Hybrid Generalized Estimator for Power Systems

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● Received: 15/10/2023. ● Accepted: 22/12/2023

■ **Abstract:**

a state estimation in Power Systems is the procedure of estimating the states of voltage magnitude and angle at all buses based on the availability of measurements. Traditionally, the Supervisory Control and Data Acquisition (SCADA) system was able to provide all quantities measured in addition to the statuses of all system switches. More recently, a measuring device called a phasor measurement unit (PMU) which can dynamically measure the phasors (both magnitude and angle) of voltage and current of a bus at which it is installed. This device is capable of measuring any dynamic changes in the phasors. Adding more PMUs to the system will improve the time-skew errors in the power system. In this paper, the improvement in the state estimation using the quantities measured by PMU has been explained. The improvement is validated for IEEE-14 bus and IEEE-30 bus systems. The proposed state estimator utilizes estimated states from the Weighted Least Square (WLS) model in addition to estimated states from PMU-function which is modeled based on Kalman filtering. The estimation is done firstly in polar formation by using the WLS model from conventional measurements then, these states from the PMU function are both used to estimate the final system state estimation expressed in rectangular coordinates. The MATLAB program has been used for simulation and verification results.

● **Keywords:** Hybrid estimation, Phasor, Weighted Least Square, Kalman Filtering, Post-processing.

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■ المستخلص:

تقدير الحالة في أنظمة الطاقة هو إجراء تقدير حالات حجم الجهد والزاوية في جميع الناقلات بناءً على توفر القياسات. تقليديًا، كان نظام التحكم الإشرافي والحصول على البيانات (SCADA) قادرًا على توفير جميع الكميات المقاسة بالإضافة إلى حالات جميع محولات النظام. في الآونة الأخيرة، تم تطوير جهاز قياس يسمى وحدة قياس الطور (PMU) والذي يمكنه قياس أطوار (المقدار والزاوية) للجهد والتيار للموصل الذي تم تركيبه عليها ديناميكيًا. هذا الجهاز قادر على قياس أي تغيرات ديناميكية في الأطوار. ستؤدي إضافة المزيد من هذه الوحدات إلى النظام إلى تحسين أخطاء الانحراف الزمني في نظام الطاقة. في هذه الورقة، تم شرح التحسن في تقدير الحالة باستخدام الكميات المقاسة بواسطة هذه الوحدات. تم التحقق من صحة التحسين لأنظمة الناقلات IEEE-14 وIEEE-30. يستخدم مقدر الحالة المقترح الحالات المقدرة من نموذج المربع الأصغر المرجح (WLS) بالإضافة إلى الحالات المقدرة من وحدات PMU التي تم تصميمها على أساس مرشح كالمان. يتم التقدير أولاً في التكوين القطبي باستخدام نموذج WLS من القياسات التقليدية، ثم يتم استخدام هذه الحالات من وظيفة PMU لتقدير تقدير حالة النظام النهائي المعبر عنه في الإحداثيات المستطيلة. تم استخدام برنامج MATLAB للمحاكاة والتحقق من النتائج.

- التقدير الهجين، الطور، المربعات الصغرى المرجَّ ، ترشيح كالمان، المعالجة اللاحقة.

■ Introduction

Nowadays, the state estimation in Power System is a procedure for synchronized estimating the phasors of voltage/currents (magnitudes and angles) at each bus in the system. Recently, this can be accomplished by direct use of very accurate synchronized PMUs of all bus in the system. However, some quantities measured would be very vulnerable to measurement errors or experience telemetry failures. Moreover, installing dedicated PMU at every bus are very costly.

Typical, the procedure of state estimation makes use of available set of redundant measurements at a given point of time in order to filter out such errors and find an optimal state estimate. The measurements include not only the conventional power measurements, but also those others such as the synchronized voltage/current phasor measurements as well. The definition of the system state in electrical power studies typically includes the steady state bus voltage phasors only.

