State Estimation Model Including Synchronized Phasor Measurements

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***Abstract*- State estimation plays an important role in real time security monitoring and control of power systems. With increasing implementation of PMUs across the electric power grids and the ability of the Phasor Measurement Unit (PMU) to directly measure the system state, the use of these measurements to improve the precision of state estimator becomes imperative. In this paper, a new state estimator including voltage and current phasors and traditional measurements is proposed. The methodology is validated by simulation results on the 14 and 30 IEEE bus test systems. Several comparisons between the use of SCADA measurements and PMU measurements are exposed. Discussion concerning statistical robustness of the implemented state estimators is presented.**

***Index Terms*-- Power system state estimation, PMU, phasor measurements.**

I. INTRODUCTION

Power system state estimation is an important EMS application to provide real time, reliable and qualitative information on the system state. State estimators process a measurement set (voltages magnitudes, power injections and active and reactive power flows) taken throughout the network provided by SCADA system at a certain time to provide the snapshot of the system. This real-time data base built by the state estimator will be the proper starting point to all other on-line applications. The SCADA system is designed to receive and process teleinformation, forming real-time databases, displaying the information, documenting the data and solving dispatching tasks. It captures only quasi-steady state operating conditions, being unable to track fast transient phenomena's. During a dynamic event on the network, such as a load or topology change, time skew errors can occur on measurements provided by SCADA system as some of these analogue measurements are taken before and others after the occurrence of the event .As the synchronisation of these measurements aren't guaranteed when using the SCADA system, this will lead to an inaccurate estimation of the state variables. Phasor measurement units are considered to be important devices used as measurement technology of power systems due to its unique ability to sample analogue voltage and current data in synchronism with a GPS-clock and compute the sinusoidal wave and the phasors representing the magnitude and phase angle of the voltage and current from widely dispersed locations in the system [1]. Synchronised PMUs samples at selected locations throughout the power system provide a system-wide snapshot of the electrical system. With the development of synchronized phasor measurement technology in recent years, it gains great interest the use of PMU measurements to help improve state estimation performances due to their synchronized characteristic and high data transmission speed [3-14]. The work presented in this paper explores the use of PMU measurements on state estimation. While traditional state estimation uses active and reactive power measurements as well as voltage measurements, state estimation using PMUs requires voltage and current phasors. Traditional state estimation provides a state estimation solution by iterations, necessary because of the non-linear equations between the measurements and the state variables. Simplicity of relations between the phasor measurements and the state variables suggests that state estimation using PMUs will be much quicker than traditional state estimation. If the system would have only voltage magnitude and voltage phase angle measurements provided by the PMU, then the error in the estimates would be equal to the error in the measurements as they would be direct measurements of states and the estimation procedure would be reduced to solve a set of linear equations. Due to their cost, the extensive use and integration of these PMUs devices will not be instantaneous therefore it will be quite useful to enable their use to improve classical state estimation since there will be not enough PMUs for the exclusive use of their measurements by the state estimator. In our study, PMU data is incorporated after non-linear state estimation. Taking into consideration the estimated data from conventional static state estimator, using a PMU measurement set and the network topology and parameters a linear state estimation is performed to update the estimated state vector of the power system.

II. THEORETICAL BACKGROUND

A. Conventional state estimation

Conventional state estimation is solved by Weighted-Least-Square method [2].

For a given set of measurements, corresponding to bus power injections, line power flows and bus voltage magnitudes, that are related to the state variables (bus voltage magnitudes and phase angles) through the measurement function and the measurement noise, the state estimation nonlinear measurement model is formulated as:

$$z = h(x) + e \qquad (1)$$

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The function $h(x)$ corresponds to the nonlinear function relating measurements to the system states. x is the n-dimensional state vector and z the m-dimensional measurement vector, where n<m. The mathematical model that aims to find the values of the state variables minimizes the weighted sum of the squares of the difference between metered and estimated values:

$$J(x) = \left[z - h(x)\right]^T R^{-1}\left[z - h(x)\right] \quad (2)$$

As shown in [2], the best estimation of state variables x can be obtained using as weighting matrix the inverse of the error covariance matrix R. If measurement variables from measurement vector z are statistically independent, matrix R has a diagonal form and $R_{ii} = \sigma_i^2$, where σ_i is the standard deviation of errors associated to measurement z_i, and i = 1…m, where, as stated before, m is the number of measurements.

