PMU based real time power system state estimation

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Abstract— **The complexity of power system monitoring, and control is increasing rapidly due to factors like long-distance power haulage, integration of renewable energy sources and large seasonal load variations, demand growth, increasing machine size. With increasing number of power system operation, it is very important to estimate the present state of a power system. In any power system the demand should be supplied by the generation if the demand requirement is not met it might result in outage. To prevent this state estimation is one of the important techniques. The Supervisory control and data acquisition (SCADA) are used to perform state estimation process. The data measured is not very accurate. Phasor measurement unit (PMU) can be used to increase the accuracy, it gives time stamped data which is more reliable when compared to normal data. In this paper we designed an algorithm to perform state estimation on IEEE-14 and IEEE-30 bus and we discuss how the measurement error has been minimized when PMU is used along with SCADA. Weighted least square (WLS) and GM-estimator are used for state estimation and the results are compared. In order to validate the results Newton Raphson method, a theoretical solution for state estimation is solved.**

Keywords—SCADA, PMU, Weighted least square, GM-estimator

I. INTRODUCTION

Various monitoring and control operations are performed on a power system, state estimation is one of the operations. Why do we need state estimation? Primarily take a system where data is not measured completely, we can use state estimation to find the states that are not measured. Secondarily we need estimation when the noise and measurement error should be removed from the measurements. In the past, without state estimation the recognition of faults was very difficult, and as a result outages occurred which were difficult to rectify. By using state estimation, the outages can be prevented, and data can be monitored continuously. For instance, if the data measured matches with historical data where a power outage has occurred it can be immediately rectified. Power system operation and reliability depends upon the real states provided by the state estimator. To monitor the power system properly we collect measurement from different part of the system [1]. This measurement contains noise or error. Error can never be zero. State estimation plays an important role in power system control centre. The state of the power system is defined by the voltage magnitudes and angle at all buses. The state estimator determines the state based on a set of redundant measurement. Therefore, state estimation process is carried to reduce noises and errors, Estimation is needed when all the inputs are not measured and to set a reference for controlling operation. State is a set of signals of the system that fully captures the effect of past inputs and it holds all the information about past inputs. State estimation is a process of telemetered or non-telemetered or incorrect data from a network measuring point to a central computer can be formed into a set of reliable data for control and recording purpose. It acts as a cross check reference helping in bad data detection. State estimation is essential for real time monitoring.

Supervisory control and data acquisition (SCADA) analog measurements have been used for several decades with measurement standards of once every few seconds. But SCADA data isn’t very accurate, it has increased measurement error. Phasor Measurement Unit (PMU) is used to overcome this.

Phasor Measurement Unit (PMU) is a device used to estimate the magnitude and phase angle of an electrical phasor quantity like voltage and current in the electricity grid along with frequency and rate of frequency using a common time source for synchronization [2]. It gives synchro phasors as output. Synchro phasor is a metered value whereas PMU is a metering device. The high precision time synchronization (via Global positioning satellite) allows comparing measured value (synchro phasors) from different substation. A Phasor measurement unit can measure 50/60 Hz AC waveform (voltage and current) typically at a rate of 48 samples per cycle.

II. STATE ESTIMATION

State estimation is process of removing noise to achieve actual values of the state. Some uncertainty in inputs is present and only few inputs are taken. Statistical characteristics of the input are known. Properties of the measurement error and initial state are known. State estimation is performed to make error power minimum.

Two types of state estimations are available

•*Static estimation*: The static state of an electric power system is defined as the vector of the voltage magnitudes and the angles at all network buses. This converts the redundant meter readings into an estimate of the static state vector. Static state estimation is obtained from measurements taken within a time interval of about 0-5seconds. This is the commonly used state estimator. This type of state estimator essentially gives a steady state snapshot of the system. Static state estimation refers to the procedure of obtaining the voltage phasors at all the system buses at a given point in time. This can be achieved by direct method it involves very accurate synchronized phasor measurement of all bus voltages in the system. This approach will be very vulnerable to measurement errors or telemetry failures.

•*Dynamic estimation*: Dynamic state estimate is obtained from measurements in a relatively shorter time (say 0.01 seconds). All such measurements are synchronized or “time stamped” using a common clock and communication from geographically distant locations to a load dispatch centre. The benefits of dynamic state estimation are its predictive ability which provides necessary information to perform preventive analysis and control. Other benefits are improvements in observability analysis and identification of bad data. These types of measurements can be used for advanced control schemes [3].

