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High Rate Report Synchrophasor Technique during Dynamic Conditions

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Current industrial applications of synchrophasors in intelligent grids depend to a great extent on highly trustable measurements, mainly during dynamic conditions of a power system, like a power swing which exhibits simultaneous variations of amplitude and phase in both voltage and current. This work presents the assessment of the performance of a novel synchrophasor technique following tests of the dynamic section of the IEEE Std. C37.118.1-2011, which requests testing the simultaneous variations of amplitude and phase.

Keywords: Power system monitoring, frequency measurement, phasor measurement units, synchrophasor estimation

Introduction

Control and observability of power flow in an interconnected power system are some of the main drivers for using reliable synchrophasor measurements in intelligent grids[1-5]. Different techniques of synchrophasor measurement devices for use under dynamic state are well described. Early approaches related to the Discrete Fourier Transform (DFT)[6].Some work on the use of synchrophasors for dynamic applications, like the Taylor expansion model based on least-squares method for convergence is well known[7].The Taylor-Kalman-Fourier transform is used reporting satisfactory results claiming to deliver synchrophasor estimators in one single processing cycle using a linear transformation[8]. However, very few works found in literature that analyze power system during dynamic conditions are suitable to be implemented in a physical instrument [9-10].In this work, an improved measurement technique for instantaneous frequency of a time varying sinusoidal signal is presented. The main contribution is, that he enhanced technique allows for the measurement of simultaneous variations of amplitude, phase and frequency that a voltage or current signal may undergo during dynamic power system conditions. The measuring technique was implemented in a processing PXI platform.

Measuring Algorithm

The synchrophasor technique is based on a pair of band-limited and orthogonal FIR filters, supported by an adaptive gain algorithm to adapt in real time the gain of the filters while keeping fixed their length to one cycle of the nominal fundamental frequency. A brief insight of the algorithm is shown in figure 1a), where $x(t)$ represents either a voltage or current input signal. Measurement of a current signal implies a robust discriminating technique to extract in real time the fundamental frequency from no stationary noise. An assessment of the reliability of the measuring technique is performed in this work. The input signal $x(t)$ is decomposed in its orthogonal components and filtered within a narrow bandwidth, where the gain of the filters is corrected by a unit-gain adaptive algorithm which allows to track the fundamental frequency in real time; the final stage calculates the estimates of frequency, amplitude and phase. The orthogonal decomposition shown in figure 1a), may be associated with the orthogonal components of the TVE shown figures 1 b) and c), i.e. the real and imaginary parts of the signal denoted by $x_r(t)$ and $x_i(t)$, respectively. When a pulse of synchronization arrives at the measurement system as in figures 1b), typically through a GPS receiver, a pair of reference signals are generated: $x_r(t)$, and $x_i(t)$. At the same time, a reference synchronization signal is triggered for the rate report. Regarding the proposed technique, if an input signal $x(t)$ is applied at its input, the adaptive orthogonal filters produce estimations of the

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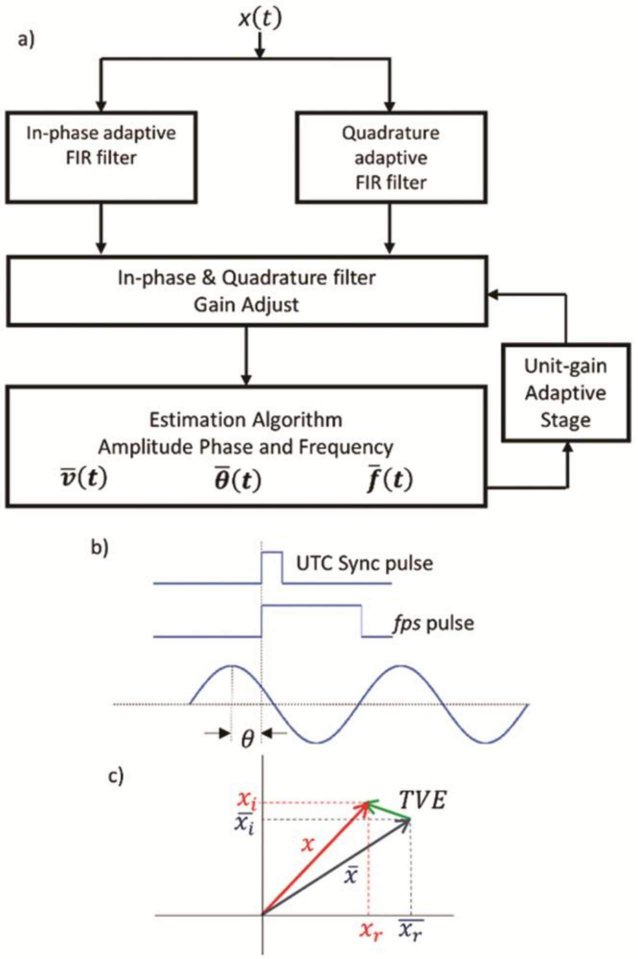