The minimization process can be achieved by setting to zero all derivatives of J with respect to variables from vector x, and using an iterative method. Thus, if x^k is the state variable at the beginning of iteration k, the next estimate x^{k+1} should be computed using the equations stated at the flowchart represented in Fig. 1, where

$H(x) = \frac{\partial h(x)}{\partial x}$ is the jacobian (m×n) matrix, $G(x) = \frac{\partial g(x)}{\partial x}$ is the gain matrix, and $R^{-1} = diag\left(\sigma_i^2\right)$ represents the covariance matrix of the measurement errors.

The iterative process terminates when either a maximum number of iterations has been reached, or the correction term falls below a certain tolerance.

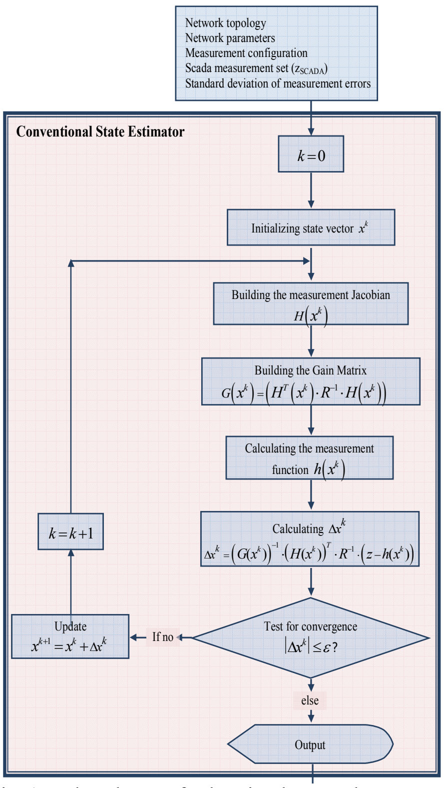

Fig. 1. Flowchart of the implemented conventional state estimation procedure.

B. Incorporating PMU measurements in conventional State Estimator measurement set

A PMU installed at a system bus can measure not only the voltage phasor of this bus, but also the current phasors in the lines connected to that bus. Current phasor measurements can be included in the measurement set [6, 12].

The approach considers the current injected in the buses with PMU, which corresponds to the sum of the line currents adjacent to the bus. The use of the data from the PMU further complicates the approach because it creates conflicts between quantities expressed in rectangular coordinates and polar coordinates. The integration of line current in a conventional estimator where the system state is expressed in polar coordinates means to express the line currents as nonlinear functions of magnitude and phase angle voltages at buses or considering that PMU measures the magnitude and the phase angle of line currents (which are still nonlinear functions of the system state). Obviously, the phase angle and magnitude can be calculated from the rectangular components, but the problem lies in the characterization of the covariance of measurement errors.

Expressing the phasor current at bus i:

$$\overline{I_i} = \overline{V_i} Y_{ii} + \sum_{j=1;\, j\neq i}^{n} Y_{ij} \overline{V_j} \quad (3)$$

where $Y_{ij} = G_{ij} + jB_{ij}$ establishes the series admittance of the branch that connects nodes *ij*. The real and the imaginary part of the injected current at bus i are expressed as:

$$I_{i_{real}} = V_i\left(G_{ii}\cos\delta_i - B_{ii}\sin\delta_i\right) + \sum_{j=1;\, j\neq i}^{n} V_j\left(G_{ij}\cos\delta_j - B_{ij}\sin\delta_j\right) \quad (4)$$

$$I_{i_{IMAG}} = V_i\left(G_{ii}\sin\delta_i + B_{ii}\cos\delta_i\right) + \sum_{j=1;\, j\neq i}^{n} V_j\left(G_{ij}\sin\delta_j + B_{ij}\cos\delta_j\right) \quad (5)$$

Adding phasor measurements, due to the use of PMU, to an existing system which already contains m measurements causes the jacobian matrix to augment with added rows corresponding to the partial derivatives of real and imaginary parts of the injected current in order to voltage magnitude and its phase angle.