A. Newton Raphson Load Flow Analysis

Newton Raphson method is an iterative technique for solving various non-linear equation with equal number of unknowns. This method works faster and possess quadratic convergence characteristics. Therefore, convergence is very fast as compared to gauss seidal method [4]. Newton Raphson method is more accurate, and solutions are obtained nearly always in two to three iterations. The sensitivity is minimum in this method when compared to other load flow analysis.

B. Weighted Least Square Method

Weighted Least Square (WLS) is also known as Weighted Linear Regression. It is generalization of ordinary least squares in which the assumption of constant variance in the errors is violated and estimation is done by giving weights to data error points based on their level of influence [5].

Weighted Least Square is very efficient method in reducing Gaussian noise. This method maximizes the efficiency of parameter estimation by giving weights to each data point. In WLS method standard deviation of random errors in the data is not constant which yields the most precise parameter. Unscented Kalman state estimation is highly accurate and reliable but computation is difficult.

Algorithm:

In this method we will start with |V| = 1 and del=0. Repeat the following steps:

- Estimate the measurement matrix Z^ with x using the initial voltage and delta values.
- Calculate Jacobian matrix H(x)
- Calculate the difference between actual measurement and estimated measurement

  i.e. $\Delta Z = Z - \hat{Z}$

- Calculate gain matrix G

  i.e. $G = (H^T(x)\ W\ H(x))$

Where W is a weight matrix whose diagonal elements shows the weight of measurement.

$$W = \begin{bmatrix} w1 & \ldots\ldots & \ldots\ldots \\ \ldots\ldots & w2 & \ldots\ldots \\ \ldots\ldots & \ldots\ldots & wn \end{bmatrix}$$

W1, W2……Wn are weights of measurement which are inversely proportional to variances of data error points.

- Calculate Δx value using ΔZ and H(x) using the below equation:

$$\mathbf{\Delta x = G^{-1} H^T(x)\ W \Delta Z}$$

- Calculate new value of x using current x value and Δx value i.e. $\mathbf{x = x + \Delta x}$

At each iteration we will check whether the value of Δx lies within the tolerance value, if it lies then the iteration will be ended or else the process repeats till Δx value lies within the tolerance level.

C. GM-Estimator:

Generalized maximum likelihood estimator is like Weighted Least Square method where weights are given to each data point. But in GM-Estimator projection statistics is used to give weights. In GM-estimator the cloud point will be selected from where the leverage (measurement) point identification is carried out by considering a distance from each point in factor space to the center of the cloud [6]. This is a standardized distance. There are two types of leverage points. The first type is bad leverage points which ruins the state estimation. The second type is a good leverage points which enhances the accuracy of the M-Estimators. Once the projection statistics is calculated they are used to define weights for robust M – estimators. The GM estimator can be computed easily by reweighted least square algorithm. This method reduces the number of probabilities by taking a cloud point and increases the accuracy. It can be implemented through a simple modification of traditional WLS method. Good leverage points are not neglected. It is as fast as traditional WLS method.

Algorithm:

- Calculation of measurement matrix h(x).
- Calculation of Jacobian matrix H(x).
- Identify leverage points (bad or good).
- Forming Sparse matrix to give corresponding weights to data points.
- Iteration using iteratively reweighted least square method
- Calculation of measurement functions h(x) and jacobian H(x) for IRLS.
- Calculate the state vector

  $dE = inv\ (H^1 * inv(Ri) * QQ * H^1 * inv(Ri) * QQ * ri)$ If

dE value lies within the tolerance value

Calculate E = E+dE, otherwise start next iteration.

III. RESULTS AND DISCUSIONS

State estimation is carried out twice, once with normal data and with PMU data as shown in figure 1. Weighted least square method is used for state estimation. Newton Raphson load flow analysis is used to get the reference values. Newton Raphson is chosen as it is more accurate for large power systems and it is more reliable. When a plot against these errors and time is take it is seen that error is minimized for the latter. This is carried out for specific period to get real time results. This can be carried out for 3 bus, 5 bus, IEEE-14 bus, and IEEE-30 bus. It can also be done using other state estimation methods.

