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State Estimation Including Synchronized Measurements

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Abstract--**The paper presents a methodology to include measurements from phasor measurement units (PMUs) as well as conventional measurements in a state estimator. A comprehensive strategy to combine conventional measurements, such as the power flow and power injection measurements, with the direct and pseudo-voltage measurements by the PMUs in a weighted least square (WLS) formulation of the state estimation problem is demonstrated. The proposed state estimator is applied on the IEEE 14-bus test system, and the simulation results are presented.**

Index Terms-- **Measurement uncertainty, weighted least squares, phasor measurement units, state estimation, synchrophasors.**

I. Introduction

PHASOR measurement units (PMUs) are finding increasing use in modern power systems for a wide range of applications such as the implementation of a wide area monitoring, protection, and control (WAMPAC) system, post-disturbance analyses, and system model development and validation [1]. The current practice is to install PMUs in an incremental fashion, in conjunction with conventional measurements such as the power flow and power injection measurements [2].

The conventional state estimator provides the estimates of the power system states, i.e., bus voltages and angles, on the basis of measurements obtained from the supervisory control and data acquisition (SCADA) system. Usually, a weighted least squares (WLS) estimator is used to find the best estimates of the states [3]. In case the system is completely observable by only PMU measurements, a linear estimator can be used to obtain the states [4]. However, such a measurement system will need a large number of PMUs for large systems, which may not be technically and economically feasible in the near future. A ‘hybrid’ state estimator is therefore the optimal solution to find the best (in the least squares sense) estimation of the states when the measurement set consists of conventional as well as PMU measurements.

In a decoupled formulation of the state estimation problem in the presence of mixed (conventional and PMU) measurements, the voltage phase angle measurements can be directly included in the active measurement vector [5]. A reference phase angle, such as the phase angle of the slack bus is required in such approach. To eliminate the need of a reference phase angle, the use of phase angle differences between the voltage phasors at the ends of transmission lines and transformers is also proposed in [5]. In [6], a two-stage state estimator is proposed, where conventional and PMU measurements are processed in separate state estimators, and then combined in a linear state estimator. This approach is difficult to implement in practice, since it requires a reference angle for each observable island in the system. In addition, a linear state estimator is proposed in [7] by transforming the power injection and power flow measurements into pseudo-current measurements. This leads to a loss of precision in the power measurements due to the transformations. Also, the estimated voltage phasors are used in the transformation process; hence the method is not truly linear. A methodology for state estimation in the presence of mixed measurements is presented in [8]. However, the transformation of direct current phasor measurements into real and imaginary quantities leads to the propagation of measurement uncertainty [9], [10].

This paper proposes a comprehensive formulation of the state estimation problem in the presence of conventional as well as PMU measurements. The measurement vector consists of only direct measurements, therefore eliminating the propagation of measurement uncertainty due to any transformation. The state estimation problem is formulated in such a way that the existing SCADA-based state estimator can be appended easily to account for the PMU measurements.

The paper is organized as follows. The issue of combining PMU measurements with conventional ones is discussed in Section II. Section III discusses the state estimation process using PMU measurements. The method to evaluate the state estimator performance is given in Section IV. The case studies are presented in Section V, and Section VI concludes the paper.

II. Combining Conventional and PMU Measurements

A SCADA system is based on conventional measurements such as power injection and power flow. These measurements are refreshed every 4-5 seconds. The refresh rate of PMU measurements can be up to 50 or 60 times a second, and each measurement from a PMU contains a time-stamp [11]. The conventional measurements used by the SCADA system carry the local time-stamps. Using the two time-stamps, the synchronous PMU measurements can be combined with the asynchronous conventional measurements. In case there is no common instant corresponding to the measurements, one set of measurements can be interpolated. The phase angles are

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measured by the PMUs with respect to a cosine function at nominal frequency, synchronized to universal time coordinated
(UTC) [11]. The estimated phase angles can be referred to this cosine function. However, the common practice is to refer all the phase angles to a common reference, usually the phase angle of the slack bus. Without loss of generality, it is assumed in the present work that there is a PMU installed at the slack bus. The phase angles measured or estimated at all the buses are referred to the phase angle measured by the PMU at the slack bus.

There have been a number of approaches proposed in the literature for inclusion of PMUs into the existing conventional measurement system. Reference [12] proposes a method to install PMUs in the system to enhance the performance of the existing state estimator that uses data from the SCADA system. The conceptual design of a ‘super-calibrator’ is described in [13], which recommends at least one PMU in each area or sub-network to coordinate among individual state estimators in those areas.