The structure of the modified measurement jacobian matrix will be as follows:

$$H(x) = \begin{bmatrix} \partial P_{ij}/\partial\delta & \partial P_{ij}/\partial V & \text{real power flows } (i-j) \\ \partial P_i/\partial\delta & \partial P_i/\partial V & \text{bus real power injection} \\ \partial Q_{ij}/\partial\delta & \partial Q_{ij}/\partial V & \text{reactive power flows } (i-j) \\ \partial Q_i/\partial\delta & \partial Q_i/\partial V & \text{bus reactive power injection} \\ \partial V_i/\partial\delta & \partial V_i/\partial V & \text{bus voltage magnitude from SCADA} \\ \partial\delta_{iPMU}/\partial\delta & \partial\delta_{iPMU}/\partial V & \text{bus voltage phase angle from PMU} \\ \partial V_{iPMU}/\partial\delta & \partial V_{iPMU}/\partial V & \text{bus voltage magnitude from PMU} \\ \partial I_{ireal}/\partial\delta & \partial I_{ireal}/\partial V & \text{real injected bus current at bus } i \text{ with PMU} \\ \partial I_{iimag}/\partial\delta & \partial I_{iimag}/\partial V & \text{reactive injected bus current at bus } i \text{ with PMU} \end{bmatrix} \quad (6)$$

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where

$$\frac{\partial \delta_{iPMU}}{\partial \delta} = \begin{cases} 1 & , \quad i = j \\ 0 & , \quad i \neq j \end{cases} \qquad (7)$$

$$\frac{\partial \delta_{iPMU}}{\partial V} = 0 \quad , \quad \forall i \qquad (8)$$

$$\frac{\partial V_{iPMU}}{\partial \delta} = 0 \quad , \quad \forall i \qquad (9)$$

$$\frac{\partial V_{iPMU}}{\partial V} = \begin{cases} 1 & , \quad i = j \\ 0 & , \quad i \neq j \end{cases} \qquad (10)$$

$$\frac{\partial I_{i_{REAL}}}{\partial \delta} \rightarrow \begin{cases} \dfrac{\partial I_{i_{REAL}}}{\partial \delta_i} = -V_i \left(G_{ii} \sin \delta_i + B_{ii} \cos \delta_i \right) \\ \dfrac{\partial I_{i_{REAL}}}{\partial \delta_j} = -V_j \left(G_{ij} \sin \delta_j + B_{ij} \cos \delta_j \right) \end{cases} \qquad (11)$$

$$\frac{\partial I_{i_{REAL}}}{\partial V} \rightarrow \begin{cases} \dfrac{\partial I_{i_{REAL}}}{\partial V_i} = \left(G_{ii} \cos \delta_i - B_{ii} \sin \delta_i \right) \\ \dfrac{\partial I_{i_{REAL}}}{\partial V_j} = \left(G_{ij} \cos \delta_j - B_{ij} \sin \delta_j \right) \end{cases} \qquad (12)$$

$$\frac{\partial I_{i_{IMAG}}}{\partial \delta} \rightarrow \begin{cases} \dfrac{\partial I_{i_{IMAG}}}{\partial \delta_i} = V_i \left(G_{ii} \cos \delta_i - B_{ii} \sin \delta_i \right) \\ \dfrac{\partial I_{i_{IMAG}}}{\partial \delta_j} = V_j \left(G_{ij} \cos \delta_j - B_{ij} \sin \delta_j \right) \end{cases} \qquad (13)$$

$$\frac{\partial I_{i_{IMAG}}}{\partial V} \rightarrow \begin{cases} \dfrac{\partial I_{i_{IMAG}}}{\partial V_i} = \left(G_{ii} \sin \delta_i + B_{ii} \cos \delta_i \right) \\ \dfrac{\partial I_{i_{IMAG}}}{\partial V_j} = \left(G_{ij} \sin \delta_j + B_{ij} \cos \delta_j \right) \end{cases} \qquad (14)$$