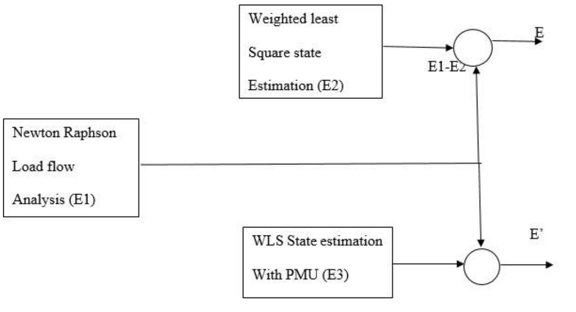

FIG 1.

Below figure2 and figure3 shows the comparison between voltage angle estimation error with PMU and without PMU. From fig. 3 it is understood that voltage angle error using PMU is minimized compared to the error without PMU in fig 2. In the same way, figure4 and figure5 shows the comparison between voltage magnitude estimation error with PMU and without PMU. From fig 5 the error is minimized by using PMU compared to the error without PMU in fig 4.

A. Figures and Tables

a) Voltage angle estimation Without PMU:

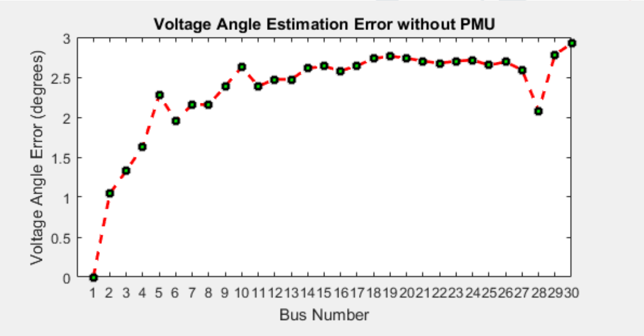

FIG 2.

With PMU:

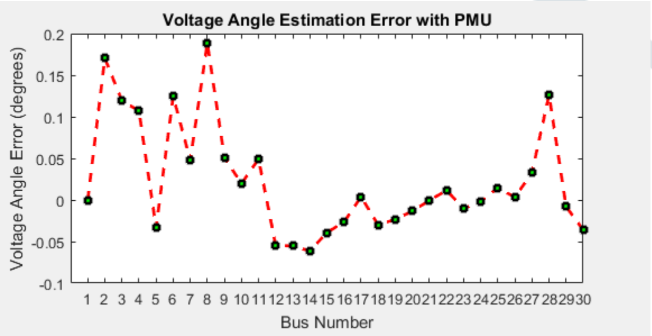

FIG 3.

TABLE 1.VOLTAGE ANGLE IEEE-30 BUS

NRLF with theoretical data	WLS With conventional data	WLS with PMU data
0	0	3.85E-11
-5.22005	-6.26348	-5.39041
-7.51195	-8.84195	-7.63135
-9.26797	-10.9021	-9.37502
-14.2128	-16.4941	-14.1795
-11.0463	-12.9975	-11.1708
-12.8838	-15.0443	-12.9316
-11.8056	-13.9608	-11.9941
-14.0932	-16.4813	-14.1441
-15.7187	-18.3445	-15.7384
-14.0932	-16.4813	-14.1425
-15.2191	-17.6918	-15.1645
-15.2191	-17.6918	-15.1638
-16.1017	-18.7137	-16.0404
-16.0929	-18.7299	-16.0537
-15.7011	-18.28	-15.6746
-15.9275	-18.5714	-15.9313
-16.6877	-19.4195	-16.6575
-16.8424	-19.6063	-16.8193
-16.6202	-19.3581	-16.6068
-16.2807	-18.9821	-16.2801
-16.0362	-18.7111	-16.0477
-16.2947	-18.9957	-16.2845
-16.3634	-19.0788	-16.3609
-16.128	-18.7784	-16.1429
-16.5676	-19.2593	-16.5709
-15.7038	-18.2962	-15.7365
-11.7111	-13.791	-11.8374
-16.979	-19.7604	-16.971
-17.8953	-20.8172	-17.8592

VOLTAGE MAGNITUDE ESTIMATION

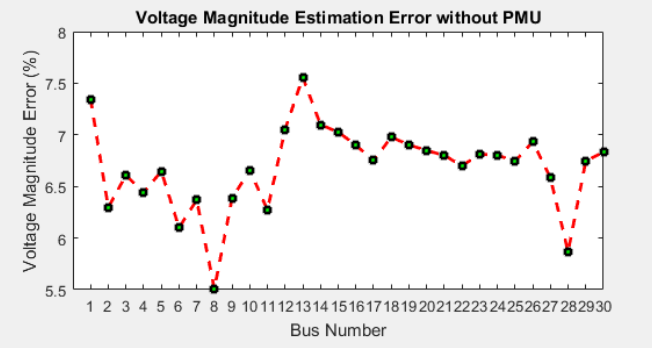

FIG 4.

