Improvement of Phasor Measurement Unit Performance

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Abstract: - Fast measurements of the instantaneous amplitude and phase angle of the fundamental components and frequency in three-phase power systems may be investigated with high accuracy through the use of modern power instruments such as Phasor Measurement Unit (PMU). However, this accuracy may be affected by several encountering power disturbances, such as abrupt frequency deviation, fast and slow dc offsets decaying due to sudden current changes, inter-harmonics, etc. To avoid these effects for improving the quality of measurements, this work presents a new method of real-time filtering for removing the unwanted DC offset and hence improving SDFT algorithm. To validate the proposed method, the performances of PMU are tested using the data generated by Simulink/MATLAB simulator. The obtained results are very encouraging.

Key-Words: - Power system, Phasor Measurement Unit, SDFT algorithm.

1 Introduction

Accurate and fast measurement of the phasors of the fundamental components and frequency in three-phase power systems that may be investigated by a Phasor measurement unit (PMU) is very important in modern power instruments/meters, digital relays, control apparatus, and power quality analyzer (PQA). In PMU instrumentation and relaying scheme, discrete Fourier transform (DFT) is the most widely used filtering algorithm [1-3] for computing the fundamental frequency components. However, The fault currents of a transmission line may contain a DC offset which decays exponentially with time (time constant of the line inductance to resistance ratio L/R), or a large number of unwanted sub-synchronous frequency or decaying DC components due to the thyristor-controlled switched capacitor (TCSC) compensated lines [4]. This latter always needs few cycles for decaying DC component or 10– 20 cycles for sub-synchronous frequency component to obtain the accurate fundamental phasors by DFT algorithm. The vital slow convergence problem will degrade the performance of PMU or protection scheme. The performances of the techniques employed directly determine the functions of this equipment and affect their behaviors under various service conditions. Hence, the real-time accurate phasor measurement of the fundamental component and/or symmetrical components is essential and crucial to the safe and economic running of modern electric power systems [5, 6].

This work proposes a method that can correctly extract the phasors of the fundamental components as well as symmetrical components in voltage or current waveforms and then accurately estimate their instantaneous amplitude, phase angle, and frequency, even when disturbances occur in a large scale and complex power systems. The proposed scheme uses the sample by sample basis instead a frame or cycle basis (data window) to obtain the accurate fundamental phasors. This is to fulfill the high speed measurement and detection feature required by the PMU and protective system. The approach consists first of removing unwanted dc components of the input measured signal using a fast digital filter algorithm, which is suitable for such a real-time application, and then provide the filtered signal to the Smart DFT[7] algorithm to accurately generate the phasor measurement components as shown in Fig.1

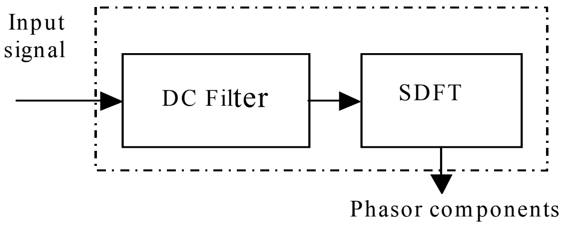


Fig.1 PMU enhancement computing algorithm

2 DC Offset Removal Filter

Three real-time digital filters are generally used for DC components removal as shown in Fig.2 [8].

