Hybrid State Estimation Approach for the Optimal Placement of Phasor Measurement Units

S. Gayathri, R. Meenakumari

Abstract— ***Power systems are rapidly becoming populated by Phasor Meaurement Units (PMU). Compared to conventional one(SCADA), PMU has synchrophasor technology and it measures the dynamic behaviour of the system. Real time monitoring operations are done through PMU in the smart grid environment. Finding a suitable location for the placement of PMU is an optimization problem which could be solved by various Optimization technique. PMUs actually measure the system state instead of indirectly estimating it, the idea to improve the quality of state estimate is that inclusion of this type of data in a state estimator. For analysis, operation and planning of power system state estimation and load flow analysis is most important. A hybrid state estimation technique (fixing a PMU in the conventional load flow analysis) is applied for the test case system and the results are validated. The true value is obtained by load flow analysis and the estimated value is obtained by weighted least squares (WLS) state estimation technique. From the simulated results it is observed that the residue will be less if PMU data's are included.***

Keywords— Newton Raphson Method, PMU, State Estimation, Load Flow, Weighted Least Squares.

I. INTRODUCTION

Phasor Measurement unit (PMU) is a device which measures both magnitude and phase angle using synchrophasor technology with respect to global time reference. PMUs are called as synchrophasors. It determines the healthiness of the electrical distribution system by providing the precise grid measurements of electrical waves. Phasor measurement units are considered as one of the most promising measuring devices in the future power systems. The birth of PMU is from the development of symmetrical component of distance relay components, importance of positive sequence and synchronised measurements. PMU measurements are often taken at 30 observations per second compared to the conventional having one every 4 seconds[1].

State Estimation (SE) is the process of assigning a value to an unknown system state variable based on measurements from that system according to specific criteria. Usually, the imperfect measurements that are redundant and the process of estimating the system states are involved and it is based on a statistical criteria that will estimate the true value of the state variables to minimize or maximize the selected criterion.

The most widely used and familiar criterion is that of minimizing the sum of the squares of the differences between the estimated and true (i.e., measured) values of a function[2]. The ideas of least-squares estimation have been known and used since the early part of the nineteenth century. State estimators has both static and dynamic power systems. These types of estimators are developed for many purpose in power systems. In a power system, the state variables are the voltage magnitudes and relative phase angles at each of the system nodes. In order to estimate the system performance in real time for both system security control and constraints on economic dispatch the measurements are required. The inputs given to an estimator are imperfect power system measurements of voltage magnitudes and power. By recognizing that there are errors in measured quantities and redundant measurements the estimator is designed to produce the best estimate of the system voltage and phase angles. For the implementation of the security-constrained dispatch and control of the system the output data are used in system control centres.

The problem of monitoring the power flows and voltages on a transmission system is very important for maintaining system security. The power system operators can tell where problems exist in the transmission system by simply checking each measured value against its limit and they can take corrective actions to relieve overloaded lines or out-of-limit voltages. Many problems are noticed in monitoring a transmission system. These problems originate primarily from the nature of the measurement and from communications problems in transmitting the measured values back to the operations control center[3]. Any measurement device will be subject to errors. If the errors are small, they may go undetected and can cause misinterpretation by those reading the measured values. A SE can smooth out small random errors in meter readings, detect and identify gross measurement errors, and due to communication failures that have failed to fill in meter readings. In general, the state variables for a power system consist of the bus voltage magnitude at all buses and the phase angles at all but one bus. The swing or reference bus phase angle is usually assumed to be zero radians. If the measurements are used to estimate the states i.e., voltage magnitudes and phase angles of the power system, then the calculation of any power flows, generation, loads, and so on is done easily[4]. SE provides an estimate for all metered and unmetered quantities and it also detect and identify the discordant measurements which is called as bad data. Implementation of synchronized phasor measurements presents an opportunity for improvements of power system state estimation and if PMU's were installed at all nodes, the state estimation wouldn't be essential but from the economical

