Transient detection in phasor measurement units with Kalman filtering

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Abstract—**This paper presents a method based on the use of the residual of an Extended Kalman filter for step transient detection in phasor measurement units. The residual in a Kalman filter, defined as the difference between the measurement and the estimation, is close to zero when the signal is in stationary state but presents a significant increase at the beginning of a sudden change, when a large mismatch appears between the measurement and the estimation. Comparing the instantaneous magnitude of the residual with an adequate detection threshold, a step transient can be detected in the input signal. The paper studies the performance of the method in the detection of step transients in magnitude and phase angle, power swings, high-frequency transients and transient harmonic distortion in power system networks.**

Index Terms--**Kalman filtering, phasor measurement units (PMUs), power system transients.**

I. INTRODUCTION

Transient disturbances in power system networks produce discontinuities and oscillations in voltage and current waveforms that can severely affect the estimation of phasors in these dynamics conditions [1]. The synchrophasor measurement standards define the performance requirements for phasor measurement units (PMUs) for steady-state and dynamic compliance [2, 3], defining two PMU performance classes: the M-class performance for applications that require high measurement accuracy and the P-class performance for applications that required fast response.

The presence of undesirable components in the input signal, such as step changes in magnitude or in phase angle, amplitude or phase angle modulation, high-frequency components, frequency ramps or step changes in frequency, could produce large errors in the estimation of the phasor magnitude and phase angle, frequency and rate of change of frequency.

A number of digital signal processing algorithms have been proposed to increase the accuracy of phasor estimation under dynamic conditions, reducing the errors, but, in general, at the cost of increasing the response time of the PMUs. However, some of these errors are difficult to correct, as is the case of the estimation of frequency and ROCOF using conventional techniques in the case of phase steps in the input signal [4].

Different methods have been proposed to detect transients and other power system disturbances at the application level using the results reported by PMUs [5, 6]. On the other hand, an adaptive method for phasor estimation in power system waveforms containing transients is proposed in [7]. A wavelet method is used for detection and identification of singularities in the signal in the sampling window, and 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.

Another alternative method could be the detection of a transient in the sampling window in order to flag this window for suitable processing in specific applications. In [8], a method is proposed to pre-analyze 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 phasor estimation. The method can be implemented on-line, detecting the step transient in the next cycle of the input signal, allowing the flagging of the sampling window.

In this paper we propose the use of an Extended Kalman filter (EKF) for on-line estimation of the magnitude, phase angle, frequency and rate of change of frequency of the phasor of the input signal and, simultaneously, the detection of a sudden step change in the signal using the residual of the Kalman filter. The paper is arranged as follows: Section II describes the algorithm proposed for transient detection with Kalman filters. Section III presents the results obtained under simulation for the detection of step changes in magnitude and phase angle, step changes in harmonic distortion and, high-frequency transients. Section IV reports some experimental results obtained in a low-voltage distribution network and, finally, Section V presents the conclusion.

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II. TRANSIENT DETECTION AND KALMAN FILTERING

A Kalman filter is a recursive algorithm that provides the best estimate of a magnitude with the smallest number of samples, in the shortest time, allowing variable parameters to be tracked over time and, so being especially useful in real-time digital signal processing.

The EKF is a modified version of the linear Kalman filter that is applied in systems with non-linear processes and measurement equations. In each step of the recursive algorithm, the non-linear equations are linearized at the latest estimate, using a first order Taylor series, and then the linear Kalman filter model is applied.

In the implementation of an EKF a mathematical model of the system in state variables is used. The estimated non-linear random process and the measurements can be modelled by:

$$x_{k+1} = f[x_k, k] + w_k$$

$$z_k = h[x_k, k] + v_k$$

where x_k and z_k are the state vector and the measurement at instant k, f and h are nonlinear functions, and w_k and v_k are the uncertainties introduced by the state transition and the measurement noise, both with zero mean and covariances Q_k and R_k respectively.

The discrete process and the measurement equation are linearized using a first order Taylor series:

$$x_{k+1} = \Phi_k x_k + w_k$$

$$z_k = H_k x_k + v_k$$

where Φ_k and H_k are the state transition matrix and the measurement matrix respectively, and

$$\Phi_k = \frac{\partial f_i[x_k, k]}{\partial x_j}$$

$$H_k = \frac{\partial h_i[x_k, k]}{\partial x_j}$$

with f_i and h_i the ith elements of functions f and h.