Fig. 1 — Proposed technique for synchrophasor. a) Unit gain orthogonal decomposition of an input signal allows measuring its amplitude and phase, b) UTC synchronization basic scheme, c) TVE composition

orthogonal components of the input signal. The estimates denoted by $\bar{x}_r$and $\bar{x}_i$ for the real and imaginary components, respectively, allow using the orthogonal components to estimate the amplitude $\bar{x}(t)$, phase $\bar{\theta}(t)$, and frequency $\bar{f}(t)$. The reference and the estimated orthogonal components are used to estimate the TVE, FE and shown in figure 1c) for TVE.

By using the values of the decomposition, it is possible to estimate the fundamental frequency as shown in Equation (1):

$$\bar{f}(t) = \frac{\bar{x}'_i\bar{x}_r - \bar{x}'_r\bar{x}_i}{2\pi T_s[\bar{x}_r{}^2 + \bar{x}_i{}^2]} + \frac{2\pi^2 T_s{}^2 \bar{f}_0}{3} + \left(\beta\bar{f}_0{}^2 + \alpha\bar{f}_0 + f_k\right) \quad \ldots (1)$$

where $\bar{f}(t)$ is the instantaneous value of the fundamental frequency; $\bar{x}_i$ and $\bar{x}_r$ represent the quadrature and in-phase components of *v(t)*; $\bar{x}'_i$and $\bar{x}'_r$ stand for the time derivative of the quadrature and in-phase components of *x(t)*. T_s is the value of the sampling frequency; finally, $\bar{f}_0$is a one-step forward estimate of the fundamental frequency. A quadratic model is required in order to automatically estimate the fractional frequency deviation compensation, being an improvement of the original technique. The values for fractional deviation adjustment are: α = 0.316 x 10^{-6}, β = 5.4 x 10^{-6} Hz^{-1}, and f_k= 6.0477 x 10^{-3} Hz. The amplitude$\bar{x}(t)$, and the phase$\bar{\theta}(t)$ components of the input signal are obtained from Equations (2) and (3) respectively,

$$\bar{x}(t) = \sqrt{(\bar{x}_r)^2 + (\bar{x}_i)^2} \quad \ldots (2)$$

$$\bar{\theta}(t) = \tan^{-1}\left(\frac{\bar{x}_i}{\bar{x}_r}\right) \quad \ldots (3)$$

When the estimates of the orthogonal components are available, the algorithm compares them against the reference orthogonal components. The reference components are available upon arrival of the GPS pulse of synchronization; these reference components represent a reference synchrophasor. The algorithm delivers report rates (*fps*) higher than the recommended in [20]. Theoretically it is possible to report estimates of amplitude, phase and frequency at the sampling frequency once the first fundamental cycle is completely recorded and processed. In the implementation of the technique on a PXI platform the reports of the measuring algorithm are fully synchronized to the universal coordinated time (*UTC*). The orthogonal band-pass filters extract the fundamental frequency component from DC, harmonic frequencies and out-of-band additive noise components that may be present in the input signal. The value of the orthogonal components is corrected by a unit-gain algorithm as the frequency of the fundamental component may deviate from nominal.

