Combined use of SCADA and PMU Measurements for Power System State Estimator Performance Enhancement

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***Abstract*--State estimator is vital for on-line power system monitoring, analysis and control. With the increasing use of synchronized phasor measurement units (PMU) in power grids, how to utilize phasor measurements to improve the precision of state estimator becomes imperative. In this paper, a state estimator including voltage phasors, injected current phasors and traditional measurements is proposed. 14 IEEE bus system and 30 IEEE bus system are used as test systems and the simulation results demonstrate that the presented state estimation algorithm combining traditional SCADA measurements with PMU (Phasor Measurement Unit) measurements for power system state estimation improves the precision greatly.**

***Index Terms*-- EMS, PMU measurements, state estimation.**

I. Introduction

State estimation is a key application of energy management system (EMS).It is a process that determines the state of the power system allowing system operator to be able to take better decisions aiming at maintaining power system security. Advanced applications performance is highly dependent on the state estimator robustness and on its output quality. Improvement in the accuracy of the state estimation of the power system network is one of the most immediate benefits of PMU application. The measurements provided by PMUs are usually superior to the conventional measurements in a power system in terms of resolution and accuracy. Accuracy is a metric of how close the measure taken is from its true value. To enhance power system estimator accuracy and allow secure operation of the EMS, a new type of measurement was introduced in the measurement set. Bus voltages and all branch currents phasor can be measured by Phasor Measurement Units (PMUs) in the network. A PMU, when placed at a bus, can measure the voltage phasor at the bus, as well as the current phasors through the lines incident to the bus. It samples the ac voltage and current waveforms while synchronizing the sampling instants with a global positioning system (GPS) clock. The computed values of voltage and current phasors are time-stamped and transmitted by the PMUs to the local or remote receiver as the PMUs are equipped with Global Positioning System receivers that allow the synchronization of several readings taken at distant points. A GPS satellite receiver provides a precise timing pulse, which is correlated with sampled voltage and current inputs, usually the three phase voltages and the currents in lines [1].

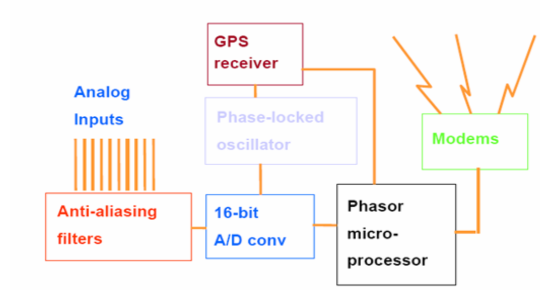

Fig. 1. Phasor Measurement Unit Block Diagram [1].

PMU measurements are of great interest for real time applications such as state estimation due to their synchronized characteristics and high data transmission speed.

Thus, there are several topics being discussed in the literature on the use of phasor measurements in state estimation. The incorporation of PMUs in state estimation is referred in the literature [2-13].

This paper presents a method that finds a combined measurement set for solving power system state estimation. This measurement set is such that insures completely system observability and the use of PMU measurements improves the performance of the state estimator. It is desired that it be able to best determine actual system behaviour. The estimated quantities should be as close as possible, to their true values. This ability determines estimator accuracy. Its outputs are also needed by other real time applications and so are very important to get on line results to increase the estimator quality.

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As PMUs provides very accurate measurements, the objective is to implement a method to power system state estimation, in order to improve convergence and enhance estimator quality in the presence of combined measurements.

II. Problem Formulation

A. Traditional WLS Method

The state estimation nonlinear measurement model is formulated based on the measurement equations, that for a given set of bus voltage, line flows and injection measurements, z, related to the vectors of state variables, x, and measurement noise e, is [16]:

$$z = h(x) + e \tag{1}$$

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 voltage magnitude and phase angle at all buses are chosen as state variables, defined by state vector x. In the conventional WLS estimator the measurement vector z comprises voltage magnitudes, active and reactive power flows and injections. Further on in this paper we are going to expand the measurement vector z with observations obtained from PMU.