The Kalman filter is a two-step prediction-correction process. Starting with an initial estimate of the process x'_k, and its error covariance matrix P'_k, the measurement at instant k, z_k, is used to improve the estimation. A linear combination of the estimate and the measurement is chosen according to the equation:

$$x_k = x'_k + K_k (z_k - H_k x'_k) \tag{1}$$

where x_k is the estimation update at instant k and K_k is the filter coefficient. Making use of the state transition matrix the filter is projected ahead using the measurement at instant k+1 and so on. Kalman filter equations can be found in [9].

In a Kalman filter the residual at instant k, ε_k, is defined as the difference between the measurement z_k and the estimation x'_k and is computed in each step of the recursive algorithm.

$$\varepsilon_k = z_k - H_k x'_k \tag{2}$$

The residual is a scalar number that is a function of the error between the estimation and the measurement. It is null when the signal is in stationary-state and presents a significant increase at the beginning of a transient disturbance, when the mismatch between the measurement and the estimation is high.

The residual in a Kalman filter allows the detection of sudden changes in a signal and has been used in power quality for different applications, such as voltage dip detection and classification, power quality disturbance detection and segmentation, transformer fault discrimination, and others [10]-[13].

The transient detection capability of the use of the residual depends on the magnitude of the change, on the suitable selection of the detection threshold and on the adequate Kalman filter model. Large sudden changes in a signal produce large residual. In our approach the EKF is not only used for detection of a step transient in the signal, but also for the estimation of the magnitude, phase angle and frequency of the phasor.

A. Transient detection threshold

When the absolute instantaneous magnitude of the residual ε_k is over a predetermined threshold a sudden transient can be detected in the input signal. The transient detection threshold is computed using the residual of the Kalman filter in stationary-state in each specific power network.

As an example, Fig. 1 shows the time evolution of the residual of the 13-state EKF when applied to a 1-second voltage record with 230.25 rms voltage, 0.11%, 2.66%, 1.09%, 0.42% and 0.08% of 3rd, 5th, 7th, 9th and 11th order harmonic components, recorded in the low-voltage distribution network of our laboratory on the university campus. The mean value $\overline{\varepsilon_k}$ and the standard deviation of the residual $\sigma_{\varepsilon k}$ are -0.09 and 0.45 respectively for this record.

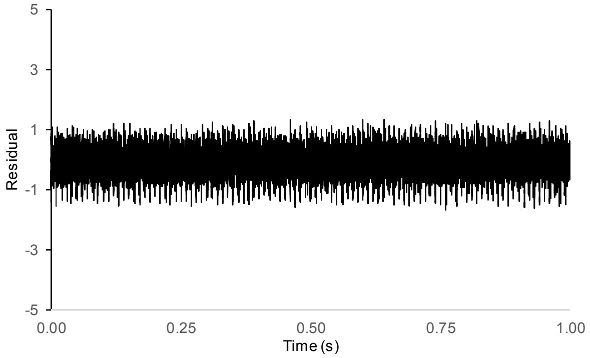


Figure 1. Time evolution of the residual of the 13-state EKF in a 1-second record of voltage supply in stationary-state in a low-voltage distribution network.

The detection threshold selected is $\overline{\varepsilon_k} + 3\sigma_{\varepsilon k}$, enough for the discrimination of a step change in the signal from the background noise in this low-voltage distribution network.

III. SIMULATION RESULTS

This section presents the results obtained in the detection of step changes using simulated voltage records with some of the disturbances described in the dynamic compliance test in the synchrophasor measurement standards [2, 3]. Abrupt step changes in magnitude and phase angle, power oscillations, high frequency transients and transient harmonic distortion, with different magnitude, point-on-wave of beginning and frequency, are considered in this section, computing the magnitude, phase angle, frequency of the phasor and the residual for each record.

Four-second records of voltage waveforms of 230 V magnitude, 50 Hz power system frequency and 6.4 kS/s sampling frequency have been used in all the simulations. A 13-state EKF with fundamental and the odd harmonic components from 3rd to 11th order and the system frequency have been selected as state variables for phasor estimation and step transient detection. This recursive filter has proven to be an efficient solution to model the power system signal and represents a good compromise between accuracy and computational complexity [9]. Once a step transient is applied to the test signal, the filter is re-initialized to improve its transient response to the step change.

