A wavelet-based transient detector for P and M class phasor measurement unit integration

Julio Barros, Matilde de Apráiz, Ramón I. Diego
Dept. Computing Engineering and Electronics
University of Cantabria
Santander, Spain
julio.barros@unican.es

***Abstract*—In this paper a wavelet-based transient detector is proposed for P and M class phasor measurement unit (PMU) integration. The input waveform in the sampling window is analyzed looking for the local maxima in wavelet coefficients in three different levels to detect a transient previous to the computation of the phasor. If no transients are detected in the wavelet coefficients, the signal is considered stationary, otherwise the signal is considered in dynamic state, so allowing the estimation of the phasor using the most appropriate measurement algorithm for the actual operation conditions. This paper presents some of the preliminary results obtained in the detection of step changes in magnitude and in phase angle and oscillatory and high-frequency transients, also studying the effect of noise and harmonic distortion on the performance of the detection method.**

***Keywords*—M-class, P-class, phasor measurement unit (PMU), power system transients, wavelet transform.**

I. Introduction

Two PMU performance classes are defined in the standard IEEE Std C37.118.1 – 2011: P class and M class. The P class is intended for applications that require fast response, such as protection applications, while the M class is intended for applications that require high measurement accuracy. The standard defines a reference algorithm for each class and the user must choose the performance class that better matches the requirements of the application [1].

A largest number of proposals have been presented in the technical literature to fulfill the performance of the two PMU classes or to improve the performance of the reference algorithm under different static and dynamic conditions. However, only a reduced number report methods for simultaneous compliance of the two PMU performance classes [2]-[7].

In references [2]-[3] an adaptive version of the Taylor-Fourier Transform (TFT) is used to detect when the signal undergoes fast changes to refine the phasor estimation in presence of fast transient events. The method is based on the evaluation of the phasor estimation error to start the refining algorithm. An index is computed for detection of a possible dynamic condition. Two detection criteria are used, the difference between the samples of the input signal and the samples reconstructed from the estimated phasor in the observation window, and the difference between the real and the reconstructed samples in two different parts of the same window. If the combination of the two detections surpasses a given threshold, the observation window is labeled as critical and an adaptive algorithm is started for a new phasor estimate under dynamic conditions in a reduced window length. The same method for detection of a possible transient condition is used in [4] for an adaptive synchrophasor measurement.

In [5] two different configurations of TFT algorithm and a step change detector are used to provide the correct phasor measurement under fast transient conditions. Two simultaneous estimates of the phasor are made using two different weighting matrices. A transient detector detects rapid changes of the phasor using the first and the second derivatives of the phasor amplitude and phase angle, allowing the choice of the better of the two parallel synchrophasor estimates.

Reference [6] proposes an algorithm to fulfill simultaneously the performance of the two PMU classes. Two TFT algorithms, with different lengths and different window parameters, process in parallel the samples of the signal. A detector of fast changes, using the first and the second derivatives of the phasor amplitude and phase angle, identifies the possible presence of a dynamic condition, selecting the most appropriate output for the actual operating condition. In this proposal the two alternative channels are not compliant, separately, with P and M classes, but are designed for complementary conditions, so, according to the authors, the overall system meets the requirements of both classes.

Instead of using P- and M-class PMU devices in parallel with selection of the appropriate result, as in other proposals, reference [7] proposes the use of a hybrid P/M class PMU with the steady-state M-class accuracy and temporary P-class behavior with a faster response time when automatically detecting a transient condition. A trigger is issued when a step change in amplitude or phase angle is detected, which switches to the P-class response for amplitude and phase angle estimation, but retains M-class response for frequency and ROCOF.

In this paper we propose a different method. Instead of using two different phasor estimation algorithms and a transient detector for identifying the possible dynamic condition in the voltage and current waveforms in order to select the most adequate estimate of the two, the method

This work received financial support from the Spanish Ministry of Economía y Competitividad, Plan Estatal de Investigación Científica y Técnica y de Innovación 2013-2016, through the grant ENE2014-54039-R.