State estimator tools are the core of any on-line security analysis since it acts like filtering technique employed to give most reliable current system states based on the system raw measurements for the applications like contingency analysis, load-flow studies etc. The raw measurements may include voltage/current states, measurements of power injections and flow. The positions of switches and circuit breakers in power substations are usually processed by specified topology processor. This topology processor should be able to generates a bus/branch model of the power system as illustrated in Fig. 1.

There are many methods that state estimator uses to estimate the state estimation at each bus in the power system (the most commonly WLS method). Some other recent developed method is the PMU. PMUs use GPS signals to synchronize quantities measured of voltage of phasors (positive sequence) at buses over the power distribution network and current phasors (positive sequence) in the line that is connected to those buses. The synchronization may achieve an accuracy better than one microsecond, and the measurements set is providing snapshot of the state of the power system in a real-time.

It should be mentioned that the positive sequence voltages at all buses of the network will constitute the state vector of the system thus, it will become a very easy to solve exclusively the problem of state estimation by using measurements of phasors. With aid of these measurements, the process can measure the system states rather than estimating them (i.e., using measurements that are nonlinear). Also, since the cost of PMUs are very high, their measurements are used as additional measurements with the traditional measurements.

Although a PMU-based estimation can be considered more reliable technique compared to traditional state estimators, it is well recognized that in many cases, it is not possible to provide PMU measurements in sufficient numbers that can accomplish estimation with high accuracy. In other words, when sufficient numbers of phasor measurements are added to the other measurements, it leads to make the accuracy of the state estimate much improved

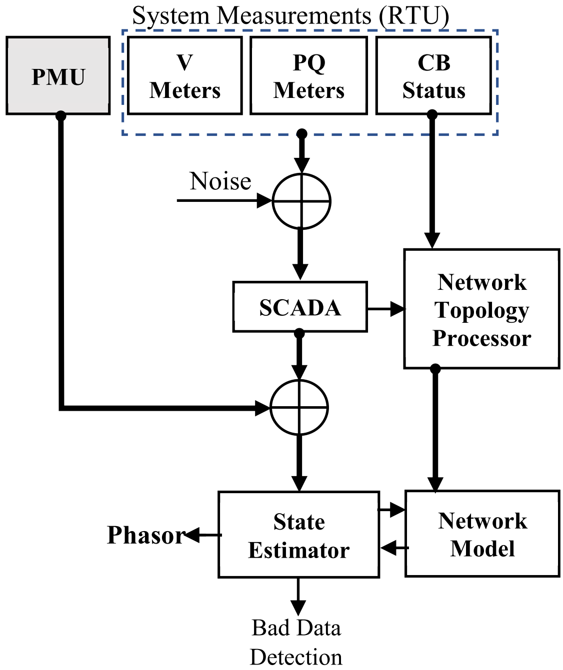

Figure 1. Block diagram of State Estimation

There are different methods that are adopted to include the set of phasor measurements into the traditional measurement set (e.g., appending the phasor measurements of currents and voltages as additional measurements to the traditional measurement set). This will produce a nonlinear state estimator which will require significant modifications to existing energy management system (EMS software). In addition, typical phasors estimators are commonly designed and implemented based on the so-called Fourier transform (FT) algorithm. One of the key shortage of adopting Phasor-Based FT algorithm is that the estimation of the fundamental phasors may has extremely destroyed when the measured signal is corrupted with noise (1-5).

Furthermore, an accurate fundamental phasor estimation requires using a full-cycle of samples. When some harmonics or inter-harmonics as defined according to IEC 61000-2-1 standard (6) are presented, this will lead to decrease the accuracy (due to the leakage effect) (7-10). Addressing the problem of state estimation in power system was started about 50 years ago. The works presented in (11-13) were the firsts to propose and develop the idea of state estimation for power systems monitoring. Since then, the subject has called the attention of many research groups like the ones presented in (14-17). Moreover, numerous publications that reported on many facets of state estimation are documented in two specialized books (18, 19).