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point of view, having PMU's installed all over network is not applicable, therefore the task of State Estimation still is crucial. The traditional measurements include a portion of the bus voltage magnitudes, active and reactive power injections at buses and active and reactive power flow through transmission lines. The nominal parameters of network and also the measurements across the network actually are not accurate and have various uncertainties[5]. The reliable communication infrastructure connecting the PMU with the phasor data concentrator (PDC), which collects all of the PMU measurements and can also be used as data source for Supervisory Control and Data Acquisition (SCADA) systems, should be provided to secure the consistency of the measurements. This issue should have a high priority if the measurement data is a critical measurement, meaning that if that specific data were missing, it would not be possible to perform the state estimation.

This motivated the researchers to find the best state estimate with the minimal number of PMU's so that the parameters of every bus in the system network is observable. The remaining section of the paper is discussed as follows. Section-II discusses about the Newton Raphson(NR) load flow analysis of power system for determining the true value. Section-III describes about the Weighted Least Squares method for determining the estimated value. Section-IV describes about the estimation of voltage and angle at each node of the IEEE-5 bus of with and without PMU and the results are validated. Section-V concludes the findings of the paper.

II. LOAD FLOW ANALYSIS

Load flow analysis is an important tool in power system for operation and planning. The analysis in normal steady state operation is called a load-flow or power-flow study. It targets on determining the voltages, currents ,and real and reactive power flows in a system under a given load conditions. It usually uses simplified notation such as a one-line diagram and per-unit system. The power flow problem consists of a given transmission network where all lines are represented by a Pi-equivalent circuit and transformers by an ideal voltage transformer in series with an impedance[6]. Once the loads, active and reactive power injections and network parameters are defined, load flow analysis solves the bus voltages and phases hence the branch power flow can be calculated. Mathematically, the power flow requires a solution of a system of simultaneous nonlinear equations.

A. Load flow methods

With the increase of power system scale continuously, the dimension of load flow equations now becomes very high and for the equations with such high dimensions, we cannot ensure that any mathematical method can converge to the right solution. Hence, choosing the reliable method is essential. The load flow methods are

- Gauss-Seidel Iterative Method
- Newton Raphson Load Flow
- Fast Decoupled Load Flow

The Newton–Raphson power flow is the most robust power flow algorithm used in practice because of its advantage such as.

- More accurate and reliable.
- For convergence it needs less number of iterations.
- Independency of the iteration number to number of buses in the system.
- Faster computations.

Comparing the Newton method with the fast decoupled method, the latter method is faster and much simpler and more efficient algorithmically and needs less storage, but it may fail to converge when some of the basic assumptions do not hold[7]. Convergence of iterative methods depends on the dominance of the diagonal elements of the bus admittance matrix.

The convergence of the Gauss-Seidel, Newton-Raphson and the fast decoupled method power flow algorithms are compared as shown in the Figure 1.

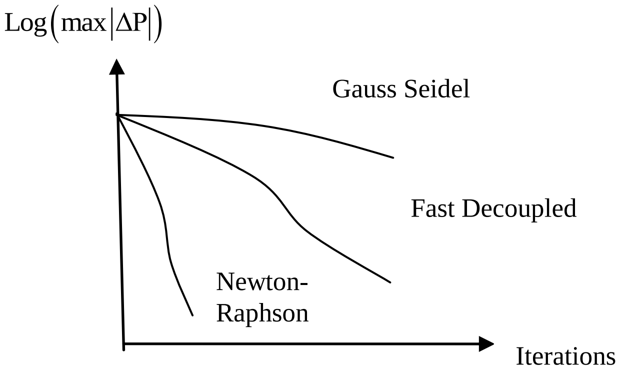

Figure 1. Comparison of various Load Flow Methods

Newton–Raphson method is a gradient method, the method is quite complicated and therefore, programming is also comparatively difficult and complicated. With this method the memory that is needed is rather large for large size systems but still the method is versatile, reliable and accurate and best matched for load flow calculation of large size systems.