978-1-5386-0343-7/17/$31.00 ©2017 IEEE

proposed analyzes the samples of the input signal in the observation window (the one with the time stamp) using the wavelet transform to detect a step transient previous to the estimation of the phasor. As a result, the most appropriate phasor estimation algorithm that adapts best to the actual conditions of the power system can then be selected.

The paper is arranged as follows: Section II describes the algorithm proposed, Section III presents the results obtained in simulation for detection of abrupt step changes in magnitude and phase angle, high-frequency transients and power oscillations, studying the effect of noise and harmonic distortion on the performance of the method, and finally, Section IV presents the conclusions.

II. TRANSIENT DISTURBANCES AND WAVELET-BASED DETECTION

The power system can suffer from a number of electromagnetic and electromechanical transient disturbances that produce discontinuities or oscillations in voltage and current waveforms.

Faults and switching operations produce steps, ramps and high-frequency components in voltage and current waveforms. Lighting produces very fast transients with high-frequency components. Power swings, produced when there is no balance between power generation and power consumption, appear as amplitude and/or phase angle modulation of voltage and current waveforms, modulated with a low-frequency signal corresponding to the deviation of the rotation speed of generators. The estimation of phasors in these dynamic conditions may produce erroneous results as is reported in [8].

Different methods, based on the use of a dynamic model of the signal, have been proposed for phasor estimation under dynamic conditions, trying to fulfill the requirements of the dynamic tests of IEEE Std C37.118.1 [9]-[12].

An adaptive method for phasor estimation in power system waveforms containing transients is presented in [13]. A wavelet method, with a quadratic B-Spline wavelet function, is used for detection and identification of singularities in the signal in the sampling window. An adaptive window using the data after or before the singular point detected, excluding the transient, is then used to compute the phasor, avoiding or minimizing in this way the impact of the transient.

In our proposal, the detection of a step transient disturbance is carried out using the wavelet-based step transient detector. Fig. 1 shows the block diagram of the detector. The proposal is based on the fact that fast transitions in a signal can be effectively located using the modulus maxima of the wavelet transform coefficients with sharp variations in different resolution levels [13]-[14].

A three-level wavelet analysis with db4 wavelet function and 12.8 kS/s sampling frequency (256 samples/cycle in a 50 Hz power system) is applied to the observation data window (the one with the time stamp for synchrophasor estimation) looking for singular points in the wavelet coefficients to detect and identify possible step transients.

Using a 12.8 kS/s sampling frequency, wavelet coefficients in level 1 to 3 of the wavelet analysis (coefficients $d_1(k)$, $d_2(k)$, and $d_3(k)$ respectively), cover the 6.4 – 3.2 kHz, 3.2 – 1.6 kHz and 1.6 – 0.80 kHz frequency bands respectively.

If there are no singular points in the wavelet coefficients in level 1 of the wavelet analysis, i.e. there is no local maxima in the coefficients over a detection threshold, the detection process is terminated, the waveform is considered in stationary state and the magnitude, phase angle and frequency of the phasor can then be computed using the appropriate estimation algorithm. Otherwise, the signal is considered to be in transient state, and the wavelet coefficients of level 2 and level 3 are computed to confirm the step transition and its possible identification. If the local maxima in coefficients of level 2 and level 3 were not over their respective detection threshold, the transient is rejected and the signal is considered in stationary state.

The magnitude, phase angle and frequency of phasor can then be computed applying the most adequate phasor estimation algorithm to the input samples in the data window for this operation condition. The method proposed can also be used to report the transient state condition in the sampling window.

Implementation and threshold

The selection of the step transient detection thresholds in the different resolution levels of wavelet analysis is one of the key points in the practical implementation of the detection method. To this end the mean value $\overline{d}_i$ and the standard deviation σ_{di} of wavelet coefficients $d_i(k)$ in stationary state for each resolution level are previously computed. The detection threshold selected is $\overline{d}_i + 5\sigma_{di}$, enough for detection of abrupt step transients in different power system conditions, discriminating them from the background noise.