Those previous works dealt only with static state estimators that their performance could be a reasonable e in practice. Challenges of adopting dynamic models for estimation was first addressed in the work presented in (20). In this work paper, a method for integrating phasor measurements with the traditional state estimation system was given. Years later, more research papers were presented in the literature which are covered the general aspects of dynamic estimation for nonlinear systems based on Kalman filtering (KF) algorithm (21-25). Those recent works not were considered phasor measurements of currents and voltages as additional measurements to traditional measurement that is the key functionality of EMS state estimators being used today.

In this paper, the phasor measurements are proposed to be added to the estimation through a post-processing step. The contribution in this paper is the WLS state estimation algorithm will be firstly used to obtain the state vector (in polar co-ordinates from conventional measurements) then, this state estimation will be combined together with the measurement vector from phasor measurements. By doing so, a new measurement set (dynamically estimated) will be formed and a straight dynamic linear state estimation procedure which does not require any iterative methods.

The remaining of the paper is structured as follows: Section II presents the procedure of estimation based on KF algorithm and how this estimation can be combined with WLS. Section III presents simulation results and discussions. Section IV is the conclusions.

II. Pmu-Aided Wls State Estimation

In this section, a straight forward application of WLS estimation by incorporating phasor measurements (currents and voltages) as additional measurements is proposed. The phasor state estimator is adopting PMU-Based KF algorithm. This adopting of KF algorithm will help to decrease the estimation errors for nonlinear systems during transients. The incorporation of phasor measurements of the adopted PMU-Based KF sited at designated buses in the power network will increase the data redundancy for WLS. The conventional measurements of SCADA system (Z_{Conv}) can be complemented by measurements of PMU (Z_{PMU}), such as bus voltages (polar) and line currents (real and imaginary parts). The schemes that can be proposed to incorporate measurements of phasor to the classical WLS algorithm as: 1)- The measurements of conventional combined with phasor and are processed by adopting a single estimator (hybrid) and 2)- The measurements of conventional and phasor are used as individual two sets and processed by two estimators.

State estimators in in today's electric power control centers are purchased as part of EMS software functions. Because estimation software cannot accommodate the measurements of phasor V and I unless they are converted into equivalent power measurements (i.e., P and Q). Thus, scheme (2) is may considered more useful since it can preserve the existent of the conventional estimator and enable the processing of bad data (BD). In other words, this scheme gives more accurate results and does not require to do any modification to the EMS software.

III. *General WLS based State Estimation*

Consider a scanned set of traditional measurements z_{conv_1} consisting of asynchronized data which map represents the flows and bus injections of any active and reactive power across network elements in addition to voltage magnitudes at the buses of the network. Also assume that BD has been eliminated from this set of measurements by any typical method. The non-linear function of the state vector *x* of those measurements (i.e., the positive sequence voltages at all the buses) can be written as:

$$z_{conv\_1} = h_1(x) + e_1 \quad (1)$$

where, h_1 is non-liner function, x is state vector (in polar coordinates), and e_1 represents the vector of measurement error (with a covariance matrix R_1). The Jacobian matrix (i.e., H_1) can be written by:

$$H_1(x) = \frac{\partial h_1(x)}{\partial x} \quad (2)$$

The Gain matrix can be written as:

$$G_1(x^k) = \left[H_1^T(x_k) R_1^{-1} H_1(x_k)\right]^{-1} \quad (3)$$

Also, the covariance matrix of error of the estimate x can be written as:

$$Cov([x]) = \left[H_1^T R_1^{-1} H_1\right] \quad (4)$$

Finally, the state vector (the estimation) can be obtained and written in an iterative way as follows:

$$\left[x^{k+1}\right] = \left[x^k\right] + \left[G_1(x^k)\right]^{-1} \left[H_1^T R_1^{-1}\right] \left[z_{conv\_1} - h_1(x^k)\right] \quad (5)$$

This iterations will continue until is $\max\left|\Delta x^k\right| \leq \varepsilon$ met or alternatively until maximum allowable number of iterations is exceeded. In equation (5), the state vector can be converted to rectangular co-ordinates using the matrix of rotation given by equation (6).