The achievement of an estimate for the system state variables vector using the weighted least square method (WLS) consists in determining the state vector that minimizes the function:

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

This estimate should satisfy, at least, the first order optimality constraints as:

$$g(x) = \frac{\partial J(x)}{\partial x} = -H^T(x) R^{-1} \left[z - h(x)\right] = 0 \tag{3}$$

The iterative equations using the Gauss-Newton method has the form:

$$\left(H^T\left(x^k\right) \cdot R^{-1} \cdot H\left(x^k\right)\right) \cdot \left(\Delta x^{k+1}\right) = H^T\left(x^k\right) \cdot R^{-1} \cdot \left(z - h\left(x^k\right)\right) \tag{4}$$

where $H(x) = \frac{\partial h(x)}{\partial x}$, $R^{-1} = diag\left(\sigma_i^2\right)$

and $g\left(x^k\right) = -H^T\left(x^k\right) \cdot R^{-1}\left(z - h\left(x^k\right)\right)$, $G(x) = \frac{\partial g(x)}{\partial x}$

B. Incorporating PMU measurements in WLS state estimator

The state estimation mathematical model including phasor measurements on the measurement set is presented in this section.

PMU has the ability to measure the voltage magnitude on buses, as well as the currents in adjacent lines of system buses. Thus, the measurement vector will contain voltage phase angle and current phasor measurements and traditional SCADA measurements such as voltage magnitude measurements and active/reactive power injections and power flows measurement.

The approach followed considers the current injected in the buses with PMU, which corresponds to the sum of the line currents adjacent to that bus.

Due to the use of PMU measurements, it is necessary to deal with the conflicts between quantities expressed in rectangular coordinates and polar coordinates. The integration of injected current in a conventional estimator where the system state is expressed in polar coordinates means to express the injected 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.

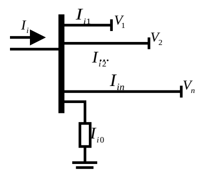

Fig. 2. Injected current at bus i

The phasor currents at bus i are expressed as:

$$\overline{I_i} = \overline{V_i} Y_{ii} + \sum_{\substack{j=1 \\ j \neq i}}^{n} Y_{ij} \overline{V_j} \tag{5}$$

where $Y_{ij} = G_{ij} + jB_{ij}$ establishes the series admittance of the branch that connects nodes ij.

The real part of the injected current at bus i is expressed as:

$$I_{i_{real}} = V_i \left(G_{ii} \cos\delta_i - B_{ii} \sin\delta_i\right) + \sum_{j=1;\, j \neq i}^{n} V_j \left(G_{ij} \cos\delta_j - B_{ij} \sin\delta_j\right) \tag{6}$$

and the imaginary part of the injected current at bus i is expressed as:

$$I_{i_{IMAG}} = V_i \left(G_{ii} \sin\delta_i + B_{ii} \cos\delta_i\right) + \sum_{j=1;\, j \neq i}^{n} V_j \left(G_{ij} \sin\delta_j + B_{ij} \cos\delta_j\right) \tag{7}$$

Adding phasor measurements, due to the use of PMU, to an existing system which already contains m measurements, the jacobian matrix is augmented with added rows corresponding to the partial derivatives of voltage phase angle in order to voltage magnitude and phase angle, determine as:

$$\frac{\partial \delta_{iPMU}}{\partial \delta} = \begin{cases} 1 & , \quad i = j \\ 0 & , \quad i \neq j \end{cases} \tag{8}$$

$$\frac{\partial \delta_{iPMU}}{\partial V} = 0 \quad , \quad \forall i \tag{9}$$

$$\frac{\partial V_{iPMU}}{\partial \delta} = 0 \quad , \quad \forall i \tag{10}$$

$$\frac{\partial V_{iPMU}}{\partial V} = \begin{cases} 1 & , \quad i = j \\ 0 & , \quad i \neq j \end{cases} \tag{11}$$

and also with the partial derivatives of real and imaginary parts of the injected current in order to voltage magnitude and its phase angle determine as:

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

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

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

$$\frac{\partial I_{i_{IMAG}}}{\partial V} \rightarrow \begin{cases} \dfrac{\partial I_{i_{IMAG}}}{\partial V_i} = \left(G_{ii} \sin \delta_i + B_{ii} \cos \delta_i \right) \\ \dfrac{\partial I_{i_{IMAG}}}{\partial V_j} = \left(G_{ij} \sin \delta_j + B_{ij} \cos \delta_j \right) \end{cases} \tag{15}$$