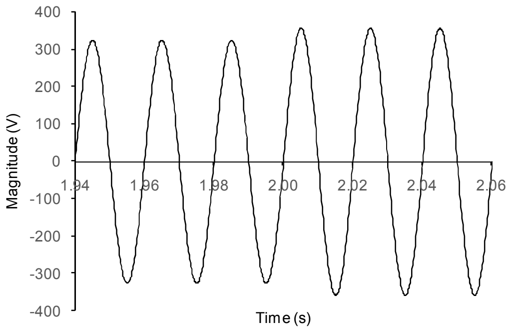
A. Step change in magnitude

Voltage waveforms records with step changes in magnitude from +1% to +10% of nominal voltage in steps of 1% at instant 2 seconds of the record, have been used to estimate the phasor and the residual for step transient detection.

As an example of the capability of the method proposed for step change detection Fig. 2 shows the voltage waveform, magnitude of the fundamental phasor and the time evolution of the residual for the case of a record with a +10% step change in magnitude, computed with the 13-state EKF. As can be seen the method used is able to track step changes in magnitude, with the residual clearly indicating the beginning of the step change, enabling the flagging of the record.

B. Step change in phase angle

To test the performance of the method in the detection of step changes in phase angle, 4-second records of voltage waveform with step changes in phase angle from +1° to +10° in steps of 1° have been used to estimate the phasor and the residuals for transient detection.



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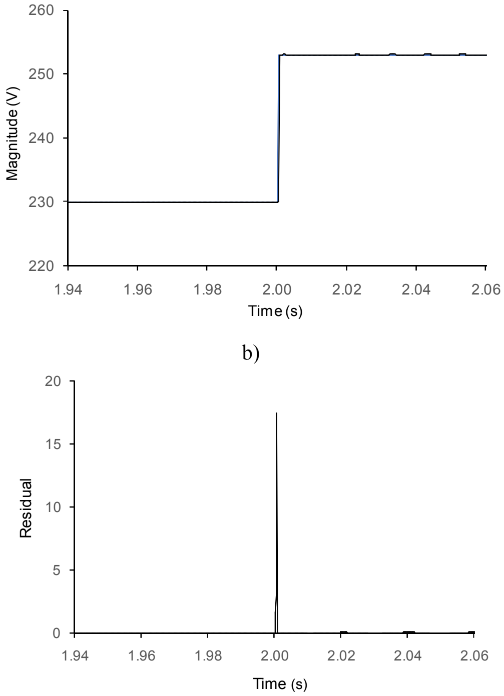

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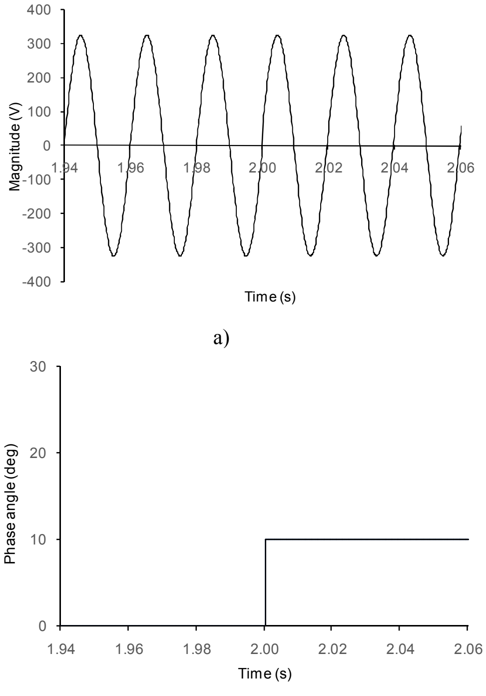
c)

Figure 2. a) Voltage waveform with a +10% step change in magnitude, b) magnitude of the phasor, and c) magnitude of the residual.

Fig. 3 shows the results obtained for the case of a +10° step change in phase angle at instant 2 seconds of the record. Again, the residual clearly indicates the beginning of the step change in phase angle.



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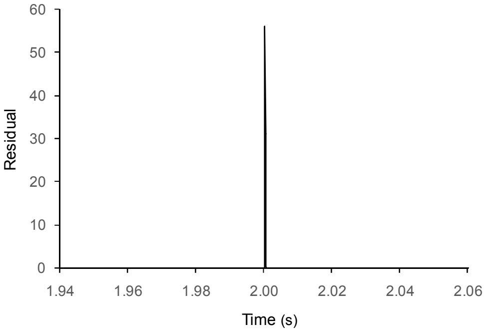

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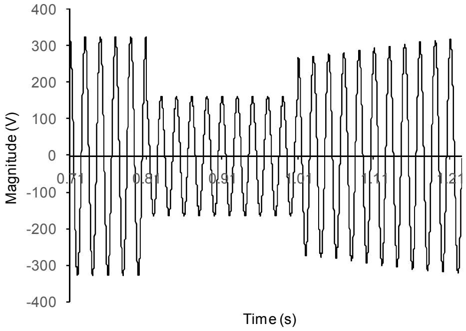
Figure 3. a) Voltage waveform with a +10º step change in phase angle, b) phase angle of the phasor, and c) magnitude of the residual.