According to the literature review[1]-[7], because of the applicability of the Newton-Raphson method on large size systems and its stability for convergence, in this paper Newton-Raphson method is implemented for the calculation of actual state of power system based on the network parameters, power injections and loads regardless of its complicated programming.

B. Newton Raphson Load Flow

The Newton–Raphson method is most efficient step-by-step procedure to solve the nonlinear equation. The procedure of solving nonlinear equations are transformed into the procedure of repeatedly solving linear equations. The real and reactive power injections are given in the eq.(1) and eq.(2).

$$P_i = \left|V_i\right| \sum_{j=1}^{N_{bus}} \left|V_j\right| \left(G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij} \right) \quad (1)$$

$$Q_i = \left|V_i\right| \sum_{j=1}^{N_{bus}} \left|V_j\right| \left(G_{ij}\cos\theta_{ij} - B_{ij}\sin\theta_{ij} \right) \quad (2)$$

The mismatch vector is calculated by using eq.(3) and eq.(4). Considering the first order of Taylor Series expansion and neglecting the higher order terms of the non-linear equations for active and reactive power the voltage magnitudes and angles are given in eq.(5):

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$$\Delta P_i = P_{sp,i} - |V_h| \sum_{j=1}^{N_{bus}} |V_j| \left(G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij} \right) = 0 \quad (3)$$

$$\Delta P_i = P_{sp,i} - |V_h| \sum_{j=1}^{N_{bus}} |V_j| \left(G_{ij}\cos\theta_{ij} - B_{ij}\sin\theta_{ij} \right) = 0 \quad (4)$$

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} A = \frac{\partial P}{\partial \theta} & B = \frac{\partial P}{\partial V} \\ C = \frac{\partial Q}{\partial \theta} & D = \frac{\partial Q}{\partial V} \end{bmatrix} \begin{bmatrix} \Delta \theta \\ \Delta V \end{bmatrix} \quad (5)$$

The ΔP and ΔQ are mismatch vector. If the mismatch vector does not converge to the specified value of the system the Jacobian matrix is calculated. The matrices of A, B, C and D are the sub-blocks of the Jacobian matrix where their elements can be calculated by differentiating the equations of active and reactive power with respect to voltage angles and magnitudes. Jacobian matrix is a sparse matrix, and the place of zeros in this matrix is the same as place of zeros in bus admittance matrix because considering the equations of Jacobian matrix for off-diagonal elements, it can be seen that each of them is related to only one element of the bus admittance matrix[8]. Therefore, if the element in the admittance matrix is zero, the corresponding element in the Jacobian matrix is also zero. The Jacobian matrix is not, however, symmetrical. The elements of Jacobian matrix are a function of node voltage phasors and so during the iterative process they vary with node voltages. The $\Delta\theta$ and ΔV are correction vector which is to be calculated and then updating the voltage and angles. The power flow results will be displayed when mismatch vector converges to the specified value.

From this method the true value is obtained. The voltage magnitude and angles of each bus are calculated. The real and reactive power generation and load at each bus is obtained as a result of laod flow. It also calculate the real and reactive power flow of each transmission line and their losses. Finally the error is calculated by comparing with the estimated value.

III. WEIGHTED LEAST SQUARES METHOD

This paper presents the mathematical basis for analyzing state estimation techniques to include phasor measurements to improve the quality of the measurement is done in MATLAB. Weighted least squares (WLS) state estimation (SE) approach is an important tool for determining the optimal estimate of power system states. WLS state estimation will minimize the weighted sum of the squares of the measurement residuals. The weight for each measurement is obtained from the accuracy of the device which is termed as the standard deviation of the measurement[9]. More accurate measurements are given more weight so that the estimation procedure influences the solution based on the measurements of greater accuracy. Full Newton Raphson (NR) method is used in linearizing and iteratively solving the states in it. The state estimator becomes WLS estimator by including the measurement covariance matrix. The commonly available measurements for state estimation are power flows, voltage magnitudes, and power injections. For state estimation the measurements are collected using supervisory control and data acquisition (SCADA). SCADA measurements are not free from errors[10]. The errors can be in the form of noise in measurements, wrong measurements, and improper circuit connection information. Consider the set of measurements given by the vector z as shown in the eq.(6).