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

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

$$H(x) = \left[\begin{array}{cc|l} \partial P_{ij}/\partial \delta & \partial P_{ij}/\partial V & real\ power\ flows\,(i-j) \\ \partial P_i/\partial \delta & \partial P_i/\partial V & bus\ real\ power\ injection \\ \hdashline \partial Q_{ij}/\partial \delta & \partial Q_{ij}/\partial V & reactive\ power\ flows\,(i-j) \\ \partial Q_i/\partial \delta & \partial Q_i/\partial V & bus\ reactive\ power\ injection \\ \hdashline \partial V_i/\partial \delta & \partial V_i/\partial V & bus\ voltage\ magnitude\ from\ SCADA \\ \hdashline \boxed{\partial \delta_{iPMU}/\partial \delta} & \boxed{\partial \delta_{iPMU}/\partial V} & bus\ voltage\ phase\ angle\ from\ PMU \\ \hdashline \boxed{\partial V_{iPMU}/\partial \delta} & \boxed{\partial V_{iPMU}/\partial V} & bus\ voltage\ magnitude\ from\ PMU \\ \hdashline \boxed{\partial I_{ireal}/\partial \delta} & \boxed{\partial I_{ireal}/\partial V} & real\ injected\ bus\ current\ at\ bus\ i\ with\ PMU \\ \boxed{\partial I_{iimag}/\partial \delta} & \boxed{\partial I_{iimag}/\partial V} & reactive\ injected\ bus\ current\ at\ bus\ i\ with\ PMU \end{array} \right]$$

The covariance matrix of state estimation algorithm is a diagonal matrix where its elements are the measurement variances. These measurement variances are typically given in terms of variance or standard deviation on the magnitude and angle. Since the voltage phasor measurements are utilized directly, its error covariance matrix can be calculated based on the error distribution. According to [17], the standard deviations of the errors of voltage phasor measurement can be set as 0.0017 rad (phase angle) and 0.002 p.u. (magnitude), and thus their squares are the corresponding diagonal elements of error covariance matrix. 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. As the approach followed requires covariance matrix elements in corresponding to phasor rectangular components it is necessary to transform them. Let us detail how to calculate covariance matrix elements of PMU measurements.

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

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

$$\begin{aligned} \sigma^2_{I_{i_{imag}}} &= \left(\frac{\partial I_{i_{imag}}}{\partial |I_i|} \right)^2 \sigma^2_{|I_i|} + \left(\frac{\partial I_{i_{imag}}}{\partial \theta_{I_i}} \right)^2 \sigma^2_{\theta_{I_i}} \\ &= \left(\sin\left(\theta_{I_i}\right) \right)^2 \cdot \sigma^2_{|I_i|} + |I_i| \cdot \left(\cos\left(\theta_{I_i}\right) \right)^2 \sigma^2_{\theta_{I_i}} \end{aligned} \tag{17}$$

where $\sigma^2_{I_{ireal}}$ and $\sigma^2_{I_{iimag}}$ are the error variances of $I_{i_{real}}$ and $I_{i_{imag}}$ respectively. Considering $\sigma_{\theta_{I_i}}$ is 0.0017 rad and $\sigma_{|I_i|}$ 0.002 p.u. the corresponding diagonal elements of error covariance matrix ($\sigma^2_{I_{ireal}}, \sigma^2_{I_{iimag}}$) are calculated using the equations 16 e 17 expressed before. The standard deviations of SCADA measurements used are 0.008, 0.01 and 0.08 for power flow, power injections and voltage magnitude measurements respectively.

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

In SCADA, usually one bus (slack bus for most cases) has to be chosen as the reference bus to get the relative phase angles of all other buses in the system. That is to say, the voltage phase angles in state vector obtained by WLS are all with respect to this reference. Synchronized phasor measurements might have a different reference which is determined by the instant synchronized sampling initiated, so incorrect results will come if the PMU measurements are used without dealing with the reference problem. The solution adopted is to place a PMU at the reference bus of traditional state estimation model.