Performance evaluation technique using dynamic section of the Std. IEEE C37.118.1-2011

In order to assess the performance of the proposed synchrophasor technique under dynamic conditions as established in the IEEE Std. C37.118.1-2011, the measuring technique was implemented on a PXI platform. This platform contains three modular items, a real-time controller (*PXI 8119*), a GPS receiver and timing card (*PXI*-6683), and a dynamic acquisition card based on Delta-Sigma Analog-to-Digital Converter (*PXI-4462*). These three elements can be seen in figure 2a). According to the standard the indices used for evaluating the performance are the

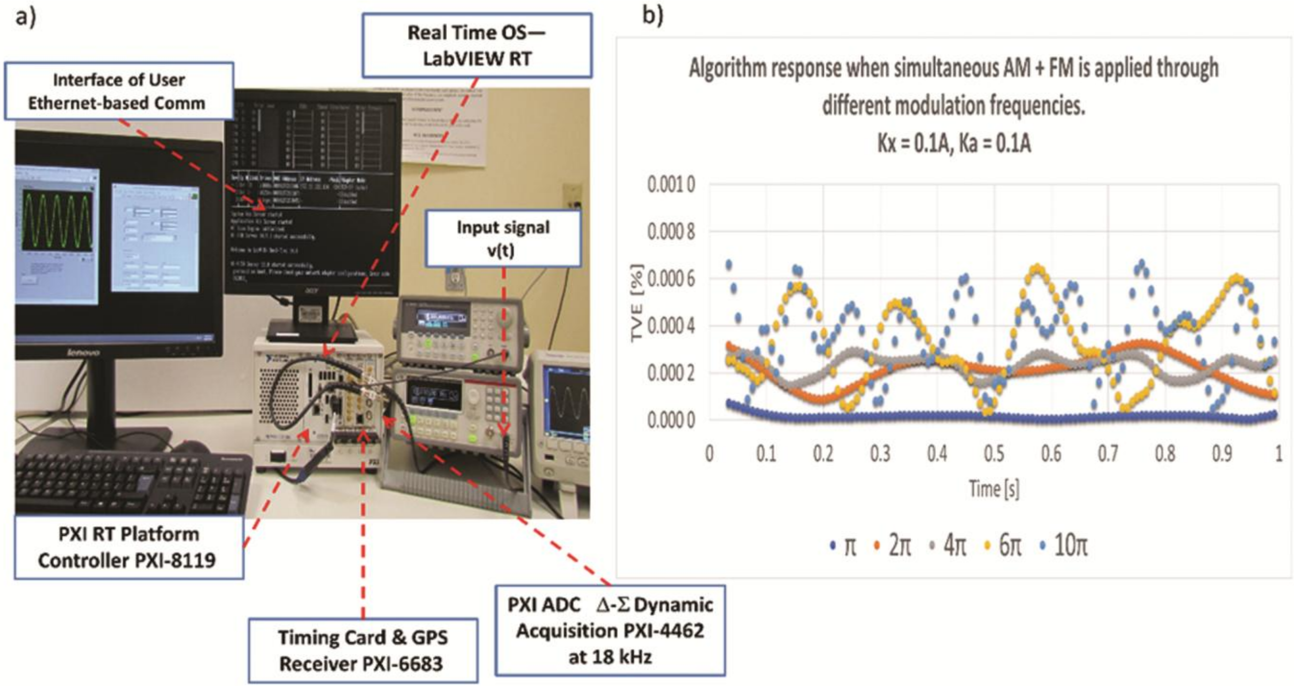

Fig. 2 — Experimentation a) Implementation of the proposed algorithm on a PXI 8119 for real time applications, b) Proposal technique results of modulation for amplitude and phase simultaneous.

TVE (*Total Vector Error*), and the FE (*Frequency Error*) and ROCOF (*Rate of Change of Frequency*). For these tests the fundamental frequency of the input signal is set at 60 Hz whereas the sampling frequency is 9 kHz, and the rate report is set at 120 frames per second (*fps*).

