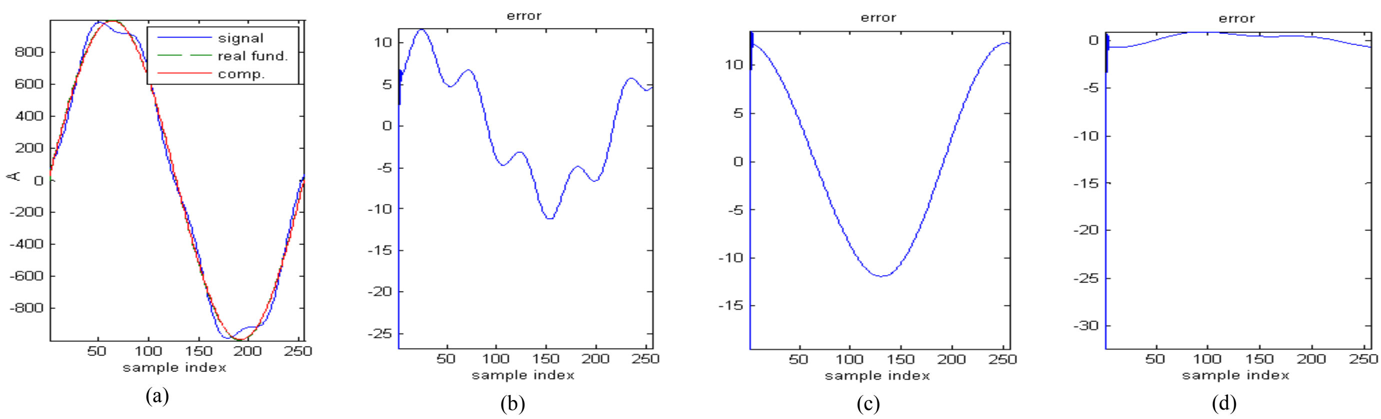

Fig. 4. (a) signal polluted by the 5-th harmonic, overlapped with the generated and computed fundamental components ; (b)…(d) errors yielded by the SWT decompositions when evaluating the fundamental component. From (b) to (d), when using ‘db4’, ‘db14’ and ‘db20’.

a harmonic of order 5, characterized by a phase difference 5π/6 and a magnitude of 10% from the fundamental magnitude.

The study concerned with signals polluted by a single harmonic revealed that the smallest errors are yielded by ‘db20’ whilst the highest are yielded by ‘db4’. Usually the extreme values of errors decrease with the harmonic order. When considering the instantaneous values, the highest errors are concentrated in the left margin of the analyzed period.

III. Study of Errors Generated by SWT while Decomposing Multi-Harmonic Signals

In order to estimate the level of errors in a multi-harmonic context, 3 signals were synthetically generated (now overlapping 4 harmonics over the pure sinusoid) and afterward were decomposed with SWT. The test signals parameters are gathered by Table I. The harmonic orders were chosen such as to allow for the evaluation of errors when the pollution is generated only by low harmonic orders (in practice this usually happens at voltages), only by high harmonic orders and respectively by harmonic orders from the whole ranges (in practice usually this is the case of highly distorted currents).

The test signals are depicted by Fig. 5, along with the instantaneous values of errors yielded by SWT when using the 3 analyzed wm-s.

TABLE I. Characteristics of Test Signals.

Test Signal ID	Harmonic parameter	1-st harm.	2-nd harm.	3-rd harm.	4-th harm.
1		3	5	7	9
2	Harmonic order	31	33	35	37
3		5	13	27	35
1,2,3	Magnitudes (% from the fundamental magn.)	20	12	7	4
1,2,3	Phase diff. [rad.]	-0.7	0.3	2.7	-1.8

Fig. 6 depicts the RMSD of the couple (SFC,CFC). The analysis of SWT decomposition’s results considering the multi-harmonic test signals revealed that ‘db20’ yielded the best results in all cases, whilst the use of ‘db4’ revealed the worst results only for the 1-st test signal.