The case studied in this paper is the one where the power system has more than one island observable by conventional measurements. This situation may arise in practice as a result of the decision to replace some of the aging or malfunctioning conventional measurement units. The PMUs are installed in this case to make the system observable as a single island [14], [15].

III. Formulation of the State Estimator

In the presence of conventional measurements, the state estimation problem becomes non-linear. The WLS estimates of the states are found by iteration as follows [3]:

$$\mathbf{x}^{k+1} = \mathbf{x}^{k} + (\mathbf{H}^{T}\mathbf{R}^{-1}\mathbf{H})^{-1}\mathbf{H}^{T}\mathbf{R}^{-1}(\mathbf{z}-\mathbf{h}(\mathbf{x}^{k})), \quad (1)$$

where $\mathbf{x}^{k}$ is the vector of state variables at the kth iteration, $\mathbf{z}$ is the vector consisting of conventional as well as PMU measurements, $\mathbf{R}$ is the measurement error covariance matrix, and $\mathbf{H}$ is the Jacobian matrix for the mixed measurements, as shown below:

$$\mathbf{H} = \begin{bmatrix} \frac{\partial P_{inj}}{\partial \theta} & \frac{\partial P_{inj}}{\partial V} \\ \frac{\partial P_{flow}}{\partial \theta} & \frac{\partial P_{flow}}{\partial V} \\ \frac{\partial Q_{inj}}{\partial \theta} & \frac{\partial Q_{inj}}{\partial V} \\ \frac{\partial Q_{flow}}{\partial \theta} & \frac{\partial Q_{flow}}{\partial V} \\ \frac{\partial \theta_{V}}{\partial \theta} & \frac{\partial \theta_{V}}{\partial V} \\ \frac{\partial V}{\partial \theta} & \frac{\partial V}{\partial V} \end{bmatrix}, \quad (2)$$

P_{inj} and Q_{inj} represent the real and reactive power injection measurements; P_{flow} and Q_{flow} stand for the real and reactive power flow measurements; θ_V and V refer to the direct or pseudo-measurements of voltage phase angles and magnitudes respectively.

By assuming pi-models of the transmission lines, as shown in Fig. 1, the elements of the measurement Jacobian matrix corresponding to the conventional measurements, i.e., the elements of the sub-matrices $\frac{\partial P_{inj}}{\partial \theta}$, $\frac{\partial P_{inj}}{\partial V}$, $\frac{\partial P_{flow}}{\partial \theta}$, $\frac{\partial P_{flow}}{\partial V}$, $\frac{\partial Q_{inj}}{\partial \theta}$, $\frac{\partial Q_{inj}}{\partial V}$, $\frac{\partial Q_{flow}}{\partial \theta}$, and $\frac{\partial Q_{flow}}{\partial V}$ can be found by differentiating the power flow equations [3]. The following analysis describes the methodology to find the elements of the other sub-matrices in the measurement Jacobian matrix.

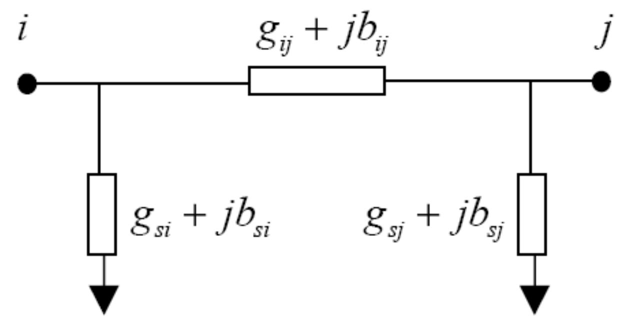

Fig. 1. Equivalent representation of a transmission line as a pi-model

The voltage phasors at a bus connected to a PMU-bus is obtained by using the voltage and current phasor measurements at the PMU-bus and the known parameters of the transmission line. With reference to Fig. 1, the voltage phasor at bus j can be expressed in terms of the voltage and current phasors measured by the PMU placed at bus i, as shown below:

$$\overline{V}_j = \frac{\overline{V}_i(g_{ij} + jb_{ij} + g_{si} + jb_{si}) - \overline{I}_{ij}}{(g_{ij} + jb_{ij})} = E + jF, \quad (3)$$