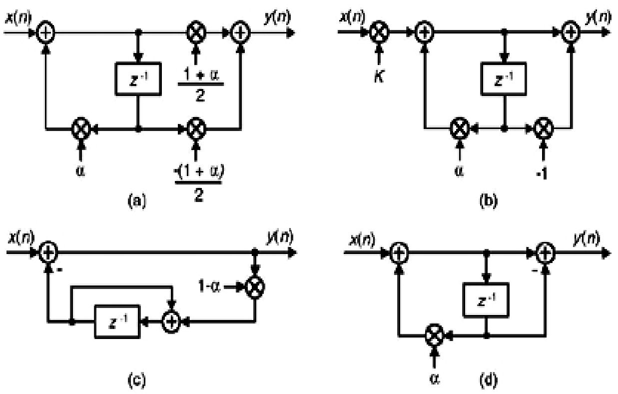


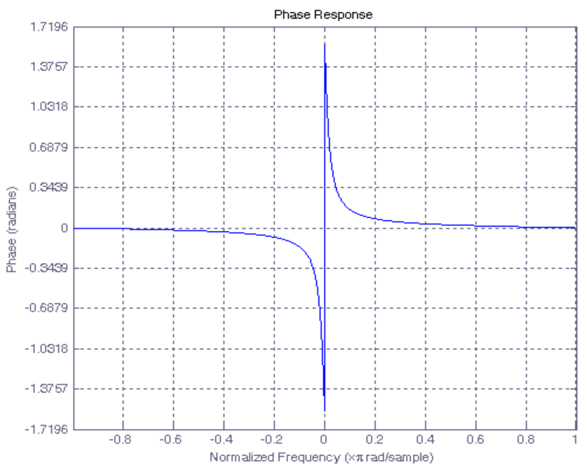
Fig.2 Filter structures for DC offset removal.

Ignoring the constant gains of those DC-removal filters, all three filters have identical performance with the general DC component removal filter structure. Their characteristics can be obtained from a z-domain transfer function:

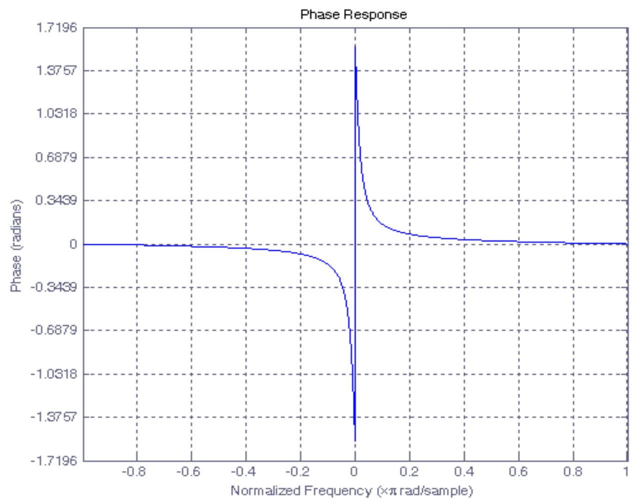
$$H(Z) = \frac{Y(Z)}{X(Z)} = \frac{1 - Z_{-1}}{1 - \alpha Z_{-1}} \quad , \qquad (1)$$

It is not immediately obvious that the filters in Fig.2(c) and (d) are equivalent [8]. We can verify that equivalency by writing the time-domain difference equations relating the various nodes in the feedback path. After that, those equations will be converted to z-transform expressions and solved for obtaining Y(z)/X(z). If the last DC-removal filter model (see Fig.2(d)) is chosen, the general filter's frequency magnitude and phase responses may be provided as shown in Figs 3(a) and (b) with α = 0.95.

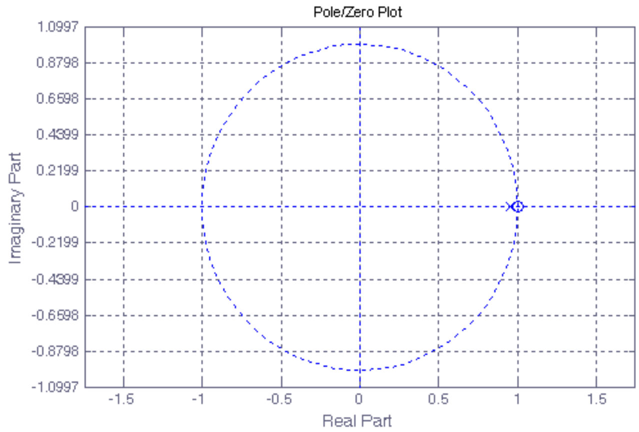
The filter's pole/zero locations are given in Fig.3 (c), where a zero resides at z = 1 providing infinite attenuation at DC (zero Hz) and a pole at z = α making the magnitude notch at DC very sharp. The closer α is to unity, the narrower the frequency magnitude notch centered at zero Hz. Fig.3(d) shows the general filter's unit-sample impulse response.