IV. Studies on Real Data

A three phase system of real currents and voltages acquired in a DSpace based experimental setup was used in order to evaluate the SWT based algorithm performances. Figs. 7 and 8

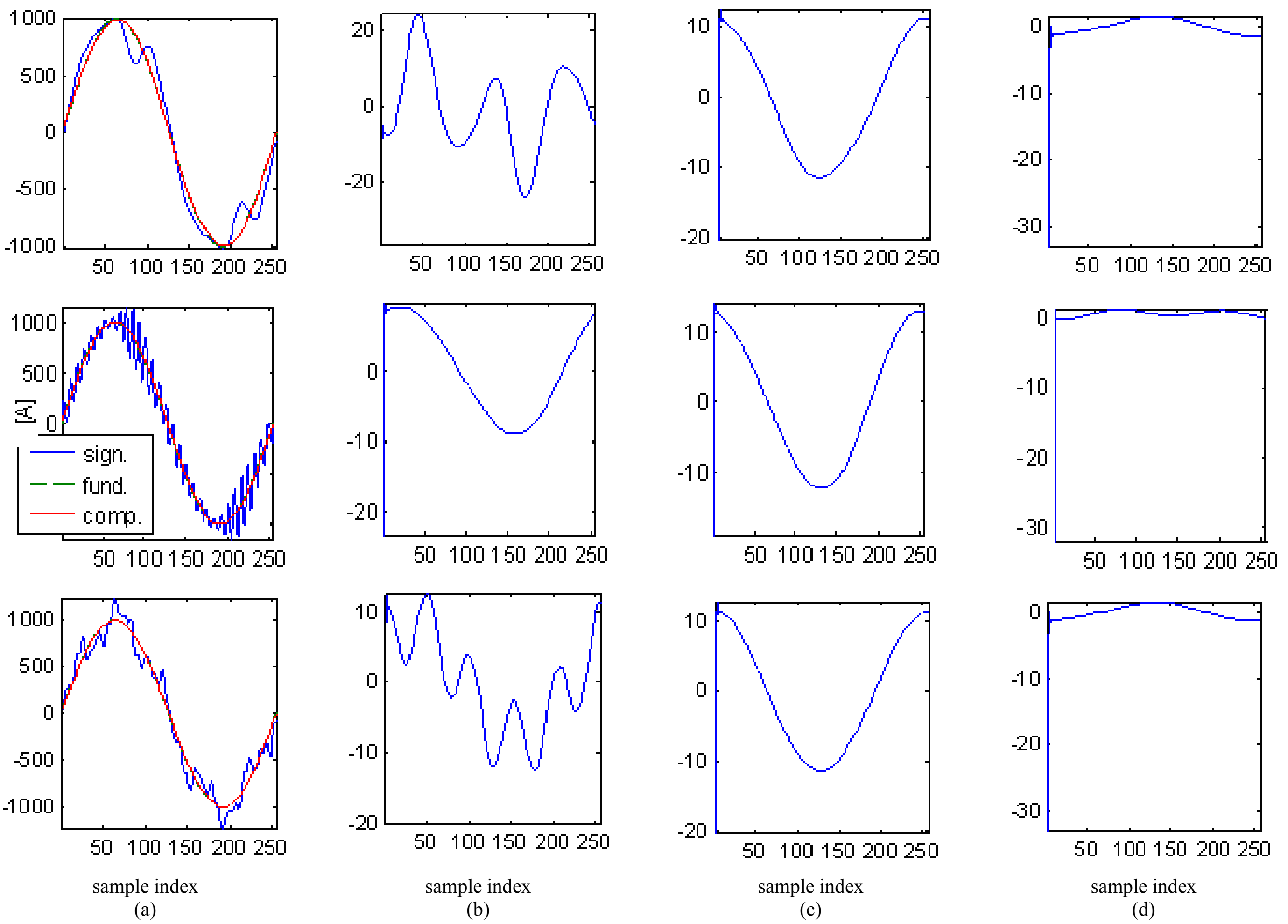

Fig. 5. (a) Test signals overlapped with computed and generated fundamental components (from top to bottom: 1-st, 2-nd and 3-rd); (b)…(d) Errors in evaluating the fundamental component yielded by SWT. From left to right , relying on : db4’, ‘db14’ and ‘db20’.