Note that for the expressions above it was considered only the susceptance of the branch as $b_{0i} \gg g_{0i}$.

The gain matrix is formed using the measurement jacobian matrix and the measurement error covariance matrix R. This covariance matrix is assumed to be the diagonal measurement variances entries. The variances of the measurements are typically given in terms of variance or standard deviation on the magnitude and angle. The approach followed requires covariance matrix elements in corresponding to phasor rectangular components. Thus, it is necessary to transform them. Let us detail how to calculate covariance matrix elements of PMU measurements. Since the voltage phasor measurements are utilized directly, its error covariance matrix can be calculated based on the error distribution. The error covariance matrix for phasor currents measurements are calculated as covariance matrix of indirect measurements according to the known error variances of the direct measurements. The variance assigned to each measurement provides an indication of the certainty about that particular measurement.

The errors variance due to the measurement transformation can be calculated by:

$$\begin{aligned} \sigma^2_{I_{i_{real}}} &= \left(\frac{\partial I_{i_{real}}}{\partial |I_i|} \right)^2 \sigma^2_{|I_i|} + \left(\frac{\partial I_{i_{real}}}{\partial \theta_{I_i}} \right)^2 \sigma^2_{\theta_{I_i}} \\ &= \left(\cos\left(\theta_{I_i}\right) \right)^2 \cdot \sigma^2_{|I_i|} + |I_i| \cdot \left(-\sin\left(\theta_{I_i}\right) \right)^2 \sigma^2_{\theta_{I_i}} \end{aligned} \qquad (15)$$

$$\begin{aligned} \sigma^2_{I_{i_{imag}}} &= \left(\frac{\partial I_{i_{imag}}}{\partial |I_i|} \right)^2 \sigma^2_{|I_i|} + \left(\frac{\partial I_{i_{imag}}}{\partial \theta_{I_i}} \right)^2 \sigma^2_{\theta_{I_i}} \\ &= \left(\sin\left(\theta_{I_i}\right) \right)^2 \cdot \sigma^2_{|I_i|} + |I_i| \cdot \left(\cos\left(\theta_{I_i}\right) \right)^2 \sigma^2_{\theta_{I_i}} \end{aligned} \qquad (16)$$

where $\sigma^2_{I_{ireal}}$ and $\sigma^2_{I_{i_{imag}}}$ are the error variances of $I_{i_{real}}$ and $I_{i_{imag}}$ respectively. According to [15] $\sigma_{\theta_{I_i}}$ is considered to be 0.0017 rad and $\sigma_{|I_i|}$ is considered to be 0.002 p.u. thus the corresponding diagonal elements of error covariance matrix ($\sigma^2_{I_{ireal}}, \sigma^2_{I_{i_{imag}}}$) are calculated using the equations 15 e 16 expressed before.

The gain matrix is formed using the measurement jacobian matrix and the measurement error covariance matrix R, both described above.