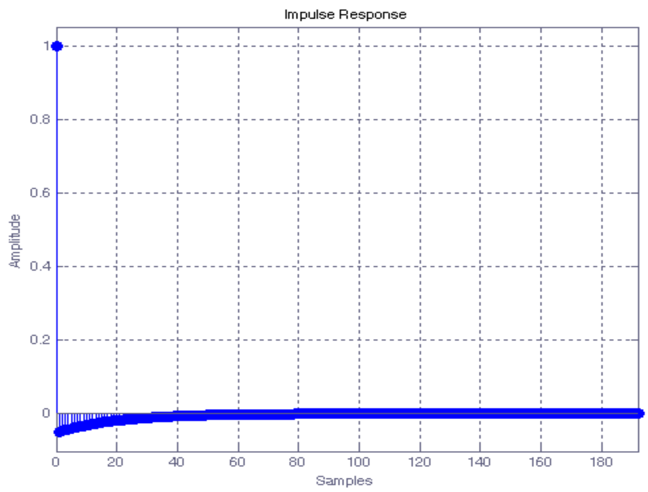
(a)



(b)



(c)



(d)

Fig. 3 DC removal filter, α = 0.95: (a) magnitude response,(b) phase response, (c) pole/zero locations; (d) impulse response.

Fig.4 shows the time-domain input/output performance of the general DC-removal filter (with α = 0.95). When filter input is fed by a sinusoid suddenly contaminated with a low frequency DC signal (solid line), that is thee fundamental components decaying exponentially having a long time constant of about five cycles, its output (dashed line) decays exponentially but with short time constant. The amplitude overshoot appears for short duration (portion of a cycle) with a small steady state error.

3 PMU Algorithm

The smart discrete Fourier algorithm (SDFT)[5] has been used in PMU as well as in digital relays, which has the ability to track the phasor values of voltage and current synchronously on power system in real time. PMU is a crucial to the detection of disturbances and characterization of transient swings [1]. The proposed scheme uses the sample by sample basis instead a frame or cycle basis (data window) to obtain the accurate fundamental phasors. This is to fulfill the high speed measurement feature required by the PMU. Besides, a developed algorithm must harmonize high frequency sampling and low frequency correcting computations to meet the communication requirements of data transfer rate between the PMU and the data center [7].

The SDFT can be mainly described by considering a sinusoidal input signal (current/voltage) of frequency offset in the following form [9]:

$$x(t) = \sqrt{2}X \sin\left[2\pi(f_0 + \Delta f)t + \varphi\right], \qquad (2)$$

Where X : the effective value of the input signal,

f0 : The nominal frequency,

Δf : The frequency offset,

φ : The initial phase angle of the input signal

The signal is conventionally represented by a phasor,

$$\overline{x}(t) = X\, e^{j(2\pi\,\Delta f t + \varphi)}\ , \qquad (3)$$

Assuming that x(t) is sampled N times per cycle of the f0(Hz) waveform to produce the sample as follows :

$$\tilde{x}(t)=\sqrt{2}X\sin\left[2\pi\left(1+\frac{\Delta f}{f_0}\right)\frac{k}{N}+\varphi\right] \qquad (4)$$

The original phasor is then calculated according to the recursive DFT algorithm as follows [6]:

$$\hat{x}(r)=\hat{x}(r-1)+j\frac{\sqrt{2}}{N}\left[\tilde{x}(r+N-1)-\tilde{x}(r-1)\right]e^{-j\frac{2\pi}{N}(r-1)} \qquad (5)$$

By defining θ as

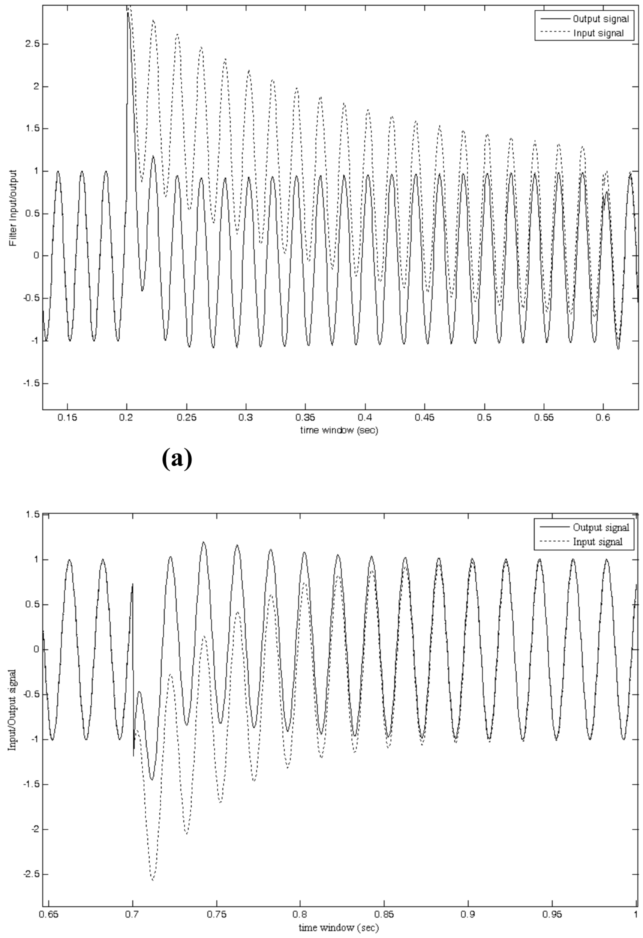
$$\theta = \frac{2\pi\,\Delta f}{f_0\,N} \qquad (6)$$

