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Estimation of synchrophasor Using Taylor Fourier Transform

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ABSTRACT: This paper proposes a modified version of the syn- chrophasor estimation algorithm which uses the non-orthogonal transform defined as a Taylor-Fourier Transform (TFT) and which is based on a Weighted Least Squares (WLS) approx- imation with respect to a second order of Taylor model. The main objective of the project is to measure the magnitude and phase angle of dynamic electrical signal by using Taylor transform algorithm. In this work, a adapted TF-WLS algorithm for Phasor estimation has been introduced to improve the performances under transient conditions. The algorithm depend on adaptation to detect fast changes and enhance Phasor estimation

Index terms-Taylor Fourier Transform (TFT),Weighted Least Squares(WLS), Synchro Phasor

1. INTRODUCTION

In the last few years the importance of Wide Area Measurement Systems (WAMSs) has been increasing for the control and the maintenance of electric networks, also due to the enormous growth of energy generation from renewable energy sources. The need to know how the electrical parameters change at distant points of the electrical transmission networks initiates for the development of new measurement instrumentation.

The Phasor Measurement Unit (PMU) is the important element of the WAMS that permits the measurement of the electric parameters like voltage and current Phasor, frequency and rate of change of frequency. PMUs also allow the synchronization and the transmission of the achieved measurements. The PMUs are described in the Standard IEEE C37.118 about synchrophasor measurement in electric power systems.

Currently, there are different vendors of PMUs and the number of devices in the electrical network is constantly increasing. One of the most important issues in WAMS is the interoperability of the commercial PMUs. If the interoperability is not

appreciated, a generic electric phenomenon could be evaluated differently from two PMUs.

The standard does not suggest one algorithm, but specifies the accuracy limits of the measurement for different tests. In scientific literature, there are different algorithms for synchrophasor estimation, but it is difficult to compare their performance without a standard index. For the evaluation, only one index is present in the standard IEEE C37.118 2005: the Total Vector Error (TVE) that represents the absolute value of the relative vector difference between the real and measured Phasor. With the release of the IEEE standard C37.118.1-2011, different indices are presented to evaluate the accuracy of a synchrophasor measurement in different scenarios and new improved definitions about the dynamic synchrophasor, frequency and rate of change of frequency (ROCOF) measurement are introduced.

Different algorithms rely on different mathematic model. The most common model is the steady state model, where the acquired electric signal is considered stationary during the observation period and is thus described by magnitude and phase, along with actual frequency. On the other hand, in order to better represent the non-stationary signals that are actually present in power grids, a more suitable approach is to consider a dynamic model, which describes the magnitude and phase as functions of time in the acquisition window. On the other hand, the standard [1] leaves to PMU manufacturer free choice on hardware, software architecture, and algorithm for Phasor, frequency, and ROCOF computation. In literatures, starting from the consideration that under dynamic conditions the classical approach based on discrete Fourier transform (DFT) may lead to incorrect synchrophasor evalu- ations, there are a great number of studies and proposals of algorithms for the estimation of synchrophasors [3]–[13].

In [2], an interpolated DFT (IpDFT) approach is used for synchrophasor and frequency estimation, in particular under off-nominal conditions. In [3]–[10], the phasor estimation is improved by approximating the slowing changing phasors with a complex Taylor series expansion around the estimation time point. In [3] and [4], better synchrophasor estimation performance is achieved by correcting the estimation errors of sequential phasor estimates computed with DFT and short- time Fourier transform in a postprocessing way. In [5], the IpDFT is extended to compute directly the phasor derivatives and thus frequency and ROCOF, from the DFT components around fundamental frequency. An algorithm using a linear nonorthogonal transform, defined as a Taylor–Fourier trans- form (TFT), is introduced in [6] and [7]. It is based on a weighted least squares (WLS) approximation of an observation window with respect to a second-order Taylor model, per- formed as a linear filter bank. Unlike the algorithms in [3] and [4], the TFT algorithm

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directly acts on the samples, without any DFT computations. As a consequence, an arbi- trary number of samples can be used and the observation window is not required to include an integer number of cycles