C. *Power oscillations*

Fig. 4 shows an example of a power swing after the clearance of a fault to test the performance of the transient detection in the case of a complex transient disturbance [7]. A record of a 230 V r.m.s., 50 Hz voltage waveform with a 50% magnitude fault at instant 0.81 seconds followed by a power swing after the clearance of the fault at instant 1.01 second is considered.

The power oscillation has an amplitude modulation of 10% of the nominal voltage and 10 Hz modulation frequency. Fig. 4 also shows the magnitude of the fundamental and the residual obtained using the 13-state EKF proposed.

As can be seen from Fig. 4, the residual clearly indicates both the beginning of the fault condition and the power swing.



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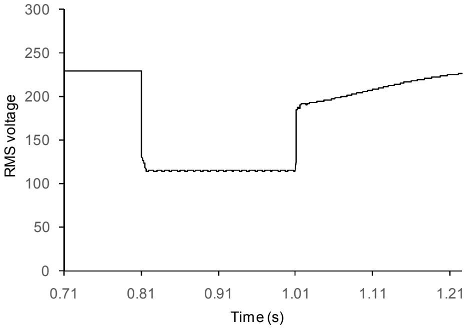

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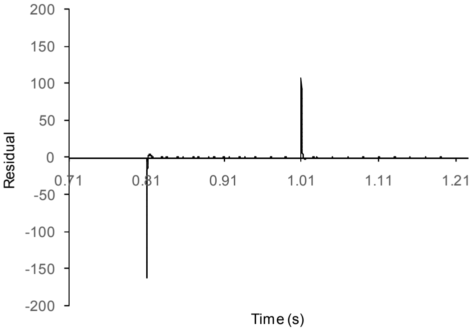

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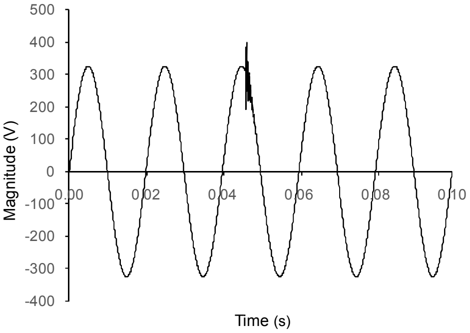
Figure 4. a) Voltage waveform of a power swing after the clearance of a fault, b) rms voltage, and c) time evolution of the residual.

D. *High frequency transients*

As an example of the performance of the method in the detection of high frequency transients, Fig. 5 shows a record of a 230 V, 50 Hz, pure sinusoidal waveform with 100 volts magnitude, 5 kHz frequency of oscillation and 0.8 ms time constant oscillatory transient and the time evolution of the residual during the record. 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.

The time evolution of the residual of the 13-state EKF shows the appropriate detection and localization of the oscillatory transient in the input signal.



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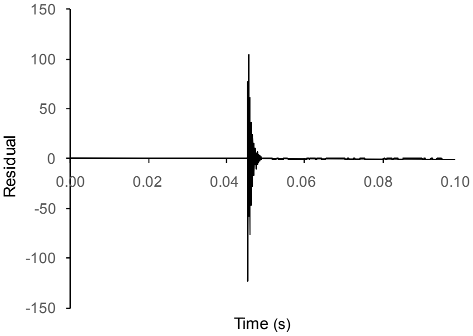