$$z = h(x) + e \quad (6)$$

where z is the measurement vector. *x* is the an state vector to be estimated; *h* is a vector of nonlinear functions that relate the states to the measurements; and *e* is an measurement error vector. The state vector includes voltage magnitudes and angles and hence can be taken as shown in the eq.(7):

$$x = [\delta_1, \delta_2, ..., \delta_N, V_1, V_2, ..., V_N] \quad (7)$$

where $\delta_1, \delta_2, ..., \delta_N$ are voltage angles of buses and $V_1, V_2, ..., V_N$ are voltage magnitudes of all the buses and N is maximum number of buses. The error vector e is assumed to be standard Gaussian with zero mean and independent covariance. The weight matrix is given in the eq.(8).

$$R = \begin{bmatrix} \sigma_1^2 & 0 & ... & 0 \\ 0 & \sigma_2^2 & 0 & 0 \\ \vdots & 0 & \ddots & 0 \\ 0 & 0 & 0 & \sigma_m^2 \end{bmatrix} \quad (8)$$

The Jacobian matrix for the measurement vector is formed which is denoted here as H. In the WLS method the measurement errors are assumed to be independent. The measurement error covariance matrix taken as the diagonal matrix. The main idea behind WLS estimation is the square of the measurement deviation from the initial estimate is minimized to obtain the best estimate[11]. The optimal state estimate vector x may be determined by minimizing the sum of weighted squares of residuals. Hence the objective function is of the form as shown in the eq.(9) and eq.(10).

$$J(x) = \sum_{i=1}^{m} \left(z_i - h_i(x) \right)^2 / R_{ij} \quad (9)$$

$$J(x) = [z - h(x)]^T R^{-1} [z - h(x)] \quad (10)$$

where R is the measurement error covariance matrix and R_{ij} is the ith row and jth column of the matrix. It should satisfy the first order optimality conditions in order to solve the above equation. These can be expressed as follows as shown in the eq.(11).

$$g(x) = \frac{\partial J(x)}{\partial x} = -H^T(x) R^{-1} [z - h(x)] = 0 \quad (11)$$

The above non-linear equation can be solved via an iterative Gauss-Newton method as shown below in eq.(12).

$$x^{k+1} = x^k - \left[G(x^k) \right]^{-1} * g(x^k) \quad (12)$$

The gain matrix is G(x). If the gain matrix is positive definite and symmetric the system is considered to be fully observable. The gain matrix is decomposed into its triangular factors for each iteration and the forward/backward substitution method is used to solve for following linear set of eq.(13). The iterations is continued and the values are updated as shown in eq.(14).

$$\left[G(x^k) \right] \Delta x^{k+1} = H^T(x^k) R^{-1} \left[z - h(x^k) \right] \quad (13)$$

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Where $\Delta x^{k+1} = x^{k+1} - x^{k}$ (14)

The PMU is incorporated in state estimation. To provide satisfactory accuracy of the estimation process, the input data should be as accurate as possible. The statement accurate data considers not only the accuracy of the measurement, but also the proper information regarding actual network topology and parameter of the network elements[12]. Generally, phasor measurement units can be used in addition to conventional measurement devices to provide more accurate data but also to transform the existing critical measurements into the redundancy measurement. PMU data with respect to voltage and angle are added with conventional measurement. The optimal placement of PMU for several IEEE standard was done. According to the placement of PMU the data's are added with the traditional measurements[13]. The WLS method of with and without PMU is done and the results are verified. The weight matrix of PMU should be given more weight when compared with traditional measurements. The error is reduced when PMU datas are added.