2. SYNCHROPHASOR AND PHASOR MEASUREMENT UNITS

2.1 Definition of synchrophasor.

A sinusoidal signal can be defined by the following formula:

$$x(t)=Xm\cdot\cos(2\pi ft+\varphi) \qquad (2.1)$$

where Xm is the amplitude and f is the frequency. Such signal is represented as the complex phasor:

$$\boldsymbol{X}=Xm\sqrt{2}ej\varphi= Xm\sqrt{2}\,(cos\varphi+j\,sin\varphi)=Xr+jXi \qquad (2.2)$$

where the magnitude is the root-mean-square (rms) value, $Xm\sqrt{2}$, and the Xr and Xi are the real and imaginary parts of the complex value. The value of phase angle φ depends on the time reference. Particularly, when t = 0 is assumed, for the standard the synchrophasor can be defined as:

*The synchrophasor representation of the signal x(t) in Equation (2.1) is the value **X** in Equation (2.2) where φ is the instantaneous phase angle relative to a cosine function at the nominal system frequency synchronized to UTC.*

Figure 1 shows the convention for the synchrophasor representation: the cosine functions *X1m* has a maximum at t = 0, so the synchrophasor angle is 0 degrees when the maximum of **X1m** occurs at the UTC second rollover (1 PPS time signal). Instead, the synchrophasor angle of the sine *X2m* function is –90° degrees when the positive zero crossing occurs at the UTC second rollover.

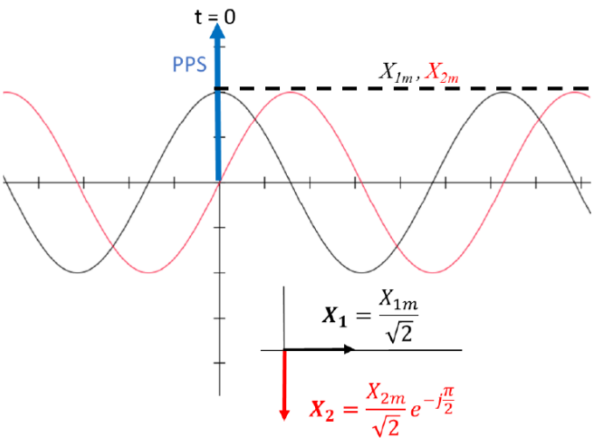

Figure 1. Convention for synchrophasor representation

In the case where the frequency *f(t)* is a function of time, it is possible to define the function *g(t) = f(t) – f0* where *f*0 is the nominal frequency and *g(t)* is the instantaneous frequency deviation from the nominal. The waveform representation becomes as follows:

$$x(t)=Xm(t)\cdot\cos(2\pi\cdot\int f(t)dt+\varphi)=Xm(t)\cdot\cos(2\pi f\,0t+(2\pi\int g(t)dt+\varphi)) \qquad (2.3)$$

where the amplitude *Xm(t)* is function of time.

The dynamic synchrophasor, where magnitude and phase angle are functions of the time is given by:

$$\boldsymbol{X(t)}=Xm(t)\sqrt{2}ej(2\pi\int g(t)dt+\varphi) \qquad (2.4)$$

A special case where *Xm* is constant and *g = Δf = f-fo* is a constant offset from the nominal frequency *f*0, is:

$$\boldsymbol{X(t)}=Xm\sqrt{2}ej(2\pi\Delta ft+\varphi) \qquad (2.5)$$

Where the Phasor rotates at the uniform rate Δ*f*, the difference between the actual frequency and system nominal frequency, that produces the effect in Figure 2.

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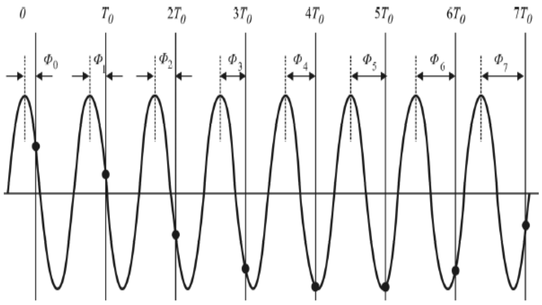

Figure 2. Sinusoid with a frequency f>fo observed at instants that are multiples of T0.