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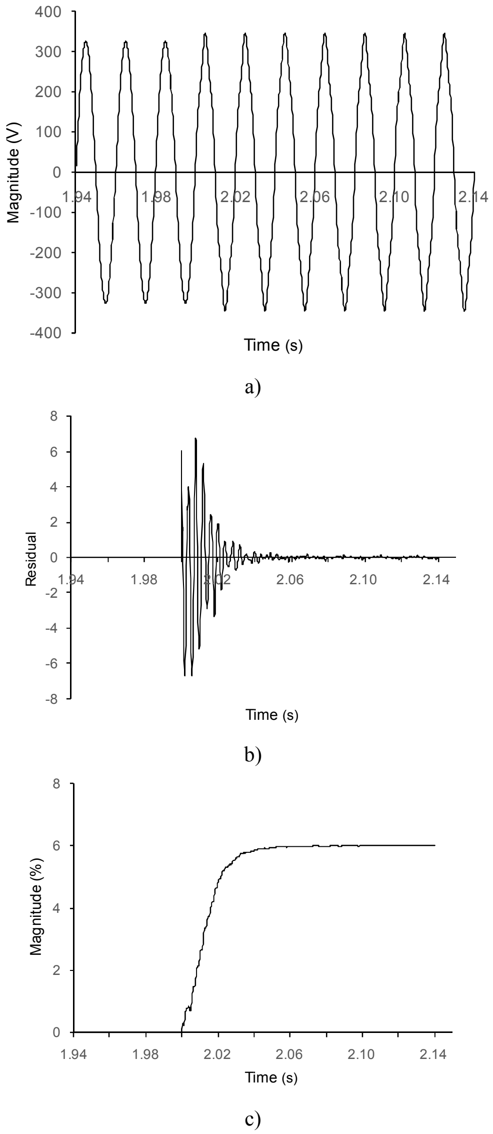
Figure 5. a) Voltage waveform with an oscillatory transient and b) time evolution of the residual.

E. Step changes in harmonic components

Simulated voltage records with different step changes in magnitude of 3rd, 5th and 7th order harmonic components have been used to test the capability of the method proposed in the detection of step transients in harmonic components.

Fig. 6 shows the results obtained in the case of a 4-second pure sinusoidal voltage supply record with a 0% to 6% step change in magnitude of 5th order harmonic component at instant 2 seconds of the record, the magnitude of the 5th order harmonic component and the time evolution of the residual during the record, clearly indicating the step change in magnitude of this harmonic component.



a)

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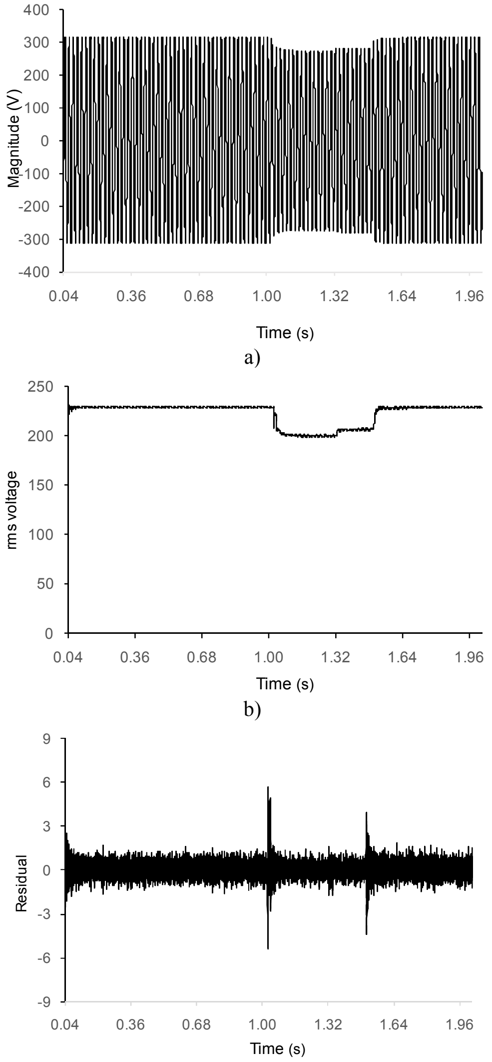
Figure 6. a) Voltage waveform with a 6% step in magnitude of 5th order harmonic component, b) time evolution of the residual, and c) time evolution of magnitude of the 5th order harmonic component.

IV. EXPERIMENTAL RESULTS

As an example of the detection capabilities of the method proposed, this section presents some of the results obtained in the detection of steps transient in voltage supply in a 230 V, 50 Hz low-voltage distribution network. A two-step voltage dip is detected in voltage supply, with the residual clearly indicating the step change in magnitude in the beginning and the end of the voltage dip.



a)

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Figure 7. a) Voltage waveform with a two-step voltage dip, b) rms voltage, and c) time evolution of the residual.

V. CONCLUSION

This paper presents the results obtained in the application of the residual of an Extended Kalman filter for step transient detection in phasor measurement units. Comparing the instantaneous magnitude of the residual with a suitable detection threshold, a step transient can be detected in the input signal. The performance of the detection method has been verified under step changes in magnitude and in phase angle, high-frequency transients, harmonic transients and power swings and also with real signals recorded in a low-voltage distribution network.

The detection method proposed can be implemented in real-time and enables the flagging of the sampling window, or the phasor computed, for appropriate processing.

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