Effects of harmonic distortion

The section of the steady state compliance tests in the standard, aims at assessing the performance of synchrophasor regarding the presence of harmonic frequencies in the input signal. A parametric waveform may be synthetized from equation (4).

$$x(t) = A * \left[\cos(2\pi f_0 t + \theta_1) + \sum_{h=2}^{H} a_h(t) * \cos 2\pi h f 0 t + \theta h \qquad \ldots (4)\right.$$

Where A is the amplitude peak value, f_0 is the fundamental frequency, θ_1 is the value of the phase of the fundamental component, whereas t is the independent variable for time. h is the index value of the h-th harmonic up to H. $a_h(t)$ is the time-dependent amplitude factor of the h-th harmonic component of the fundamental and θ_h is the h-th harmonic phase value. For these tests, the values of the fundamental frequency f_0, the phase of the fundamental component, and the phase of each harmonic component θ_h are fixed. Only one harmonic component is evaluated at once. According to the standard, in this test the TVE is obtained by applying a single harmonic at a time, where harmonics range from the 2nd up to the 50th harmonic. The amplitude of each harmonic is rated at 10% of the fundamental signal.

Effects of fundamental frequency deviations

The steady state compliance tests in the Standard aim at assessing the performance of synchrophasor to the effects of off-nominal frequency conditions in the input signal. For such purpose the Standard proposes using equation (5).

$$x(t) = A * [\cos(2\pi(f_0 + \Delta f)t + \theta_1)] \qquad \ldots (5)$$

where A is the amplitude peak value, f_0 is the fundamental frequency, θ_1 is the value of the phase of the fundamental component, whereas t is the independent variable for time, Δf is the deviation in the fundamental frequency from -5 Hz up to 5 Hz in discrete steps. In this work four deviations are evaluated, they cover the 10 Hz bandwidth required by the Standard: -5 Hz, -1 Hz, +1 Hz and +5 Hz.

Effects from simultaneous modulation of amplitude and phase

For assessing the performance of the proposed synchrophasor to the effects of simultaneous modulation of amplitude and phase, the section of dynamic compliance in the 2011 version of the Standard is followed. To conduct this test, the input signal to the synchrophasor is formulated on equation (6) for each phase.

$$x(t) = A * (1 + k_a \cos(\omega_m t)) * \big(\cos\big(2\pi f_0 t + kp\cos\omega m - \pi \quad \ldots (6)$$

wherek_a is the amplitude modulation factor, k_p is the phase modulation factor, and ω_m the modulation frequency. For this test, the amplitude and phase modulation values are k_a= 0.1, k_p = 0.1, and ω_m = 10π, respectively, which is the more severe case that the Standard requires. The other variables are set the same as in equation (1).

Effects of Amplitude and Phase Step

For assessing the performance of the proposed synchrophasor to the effects of step changes of amplitude and phase, located in the dynamic compliance section in the standard, is followed. To conduct this test, the input signal to the synchrophasor is formulated on equation (7).

$$x(t) = A * \big(1 + d_a \mu(t)\big) * \Big(\cos\Big(2\pi f_0 t + d_p \mu(t)\Big)\Big) \quad \ldots (7)$$

Where d_a is the amplitude factor step and d_p is the phase factor step; $\mu(t)$ is the Heaviside step function. The test is made in two stages, first d_a = 0.1 and d_p = 0 and the second one d_a = 0 and d_p = π/18.

Effects of a Frequency Ramp

The dynamic compliance section includes a test related with fast frequency changes, consisting of a frequency modulation test with an acceleration of ± 1 Hz/s. In order to conduct this test, the input signal to the synchrophasor is formulated on equation (8).

$$x(t) = A * \cos\big(2\pi f_0 t + \pi R_f t^2\big) \quad \ldots (8)$$

where R_f is the rate of change in the frequency. For the test the value is set to 1 Hz/s during 5 s, i.e.: the initial and final values of the frequency are 60 Hz and 65 Hz, respectively.