The wavelet-based step transient detection method developed enables the real-time detection of a transient during the next cycle of the sampling window, because of the reduced number of multiplications and additions required for the computation of the wavelet coefficients.

III. SIMULATION RESULTS

This section considers the most important transient disturbances that can severely affect the estimation of the phasor in power system networks in order to demonstrate the performance of the transient detection method proposed.

Abrupt step changes in magnitude and phase angle, high frequency transients and power oscillations, with different magnitude, point-on-wave of beginning and frequency, are studied in this section, also considering the effect of noise and harmonic distortion on the performance of the method.

In all the test signals the sampling frequency used is 12.8 kS/s, with 0.1% gaussian noise and 0.5%, 2.7% and 1.1% magnitude of 3rd, 5th and 7th order harmonic components respectively having been superimposed onto the signal.

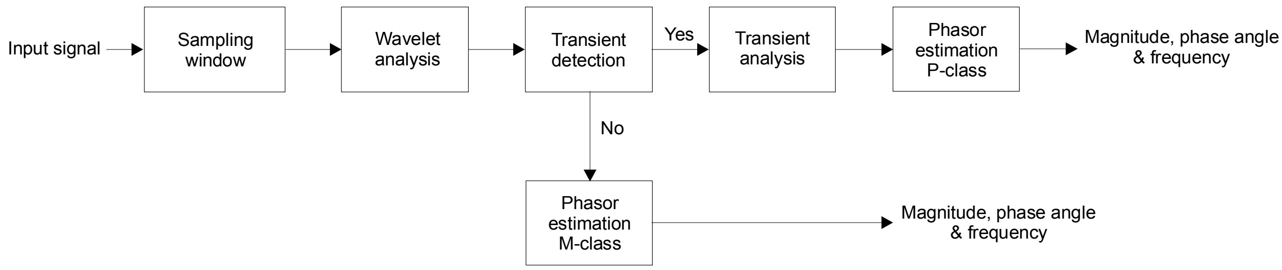

Fig. 1. Block diagram of the wavelet-based step transient detector.