As measurements errors typically are of a statistical nature, thus the results obtained from the state estimation procedure for the various scenarios were for the exactly same error characteristics and measurements either with or without the phasor measurements.

The measurements received from PMUs are more accurate when compared to traditional SCADA measurements, thus including PMU measurements in state estimator is expected to produce more accurate estimates. The impact of these phasor measurements on state estimator are defined in terms of state estimator accuracy, performance, robustness, and completeness according to the metrics suggested in the study [18]. Accuracy is a metric to determine how close the estimated voltage magnitudes and phase angles are to their true values. The performance of the estimator determines the estimator capability to provide the outputs in due time to be use by other applications in the control center.

The behaviour of state estimator can be evaluated by performance indexes.

The metric $Mconv_{obj}$ evaluates the relative change in the value of objective function at the kth iteration, evaluating its ability to converge. Such metric is defined as:

$$Mconv_{obj} = \left| 1 - \frac{J^{k^n}}{J^{k^n - 1}} \right| \tag{18}$$

The metric $Mconv_V$ measures the largest final relative change in bus voltage magnitude

$$Mconv_V = \max \left| 1 - \frac{V_i^{k^n}}{V_i^{k^n - 1}} \right| \tag{19}$$

The metric $Mconv_\theta$ measures the largest final relative change in bus voltage phase angle; it uses the absolute difference to avoid problems when the angle is near zero, which will occur near the system reference bus

$$Mconv_\theta = \max \left| \theta_i^{k^n} - \theta_i^{k^n - 1} \right| \tag{20}$$

Also it can be used a norm metric $Macc_v$ that captures the effect of both voltage magnitude errors and voltage angle errors

$$Macc_v = \sqrt{\sum_i \left| \vec{V}_i^{real} - \vec{V}_i^{estimated} \right|^2} \tag{21}$$

III. SIMULATION RESULTS

Studies were carried out on two bus test systems to evaluate the performance of the proposed method. The systems used are the IEEE 14, and 30 bus test systems [19]. The measurement values are generated by adding low variance noise to the calculated measurements using a standard power flow solution. Thus, all measurements had the exactly same error characteristics. The results of the proposed method are analysed to validate and demonstrate its efficiency.

The algorithms are tested with a flat start and a convergence tolerance of 10^{-5}. In order to verify the accuracy of the resulting estimates, the performance indices are calculated.

For all simulations it was assumed that traditional SCADA measurements are enough to make the entire system observable.

The approach followed measured the phase angle of the bus considered the reference in the conventional estimator by placing a PMU in that bus, to deal with the reference problem.

The state estimation was performed for different percentage of PMUs placed on the network, thus allowing comparing the behaviour of the estimator in terms of its performance indexes.

The simulation has considered six scenarios for the number of PMUs to be placed in the network: none, PMUs on approximately 20% of system buses, PMUs on approximately 40% of system buses, PMUs on approximately 60% of system buses, PMUs on approximately 80% of system buses and PMUs placed on each system bus.

A. 14 IEEE bus test system results

The incorporation of PMU measurements on the measurement set of 14 IEEE bus test system was studied.

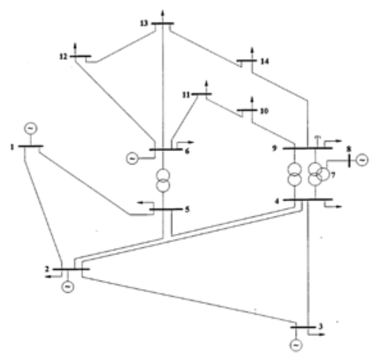

Fig. 3. 14 IEEE bus test system [19].

To analyse the accuracy of the solution given by state estimator and also to compare the results obtained for all the scenarios, the performance indexes referred earlier are presented in Table 1.