Parameters E and F are given by,

$$E = (V_i a\cos\theta_i - V_i b\sin\theta_i - I_{ij}g_{ij}\cos\theta_{ij} - I_{ij}b_{ij}\sin\theta_{ij})/c \quad (4)$$

$$F = (V_i a\sin\theta_i + V_i b\cos\theta_i + I_{ij}b_{ij}\cos\theta_{ij} - I_{ij}g_{ij}\sin\theta_{ij})/c \quad (5)$$

where

$$a = g_{ij}^2 + b_{ij}^2 + g_{si}g_{ij} + b_{si}b_{ij} \quad (6)$$

$$b = b_{si}g_{ij} - g_{si}b_{ij} \quad (7)$$

$$c = g_{ij}^2 + b_{ij}^2 \quad (8)$$

Here $\overline{V}_i = V_i\angle\theta_i$ and $\overline{V}_j = V_j\angle\theta_j$ are the voltage phasors at the buses i and j; $\overline{I}_{ij} = I_{ij}\angle\theta_{ij}$ is the current phasor measured by the PMU at bus i; $(g_{si} + jb_{si})$ is the shunt admittance connected at bus i, and $(g_{ij} + jb_{ij})$ is the series admittance of the transmission line connecting bus i and j.

The magnitude and the phase angle of the voltage pseudo-measurement at bus j is given by,

$$V_j = \sqrt{E^2 + F^2}, \quad (9)$$

$$\theta_j = \tan^{-1}(F/E) \quad (10)$$

The partial derivatives of V_j and θ_j that are needed to construct the sub-matrices $\frac{\partial \theta_V}{\partial \theta}$, $\frac{\partial \theta_V}{\partial V}$, $\frac{\partial V}{\partial \theta}$, and $\frac{\partial V}{\partial V}$ can be found by using the following:

$$\dot{\theta}_j = \frac{E\dot{F} - F\dot{E}}{E^2 + F^2} \tag{11}$$

$$\dot{V}_j = \frac{E\dot{F} + F\dot{E}}{\sqrt{E^2 + F^2}} \tag{12}$$

where the dots above imply partial derivative of the associated variable, irrespective of the independent variable. The partial derivatives obtained by using (9) to (12) are as follows:

$$\frac{\partial V_j}{\partial \theta_i} = V_i I_{ij}[\sin(\theta_i - \theta_{ij})(ag_{ij} - bb_{ij}) + \cos(\theta_i - \theta_{ij})(ab_{ij} + bg_{ij})] / c^2\sqrt{E^2 + F^2} \tag{13}$$

$$\frac{\partial V_j}{\partial \theta_{ij}} = V_i I_{ij}[\sin(\theta_i - \theta_{ij})(bb_{ij} - ag_{ij}) - \cos(\theta_i - \theta_{ij})(bg_{ij} + ab_{ij})] / c^2\sqrt{E^2 + F^2} \tag{14}$$

$$\frac{\partial V_j}{\partial V_i} = [V_i(a^2 + b^2) + I_{ij}(\cos(\theta_i - \theta_{ij})(bb_{ij} - ag_{ij}) + \sin(\theta_i - \theta_{ij})(ab_{ij} + bg_{ij})] / c^2\sqrt{E^2 + F^2} \tag{15}$$

$$\frac{\partial V_j}{\partial I_{ij}} = [I_{ij}(g_{ij}^2 + b_{ij}^2) + V_i(\sin(\theta_i - \theta_{ij})(bg_{ij} + ab_{ij}) + \cos(\theta_i - \theta_{ij})(bb_{ij} - ag_{ij})] / c^2\sqrt{E^2 + F^2} \tag{16}$$

$$\frac{\partial \theta_j}{\partial \theta_i} = [V_i(a^2 + b^2) + V_i I_{ij}(\sin(\theta_i - \theta_{ij})(bg_{ij} + ab_{ij}) + \cos(\theta_i - \theta_{ij})(bb_{ij} - ag_{ij})] / c^2(E^2 + F^2) \tag{17}$$

$$\frac{\partial \theta_j}{\partial \theta_{ij}} = [I_{ij}^2(b_{ij}^2 + g_{ij}^2) + V_i I_{ij}(\sin(\theta_i - \theta_{ij})(ab_{ij} + bg_{ij}) + \cos(\theta_i - \theta_{ij})(bb_{ij} - ag_{ij})] / c^2(E^2 + F^2) \tag{18}$$

$$\frac{\partial \theta_j}{\partial V_i} = I_{ij}[\sin(\theta_i - \theta_{ij})(bb_{ij} - ag_{ij}) - \cos(\theta_i - \theta_{ij})(ab_{ij} + bg_{ij})] / c^2(E^2 + F^2) \tag{19}$$

$$\frac{\partial \theta_j}{\partial I_{ij}} = V_i[\sin(\theta_i - \theta_{ij})(ag_{ij} - bb_{ij}) + \cos(\theta_i - \theta_{ij})(ab_{ij} + bg_{ij})] / c^2(E^2 + F^2) \tag{20}$$

The error covariance matrix **R** is a diagonal matrix, and its elements are determined by the standard uncertainties in the measurements, as shown below:

$$\mathbf{R} = \mathrm{diag}(u_1^2, u_2^2, ..., u_m^2) \tag{21}$$

where m is the number of measurements, and u_i, $i = 1,...,m$ are the standard uncertainties in the measurements.