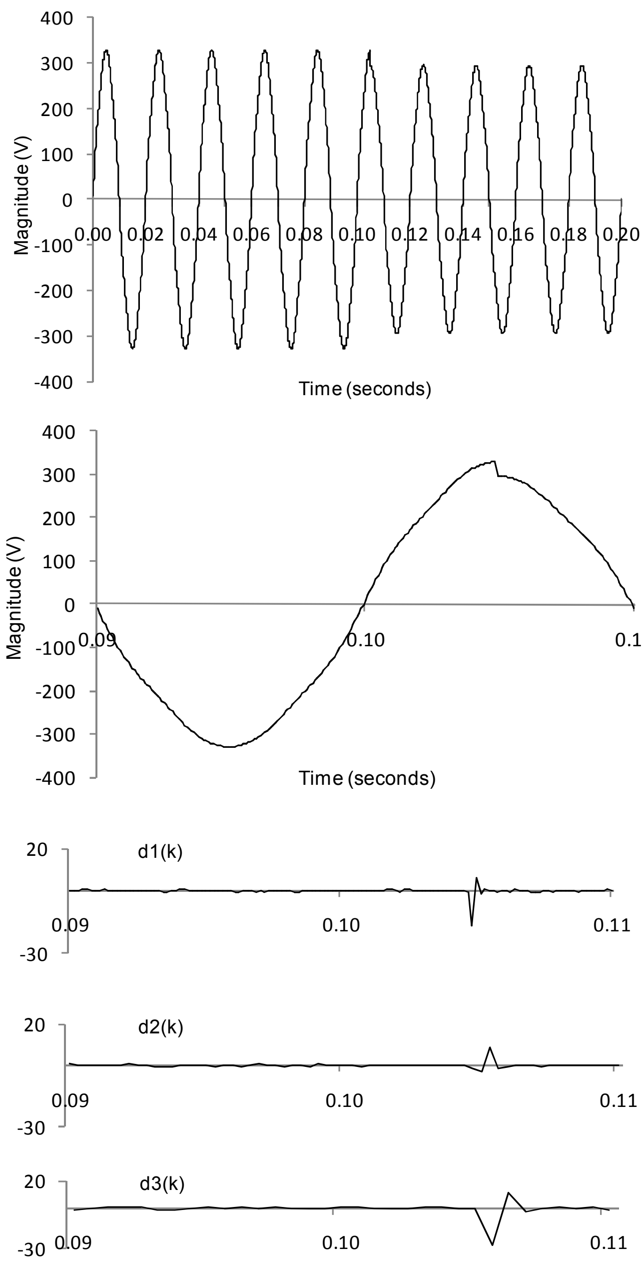

Fig. 2. Input signal with an 10% step change in magnitude and wavelet coefficients in level 1 to 3 of the transient detector.

Step change in magnitude. Fig. 2 shows a ten-cycle record of a 230 V sinusoidal waveform with a 10% step change in magnitude at instant 0.105 seconds of the record. The cycle of the input signal with the transient and the time evolution of the wavelet coefficients of the three-level wavelet analysis applied on the cycle with the transient are also shown.

Table I shows the detection thresholds in the different resolution levels and the modulus maxima $|d_i(k)|$ of wavelet coefficients in the sampling window. As can be seen from Fig. 2 and Table I, the step change in magnitude is clearly detected and time located in levels 1-3 of the wavelet coefficients computed by the transient detector.

TABLE I. WAVELET COEFFICIENTS FOR THE STEP CHANGE IN MAGNITUDE IN FIG. 2

	Wavelet coefficients		
	Level 1	***Level 2***	***Level 3***
Detection threshold	1.52	1.74	3.18
Modulus maxima |di(k)|	16.55	8.5	26.87

Step change in phase angle. As an example of the performance of the method in the detection of a step change in phase angle, Fig. 3 shows a 10 cycle record of a 230 volt sinusoidal waveform with a -10º step change in phase angle at instant 0.107 of the record. Fig. 3 also shows a zoom area of the cycle with the transient and the time evolution of the wavelet coefficients computed by the transient detector in the cycle with the transient.

The modulus maxima $|d_i(k)|$ of wavelet coefficients in the sampling window, shown in Table II, are clearly over the detection threshold in each resolution level, enabling the precise detection of the step change in phase angle.

TABLE II. WAVELET COEFFICIENTS FOR THE STEP CHANGE IN PHASE ANGLE IN FIG. 3

	Wavelet coefficients		
	Level 1	***Level 2***	***Level 3***
Detection threshold	1.52	1.74	3.18
Modulus maxima |di(k)|	9.13	17.48	24.24

High-frequency transients. Fig. 4 shows a ten-cycle record of a 230 V sinusoidal waveform with 100 volts magnitude, 5 kHz frequency of oscillation and 0.8 ms time constant oscillatory transient at instant 0.105 seconds of the record and a zoom with the cycle of the signal with the transient.

The oscillatory transient has been modeled using the expression A exp(-t/τ) cos(2πf$_t$t), where A is the magnitude, f$_t$ the frequency of the oscillation and τ the time constant [15].

Table III shows the detection thresholds and the modulus maxima $|d_i(k)|$ of wavelet coefficients in the sampling window. The time evolution of the wavelet coefficients of the three-level wavelet analysis applied on the signal shows the adequate detection and localization of the oscillatory transient in the input signal.

