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Real-Time Monitoring and Analysis of Power Systems with Synchronized Phasor Measurements

Hongrae Kim*

Abstract

State estimators are used to monitor the operating states of power systems in modern EMS. It iteratively calculates the voltage profile of the currently operating power system with voltage, current, and power measurements gathered from the entire system. All the measurements are usually assumed to be obtained simultaneously. It is practically impossible, however, to maintain the synchronism of the measurement data. Recently, phasor measurements synchronized via satellite are used for the operation of these power systems. This paper describes the modified state estimator used to support the processing of synchronized phasor measurements. Synchronized phasor measurements are found to provide synchronism of measurement data and improve the accuracy/redundancy of the measurement data for state estimation. The details of the developed state estimation program and some numerical results of operation are presented.

Key Words : Power System State Estimation, Phasor Measurement, Ems, Real-Time Monitoring

1. Introduction

Various measures are taken to provide electrical power to consumers in a stable and efficient manner. Utility companies have tried to monitor and analyze the operating conditions of the entire system with on-line measurement data. Technologies for phasors that implement measurements using satellite clocks have recently been developed and are able to be used to operate power systems [1-6].

* Main author : professor, Dept. of Electronic Information Engineering, Soonchunhyang University
Tel : +82-41-530-1336, Fax : +82-41-530-1548
E-mail : hongkim@sch.ac.kr
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These synchronized phasor measurements can provide valuable information about power systems and can be used for improving the accuracy of the EMS functions. More precise measurements can be collected without additional costs through PMUs (phasor measurement units) already installed in power systems for security [7-9].

PMUs have been installed and operated at several nuclear power plants and 345kV substations in Korea [10]. These PMUs are designed for gathering real-time system operating data synchronized by GPS, monitoring power systems, and evaluating transient system stability on-line.

It has been determined that one of the main reasons for the US/Canada blackout in 2003 is that there were not enough information exchanges on interconnected power networks. Therefore, wide-area monitoring systems utilizing PMUs and the construction of swift and reliable protection/control schemes on power networks have become important issues.

It is important that synchronized phasor measurements offer highly accurate data apart from the conventional measurement data of power systems. Naturally, the interest in using PMU data for state estimations which require an accurate database for stable systems operation is growing.

In modern EMS, a state estimator plays an important role for real-time monitoring and control of power systems. It works to estimate the state variables of the entire system by using measurement data obtained from several measurement points in the power systems. The operating conditions of the current power systems can be understood using state variables obtained from the results of state estimation. Concerns about state estimation are also growing in Korea [11].

With synchronized phasor measurements, the problem of time skew in measurements for state estimation can be resolved. Furthermore, the robustness of the state estimator, and precision and effectiveness in calculations can be enhanced. In this paper, a new state estimator using PUM data that are already available for power system protection and security evaluation is suggested.

2. State Estimation

State estimation is one of the most basic tools for power system analysis, providing a database for system security analysis, and contingency analysis, among other features. State estimation studies in Korea have not been very active up to the recent times. Need for a robust state estimator is growing due to deregulation and studies of power system applications for time synchronized phasor measurements have also aroused people's interest [12-14]. Even though phasor measurements are primarily measured for system security analysis, using those measurements for state estimation could lead to results of increased reliability regarding power supply and to improved system stability.

The mathematical model of state estimation is based on the relationship between the measurement data z and the state vector x [15],

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

where, x : the state vector,
h(x) : the nonlinear measurement function,
e : the measurement error vector.

In WLS(weighted least square) state estimation, the following quadratic objective function is used in order to minimize the error between actual and estimated measurements.

$$\begin{aligned} J(x) &= \{z - h(x)\}^T R^{-1} \{z - h(x)\} \\ &= \sum_{i=1}^{m} \frac{1}{\sigma^2} \{z_i - h_i(x)\}^2 \end{aligned} \tag{2}$$

The best condition under which to minimize the quadratic objective function J(x) is as in Equation (3). In the equation, H(x) is the Jacobian matrix of the measurement functions and can be obtained by taking the partial derivatives of the measurement functions with respect to several state vectors.

$$\partial J / \partial x = H^T(x) R^{-1} \{z - h(x)\} = 0 \tag{3}$$

In order to devise a new state estimator, a nonlinear measurement function h(x) and corresponding Jacobian matrix H(x) must be newly derived. For measurement functions and

Jacobian matrix regarding powers and voltages that are used in conventional state estimator, refer to the reference [16]. Further, new measurement equations and Jacobian elements can be introduced for voltage and current phasors.