C. *Use of PMU measurements and output vector of conventional state estimation in linear system state estimation procedure*

For a given set of measurements, corresponding to voltages magnitudes and phase angles and current line flows provided by PMU placed in different locations in the system and the output vector from conventional state estimation, the state estimation model is formulated as [3, 7, 13]:

$$\underbrace{\begin{bmatrix} \begin{bmatrix} |V_i| \\ \theta_i \end{bmatrix}_{estimated} \\ \begin{bmatrix} |V_i| \\ \theta_i \\ I_{ireal} \\ I_{i\,imag} \end{bmatrix}_{fromPMU} \\ \begin{bmatrix} I_{ireal} \\ I_{i\,imag} \end{bmatrix} \end{bmatrix}}_{Z_{comb}} = \underbrace{\begin{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \\ \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ \hdashline \dfrac{\partial I_{ireal}}{\partial |V_i|} & \dfrac{\partial I_{ireal}}{\partial \theta_i} \\ \dfrac{\partial I_{iimag}}{\partial |V_i|} & \dfrac{\partial I_{iimag}}{\partial \theta_i} \end{bmatrix} \\ \begin{bmatrix} \dfrac{\partial I_{ireal}}{\partial |V_i|} & \dfrac{\partial I_{ireal}}{\partial \theta_i} \\ \dfrac{\partial I_{iimag}}{\partial |V_i|} & \dfrac{\partial I_{iimag}}{\partial \theta_i} \end{bmatrix} \end{bmatrix}}_{H_{comb}} \underbrace{\begin{bmatrix} |V_i| \\ \theta_i \end{bmatrix}}_{x_{final}} + [e] \qquad (17)$$

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H_{comb} is a matrix that relates voltage magnitude and phase angle measurements from output vector of conventional and/or voltage phasors from PMU, $\frac{\partial I_{ireal}}{\partial |V_i|}\ \frac{\partial I_{ireal}}{\partial \theta_i}\ \frac{\partial I_{iimag}}{\partial |V_i|}$ are partial derivatives of real and imaginary parts of the injected current in order to voltage magnitude and its phase angle. The estimate $x_{estimated}$ will be computed using the equation:

$$x_{estimated} = \left(\left[H_{comb}\right]^T \cdot R^{-1} \cdot \left[H_{comb}\right]\right)^{-1} \cdot \left[H_{comb}\right]^T R^{-1} \cdot z_{comb} \quad (18)$$

where R is diagonal covariance matrix with $R_{ii} = \sigma_i^2$, and σ_i the standard deviation of errors associated to measurement vector z_{comb}. The subscript *comb* denotes the combination of matrix components taken from conventional estimation and from PMU.

The detailed algorithm for the incorporation of PMU data in state estimation is presented in figure 2 and 3.

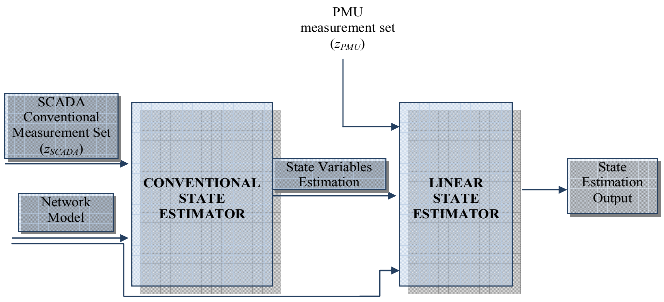

Fig. 2. State estimation diagram incorporating PMU measurements.

III. CASES STUDY

To test the models studied, a MATLAB software package was developed and used in this work. The simulation results were carried out on the 14 and 30 IEEE bus test system and using several performance indexes to validate the results. In Case I it is performed a state estimation, using both models to deal with the inclusion of PMU measurements on 14 IEEE bus test system while in Case II it was studied the results on 30 IEEE bus test system [16].

The voltage phase angles in state vector obtained by WLS are all with respect to slack bus as a reference. Synchronized phasor measurements might have a different reference which is determined by the instant synchronized sampling initiated, so to deal with the reference problem the solution adopted is to place a PMU at the reference bus of conventional state estimation model.