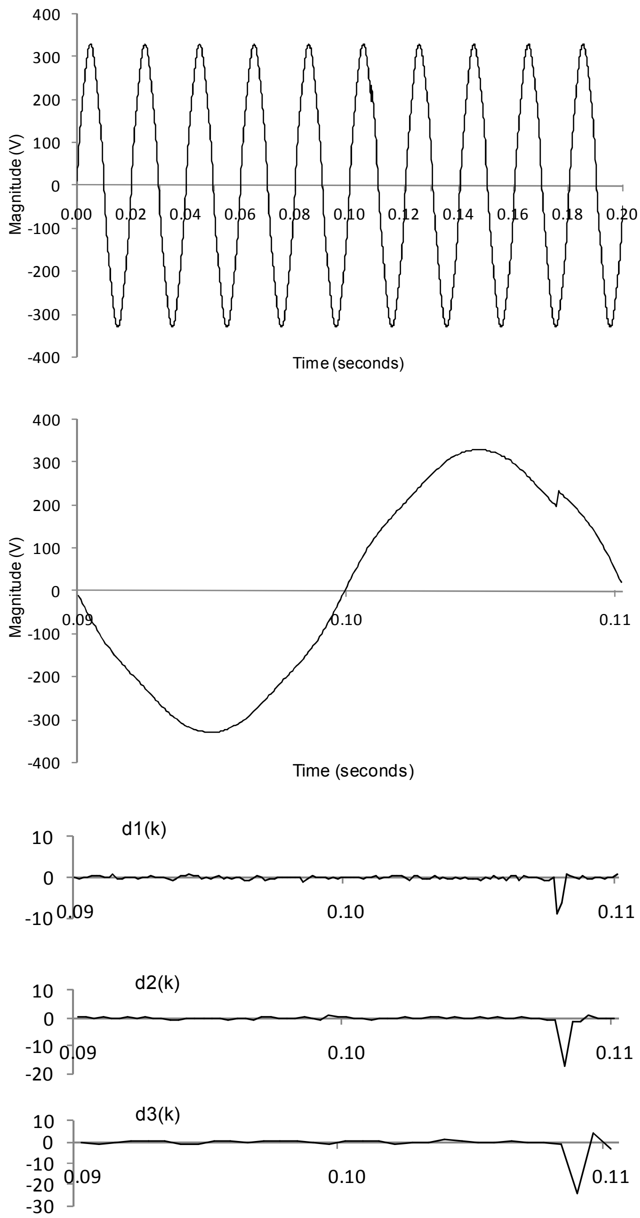

Fig. 3. Input signal with a step change in phase angle and magnitude of wavelet coefficients in level 1 to 3 of the transient detector.

TABLE III. WAVELET COEFFICIENTS FOR THE HIGH FREQUENCY TRANSIENT IN FIG. 4

	Wavelet coefficients		
	Level 1	***Level 2***	***Level 3***
Detection threshold	1.52	1.74	3.18
Modulus maxima |di(k)|	154.17	18.17	6.53