The general method for obtaining the phasor measurement data is to compare bus voltage phase angles in both sides of the lines. The measurement functions of voltage phasors for state estimation can be shown as differences of phase angles between buses as in the following Equation (4). Equation (4) can also be used when a reference bus is established for the entire system and phasor measurement data are made up of angle differences in it.

$$\theta_{km} = \theta_k - \theta_m \tag{4}$$

The measurement equation of the current measurement data is derived as follows:

$$I_{km} = \frac{S_{km}^*}{V_k^*} \tag{5}$$

From Eq. (5), real and reactive currents are written in Eq. (6) and (7).

$$I_{km}^r = \frac{1}{V_k}(P_{km}\cos\theta_k + Q_{km}\sin\theta_k) \tag{6}$$

$$I_{km}^x = \frac{1}{V_k}(P_{km}\sin\theta_k - Q_{km}\cos\theta_k) \tag{7}$$

The Jacobian matrix, including voltage and current phasor measurement data, is formed as follows:

$$H(x) = \begin{bmatrix} 0 & \partial|V_k|/\partial|V| \\ \partial P_k/\partial\theta & \partial P_k/\partial|V| \\ \partial Q_k/\partial\theta & \partial Q_k/|V| \\ \partial P_{km}/\partial\theta & \partial P_{km}/\partial|V| \\ \partial Q_{km}/\partial\theta & \partial Q_{km}/|V| \\ \partial\theta_{km}/\partial\theta & 0 \\ \partial I_{km}^r/\partial\theta & \partial I_{km}^r/\partial|V| \\ \partial I_{km}^x/\partial\theta & \partial I_{km}^x/\partial|V| \end{bmatrix} \tag{8}$$

The Jacobian matrix elements of bus power injections and line power flows can be calculated by the partial differentiation of measurements. Equations for the current measurements are formed as follows:

$$\frac{\partial I_{km}^r}{\partial\theta_i} = \frac{1}{V_k}\left(\frac{\partial P_{km}}{\partial\theta_i}\cdot cos\theta_k + P_{km}\cdot\frac{\partial cos\theta_k}{\partial\theta_i} + \frac{\partial Q_{km}}{\partial\theta_i}\cdot sin\theta_k + Q_{km}\cdot\frac{\partial sin\theta_k}{\partial\theta_i}\right) \tag{9}$$

$$\begin{aligned}\frac{\partial I_{km}^x}{\partial\theta_i} &= \frac{1}{V_k}\cdot\frac{\partial}{\partial\theta_i}(P_{km}\sin\theta_k - Q_{km}\cos\theta_k) \\ &= \frac{1}{V_k}\left(\frac{\partial P_{km}}{\partial\theta_i}\cdot\sin\theta_k + P_{km}\cdot\frac{\partial\sin\theta_k}{\partial\theta_i} - \frac{\partial Q_{km}}{\partial\theta_i}\cdot\cos\theta_k - Q_{km}\cdot\frac{\partial\cos\theta_k}{\partial\theta_i}\right)\end{aligned} \tag{10}$$

$$\frac{\partial I_{km}^r}{\partial V_i} = \frac{\partial}{\partial V_i}\left(\frac{1}{V_k}\right)\cdot(P_{km}\cos\theta_k + Q_{km}\sin\theta_k) + \frac{1}{V_k}\cdot\frac{\partial}{\partial V_i}(P_{km}\cos\theta_k + Q_{km}\sin\theta_k) \tag{11}$$

$$\frac{\partial I_{km}^x}{\partial V_i} = \frac{\partial}{\partial V_i}\left(\frac{1}{V_k}\right)\cdot(P_{km}\sin\theta_k - Q_{km}\cos\theta_k) + \frac{1}{V_k}\cdot\frac{\partial}{\partial V_i}(P_{km}\sin\theta_k - Q_{km}\cos\theta_k) \tag{12}$$

i) In case of i = k,

$$\frac{\partial I^r_{km}}{\partial \theta_i} = \frac{1}{V_k}(\frac{\partial P_{km}}{\partial \theta_k} \cdot cos\theta_k - P_{km} \cdot \sin\theta_k + \frac{\partial Q_{km}}{\partial \theta_k} \cdot sin\theta_k + Q_{km} \cdot \cos\theta_k) \quad (13)$$