And Assuming that the sampling rate is m times of the correcting computation frequency, the exact solution of phasor can obtained by the following equations:

$$\overline{x}(r)=\left[\hat{x}(r)+C_2(r)\right]\frac{N\sin(\theta/2)}{\sin(N\theta/2)}e^{-j\theta(N-1)/2} \qquad (7)$$

Where,

$$C_2(r)=\frac{\hat{x}(r-m)-\hat{x}(r)\alpha_{-m}(\theta)}{\alpha_{-m}(\theta)-\alpha_{m}(\theta)e^{j\frac{4\pi}{N}m}}$$



(a)

(b)

Fig.4 Filter dc removal performances: (a) transient positive and (b) negative dc input signal and filtered output signal.

and,

$$\alpha_{-m}(\theta)=f(r-2m)+\sqrt{\left[f(r-2m)\right]^2-e^{j\frac{4\pi}{N}m}}$$

The frequency can be estimated from the following [9]:

$$f(r-2m) = \frac{\hat{x}(r-2m)/\hat{x}(r-m) + e^{j\frac{4\pi}{N}m}\,\hat{x}(r)/\hat{x}(r-m)}{2} \qquad (8)$$

4 PMU Performance Tests

To ensure the reliability of PMU operation, steady state as well as dynamic tests may be undertaken in the developed PMU with new techniques implementation. The performances of a proposed PMU algorithm are tested under transient and dynamic power system conditions, which is important for the protective relaying applications as well as generating of accurate phasor components in the case of wide area measurement. These tests are performed for signals as function of time by varying magnitudes and/or frequencies.