If the sinusoid frequency f if different from $f0$ but $f < 2f0$, the Phasor calculated from the waveform will have a constant magnitude, but the phase angles of the sequence of Phasor calculated every T0 will change uniformly at a rate $2\pi(f-f0)T0$

2.2 TVE

The TVE is an important index to evaluate the performance of synchrophasor estimation. For many years, it was the only parameter to evaluate the accuracy of a measure in steady state and dynamic conditions. The TVE is an aggregated index, which represents the vector error between the theoretical synchrophasor and the estimated one, given by the unit under test at the same instant of time. The formula of TVE is:

$$TVE(n)=\sqrt{(\hat{X}r(n)-Xr(n))2+(\hat{X}i(n)+Xi(n))2(X r(n))2+(Xi(n))2} \quad (2.6)$$

where $\hat{X}r(n)$ and $\hat{X}i(n)$ are the real and the imaginary parts of the estimated synchrophasor at the time instant (n).

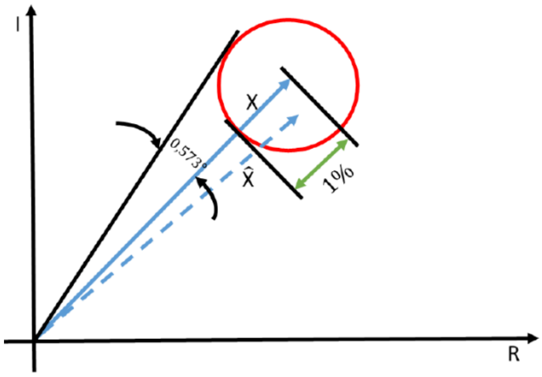

Figure 3. The TVE criterion shown on the end of Phasor

Figure 3, presents the graphical representation of the permitted TVE error (the small circle drawn on the end of the Phasor). For example, when the maximum TVE error is 1 % and the magnitude error is zero, the maximum error in angle is just under 0.573º.

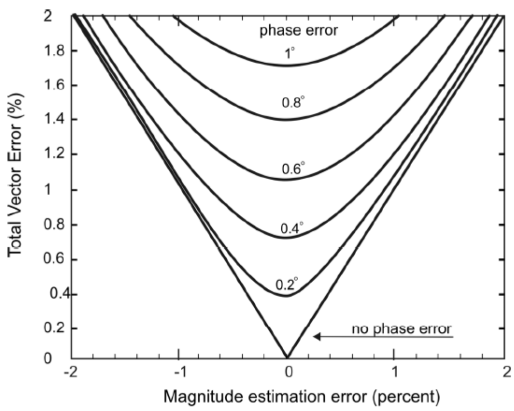

Figure 4. TVE % as a function of magnitude for various phase errors.

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TVE combines magnitude and phase errors. In Figure 4 and Figure 5 there is the TVE as function of the magnitude and of the phase error respectively. The TVE is computed relative to measurement magnitude and phase at the given system frequency. Time synchronization errors will result in different TVE depending on the actual system frequency. A cycle at system frequency is 20 ms at 50 Hz and 16.67 ms at 60 Hz. One degree of phase angle at 50 Hz is 55.6 µs and at 60 Hz is 46.3 µs. Therefore the timing error that will cause a 1 % TVE error are ±31.7 µs at 50 Hz and ±26 µs at 60 Hz.

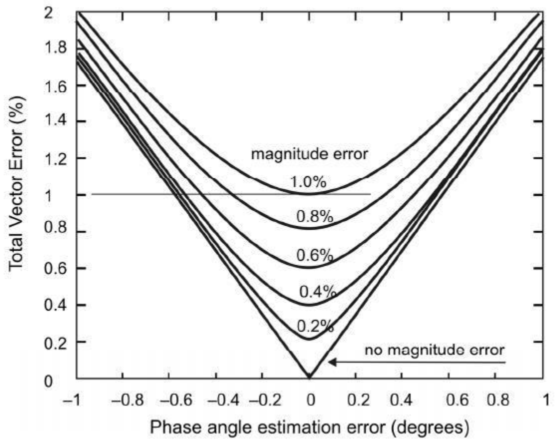

Figure 5. TVE as a function of phase for various magnitude errors.