$$K = \begin{bmatrix} \cos\delta_1 & 0 & 0 & -|E_1|\sin\delta_1 & 0 & 0 \\ 0 & \cos\delta_2 & 0 & 0 & -|E_2|\sin\delta_2 & 0 \\ 0 & 0 & \vdots & 0 & 0 & \vdots \\ \sin\delta_1 & 0 & 0 & |E_1|\cos\delta_1 & 0 & 0 \\ 0 & \sin\delta_2 & 0 & 0 & |E_2|\cos\delta_2 & 0 \\ 0 & 0 & \vdots & 0 & 0 & \vdots \end{bmatrix} \quad (6)$$

The magnitudes ($|E_1|$, $|E_2|$, … $|E_n|$) and their respective angles ($|\delta_1|$, $|\delta_2|$, … $|\delta_n|$) can be converted state vector as follows:

$$\begin{bmatrix} V_R \\ V_I \end{bmatrix}_{conv} = [K][x] \quad (7)$$

where subscripts R and I denote the real and imaginary components of voltage, respectively.

IV. *PMU based State Estimation*

Post-processing method requires combine set of traditional measurements with phasors of voltage/currents (magnitudes and angles) at each bus in the system. Recent works that have been mentioned before (21-24) adopted traditional algorithms of KF for those phasors estimation.

One of major drawback of adopting adopted traditional algorithms of KF for phasors estimation is the estimation is extremely distorted when the measured signal is corrupted with noise or when the degree of system's non-linearity is high. In contrast to the traditional algorithms of KF, Unscented Kalman Filter (UKF) can combine between better flirtation of noise and linearization of a highly non-linear system. In this paper, estimating the phasors is done according the procedure the functional block diagram shown in Fig. 2.

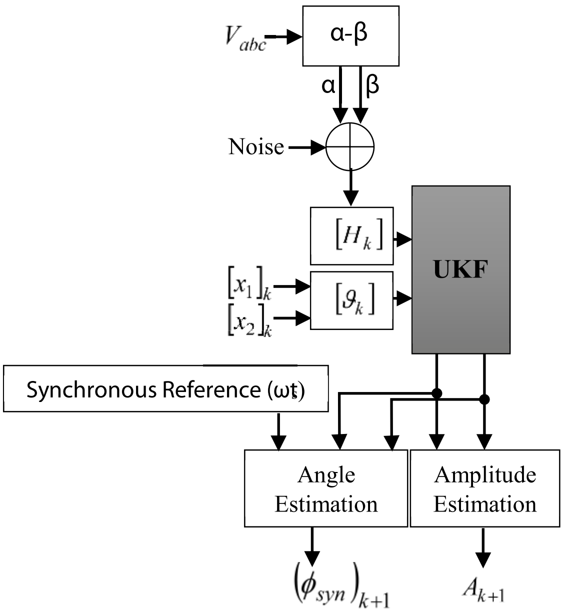

Figure 2. Schematic diagram of UKF based PMU function

The state estimation (phasors) are estimated by using first the Clark Transformation (*T*). The measured signals are firstly transformed to *α-β* components in a discrete as in equation (8) and then, this equation can be expressed in as in equation (9) whereand .$[V_\alpha]_k = A_k \cos(\omega\Delta t + \phi_k)$ and $[V_\beta]_k = A_k \sin(\omega\Delta t + \phi_k)$

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix}_k = T \cdot \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}_k + [r_{\alpha\beta}]_k \quad (8)$$

$$\lfloor V_{\alpha\beta}\rfloor_k = [V_\alpha]_k + j\lfloor V_\beta \rfloor_k \quad (9)$$

Let $[V_\alpha]_k = [x_1]_k$ and $\lfloor V_\beta \rfloor_k = [x_2]_k$, the states $[x_1]_k$ and $[x_2]_k$ can be written in transition form as follows:

$$[x_1]_{k+1} = [x_1]_k \cos(\omega\Delta t) - [x_2]_k \sin(\omega\Delta t) \quad (10)$$

$$[x_2]_{k+1} = [x_1]_k \sin(\omega\Delta t) + [x_2]_k \cos(\omega\Delta t) \quad (11)$$