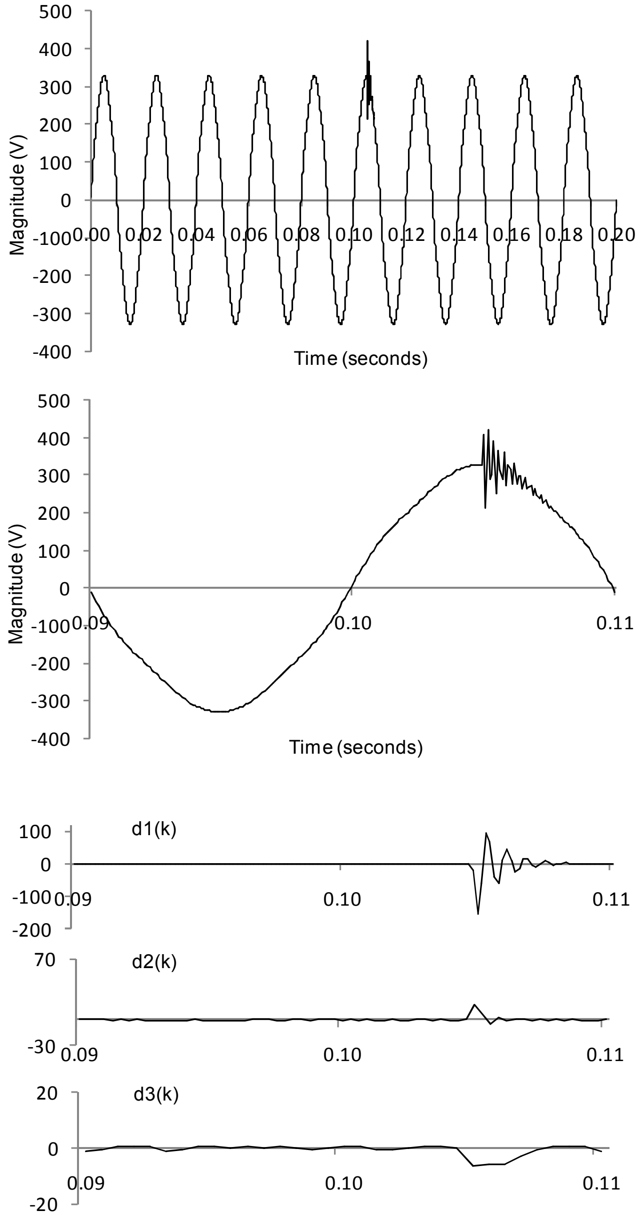

Fig. 4. Input signal with an oscillatory transient and wavelet coefficients in level 1 to 3 of the transient detector.

On the other hand, Fig. 5 shows a ten-cycle record of a 230 V sinusoidal waveform, in this case with an impulsive transient at instant 0.105 seconds of the record. The figure also shows the cycle with the transient and the time evolution of the wavelet coefficients. The impulsive transient is modeled using expression [16]:

$$A\,[1-\exp(-\frac{t}{\tau_1})]\exp(-\frac{t}{\tau_2})$$

with A = 3 p.u., τ_1= 1 ms and τ_2 = 2 ms.

The modulus maxima $|d_i(k)|$ of wavelet coefficients in the sampling window are 12.10, 26.65 and 14.71 for level 1 to 3 respectively. As can be seen the modulus maxima of wavelet coefficients are clearly over the detection threshold in each resolution level, enabling the precise detection of the impulsive transient.