As measurements errors typically are of a statistical nature, thus the results obtained from state estimation procedures for the various scenarios for both cases were for the exactly same error characteristics and measurements either with or without the phasor measurements. The SCADA measured values are produced by adding the SCADA measurements errors yielding the normal distribution with zero mean and the standard deviation 0.008, 0.01 and 0.08 to the true values of power-flow power injections and voltage magnitude respectively. For all simulations it was assumed that conventional SCADA measurements were enough to make

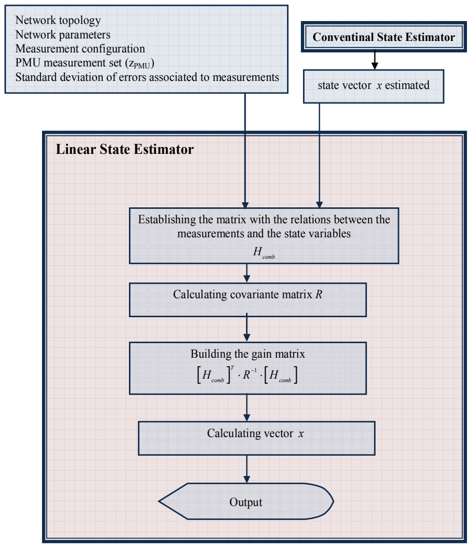

Fig. 3. Flowchart of the implemented linear state estimation procedure.

the entire system observable. It was used a steady state power flow condition to generate the real-time measurement sets and consider these the true values.

In both cases it was simulated with a flat start and a convergence tolerance of 10^{-5}.

A. *Case I*

In this case simulations were carried out on 14 IEEE bus test system. The measurement configuration used consists of 6 synchronized voltage measurements, 6 synchronized injected currents and 6 unsynchronized voltages and active and reactive flow measurement at all branches of the system. Results were obtained for 3 scenarios: state estimation with no synchronized measurements (scenario A), state estimation with a combined measurement set consisting on SCADA and PMU measurements (Scenario B), and conventional state estimation with no synchronized measurement in a first step and then in a second step use of PMU measurements and output vector of conventional state estimation in a linear system state estimation procedure (Scenario C).

In Fig. 4 it is shown the voltage magnitude error for all 14 buses, and also the behaviour of the errors when using different approaches on the use of PMU measurements. Figure 5 presents voltage angle error for all 14 buses also for the 3 scenarios. ‘Error’ indicates the difference between the estimated value and the actual value.

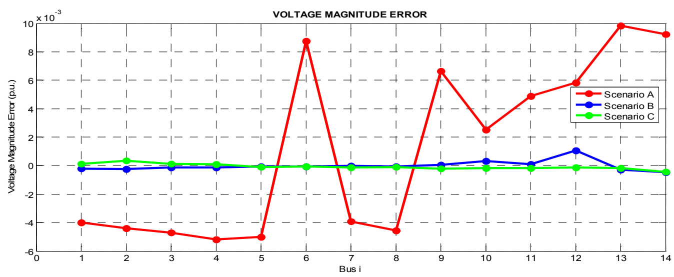

Fig. 4. State estimation results on voltage magnitude errors for 14 IEEE bus test system.

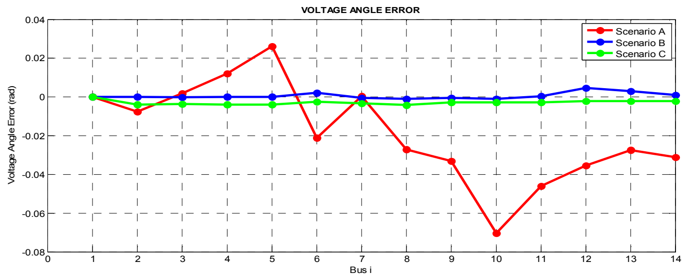

Fig. 5. State estimation results on voltage angle errors for 14 IEEE bus test system.

A comparison using several metrics [17] for the different state estimation scenarios is summarized in table I.