$$\frac{\partial I^x_{km}}{\partial \theta_i} = \frac{1}{V_k}(\frac{\partial P_{km}}{\partial \theta_m} \cdot \sin\theta_k + P_{km} \cdot \cos\theta_k - \frac{\partial Q_{km}}{\partial \theta_m} \cdot \cos\theta_k - Q_{km} \cdot \sin\theta_k) \quad (14)$$

$$\frac{\partial I^r_{km}}{\partial V_i} = -\frac{1}{V_k^2}(P_{km} \cdot cos\theta_k + Q_{km} \cdot \sin\theta_k) + \frac{1}{V_k}(\frac{\partial P_{km}}{\partial V_k} \cdot \cos\theta_k + \frac{\partial Q_{km}}{\partial V_k} \cdot \sin\theta_k) \quad (15)$$

$$\frac{\partial I^x_{km}}{\partial V_i} = -\frac{1}{V_k^2}(P_{km} \cdot \sin\theta_k - Q_{km} \cdot \cos\theta_k) + \frac{1}{V_k}(\frac{\partial P_{km}}{\partial V_k} \cdot \sin\theta_k - \frac{\partial Q_{km}}{\partial V_k} \cdot \cos\theta_k) \quad (16)$$

ii) In the case of i = m,

$$\frac{\partial I^r_{km}}{\partial \theta_i} = \frac{1}{V_k}(\frac{\partial P_{km}}{\partial \theta_m} \cdot \cos\theta_k + \frac{\partial Q_{km}}{\partial \theta_m} \cdot \sin\theta_k) \quad (17)$$

$$\frac{\partial I^x_{km}}{\partial \theta_i} = \frac{1}{V_k}(\frac{\partial P_{km}}{\partial \theta_m} \cdot \sin\theta_k - \frac{\partial Q_{km}}{\partial \theta_m} \cdot \cos\theta_k) \quad (18)$$

$$\frac{\partial I^r_{km}}{\partial V_i} = \frac{1}{V_k}(\frac{\partial P_{km}}{\partial V_m} \cdot \cos\theta_k + \frac{\partial Q_{km}}{\partial V_m} \cdot \sin\theta_k) \quad (19)$$

$$\frac{\partial I^x_{km}}{\partial V_i} = \frac{1}{V_k}(\frac{\partial P_{km}}{\partial V_m} \cdot \sin\theta_k - \frac{\partial Q_{km}}{\partial V_m} \cdot \cos\theta_k) \quad (20)$$

iii) In other cases,

$$\frac{\partial I^r_{km}}{\partial \theta_i} = \frac{\partial I^x_{km}}{\partial \theta_i} = \frac{\partial I^r_{km}}{\partial V_i} = \frac{\partial I^x_{km}}{\partial V_i} = 0 \quad (21)$$

3. Accuracy Decision of Estimated Variables

In order to inspect the improvement on state estimation accuracy with the addition of PMU data, covariances of estimated state variables can be calculated. The covariances of the estimated state variables are equal to the following equation.

$$Cov(\hat{x}) = Cov((H^T R^{-1} H)^{-1} H^T R^{-1} z) = Cov(G^{-1} H^T R^{-1} z) \quad (22)$$

The covariance of measurement vector z can be calculated as in the following equation.

$$Cov(z) = Cov(h(x) + e) = Cov(e) = R \quad (23)$$

From Eq. (22) and Eq. (23)

$$Cov(\hat{x}) = (G^{-1} H^T R^{-1}) Cov(z) (G^{-1} H^T R^{-1})^T = G^{-1} \quad (24)$$

Therefore, the inverse of gain matrix stands for the covariance of state variable x. By using the standard deviations of state variables from these covariances, it can be determined how the accuracy of the state estimation results (voltage magnitudes and phase angles) can be improved with PMU data.

4. Case Studies

The developed state estimation program has been tested with sample cases using the Jeju Island system as in Fig. 1. As the system has 35 buses and 37 branches, the accuracy and efficiency of state estimator is inspected for the proposed algorithm using voltage and current phasor measurements. Cases are studied with the analog measurements and different number of PMUs installed in the Jeju Island system, as in Table 1. The effects on the results of state estimation are compared when the number of added PMUs (at buses 1, 5, 9 and 27) increases gradually.

Gaussian noise is added to the measurement data used in state estimation calculations under the assumption that the measurements contain random errors. The standard deviation of added errors for conventional analog measurements such as bus power injections, and line power flows is assumed to be 0.01. Voltage magnitudes and line current measurements are assumed to have a standard deviation of 0.0001, since those measurements are from PMUs that can provide highly accurate data on the system.