Equations (10) and (11) can be rearranged in matrix form as:

$$\begin{bmatrix} x_1 \\ x_2 \end{bmatrix}_{k+1} = \underbrace{\begin{bmatrix} \cos(\omega\Delta t) & -\sin(\omega\Delta t) \\ \sin(\omega\Delta t) & \cos(\omega\Delta t) \end{bmatrix}}_{Transition-Matrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}_k \quad (12)$$

Now, phasor (amplitude and angle) can be calculated straight-forwardly by using $A_{k+1} = \sqrt{[(x_1)_{k+1}]^2 + [(x_2)_{k+1}]^2}$ and $\phi_{k+1} = \tan^{-1}(\frac{(x_1)_{k+1}}{(x_2)_{k+1}})$, respectively. The angle is not yet synchronized and it can be made synchronized by using the following relationship in equation (13).

$$(\phi_{syn})_{k+1} = \left(\frac{e^{-j(\phi_{k+1}) + \frac{\pi}{2}}}{e^{-j(2\pi f t_s)}} \right) \times \frac{180}{\pi} \quad (13)$$

where t_s represents a synchronous time reference. Finlay, those values of phasor $\left((z_{PMU})_{k+1} = \begin{bmatrix} A_{k+1} \\ (\phi_{syn})_{k+1} \end{bmatrix} \right)$ is substituted in the discrete measurements equation of the recursive non-linear system discrete equations of Kalman filter the represented in equations (14) and (15).

$$\underbrace{(x_{PMU})_{k+1} = \vartheta_k x_k + w_k}_{Discrete-state-equation} \quad (14)$$

$$\underbrace{(z_{PMU})_{k+1} = H_k + v_k}_{Discrete-measurment-equation} \quad (15)$$

The procedure followed in estimating voltage phasor can be same in estimating current phasor. After transforming those phasors into rectangular coordinates, the following equation can be written:

$$\begin{bmatrix} \begin{bmatrix} V_R \\ V_I \end{bmatrix}_{PMU} \\ \begin{bmatrix} I_R \\ I_I \end{bmatrix}_{PMU} \end{bmatrix} = [K] \begin{bmatrix} (z_{PMU})^V \\ (z_{PMU})^I \end{bmatrix} \quad (16)$$

Thus, the general model of measurement can be written as:

$$\begin{bmatrix} \begin{bmatrix} V_R \\ V_I \end{bmatrix}_{conv} \\ \begin{bmatrix} V_R \\ V_I \end{bmatrix}_{PMU} \\ \begin{bmatrix} I_R \\ I_I \end{bmatrix}_{PMU} \end{bmatrix} = \begin{bmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \\ H_{31} & H_{32} \\ H_{41} & H_{44} \\ H_{51} & H_{52} \\ H_{61} & H_{62} \end{bmatrix} \begin{bmatrix} V_R \\ V_I \end{bmatrix} + \begin{bmatrix} (e_{V_R})_{conv} \\ (e_{V_I})_{conv} \\ (e_{V_R})_{PMU} \\ (e_{V_I})_{PMU} \\ (e_{I_R})_{PMU} \\ (e_{I_I})_{PMU} \end{bmatrix} \quad (17)$$

Or

$$[M] = [H] \cdot [V] + [e] \quad (18)$$

The solution to the WLS will be given as:

$$[V] = [G']^{-1} \cdot [H'][R']^{-1} \cdot [M] \quad (19)$$

where $[G']$ and $[R']$ are the new gain matrix and the new covariance matrix and they are given by $[H']^t [R']^{-1} \cdot [H']$ and $\begin{bmatrix} [K'] \cdot [H_1^t R_1^{-1} H_1] \cdot [K']^t & 0 \\ 0 & K \cdot R_2 \cdot K^t \end{bmatrix}$, respectively.