TABLE I

Scenario	Converges	$Mconv_V$	$Mconv_\theta$	$Macc_v$
A	178 iter.	0,0017	$9{,}10\times10^{-4}$	1,6597
B	9 iter	$9{,}84\times10^{-4}$	$5{,}45\times10^{-4}$	1,7483
C	----	----	-----	0,0120

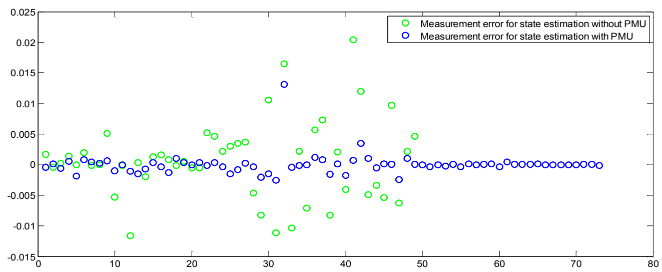

Fig. 6. State estimation results on measurements errors for 14 IEEE bus test system.

Figure 6 represents a plot representing a comparison on measurement errors of state estimation with or without the inclusion of PMU measurements.

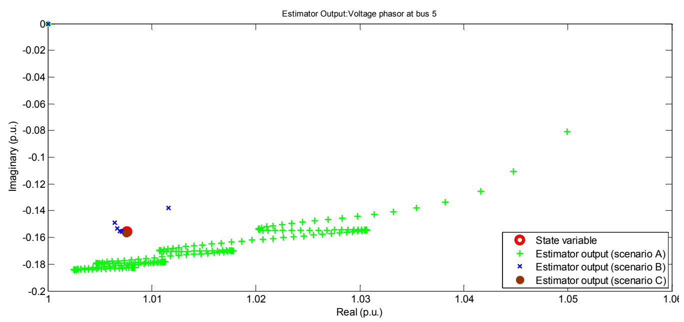

Fig. 7. State estimator output on state variable corresponding to voltage phasor at bus 5 of 14 IEEE bus test system.

Figure 7 corresponds to a plot showing a single state variable. This state variable corresponds to a substation 14 IEEE bus test system which is monitored by a PMU.

B. *Case II*

30 IEEE bus test system was used in this case. The simulations were carried out considering a measurement set consisting of 12 synchronized voltage measurements, 12 synchronized currents and 9 unsynchronized voltages, 23 injections and 29 flow measurements. Results were also obtained for 3 scenarios referred in case I.

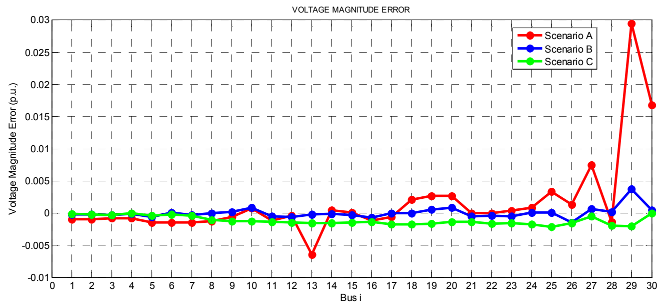

Fig. 8. State estimation results on voltage magnitude errors for 30 IEEE bus test system.

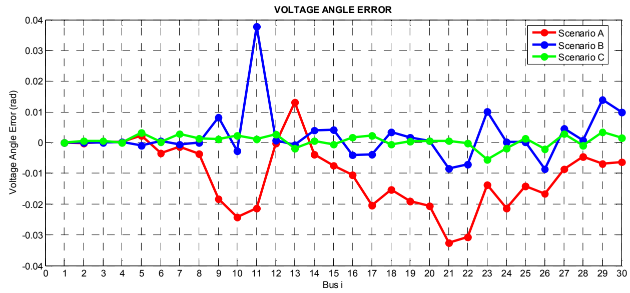

Fig. 9. State estimation results on voltage angle errors for 30 IEEE bus test system.

Figures 8 and 9 presents the voltage phasor error allowing a comparison of results for the approaches followed.

Table II comprises the performance indexes [17] of the estimator for all three scenarios simulated for the 30 IEEE bus test system.