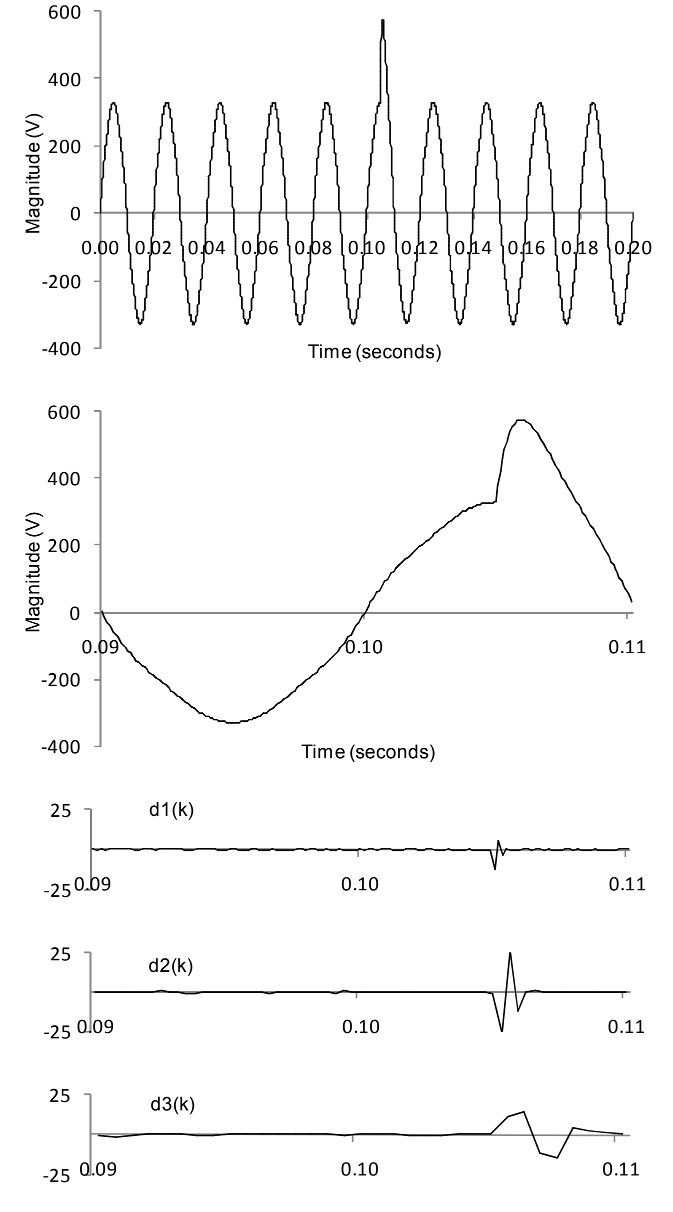

Fig. 5. Input signal and wavelet coefficients for the cycle of the signal with the impulsive transient.

Power swing after a fault. Finally, to test the performance of the method in the case of a complex transient disturbance, the record shown in Fig. 6 of a 230 V magnitude voltage waveform with a fault at instant 0.1 seconds followed by a power swing after the clearance of the fault at instant 0.3 seconds is used as the input signal for the step transient detector. The power oscillation has an amplitude modulation of 10% of the nominal voltage and 10 Hz modulation frequency.

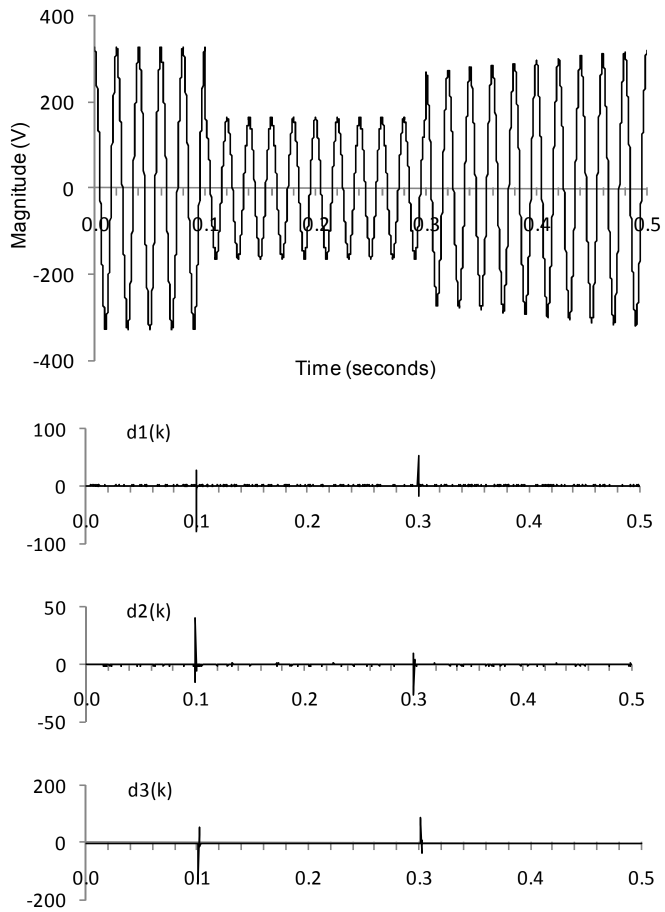

Fig. 6. Wavelet coefficients of the transient detector for a signal with a fault followed by a power swing.

As can be seen in Fig. 6, the modulus maxima of the wavelet coefficients at the different resolution levels are clearly over the different detection thresholds, detecting both, the fault condition and the power swing.

IV. CONCLUSIONS

This paper presents the preliminary results obtained in the application of a simple wavelet-based step transient detector for P and M class phasor measurement unit integration. The sampling window with the time stamp is analyzed looking for the local maxima in wavelet coefficients in three different levels to detect a step transient previous to the estimation of the phasor. The performance of the detector has been verified under abrupt step change in magnitude and in phase angle, high-frequency transients (oscillatory and impulsive) and in the case of a fault followed by a power swing after the clearance of the fault, also studying the effect of noise and harmonic distortion on the performance of the detector. The detection method proposed, which is insensitive to off-nominal frequency conditions and to out-of-band interference, can be implemented in real-time and enables the presence of a step transient in the sampling window to be reported.