V. Simulation Results and Discussion

The proposed algorithm of estimation has been carried out for IEEE-14 and IEEE-30 bus systems. The set of traditional measurement of is consisting of active and reactive power flows (flows and injections) and magnitudes of voltage at buses. The solution is found by load flow algorithm at appropriate errors of measurement. Also, the solution is found for base case load flow at starting point. Measurements of phasor are consisting of phasors of voltages and currents. All measurements have been distributed evenly across the system. The solution of the load flow is expected to afford a state vector (true value). It is also expected that the solution is able to add the errors to the measured quantities with appropriate standard deviation (s) that has been assigned.

Moreover, each UKF based-PMU that has been allocated at a bus is assumed to measure the voltage of this bus and the currents in all the lines that originate on that bus. The angle of the swing bus angle is designated as 0° and all other bus's angles are adjusted in order that they conform with the convention (angle of swing bus= 0°). The results of the simulation that is shown in Error! Reference source not found. is for voltage magnitude estimation with and without UKF based-PMU measurements in the post-processing on IEEE-30 bus system.

Fig. 3 is presenting the errors of voltage magnitude estimation (in %) for the IEEE-30 bus system. It is clear that the percentage error has decreased to a very low value (about 10^{-4}%) for bus-2. Also, it is clear from Fig. 4 and Fig. 5 that the angle estimation error is decreased for all bus records with minimum value of about 0.02% for bus-5. Similarly, Fig. 6 and Fig.7 are presenting the value of error that was recorded for voltage magnitude estimation for the IEEE-14 bus system.

The error is decreased when the UKF based- PMU measurements was combined with the traditional measurements. In Fig. 8, the minimum error is recorded for bus-12 at value of about 10^{-5} %. Fig. 9 and Fig. 10 are presenting the estimation of angle. As presented in these Figures, the error is very small (about 10^{-10} shift) for bus-1 and this value is the smallest one that has been recorded among all error records for bot system (IEEE-14 and IEEE-30).

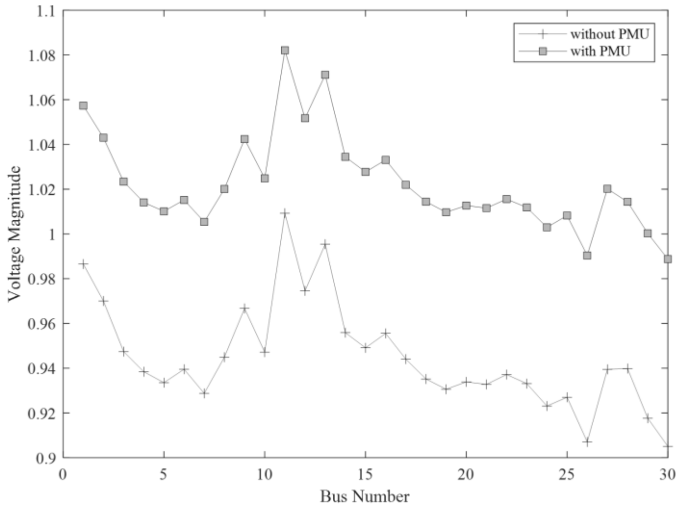

Figure 3. Voltage Magnitude Estimation (IEEE-30).

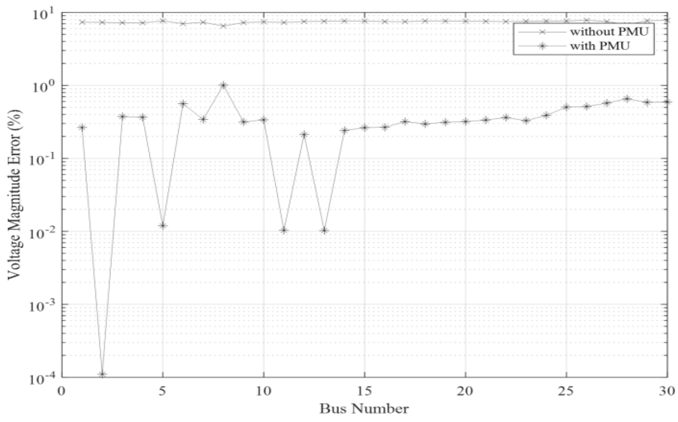

Figure 4. Voltage Magnitude Estimation Error (IEEE-30)