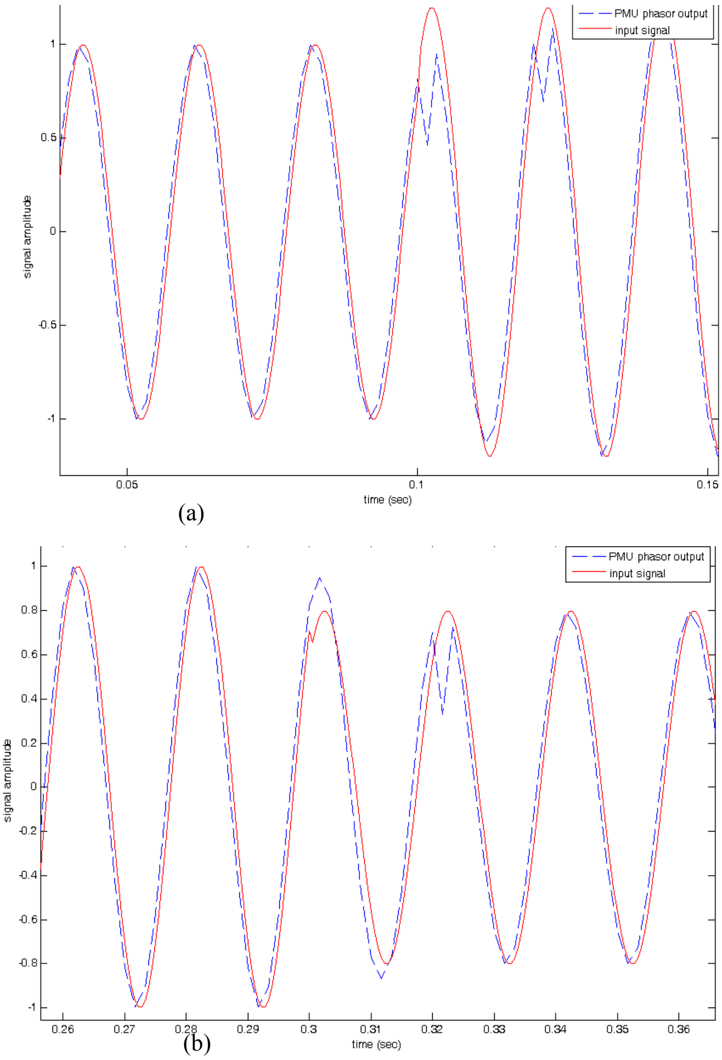


Fig.5 Change of signal magnitude from nominal level to (a)+20% and (b) to -20%.of the nominal level.

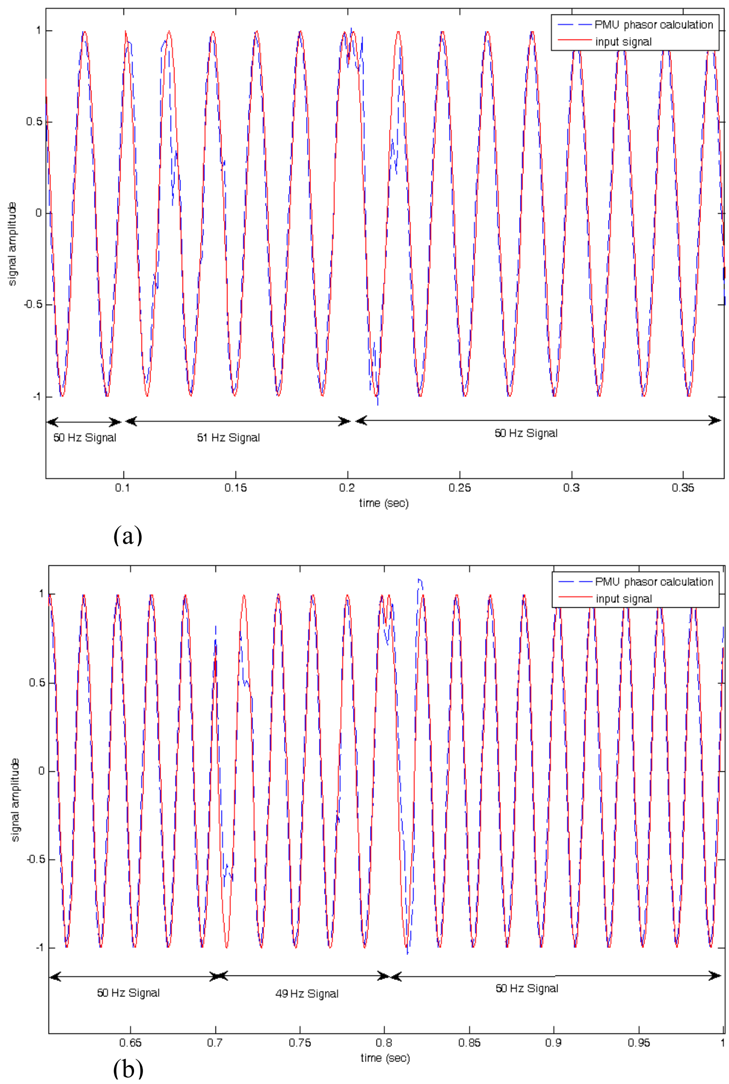


Fig.6: A frequency step variation at off nominal frequency withconstant magnitude: (a) +1Hz and (b) -1Hz freq change.

4.1 Amplitude Step Change Response

PMU performance can be determined from response to amplitude step changes that includes voltage/current signal. Step response can be characterized by rising time, overshoot, and steady state error.

For a phasor input ranges from steady state nominal signal level at nominal frequency (50 Hz) to the magnitude that is instantly changed to +20% of the nominal signal level (Fig.5-a). After a short time, it is changed instantly back to nominal. The test signal is also repeated for 80% of the nominal magnitude as shown in Fig.5-b.

It can be noted that overshoot is very small and the amplitude ranging for both positive signal variation +20% from the nominal and negative variation -20% is of small duration (less than half cycle) as shown in Fig.5.