The standard uncertainties in the quantities measured directly can be obtained from the specified maximum uncertainty, by assuming a uniform probability distribution over the entire range of uncertainty, as shown below [16]:

$$u_i = \frac{\Delta u_i}{\sqrt{3}} \tag{22}$$

where Δu_i is the manufacturer-specified maximum uncertainty in the *i*th measurement.

For the voltage pseudo-measurements, the combined standard uncertainties can be found by utilizing the standard uncertainties of the individual measurements [16]. The standard uncertainty in the measurement of the voltage magnitude and phase angle at bus *j*, obtained by using the PMU measurements at bus *i*, can be expressed as,

$$u_{V,ij} = \sqrt{\sum_{k=1}^{4} (\frac{\partial V_j}{\partial p_k})^2 u_{p_k}^2} \tag{23}$$

where $\mathbf{p} = (\theta_i, \theta_{ij}, V_i, I_{ij})$, and u_{p_k} is the standard uncertainty in the measurement p_k.

The methodology described above can easily accommodate changes in the measurement configuration in the system. For example, if some of the conventional measurements are removed from the system, the corresponding rows of the measurement Jacobian matrix are removed. For removal or addition of any PMU into the measurement system, the rows in the measurement Jacobian matrix corresponding to the direct and pseudo-voltage measurements by that PMU can be removed or added accordingly.

IV. Performance Evaluation of the State Estimator

The variance of the estimated states is an indicator of the state estimator performance [8]. In the present study, the average value of the sum of variances of the states, as shown below, is taken as the performance indicator of the proposed state estimator.

$$\sigma_{\Sigma}^2 = \sum_{i=1}^{M} (\frac{1}{M} \sum_{j=1}^{M} (\hat{x}_{i(j)} - x_i)^2) \tag{24}$$

where σ_{Σ}^2 is the average value of the sum of the variances over M number of Monte Carlo trials, N is the number of state variables in the system, x_i is the i^{th} state variable, and $\hat{x}_{i(j)}$ is the estimated value of the i^{th} state variable for the j^{th} trial.

For each Monte Carlo trial, the sample of a measurement is randomly taken from the uniform distribution of the measurement around the measured value. For example, for the i^{th} measurement, the distribution is assumed to span from $(-\Delta u_i / 2 + u_i)$ to $(\Delta u_i / 2 + u_i)$, and a sample is taken randomly from this range of values.

V. Case Study

The proposed hybrid state estimator is applied on the IEEE 14-bus test system having conventional as well as PMU measurements [17]. Fig. 2 shows the location and the number of the measurements. The conventional measurements, i.e., the power flow and power injection measurements alone cannot make the system completely observable. The optimal locations of the PMUs to make the system completely observable, while minimizing the number of PMUs and maximizing the measurement redundancy, are the buses 6 and 9 [15]. Bus 1 is the reference bus in the test system. An additional PMU is placed on bus 1 to provide the reference phase angle.

Table I shows the maximum measurement uncertainties assumed in this study for different types of measurements [18], [19]. These values are usually specified by the manufacturers. Using the specified values of maximum uncertainties, the standard uncertainties in the measurements are computed by using (22). The measurement error covariance matrix is formulated by using the computed values of the standard uncertainties, as shown in (21).

TABLE I
MAXIMUM MEASUREMENT UNCERTAINTIES FOR MEASURED QUANTITIES

Conventional measurements		**PMU measurements**		
Power injection	Power flow	Voltage	Current	Phase angle
3%	3%	0.02%	0.03%	0.01°

To evaluate the performance of the proposed state estimator in terms of the variance in the estimated states, 1000 Monte Carlo trials are executed by randomly selecting samples of measurements from the specified range of variation of the measurements. The WLS estimates of the states are found for each trial of the Monte Carlo simulation. Table II shows the variation in the average value of the sum of variances for different number of PMUs in the system. The first case study corresponds to the measurement configuration shown in Fig. 2. The next case study corresponds to the measurement system consisting of the existing conventional measurements shown in Fig. 2 and 4 PMUs. In the next case study, 5 PMUs are considered in addition to the existing conventional measurements. Finally, the last case study corresponds to a measurement system consisting of PMU measurements only. The average value of the sum of variances reduces as the number of installed PMUs increases in the system. This is due to the lower level of uncertainty associated with the PMU measurements. The state estimator performance improves as more PMU measurements are added to the existing set of measurements.