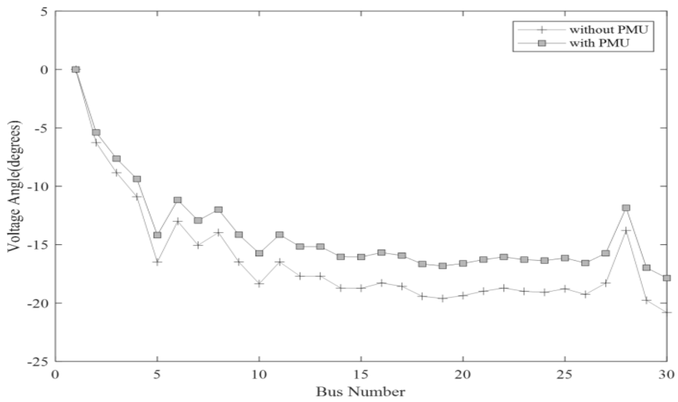

Figure 5. Voltage Angle Estimation (IEEE-30)

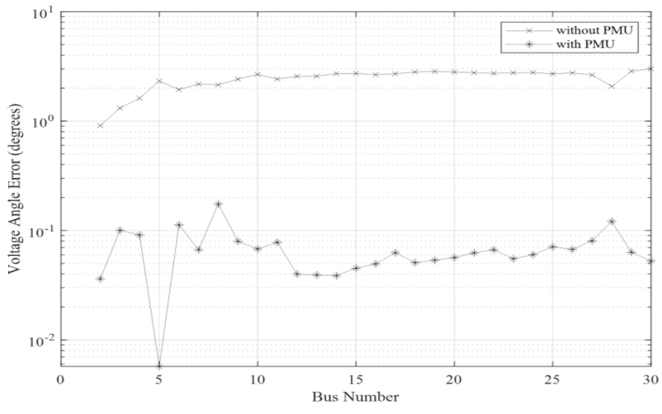

Figure 6.Voltage Angle Estimation Error (IEEE-30)

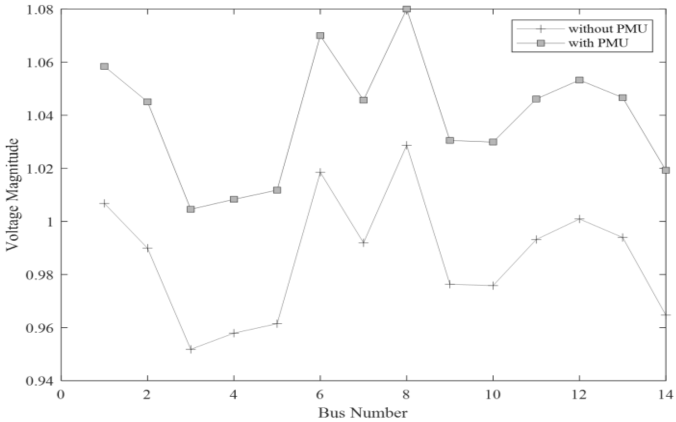

Figure 7. Voltage Magnitude Estimation (IEEE-14)