Results and Discussion

An experimental setup using real signals has been developed. According with the diagram in figure 1a), a 1 V signal from an Agilent 33250 A is applied directly to the PXI-ADC platform. This experiment explores the capability of the synchrophasor technique to follow the abrupt changes of amplitude of the input signal. The duration of the test is up to 10 s, while the amplitude of the input signal is step changed as follows: step 1, $v(t)$ = 1V; step 2, $v(t)$ = 1.1 V; step 3, $v(t)$ = 1.2 V; step 4, $v(t)$ = 1.1 V; step 5, $v(t)$ = 0.6 V; step 7, $v(t)$ = 0.7 V; step 8, $v(t)$ = 0.8 V; step 9, $v(t)$ = 0.9 V; step 10, $v(t)$ = 1.0 V; the fundamental frequency of $v(t)$ is 60 Hz. The report is 120 *fps.*Figure 2b) illustrates the response of the algorithm toresults of modulation for amplitude and phase simultaneous. An experimental assessment of the performance of the proposed algorithm shows that this technique is suitable for implementation on platforms for real-time tracking of amplitude, phase and frequency quantities of a voltage signal in a power system. The proposed algorithm complies well the limits established in the IEEE Std. C37.118.1-2011 and 2014for dynamic conditions. For steady state conditions, the measurement errors of the algorithm regarding to measurements of amplitude, phase and frequency are lower than some parts of 10^4. Specifically, under the presence of harmonics, measurement results are at least 1000 times better than the requirements of the Standard, and for FE shows agreement on 3 x 10^{-5}, overcoming the limit established in the Standard for both classes of PMU. The result shows that the algorithm is nearly insensitive to off-nominal frequency conditions. The agreement in each case is about some parts in 10^{-5} for TVE using an observation window of one fundamental cycle. When the reference synchrophasor is tested for dynamic conditions, the results confirm that the technique complies well with the limits established in the Standard. From the tests of simultaneous modulation of amplitude and phase, experimental results show that the reference synchrophasor is capable of correctly following the simultaneous changes in amplitude and phase without the need of separating the tests. The error in the measurement of amplitude is lower than 0.05 % in positive sequence amplitude. The report rate is set in 120 *fps*. This feature is relevant for applications on distribution networks, when dealing with sudden changes of amplitude and frequency along with highly distorted components. By using the approach in this work it might be possible to monitor PQ events and provide reports as fast as 120 *fps*, i.e. half of a fundamental cycle. The algorithm can overcome the limits of the two classes of PMU defined in the Standard; this feature is possible due to the design of the adaptive orthogonal filter described in this work in combination with corrections in phase and frequency. The observation window is one fundamental cycle and the filter has a sliding window of one sample at the time that allows reaching higher report rates, this represents an advantage over traditional approaches that requires complete sequential windows to process. The experimental results confirm the capability of the algorithm to report at each half cycle of the fundamental; this feature allows to observe simultaneous changes in amplitude, phase and frequency in voltage signals. For environments such as distribution networks where the amplitude, phase and frequency conditions suddenly change with time, having a measuring tool that is capable of determining accurately these changes is a key element for observability of a power system. The main application of a PMU is mainly related to transmission networks. For applications on distribution networks it is highly appreciated an enhanced PMU with improved measurement capabilities of amplitude, phase and frequency, which ensures to be robust against severe power quality events, as the measuring synchrophasor described in this work.

Conclusions

The simultaneous deviation of amplitude, phase and frequency of a signal may be considered as a remarkable feature test for a given synchrophasor measuring technique. The measurement technique proposed in this work provides a real time tracking of the amplitude, phase and frequency of the fundamental frequency component even if it deviates from nominal values. Tests reported in this work account for the capability of the proposed technique for the instantaneous measurement of the fundamental frequency, phase and amplitude, and its feasibility for being implemented in a real-time system in high report rates beyond those found in the Standard. The proposed algorithm is tested using the parameters established in standard, presenting acceptable performance in dynamic tests, even in the case of simultaneous events, which overcome the requirements of the version 2014 of the Standard. The reference synchrophasor was implemented on a PXI platform. Computational effort is lower than other synchrophasor estimation approaches. Future work in this research will be focused to determine the uncertainty of measurement of amplitude, phase, frequency, and ROCOF of the proposed reference synchrophasor. The analysis of the results of tests on the synchrophasor conducted so far show that it may be used as a reference measurement standard for providing measurement traceability to PMU technologies.

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