IV. RESULTS AND DISCUSSION

The IEEE-30 bus system shown in figure 2 is taken as an example for estimating its voltages and currents of each bus.

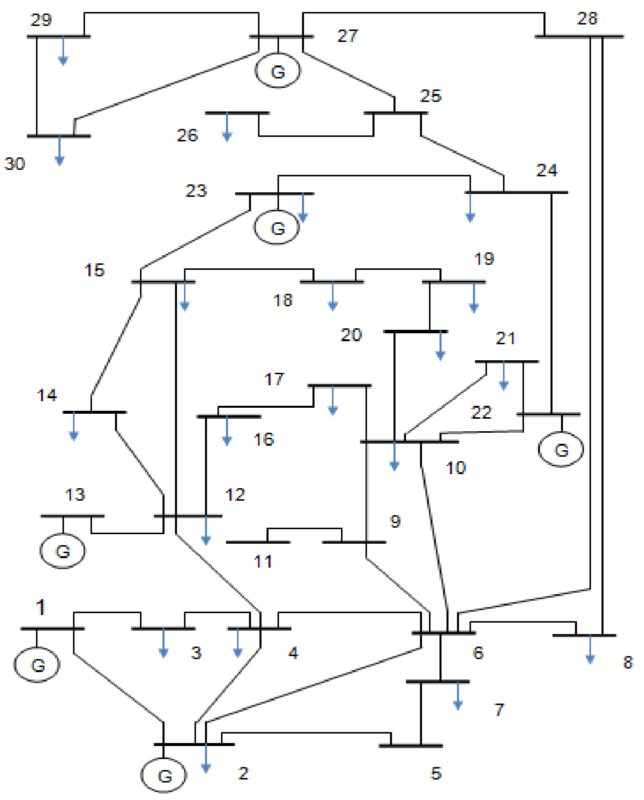

Figure 2. IEEE 30 bus system

The IEEE 30 bus system has the following data:

1. Number of buses - 30
2. Number of Transformers - 3
3. Number of Transmission Lines - 41
4. Number of Generators - 6
5. Number of Loads - 20

The bus which satisfies three criteria such as maximum observability, maximum redundancy and minimum cost is choosen for the optimal placement of PMUs. For IEEE 30 bus system in order to reduce the cost considering pseudo measurements the optimal location of PMUs are 6, 10, 12, 15 and 27. The SE of bus voltages and angles of each bus was found. The true value is obtained from NR method and the estimated value is obtained from WLS and it is done by using MATLAB. The error is found out by the difference between true and estimated value. With the inclusion of PMUs the error is reduced compared with the SE of without PMU. The real and reactive power flow through each line can be calculated, once the bus voltage magnitudes and their angles are found. Totally 83 measurements are selected for reducing the observability problem. The measurement redundancy ratio(η) will be approximately equal to 1.4. The results of WLS SE without and with PMU is shown in the table I and II respectively.

Table I
WLS Method for IEEE 30 Bus System Without PMU

Bus	V(p.u.)		Angle(Degrees)	
No.	True	Estimated	True	Estimated
1	1.0600	0.9865	0.000	0.000
2	1.0430	0.9700	-5.347	-6.2635
3	1.0217	0.9474	-7.544	-8.8420
4	1.0129	0.9384	-9.298	-10.902
5	1.0100	0.9335	-14.15	-16.494
6	1.0121	0.9395	-11.08	-12.997
7	1.0035	0.9287	-12.87	-15.044
8	1.0100	0.9449	-11.80	-13.960
9	1.0507	0.9667	-14.13	-16.481
10	1.0438	0.98472	-15.73	-18.344
11	1.0820	1.0093	-14.13	-16.481
12	1.0576	0.9746	-14.94	-17.691
13	1.0710	0.9954	-14.94	-17.691
14	1.0429	0.9559	-15.82	-18.713
15	1.0384	0.9491	-15.91	-18.729
16	1.0445	0.9555	-15.54	-18.280
17	1.0387	0.9441	-15.88	-18.571
18	1.0282	0.9352	-16.54	-19.419
19	1.0252	0.9306	-16.72	-19.606
20	1.0291	0.9339	-16.53	-19.358
21	1.0293	0.9328	-16.24	-18.982
22	1.0353	0.9372	-16.07	-18.711
23	1.0291	0.9331	-16.25	-18.995
24	1.0237	0.9231	-16.44	-19.078
25	1.0202	0.9270	-16.05	-18.778
26	1.0025	0.9070	-16.47	-19.259
27	1.0265	0.9398	-15.55	-18.296
28	1.0109	0.9398	-11.74	-13.791
29	1.0067	0.9177	-16.77	-19.760
30	0.9953	0.9051	-17.65	-20.817