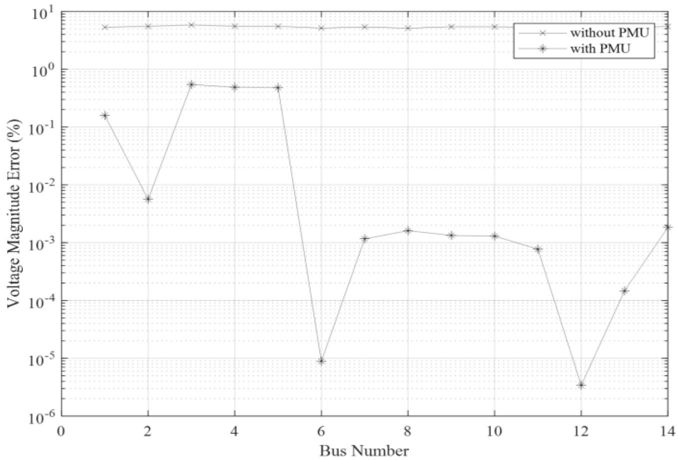

Figure 8.Voltage Magnitude Estimation Error (IEEE-14)

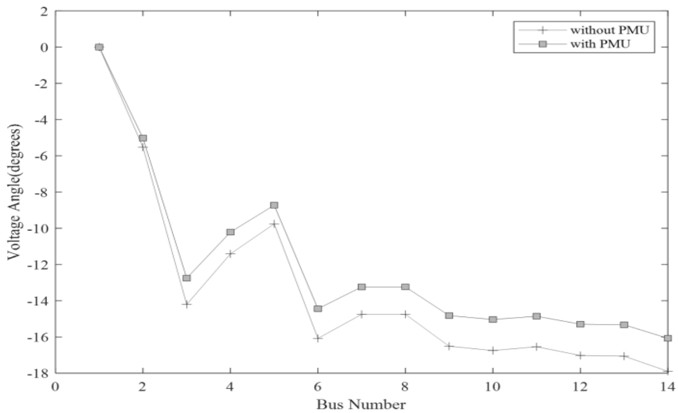

Figure 9. Voltage Angle Estimation (IEEE-14)

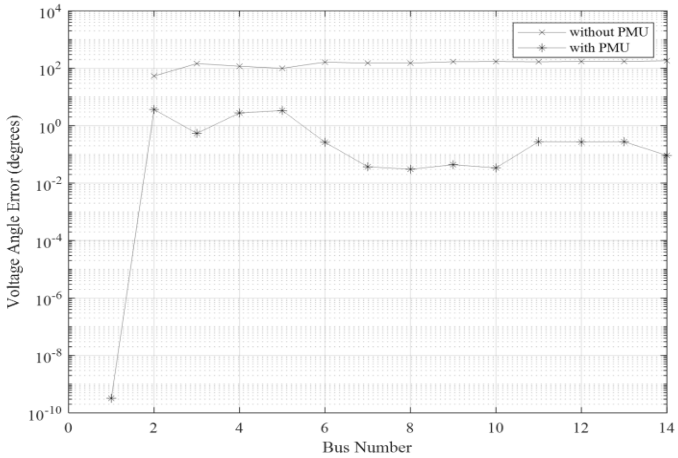

Figure 10. Voltage Angle Estimation Error (IEEE-14)

■ VI. Conclusion

In this paper, an effective method for hybrid state estimation in power system which incorporate measurements provided by dynamic UKF based-PMU with WLS based- estimation has been proposed. The estimation has been done for The following IEEE-14 and IEEE-30 bus systems. After simulations, it has been found that the estimation's error resulted when the dynamic UKF based-PMU being used was more accurate when it compared to the error resulted to the case when the dynamic UKF based-PMU not being in use. The results show that the percentage error in magnitude estimation was decreased from about 10% to 1.5% and from about 10% to about 10^{-5}% for IEEE-14 and IEEE-30 bus system, respectively. Moreover, the error for angle estimation is decreased from about 5% to about 0.02% and from 10^{2} to about 10^{-10} which implied that estimation could effectively enhance by adopting this hybrid estimation. It been found also that the computation time is totally decreased when this dynamic UKF based-PMU is adopted. The results of the traditional state estimate (voltage phasors) and the phasor measurements (voltage and current phasors) are a set of measurements that are linear functions of the state vector. This leads to a linear (non-iterative) estimation step. By adding the measurements of the proposed dynamic UKF based-PMU through the post-processing step, the proposed method can be implemented as an additional function and no modification is required of the traditional EMS software

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