2.3 Standard of synchrophasor IEEE C37.118.1-2011

The original synchrophasor standard was IEEE Std 1344-1995. It was replaced by IEEE Std C37.118-2005 and the new version of the 2011 is divided into two standards: IEEE Std C37.118.1-2011, in the following called "the synchrophasor standard", covering measurement provisions, and IEEE C37.118.2-2011, covering data communication.
In the new synchrophasor standard, the Phasor and synchronized Phasor definitions, as well as the concepts of total vector error (TVE) are presented and also the important dynamic performance tests have been introduced along with other indices used to evaluate the new compliance tests. In addition, measurement of frequency and rate of change of frequency (ROCOF) have been regulated.
The PMUs are used in many protection and data acquisition functions in transmission and distribution electrical networks. The PMU refers the measurements to a common time base, generally the Universal Coordinated Time (UTC) obtained from the Global Position Systems (GPS). In this way the measurements become comparable over a wide area. A synchrophasor is a Phasor value obtained from voltage or current signals and referenced to a common time base.
The goal of PMU devices connected to the power grid is to monitor power system parameters and to track power system dynamic characteristics for improved power system monitoring, protection, operation, and control. The aim of the synchrophasor standard is to describe and quantify the performance of the PMU deployed to monitor the power grid. The PMU measures the magnitude, phase angle, frequency, and ROCOF from the voltage and current signals. These signals may be corrupted by distortion, noise, and abrupt changes caused by system loads, control and protective actions. These different disturbs complicate the process of measuring.

2.3.1 Phasor model

Several algorithms have been presented in the literature to estimate Phasor [2], [3], [13-20]. Every algorithm requires a Phasor model and uses specific techniques to match the model parameters. In particular, the algorithms can be divided into two main classes with respect to the measurement model: algorithms relying on a steady state Phasor model and algorithms based on an intrinsically dynamic Phasor model.
A general Phasor model, which can be used as a common framework for both classes, describes the Phasor in a specific time interval by means of a complex Taylor expansion

$\bar{\boldsymbol{X}}\boldsymbol{Tr}(\Delta t)=\Sigma a(k)k!\Delta tkKk=0ej\Sigma\varphi(h)h!\Delta thkh$ (2.7)

$=0=\Sigma\bar{\boldsymbol{X}}(k)k!\Delta tkKk=0$

where $\Delta t = nTs - Tr$ is the time shift with respect to the reference time Tr, K is the Taylor expansion order, and $a(k)$, $\phi(k)$, and $\boldsymbol{X}(k)$ are the kth derivatives at the time reference (a subscript Tr is dropped in the equations for the sake of clearness) of the phasor amplitude, angle, and complex representation, respectively. In such a model, the synchrophasor at time reference Tr is given by $\boldsymbol{X}(0)$.

2.3.2 Algorithm TFT-WLS

In [3] and [29], a Phasor estimation algorithm that applies a WLS approximation of the Phasor in a given observation

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window based on a K-th order Taylor model has been introduced. Thus, the algorithm relies on the TFT-WLS to better follow Phasor. A general model for the dynamic Phasor ***p*** for *k > 0* is in (2.7).
Given a N samples observation window, the dynamic Phasor model can be translated in the following vectorial form:
s=**B** ·**p** (2.8)
where s is the vector of signal samples and
p= 12[(𝑘)!⋯𝑝(0) 𝑝−(0) ⋯𝑝−(𝑘)𝑇𝑠𝑘𝑘!]𝑇 (2.9)
and the matrix B can be expressed by its generic element:
𝑏ℎ,𝑘=(ℎ−𝑁2)|𝐾−𝑘|𝑒(−1)1+(𝑘𝐾)𝑗2𝜋(ℎ−[𝑁2]) 𝑓0𝑇𝑠 (2.10)
for *h = 0, . . . , N − 1* and *k = 0, . . . ,2K*. To obtain an evaluation of **p** vector a WLS method is used, that is:
p̂ = (𝑩𝐻𝑾𝐻𝑾𝑩)−1𝑩𝑾𝐻𝑾𝒔 (2.11)
where **W** is the weighting matrix:
W=(𝑤110…00𝑤22…0⋮⋮⋱0000 𝑤𝑛𝑛) (2.12)

The weights are obtained from the Kaiser windows how it is suggested in [21].