Table II
WLS Method for IEEE 30 Bus System With PMU

Bus	V(p.u.)		Angle(Degrees)	
No.	True	Estimated	True	Estimated
1	1.0600	1.0536	0.000	0.0000
2	1.0430	1.0408	-5.3474	-5.4228

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3	1.0217	1.0192	-7.5448	-7.6597
4	1.0129	1.0108	-9.2989	-9.4303
5	1.0100	1.0068	-14.154	-14.2631
6	1.0121	1.0121	-11.088	-11.2412
7	1.0035	1.0018	-12.873	-13.0064
8	1.0100	1.0172	-11.803	-12.0755
9	1.0507	1.0378	-14.136	-14.2385
10	1.0438	1.0201	-15.734	-15.8429
11	1.0820	1.0777	-14.136	-14.2359
12	1.0576	1.0469	-14.941	-15.2631
13	1.0710	1.0664	-14.941	-15.2619
14	1.0429	1.0295	-15.824	-16.1481
15	1.0384	1.0229	-15.910	-16.1606
16	1.0445	1.0283	-15.548	-15.7791
17	1.0387	1.0171	-15.885	-16.0360
18	1.0282	1.0096	-16.542	-16.7537
19	1.0252	1.0049	-16.727	-16.9163
20	1.0291	1.0079	-16.536	-16.7050
21	1.0293	1.0067	-16.246	-16.3884
22	1.0353	1.0106	-16.073	-16.1535
23	1.0291	1.0070	-16.252	-16.3989
24	1.0237	0.9977	-16.440	-16.4699
25	1.0202	1.0015	-16.053	-16.2167
26	1.0025	0.9832	-16.471	-16.6142
27	1.0265	1.0131	-15.555	-15.8104
28	1.0109	1.0126	-11.743	-11.9311
29	1.0067	0.9931	-16.777	-17.0452
30	0.9953	0.9815	-17.654	-17.9311

From these methods it is proved that when PMU measurement data's are added to the conventional measurements the error is reduced. The optimal placement of PMU is done based on maximum number of incident lines leads to maximum number of directly observable remaining buses which will enhance the observability. Placing PMUs at roughly one third of the system buses, the entire system can be made observable with only PMUs and its redundancy is achieved. Pseudo measurements are considered for reducing the required number of PMUs and this will reduce the cost of entire system. According to the placement of PMUs the measurement data's are included and its voltages and angles of each bus is obtained. The error got reduced when the PMU measurements are added at suitable location.

V. CONCLUSION

This paper proposes a combined Newton Raphson method and Weighted Least Squares State Estimation for estimating each bus voltages and angles. The comparison of results of WLS method considering with and without PMU is presented. These methods are tested in IEEE 30 bus system and its results are validated. The true value which is obtained from NR method is compared with estimated value obtained from WLS method. Without PMU the residue obtained from the system is large therefore it affects the accuracy. For improving the accuracy the PMU measurements for state estimation are included. The SE of voltages and angles at each node of the bus are obtained. The error got reduced after introducing PMU measurements in the system.

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