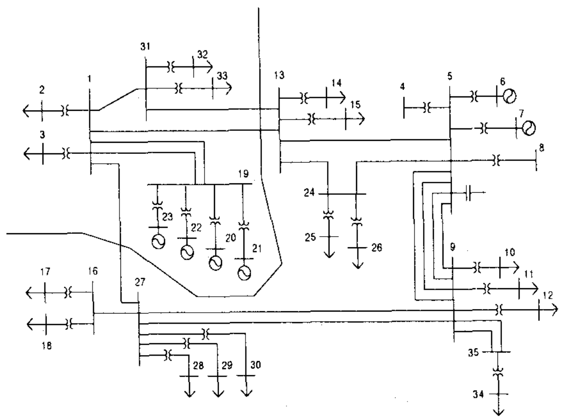

Fig. 1. Jeju Island 35 Bus System

The developed state estimator successfully converged to the exact solution in all cases, as seen in Fig. 2 and Fig. 3. Covariances of estimated state variables are calculated to inspect the effect on state estimation accuracy with PMU data. In Figs. 4 and 5, as the number of installed PMUs increases, the covariances of the estimated state variables decrease. Namely, the accuracy of the estimated state variables is improved with the number of installed PMUs in the system.

Table 1. Number of Analog Meas. & PMU Data

	V	Power Injection	Power Flow	PMU	I	θ
Case 1	2	48	48	0	0	0
Case 2	4			2	12	1
Case 3	5			3	19	2
Case 4	6			4	25	3

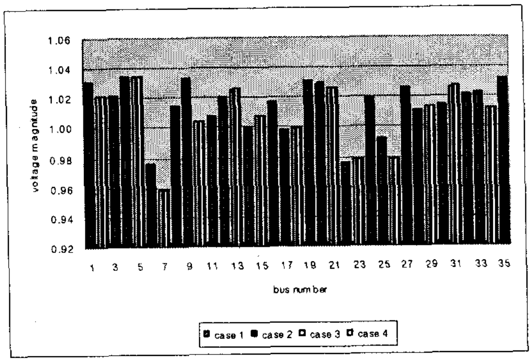

Fig. 2. Comparison of Estimated Voltage Magnitudes

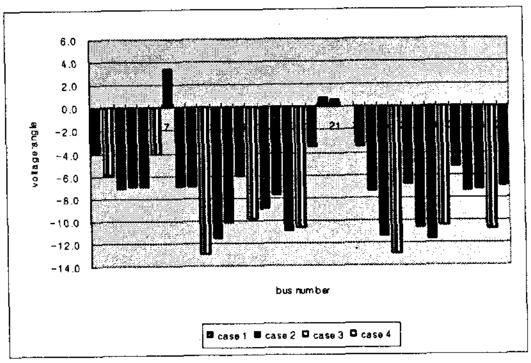

Fig. 3. Comparison of Estimated Voltage Angles

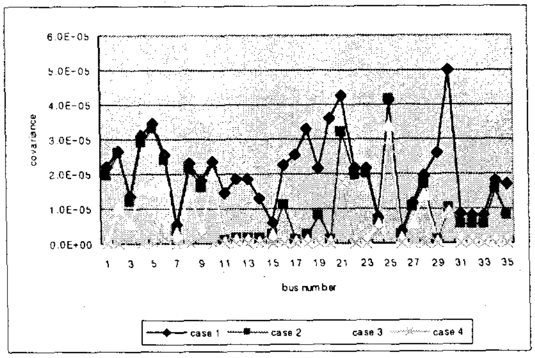

Fig. 4. Covariances of Voltage Magnitudes

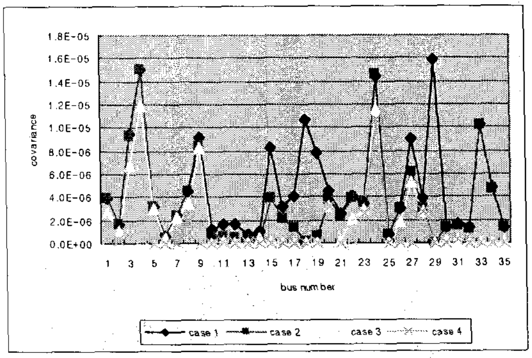

Fig. 5. Covariances of Voltage Phase Angles

The system is said to be 'unobservable' if there is not enough redundancy in measurements and consequently the state estimator cannot calculate all of the state variables. State estimators usually run an observability analysis routine before the main estimation process starts. If the system is found to be unobservable, the state estimator attempts to find a way to secure system observability.