3 PROPOSED MODIFIED ALGORITHM

The Phasor estimation algorithm TFT-WLS is based on a fixed number of samples and a fixed weighting window. To obtain a faster response to abrupt phasor dynamic changes, like amplitude or phase steps, an adaptive approach is proposed here. The underlying idea is to detect degradation in the TFT estimation, due to a mismatch between the signal and the chosen model, and to adapt the estimation algorithm to changing conditions.
The modified algorithm follows three main steps:
1. Calculation of standard phasor.
2. Evaluation of the estimation error and detection of critical conditions.
3. Computation of adapted estimation.

After the TFT computation of the Phasor, a procedure of error evaluation is needed to start any adaptation algorithm to refine the estimation. An index relying on the signal reconstruction has been chosen to detect the quality of Phasor estimation. In particular, the following Error Monitor function has been used, inspired by the transient monitor in [1]:
EM ≜ Σ|𝑠(𝑘)−𝑠̃(𝑘)|2𝑁𝑁−1𝑘=0 (3.1)

where N is the number of samples in the observation window and 𝑠̃(𝑘) is the signal reconstructed from the estimated Phasor parameters. 𝑠̃(𝑘) is obtained by using the estimated phasor parameters in (3.2):
ŝ=**B**·**p̂** (3.2)
The EM function represents the average error energy in signal reconstruction and thus allows understanding when the signal is not perfectly described by the Taylor series parameters given by (2.11) in the whole observation window. If the EM overcomes a given threshold, an observation window can be labelled as critical and the adaptive algorithm is started. In some cases, for instance in presence of harmonics, such criterion can be too soft and may not be perfectly tuned to detect only transient conditions. Then, other criteria can be added, such as an evaluation of the degree of unbalance of the energy of the reconstruction error along the observation window. For instance, in the tests of the following section, a combined criterion has been used:
(𝐸𝑀𝑎2>𝛼𝑡ℎ)∧(|𝐸𝑀1−𝐸𝑀2|𝑎2>𝛽𝑡ℎ)→ 𝑐𝑟𝑖𝑡𝑖𝑐𝑎𝑙 𝑐𝑜𝑛𝑑𝑖𝑡𝑖𝑜𝑛 (3.3)
where *a*=|*p(0)*| is the amplitude of the estimated Phasor, 𝛼𝑡ℎ and 𝛽𝑡ℎ are the thresholds, and EM1 and EM2 are error monitor functions computed on the two halves of the observation window. When a critical condition is detected, the observation window length is reduced. In fact, a Phasor estimation based on a shorter samples window is expected to feel later the effect of an incoming fast transient and to exit sooner from a critical condition. A shorter filter presents a wider pass-band, thus leading to a higher promptness and a lower rejection of wide-band noise. A trade-off is needed between these two aspects and, for this reason, it has been chosen to reduce the window length from four to three cycles. Thus the new Phasor estimation is obtained by a further application of WLS algorithm:
p̂= (**B̃**H**W̃**H**W̃B̃**)−1**B̃W̃**H**W̃s̃** (3.4)
where ***s̃*** is the new reduced window of samples. **B̃** is obtained from **B** by suppression of the rows corresponding to the suppressed samples and **W̃** is the new weighting matrix. In Figure 6 the flux diagram of the Adaptive TF-WLS method is shown:

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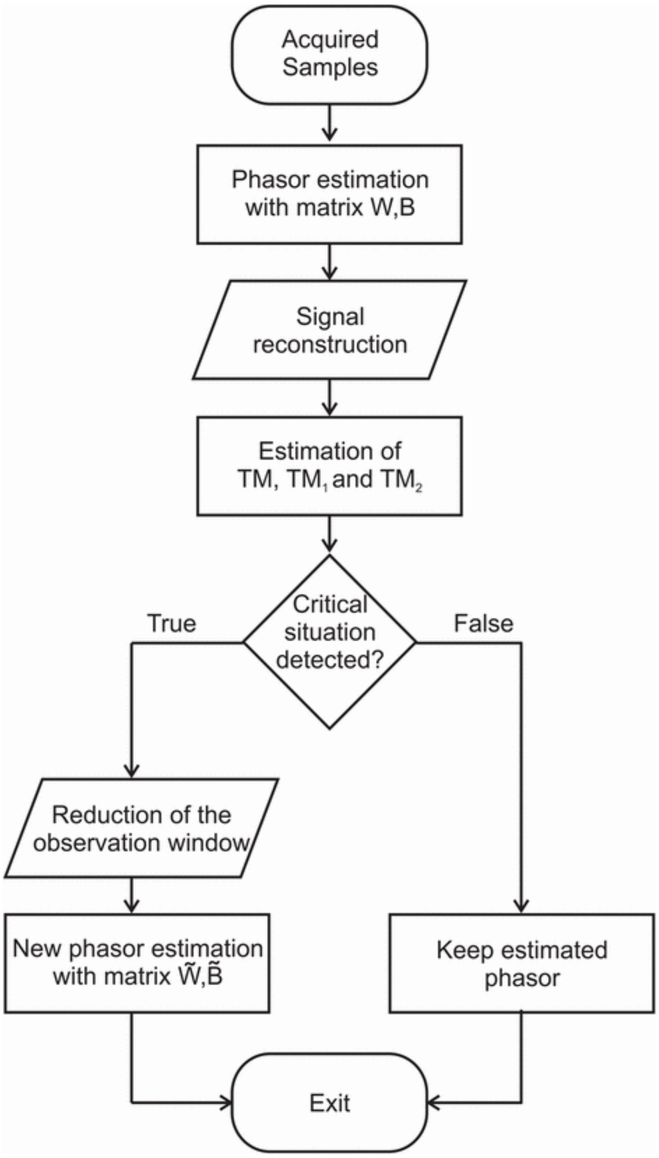

Figure 6. Flux diagram of the modified method.

The described algorithm has a general approach that can be synthetically described as a re-weighting of the samples based on an evaluation of the first-step Phasor estimation error.

4. RESULTS AND DISCUSSION

In this section, the proposed method has been tested with various types of IEEE 30 bus test system, BD and non-Gaussian measurement noise. Measurement configuration of the test system is same, 38 power measurement pair including the measurement of active power and reactive power flow of active and reactive power injected and of 23 pairs only 15 pairs are considered. On the bus, 11, 12, 24, 27, 30 and active and reactive power of the active power flow through injection 24～23, 25～26, 30～27 and reactive power important measurements without considering PMU measurements is the value. PMU deployment 8, 9, 6 to the bus, 12,24,25,26, enhanced redundancy test system for suggesting some important measurement unimportant. PMU can measure magnitude and phase angle of the bus voltage and current phasor in all branches adjacent to the bus. In the simulation, the parameters of the proposed robust estimators are set as follows: C = d = 1.5, the maximum iteration 20, convergence threshold 10-2; Use SCADA and PMU non Robust measure the stage estimator. Two stages that are called at the same time, is the simulation results and various types of bad data. Obviously, due to the use of projection statistics and TFT- estimation is very small deviation due to various types of impact of incorrect data is limited. But here, it cannot be identified by any of the bad data to unauthorized key measurements to process the method.