% PMU	Converges	$Mconv_{obj}$	$Mconv_V$	$Mconv_\theta$	$Macc_v$
None	178 iter.	0,3885	0,0017	$9{,}10\times10^{-4}$	1,6597
20%	187 iter.	0,4079	0,0019	0,0010	1,7140
40%	9 iter	0,6267	$9{,}84\times10^{-4}$	$5{,}45\times10^{-4}$	1,7483
60%	10 iter.	0,2295	0,0010	0,0020	1,7458
80%	4 iter.	0,8542	$4{,}87\times10^{-4}$	0,0010	1,7461
100%	3 iter.	0,9709	$4{,}21\times10^{-4}$	$6{,}00\times10^{-5}$	1,7461

Table 1. Performance indexes for the six scenarios studied on 14 IEEE bus test system

To investigate the accuracy of the solution given by state estimator algorithm and also compare the results obtained for the all scenarios, the error for estimated voltage magnitude and phase angle are showed in Fig 4 and Fig. 5.

The addition of PMUs in the presence of conventional SCADA measurements results in an improvement of the state estimator accuracy and performance. The performance of the state estimator improves as we increase the number of PMU placed at system buses as it converges in a less number of iterations.

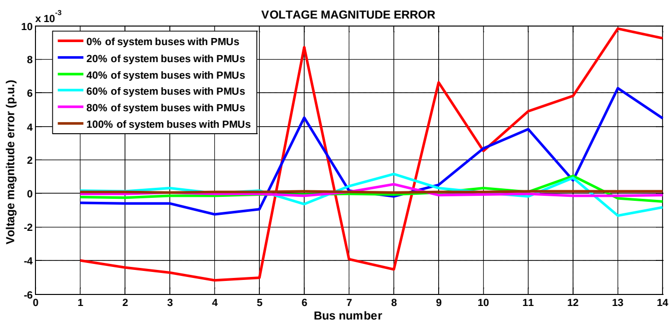

Fig. 4. 14 IEEE bus test system voltage magnitude error for all scenarios simulated.

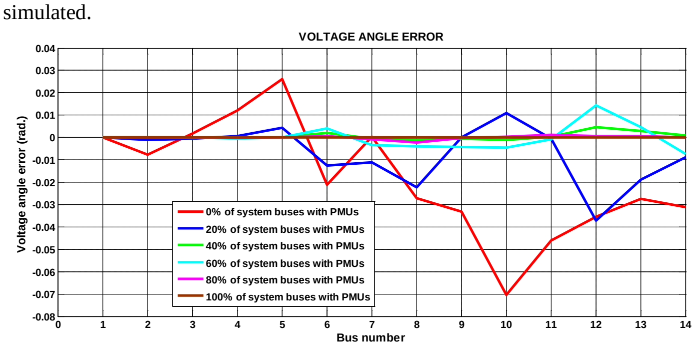

Fig.5. 14 IEEE bus test system voltage angle error for all scenarios simulated.

It is clear in Fig 4 and 5 that voltage magnitude error and voltage angle error approaches zero for scenarios where there are more PMUs installed in the network. Scenarios where more PMU measurements are used reflect an improvement of state estimator accuracy.

However, having such measurement configuration is difficult to achieve at this moment due to cost and installation limitations of these devices. The number of PMUs that can be available in an existing measurement system is limited so the choice must be for a minimum number of PMUs that assures a significant system state estimator performance enhancement when compared with conventional state estimators.

In this study, it can be said that having 40% of system buses equipped with PMUs produces a satisfying state estimation performance enhancement.

B. 30 IEEE bus test system results

Before performing the state estimation on 30 IEEE bus test system it was necessary to guarantee network observability too. Thus, the measurement set with conventional SCADA measurements ensured system observability. Then, for each simulation, six more PMUs were placed at the network. They were placed, initially at zero injection buses, and buses with a large number of connected branches, thus maximizing the coverage.

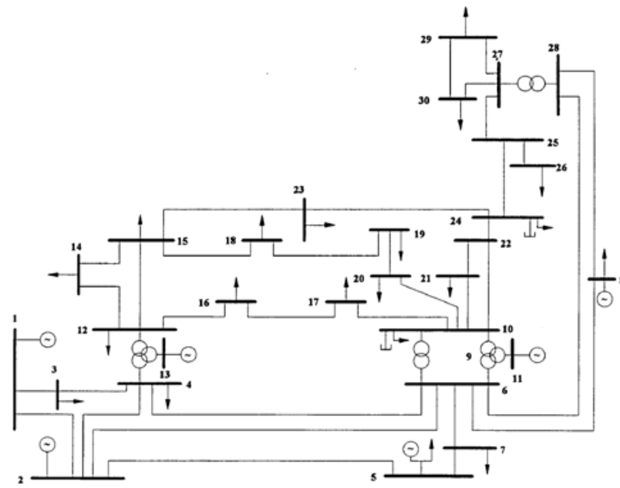

Fig. 6. 30 IEEE bus test system [19].