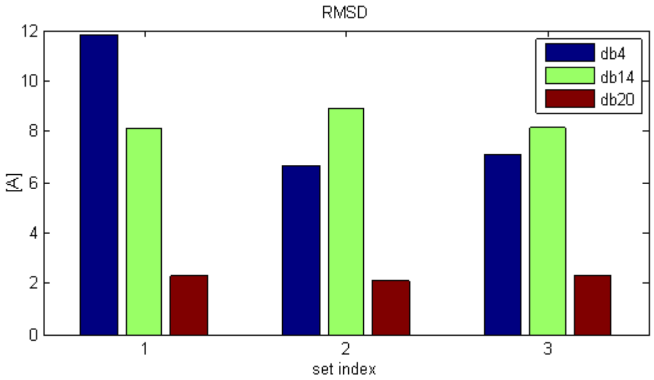

Fig. 6. RMSD of the couple (SFC, CFC) for the multi-harmonic test signals.

depict the currents, respectively voltages overlapped with the fundamental components evaluated with SWT. Fig. 9 depicts the instantaneous values of fundamental components yielded by SWT for currents overlapped with perfect sinusoids generated by using the phase difference and maximum magnitude computed for fundamental by FFT, which assumes that the half-periods are symmetrical.

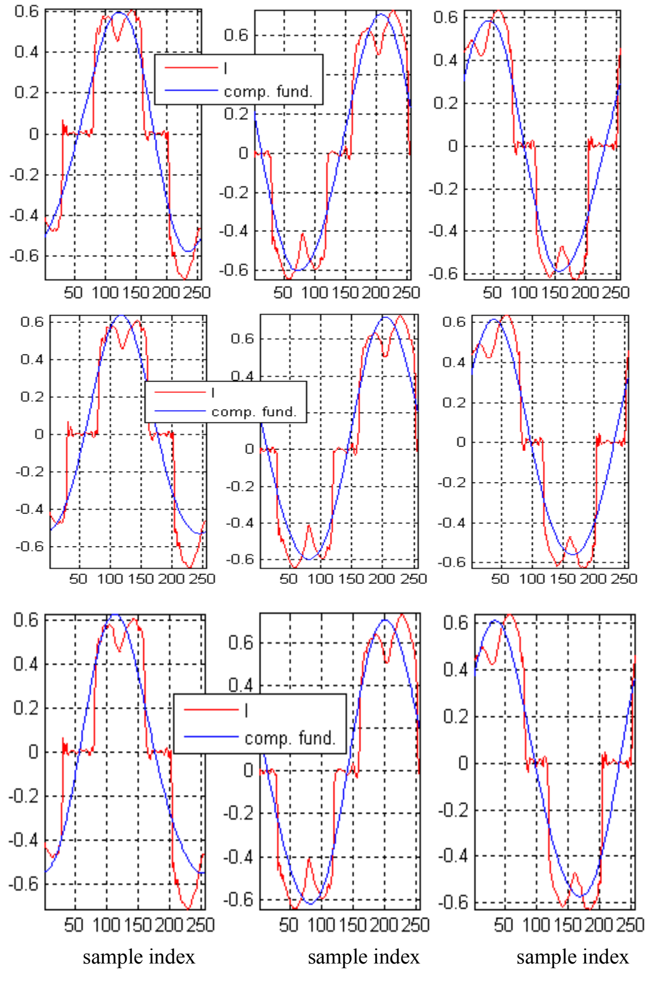

Fig. 7. Real studied currents overlapped with the fundamental components evaluated with SWT : 'db4' (top), 'db14' (middle) and 'db20' (down). From left to right: 1-st, 2-nd and 3-rd phase.