PMU:

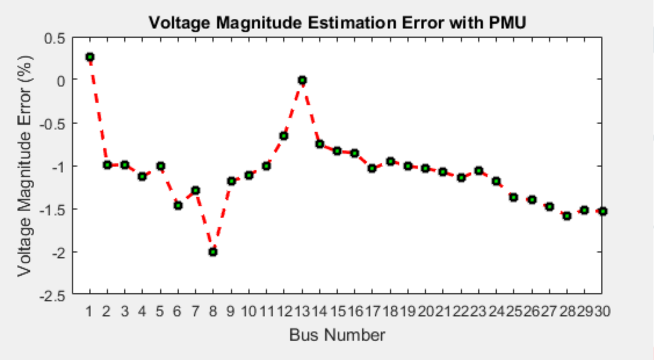

FIG 5.

TABLE 2. VOLTAGE MAGNITUDE AT IEEE-30 BUS

1.01936235	0.94908871	1.0277148
1.02453623	0.95554858	1.03308172
1.01156642	0.94406479	1.02194292
1.00494682	0.935172	1.01441397
0.99962132	0.93058985	1.00969049
1.00235975	0.93387763	1.01269013
1.00076708	0.93275597	1.01154745
1.00414369	0.93715628	1.01558198
1.0012451	0.93311253	1.01183815
0.99112411	0.92309244	1.00296607
0.99445408	0.92701989	1.00821843
0.97635349	0.90702327	0.99037342
1.00533028	0.93949243	1.02017241
0.9985239	0.93984109	1.01433875
0.98509805	0.91765094	1.00026953
0.97339763	0.90506316	0.98877118

GM-estimation for one more set of data is been performed and it is seen from table 3 that when PMU readings are taken state estimation was more accurate

TABLE 3. VOLTAGE MAGNITUDE AT IEEE-30 BUS

Voltage magnitude without PMU	Voltage magnitude with PMU
1.059999986	1.412499915
1.043128994	1.210161201
1.020733426	1.182994042
1.011755335	1.150624417
1.009980241	1.08216881
1.010246288	1.127681889
1.002355651	1.097671432
1.009987944	1.122109325
1.050912721	1.100545655
1.045122703	1.067572616
1.081997452	1.132086131
1.057107041	1.069325973
1.070966981	1.085409687
1.04228878	1.046046421
1.037674185	1.034500255
1.044381402	1.048720571
1.039897038	1.063147156
1.028144201	1.033096189

NRLF with theoretical data	WLS With conventional data	WLS with PMU data
1.06	0.98654006	1.05735519
1.033	0.97002902	1.0429989
1.01348533	0.94741083	1.02338019
1.00281647	0.93841496	1.01407533
1	0.93352549	1.01011923
1.00053236	0.93953419	1.01518568
0.99243604	0.92874906	1.00537628
1	0.94492361	1.02008808
1.03054591	0.96669764	1.04239606
1.01376575	0.94717674	1.02484759
1.072	1.00927551	1.08210325
1.045095	0.97456409	1.05171259
1.071	0.99542159	1.07110258
1.0268691	0.9558922	1.03443364

1.025641008	1.027619967
1.029725033	1.033972362
1.032721968	1.051180794
1.033253238	1.056908063
1.027168641	1.029091972
1.021560604	1.037976506
1.017271616	1.017486032
0.999567564	0.998245589
1.023184872	1.02963299
1.006808425	1.119475735
1.003316993	0.97336715
0.991853201	0.95643619

IV. CONCLUSION

This paper has shown the State estimation using PMU. The traditional WLS method with its algorithm has been explained. The algorithm has been conceived in order to specifically take advantage of PMUs measurement.

By referring to the IEEE-30 bus, the paper has shown a comparative analysis of voltage angle and voltage magnitude with PMU and without PMU. Further taking the same reference bus, the paper has shown a comparative analysis of the developed WLS algorithm and Robust GM estimator. In particular, the analysis has been focused on the evaluation of measurements and process covariance error matrices on the performances of two SE methods.

Future research will focus on the usage of PMU on distribution side and its applications.

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