TABLE II

Scenario	Converges	$Mconv_V$	$Mconv_\theta$	$Macc_v$
A	12iter	6.66×10^{-4}	$1{,}7\times10^{-3}$	0,4892
B	12iter	0,0095	$2{,}659\times10^{-4}$	0,4070
C	----	----	-----	0.0072

Figure 10 presents a plot representing a comparison on measurement errors of state estimation with or without the inclusion of PMU measurements. Figure 11 corresponds to a plot showing a single state variable that corresponds to a substation of 30 IEEE bus test system which is monitored by a PMU.

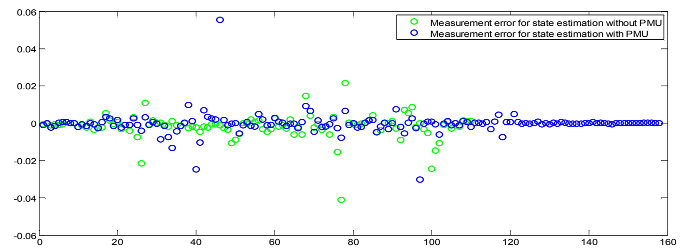

Fig. 10. State estimation results on measurements errors for 30 IEEE bus test system.

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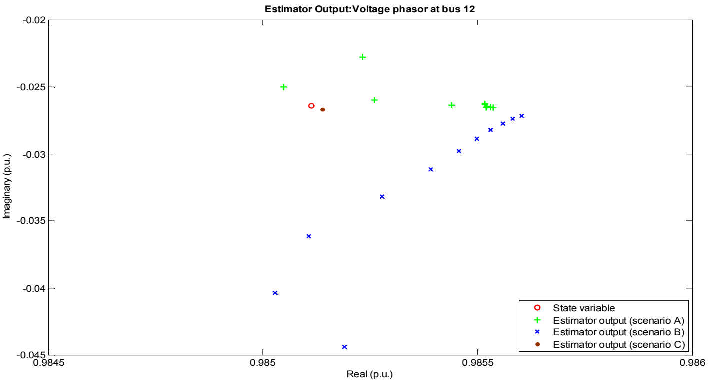

Fig. 11. State estimator output on state variable corresponding to voltage phasor at bus 12 of 30 IEEE bus test system.

IV. Discussion of Results

It can be observed that, generally, both techniques on dealing with PMU measurements on state estimation enhance state estimator accuracy. The method conventional state estimator with additional PMU measurements in a linear approach provides slightly higher precision. Simulations implemented converged in less iterations when using synchronized measurements and the measurements error is clearly lower when state estimator includes PMU measurements on its measurement set.

The true value of the system state is known from load flow, it is compared to the corresponding voltage measurements and estimated state vector. It can be seen from these plots that the state estimator using PMU measurements can effectively filter out measurement normally distributed random additive errors and estimate with a good degree of precision the system state. The results were similar on both IEEE bus test system.

V. Conclusion

PMU brings a whole new perspective in power system applications as it provides a more accurate and time-sensitive measurement set and therefore the inclusion of PMU data in state estimation is inevitable. In this context this paper presents a study on techniques for using PMU data in state estimation. Two techniques, conventional state estimator with SCADA and PMU measurements on its measurement set, conventional state estimator with additional PMU measurements in a linear approach for including synchronized phasor measurements on state estimation were tested and validated on IEEE 14 bus test system and IEEE 30-bus test system. The simulation results show that both techniques tested presents good results. Conventional state estimator with additional PMU measurements in a linear approach technique has the advantage to include the phasor measurements in the estimation process without altering the existing state estimator structure, taking the estimated state from the conventional state estimator and using synchronized measurements with a linear estimation procedure to enhance the estimated system state. Also the linear part of the procedure may be solved more frequently as phasor data is sampled at much higher rates than SCADA data for the conventional state estimator.

Further tests need to be done for larger power systems.

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