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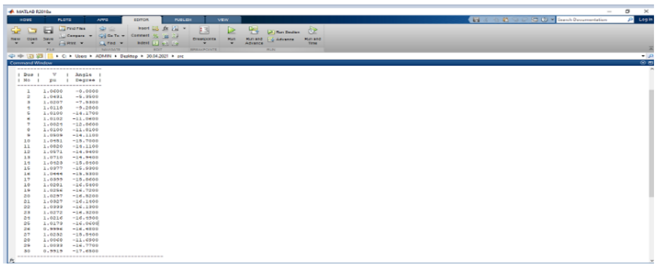

Figure 7 Magnitude Value

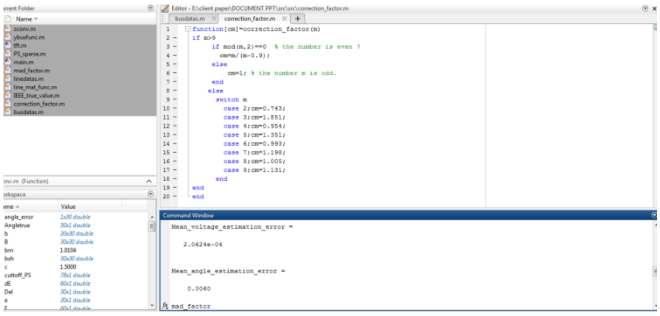

Figure 8 Phase Angle Value

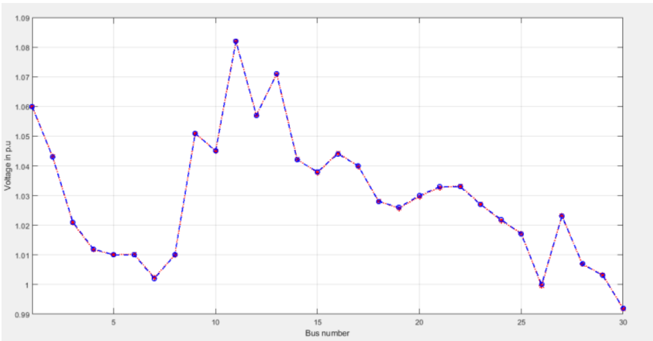

Figure 9 Plot of Magnitude Value w.r.t grid system

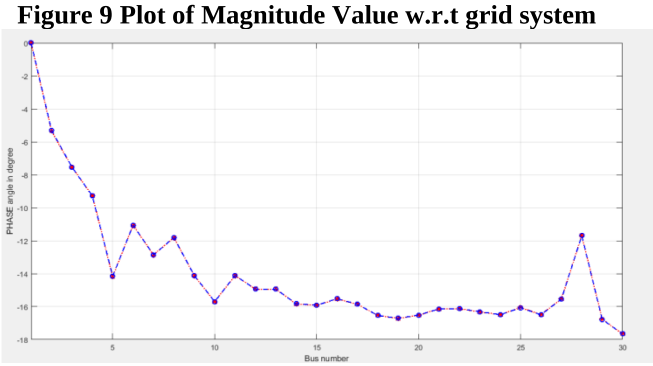

Figure 10 Plot of Phase Angle Value w.r.t grid system

5. CONCLUSION

In this work, a adapted TF-WLS algorithm for Phasor estimation has been introduced to improve the performances under transient conditions. The algorithm depend on adaptation to detect fast changes and enhance Phasor estimation .Besides presenting the overall approach, the emphasis was mainly
on defining suitable principles to detect fast changes, even in the presence of other kinds of instabilities (e.g. modulation and harmonics) overlaid to the sinusoidal signal. On the other hand, the variation of the algorithm was simply represented by a reduction in the observation window length .The investigations show that, even with this simple solution, the proposed algorithm has better concerts with respect to the classic TF-WLS in term of TVE response time, when the observed signal is affected by fast transient. This work proposes the TFT estimator proposed

robust power system state estimation method using SCADA and PMU measurements simultaneously, using traditional SCADA measurement. In the first stage, and combined with the results of the further PMU measurement. In order to achieve the first stage. Linear robust estimation Laplacian-Gaussian mixture such while maintaining good statistical efficiency, robust scale estimation and TFT- estimation such as, by using a thick tail non-Gaussian noise, can be handled effectively. By using the projection statistics and Hoover of estimation, it has been limited the impact of various types of illegal data. Numerical experiments on the bus system under a variety of conditions to verify the validity and robustness of the method. Future work will Concern the enhancement of the adaptation procedures, so that further improvements in the performance could be achieved. The IEEE Standard C37.118.1 defines two performance classes, P and M, for Phasor measurement units (PMUs), respectively for protection and monitoring oriented applications.

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