The state estimator finds the unobservable branches connecting islands and their boundary buses. If pseudo measurements for these branches of buses are available, the state estimator adds these pseudo measurements to the set of input measurement and proceeds with the state estimation routine. If there are no pseudo measurements available, the state estimator then finds the solutions for each island separately. In this case, slack buses are assigned to each island.

It is assumed that the Jeju system is divided into two islands as in Fig. 1. Branches 1-13, 1-27, and 13-31 are unobservable. Since there were no pseudo measurements available, the state estimator calculates voltage phasors separately for each island. There are two different slack buses used for determining bus voltage angles as relative angles to the slack in each island.

PMU measurements can be an aid for securing system observability in this case. It is assumed that PMUs are installed in both islands, so that the voltage phase angles can be matched to each other. As can be seen in Table 2, the voltage phase angles in the islanded system can be adjusted into angles in one combined system by using phase angle measurements from PMUs. Consequently, estimates of the state variables (e.g. voltage phasors) are available for the entire Jeju Island system.

5. Conclusion

In this paper, a novel state estimator using voltage and current phasor measurements as well as conventional analog measurements is introduced. The effect of the PMU data on the state estimation result is tested. In order to implement the state estimator using voltage and current phasors, new measurement equations for the measurement data from PMU and a suitable Jacobian matrix are newly derived.

The developed state estimator displays very good convergence characteristics and accuracy. It also shows that the accuracy of state estimation can be improved with the addition of PMU data to the conventional measurement set. Adding PMU to the system can provide much better redundancy for the state estimation as well as more precise measurements.

A complete snap-shot of the operating power system at a certain moment can be obtained with synchronized measurement. Moreover, state estimation in the islanded system due to lack of measurements can be performed with phase angle measurements from PMUs, without any additional pseudo measurements.

By using the newly developed state estimator, accurate states of the operating system can be determined, and a database can be offered for functions such as contingency analysis, and system security analysis, among others.

Table 2. Comparison of Estimated State Variables

bus no.	islanded system		combined system	
	$\|V\|$	θ	$\|V\|$	θ
1	1.0430	-3.92	1.0430	-3.92
2	1.0341	-5.84	1.0341	-5.84
3	1.0338	-6.97	1.0338	-6.97
19	1.0420	-3.45	1.0420	-3.45
20	1.0291	0.83	1.0291	0.83
22	0.9762	0.00	0.9762	0.00
23	0.9891	-3.45	0.9891	-3.45
31	1.0411	-5.23	1.0411	-5.23
32	1.0355	-7.39	1.0355	-7.39
33	1.0373	-7.21	1.0373	-7.21
4	1.0553	0.13	1.0553	-6.90
5	1.0553	0.13	1.0553	-6.90
6	0.9755	2.93	0.9755	-4.09
7	0.9748	10.05	0.9748	3.02
8	1.0352	0.13	1.0352	-6.90
9	1.0538	0.03	1.0538	-6.99
10	1.0263	-5.64	1.0263	-12.66
11	1.0297	-4.27	1.0297	-11.30
12	1.0419	-3.02	1.0419	-10.04
13	1.0420	1.04	1.0420	-5.98
14	1.0173	-2.75	1.0173	-9.77
15	1,0245	-1.86	1,0245	-8.88
16	1.0358	-0.68	1.0358	-7.70
17	1.0179	-3.77	1.0179	-10.80
18	1.0189	-3.43	1.0189	-10.45
21	1.0298	0.70	1.0298	0.70
24	1.0387	-0.42	1.0387	-7.44
25	1.0119	-4.21	1.0119	-11.23
26	0.9988	-5.62	0.9988	-12.64
27	1.0455	0.22	1.0455	-6.81
28	1.0307	-3.48	1.0307	-10.50
29	1.0327	-4.53	1.0327	-11.55
30	1.0340	-3.31	1.0340	-10.34
34	1.0341	-3.58	1.0341	-10.61
35	1.0538	0.00	1.0538	-7.02

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Biography

Hongrae Kim

Mr. Kim was born in Seoul, Korea, in 1963. He received his B.S. and M.S. degrees from Yonsei University, Seoul, Korea, in 1986 and 1989, respectively. He received his Ph. D. degree in Electrical Engineering from Texas A&M University, College Station, Texas in 1995. He is currently a Professor in the Department of Electronic Information Engineering, Soonchunhyang University, Asan, Korea.