References

[1] IEEE Std C37.118.1-2011, IEEE standard for synchrophasor measurements for power systems, IEEE Power and Energy Society, 2011.

[2] P. Castello, M. Lixia, C. Muscas, and P.A. Pegoraro, "Adaptive Taylor-Fourier synchrophasor estimation for fast response to changing conditions," IEEE I2MTC 2012, 13-16 May 2012, pp. 294-299.

[3] P. Castello, P. Ferrari, A. Flammini, C. Muscas, and S. Rinaldi, "An IEC 61850-compliant distributed PMU for electrical substations," Proc. 2012 IEEE AMPS, Aachen, Germany, September 2012, pp. 1-6.

[4] P. Castello, P. Ferrari, A. Flammini, C. Muscas, and S. Rinaldi, "A new IED with PMU functionalities for electrical substations," IEEE Trans. on Instrumentation and Measurement, vol. 62, no. 12, December 2013, pp. 3209-3217.

[5] P. Castello, J. Liu, A. Monti, C. Muscas, P.A. Pegoraro, and F. Ponci, "Toward a class 'P+M' phasor measurement unit," Proc. 2013 IEEE AMPS 2013, Aachen, Germany, September 2013, pp. 91-96.

[6] P. Castello, J. Liu, C. Muscas, P.A. Pegoraro, F. Ponci, and A. Monti, "A fast and accurate PMU algorithm for P+M class measurement of synchrophasor and frequency," IEEE Trans. on Instrumentation and Measurement, vol. 63, no. 12, December 2014, pp. 2837-2845.

[7] A.J. Roscoe, "Exploring the relative performance of frequency-tracking and fixed-filter phasor measurement unit algorithm under C37.118 test procedures, the effects of interharmonics, and initial attempts at merging P-class response with M-class filtering," IEEE Trans. on Instrumentation and Measurement, vol. 62, no. 8, August 2013, pp. 2140-2153.

[8] A.G. Phadke and B. Kasztenny, "Synchronized phasor and frequency measurement under transient conditions," IEEE Trans. on Power Delivery, vol. 24, no. 1, January 2009, pp. 89-95.

[9] J. A. de la O Serna, "Dynamic phasor estimates for power systems oscillations," IEEE Trans. on Instrumentation and Measurement, vol. 56, no. 5, Oct. 2007, pp. 1648–1657.

[10] M. A. Platas-Garza and J. A. de la O Serna, "Dynamic phasor and frequency estimates through maximally flat differentiators," IEEE Trans. on Instrumentation and Measurement., vol. 59, no. 2, Apr. 2010, pp. 1803–1811.

[11] J. A. de la O Serna and J. Rodriguez-Maldonado, "Taylor–Kalman–Fourier filters for instantaneous oscillating phasor and harmonic estimates," IEEE Trans. on Instrumentation and Measurement, vol. 61, no. 2, Apr. 2012, pp. 941–951.

[12] R. Mai, Z. He, L. Fu, B. Kirby, and Z. Bo, "A dynamic synchrophasor estimation algorithm for online application," IEEE Trans. on Power Delivery, vol. 25, no. 2, Apr. 2010, pp. 570–578.

[13] J. Ren and M. Kezunovic, "An adaptive phasor estimator for power system waveform containing transients," IEEE Trans. on Power Delivery, vol. 27, no. 2, April 2012, pp. 735-745.

[14] S. Mallat and W.L. Hwang, "Singularity detection and processing with wavelets," IEEE Trans. on Information Theory, vol. 38, no. 2, Nov. 1986, pp. 679-698.

[15] IEEE Std 1159-2009, IEEE Recommended practice for monitoring electric power quality, 2009.

[16] IEEE C62.41-2002, IEEE Recommended practice on surge voltages in low-voltage ac power circuits, 2002.