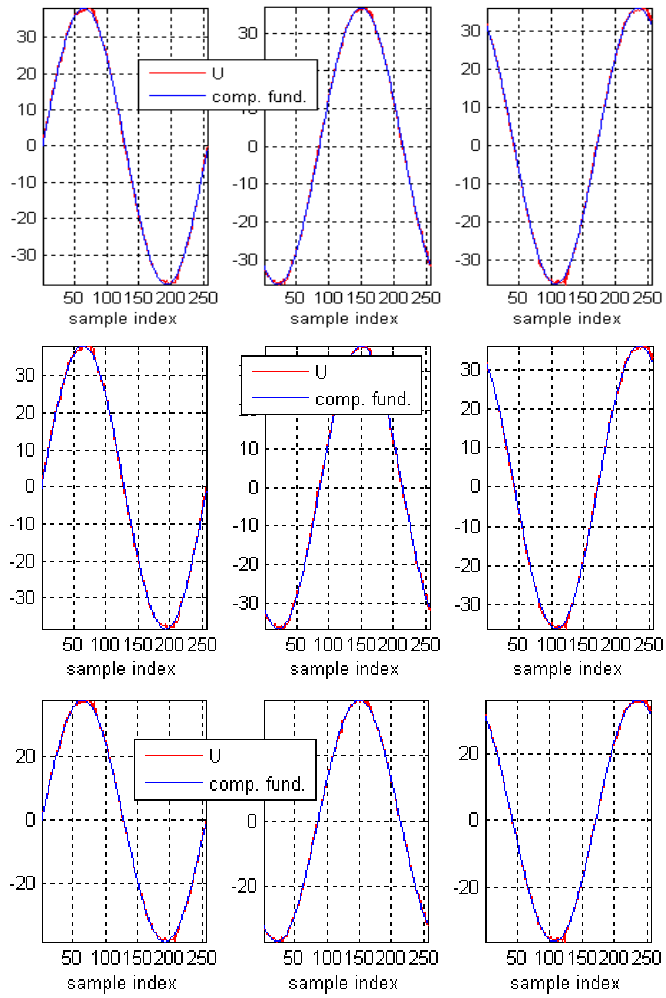

Fig. 8. Real studied voltages overlapped with the fundamental components evaluated with SWT : 'db4' (top), 'db14' (middle) and 'db20' (down). From left to right: 1-st, 2-nd and 3-rd phase.

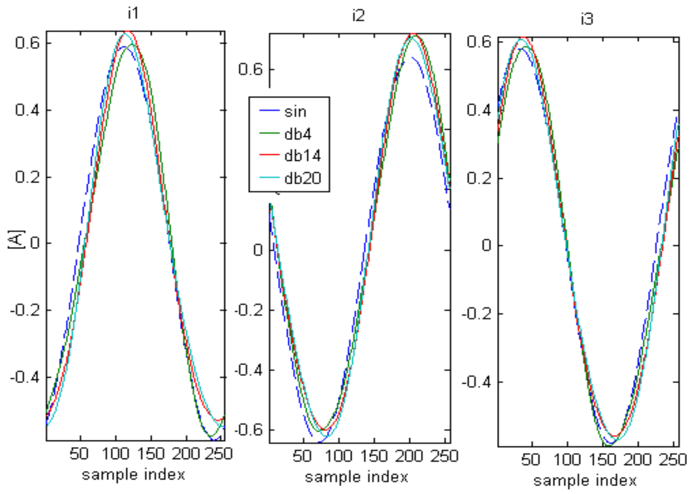

Fig. 9. Instantaneous values of fundamental components yielded by SWT for currents overlapped with perfect sinusoids generated by using the phase difference and maximum magnitude computed for fundamental by FFT.

TABLE II. MAXIMUM MAGNITUDES AND RMS OF FUNDAMENTAL COMPONENTS EVALUATED WITH FFT AND SWT.