4.2 Frequency Step Change Response

Method for determining PMU performance in response to frequency step changes may be investigated by applying a steady state signal at nominal frequency (50 Hz), then instantly changing the frequency to 51 Hz and back after settling time. The test signal is repeated for 49Hz as shown in Fig.6. Step response can be characterized by rise time, overshoot, and steady state error.

It can be noticed that overshoot is very small and the ranging of amplitude for both positive frequency variation (+1Hz) and negative frequency variation (-1Hz) at off nominal frequency (50 Hz), is of small duration (less than a half cycle).

4.3 Amplitude and Frequency Variations

The experiments have been performed for testing the developed PMU under different conditions such as frequency and amplitude variations. In this case, significant step variation for both magnitude and frequency are applied as shown in Fig.7 for a time scan of 1 second.. The step frequency changes is subjected to variations 50<f<56 Hz and the signal magnitude is subjected to variations for 4 level step changes from nominal value as shown in Fig.7. It can be noticed that

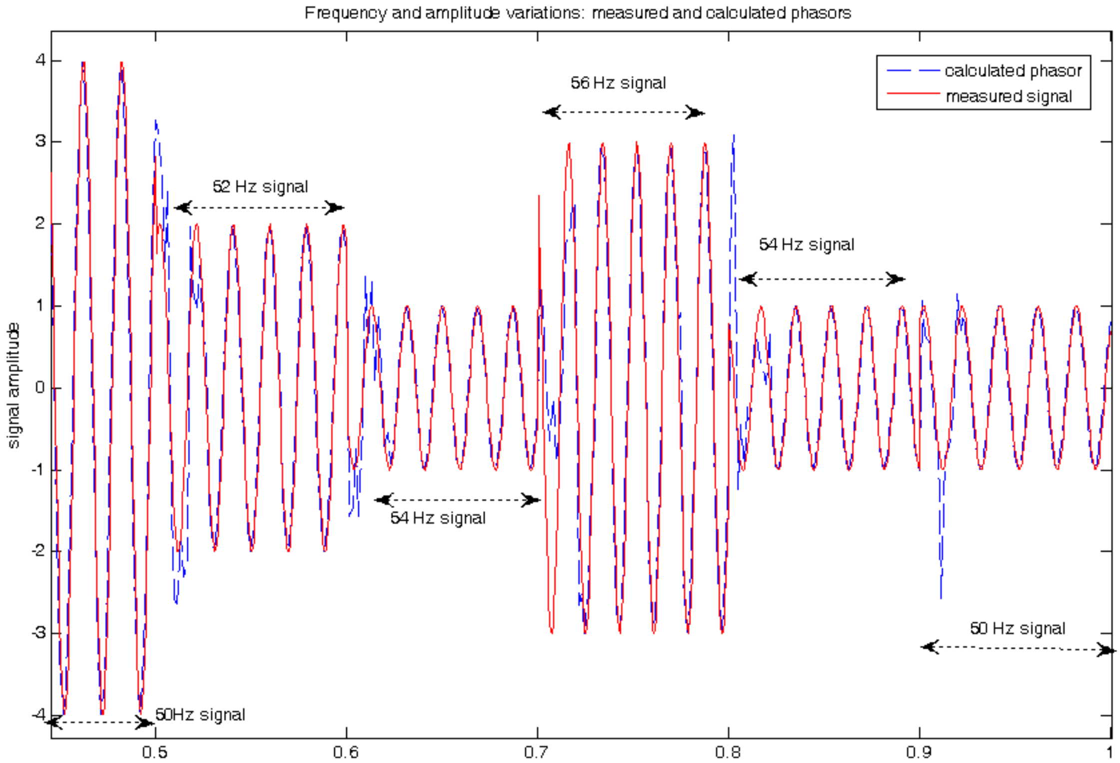


Fig.7 Signal magnitude step changes from nominal level

measured values by the PMU when the variations applied to both frequency and amplitude, are in a good agreement with the actual ones even at off-nominal frequency.

5 Conclusion

The PMU is tested by applying to it a fault current signal generated by computer simulation. The obtained results show that the used method is capable of completely eliminating the dc offset and thus greatly improving the performance of the full-cycle DFT algorithm.

Moreover, the performance of the proposed PMU algorithm has been tested under transient and dynamic power system conditions, which is important for the protective relaying applications. These tests have been performed for signals as function of time by varying magnitudes and/or frequencies. It can be noticed that the PMU tests results are very encouraging.

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