Table 2 comprises the performance indexes of the estimator for all scenarios simulated for the 30 IEEE bus test system.

% PMU	Converges	$Mconv_{obj}$	$Mconv_V$	$Mconv_\theta$	$Macc_v$
None	75 iter.	0,0193	0,0014	0,0013	0,6889
20%	63 iter.	0,0232	0,0019	0,0015	0,6036
40%	6 iter	0,2765	0,0018	0,0012	0,4811
60%	4 iter.	0,4391	$7{,}065\times10^{-4}$	0,0016	0,4786
80%	3 iter.	0,7452	$2{,}462\times10^{-4}$	0,0015	0,4774
100%	2 iter.	0,9976	$3{,}162\times10^{-4}$	$3{,}67\times10^{-4}$	0,4762

Table 2. Performance indexes of simulation results for the six scenarios studied on 30 IEEE bus test system

It was shown that state estimator converges more rapidly to a solution with the increase use of PMUs in the network.

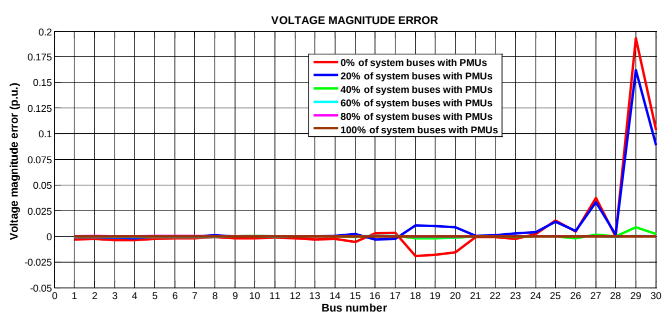

Fig. 7. Voltage Magnitude Error for 30 IEEE bus test system for all the scenarios.

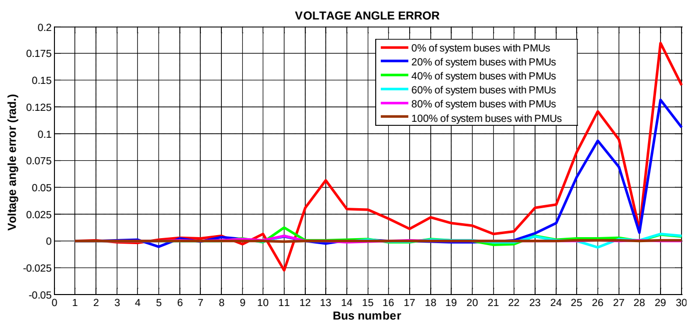

Fig. 8. Voltage Angle Error for 30 IEEE bus test system for all the scenarios.

Fig.7 and Fig .8 show the effect on voltage magnitude and phase angle of the increase system buses with PMUs. It demonstrates that voltage magnitude error and voltage angle error decreases significantly for the scenarios of having more than 40% of system buses with PMUs. For these scenarios system state vector is very accurate, as the error is approaching zero.

IV. Conclusions

Expecting the gradual penetration of PMUs this paper discusses a state estimation method, integrating PMU measurements into the classical state estimation systems for a performance enhancement.

A comprehensive formulation of the state estimator incorporating conventional, as well as PMU measurements, is presented.

The methodology is validated by the results on the simulation of 14 IEEE bus test system and 30 IEEE bus test system. Several comparisons between the use of SCADA measurements and more PMU measurements are exposed.

PMUs' outputs affect the state estimation analysis in a precious way. It improves the response, measurement redundancy levels and accuracy and the output of the traditional state estimators.

Although this approach does not yet returns an optimal solution that minimizes the number of PMUs placed, nevertheless it can be use to obtain system state estimation performance enhancement as power systems are becoming more populated by PMUs.

V. Acknowledgment

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