TABLE II
STATE ESTIMATION PERFORMANCE FOR VARYING NUMBER OF PMUS

Case study	σ_Σ^2
3 PMUs (configuration of Fig. 2)	1.85×10^{-6}
4 PMUs (at 1, 4, 6, 9)	9.01×10^{-7}
5 PMUs (at 1, 4, 6, 9, 13)	7.99×10^{-7}
5 PMUs (at 1, 2, 6, 7, 9) and no conventional measurements	2.50×10^{-7}

The first case study in Table II presents the state estimator performance with the minimum number of PMUs required to make the system completely observable, along with the existing conventional measurements. A significant reduction in the variance of the estimated states is observed after adding one more PMU, as reflected in the second case study. Further addition of PMUs in the presence of conventional measurements, as shown for the next case study, results in only marginal improvement of the state estimator performance. The performance of the state estimator improves manifold if only PMU measurements are used, as reflected by the last case study. However, such measurement configuration is difficult to achieve at this moment. The proper location and number of PMUs in an existing measurement system consisting of conventional measurements can be determined after evaluating the resulting variance in the estimated states.

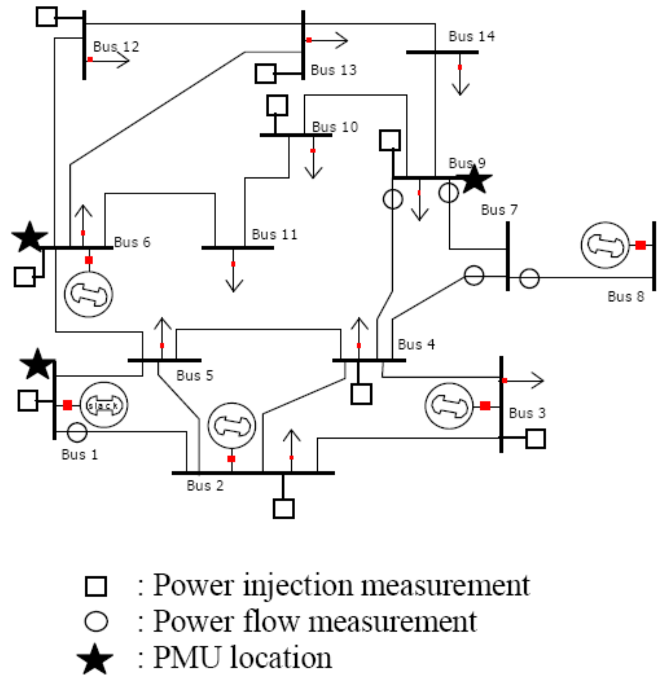

Fig. 2. IEEE 14-bus test system with conventional and PMU measurements

VI. CONCLUSION

A methodology to formulate the WLS state estimation problem, when both conventional and PMU measurements are present in the system, is proposed in this paper. The weights assigned to the measurements correspond to the square of the standard uncertainties derived from the specified maximum uncertainties in the measurements. The proposed hybrid state estimator can be easily modified in case of changes in the measurement configuration. The performance of the state estimator is evaluated in terms of the average variance in the estimated states. The proposed methodology is tested on the IEEE 14-bus test system. The methodologies can be used as a screening method to determine the optimal location and number of the PMUs so that maximum enhancement in the performance of the existing state estimator is achieved.

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VIII. Biographies

S. Chakrabarti (S'06, M'07) obtained the Ph.D. degree in Electrical Engineering from Memorial University of Newfoundland, Canada, in 2006. Currently he is working as a Lecturer in the School of Engineering Systems, Queensland University of Technology, Brisbane, Australia. His research interests include power system dynamics and stability, state estimation, and renewable energy systems.

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Gustavo Valverde (S'08) obtained the B.Sc degree in Electrical Engineering from the University of Costa Rica in 2005 and the M.Sc degree in Electrical Power Systems from the University of Manchester in 2008. Currently he is a PhD student at the University of Manchester working on the next generation of state estimators in power systems.

Vladimir Terzija (M'95, SM'2000) is the EPSRC Chair Professor in Power System Engineering in the School of Electrical and Electronic Engineering, The University of Manchester, where he has been since 2006. From 1997 to 1999, he was an Assistant Professor at the University of Belgrade. In 1999, he was awarded a prestigious Humboldt Research Fellowship. From 2000 to 2006, he was with ABB AG, Germany, working as an expert for switchgear and distribution automation. His main research interests are application of intelligent methods to power system monitoring, control, and protection, switchgear and fast transient processes, as well as DSP applications in power systems.