I/U	Method	Max. magnitude of fundamental			RMS of fundamental		
		1-st phase	2-nd phase	3-rd phase	1-st phase	2-nd phase	3-rd phase
I [A]	FFT	0.59	0.64	0.58	0.42	0.45	0.41
	'db4'	0.58	0.66	0.59	0.41	0.46	0.41
	'db14'	0.59	0.66	0.59	0.42	0.47	0.42
	'db20'	0.59	0.66	0.59	0.42	0.47	0.42
U [V]	FFT	38.28	36.56	36.33	27.07	25.85	25.69
	'db4'	38.06	36.36	36.1	26.92	25.71	25.53
	'db14'	38.28	36.57	36.30	27.07	25.86	25.67
	'db20'	38.28	36.57	36.30	27.07	25.86	25.67

The most visible differences between instantaneous values (FFT versus SWT) were revealed at the current flowing through the 2-nd phase (Fig. 9). Therefore an evaluation of maximum values across all instantaneous values, respectively of RMS corresponding to phase voltages and currents was made, under the frame of Budeany's theory (by using FFT), respectively of Morsi's theory [14]. The results are gathered by Table II. In all cases the values yielded by 'db14' are identical to those yielded by 'db20" and very close to those yielded by 'db4' (usually a little bit smaller). The values yielded by FFT are almost identical to those obtained with wm-s with longer filters, unless the case of the current through the 2-nd phase. A simple visual inspection of this current in Fig. 7 reveals an increase in the second period. Unlike SWT, this increase is not detected by FFT (which assumes a second half-period symmetrical to the 1-st one).

On the other hand, the less significant harmonic content of voltages and their properties of symmetry when considering the half-periods are reflected by smaller differences between the instantaneous values (FFT versus SWT), as reflected by Fig. 10. Very small differences can be noticed in this figure (in terms of percent relative deviations, they are at most 3.5%). This comes to certify the results from the preliminary evaluations made on synthetic signals from Sections II and III, both relative to the extreme values and respectively to the shape of differences. A special mention should be done relative to the differences recorded by 'db20' , which generates the smallest differences only in 2 out of 3 cases (Fig. 10). Considering all phase voltages, a good alternative seems to be

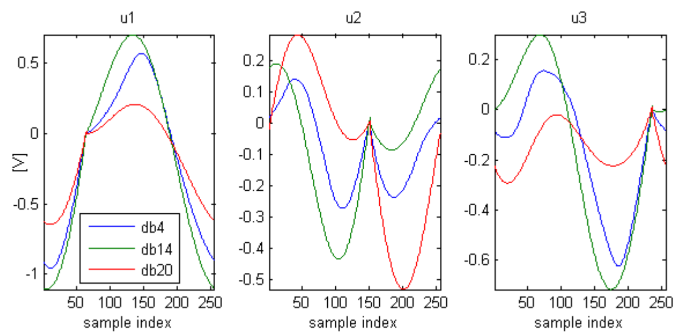

Fig. 10. Differences between the instantaneous values of fundamental components (SWT-FFT) at voltages.

'db4', whose associated runtime is almost 4 times smaller than that involved by 'db20'. In a multithreading implementation [15], the runtime should not be a critical problem. Instead the use of wm-s with longer filters should raise problems when evaluating the components nearby the right edge of the currently evaluated period. When they are not identical to those from the beginning of the above mentioned period, the uncertainty in evaluating the components from the levels of higher orders increases with the length of wm.

V. CONCLUSIONS

A study on SWT capabilities relative to the correct extraction of instantaneous values of fundamental components from distorted signals was made.

Three wavelet mothers were considered, from the Daubechy family. The study of errors considering synthetically generated data (polluted by a single harmonic, respectively by 4 harmonics) revealed good performances of all analyzed wm-s, the filter of length 40 being the best when considering the accuracy and the filter of length 8 being the best when considering the runtime and possibility to evaluate more accurate the components nearby the analyzed period's edges for non-stationary waveforms.

The study on real data confirmed the good results obtained on synthetic signals and revealed the superiority of SWT decomposition relative to the FFT analysis in particular situations as that when the deviations from symmetry of the half-periods is more significant.

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