PMU Based Real Time Power System State Estimation

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Abstract— Power system State Estimation is a process where the real time data from the network is fed to central computers and these data are used to know the status of the network and also used for calculation and recording purpose. The real time status of the network is atmost important in a smart grid. With the implementation of PMUs , the status of the system can be known. In addition with it, the reliability and efficiency of the system can be improved. In this paper, real time state estimation of two systems IEEE 14-bus and IEEE 30-bus system, have been performed with PMU and without PMU. Simulation results are compared with respect to accuracy.

Index Terms—State Estimation, IEEE 14-bus , IEEE 30-bus, Phasor Measurement Unit(PMU)

1 INTRODUCTION

Power system network is need to be operated with reliability and stability. As the network consist of large number of components associated with it. The real-time status of the components need to be known in a smart-grid network. With the real time status, one can modify the values according to the requirements and can replace the components during the fault condition. Traditionally the real time observation of the network is done using SCADA (supervisory control and data acquisition) system. The data scanning rate of SCADA system is typically 5-8s and it is quite higher for larger systems. Thus the state of the system gets changed by the time total system gets scanned. As a result an erroneous data is calculated. With the advancement of Technology the Phasor Measurement Unit(PMU) are introduced for real time measurement. The scanning rate of PMUs are quite higher i,e 50/60 frames per second as a result the online monitoring of the power system becomes easier. But due to the cost component of PMUs, we cannot place them at all the buses. Thus care need to be taken for the placement of PMUs in a power system by performing proper state estimation.

In recent decades the Phasor Measurement Unit(PMU) has the capacity of online monitoring and controlling the power system network. PMUs are used to upgrade the traditional grid into smart grid. These PMUs are installed at various buses which provides real time phasor measurement data. These data are gathered by the device called phasor data concentrator which syncronises the measurement taken at every time instant independent of when the data was received. Then these time synchronized datas are fed to the advanced application software for the analysis of power system.

In this paper, a method has been proposed which improves the efficiency and reliability of the power system network by reducing the mean squared errors(MSE) . Initially two systems are considered and the Load flow analysis of both systems are performed using Newton Raphson Method(NR).Once the load flow is done, the next step is to find the State Estimation(SE) using Weighted Least Square criterion(WLS) by calculating the mean squared error (MSE). This state estimation is done with and without insertion of PMU and thus the results are obtained and compared using MATLAB software.

This paper is divided into six sections. The load flow analysis using Newton Raphson method is discussed in section II. State Estimation without PMU has been performed by using weighted least square (WLS) technique in section III. Section IV contains the algorithm of PMU for State Estimation. Section V compares the results of State Estimation using with and without PMU. Section VI contains the discussion and conclusion of the work respectively.

2. NEWTON RAPHSON LOAD FLOW ANALYSIS

Load flow analysis is the study of load power consumption at all the buses of known electric power configuration and power generation at each generator, finding out the power flow in each line and transformer of interconnecting network and voltage magnitude and phase angle at each bus. NR method is one of the method to perform load flow analysis. It is solved till convergence criterion is satisfied. Consider a Jacobian matrix whose element is first order derivative given by

$$f^{o} + [J^{0}]\,[\Delta x^{0}] \cong 0$$

By taking the inverse of Jacobian matrix, the value of Δx^0 can be obtained and then update the value ($x^1 = x^0 + \Delta x^0$). Iterations are continued till a specified condition is satisfied $|f_i(x^r)| < €$ and then stops. For load flow analysis,the values of $P_i(x)$ and

$Q_i(x)$ are calculated . These calculated values are subtracted with the scheduled values i,e $f(x)=\begin{bmatrix} Psch - Pcal \\ Qsch - Qcal \end{bmatrix}=\begin{bmatrix} \Delta P(x) \\ \Delta Q(x) \end{bmatrix}$

where $\Delta P(x)$ and $\Delta Q(x)$ are residuals, which are need to be calculated with the help of Jacobian matrix and correction vector i,e

$$\begin{bmatrix} \Delta P(x) \\ \Delta Q(x) \end{bmatrix} = \begin{bmatrix} \frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial |V|} \\ \frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial |V|} \end{bmatrix}$$

where Jacobian matrix is a sparse matrix and it is evaluated at trial values and then multiplied with correction vector as shown above. Jacobian matrix has two rows of PQ bus and one row of PV bus.

NR method works on iterative algorithm. Assume the real and imaginary part, as voltage can be given as (v=e+jf). Let the real part be $e_i^r = |v_i|^r \cos\delta_i^r$ and imaginary part be $f_i^r = |v_i|^r \sin\delta_i^r$. Now consider the real and imaginary part of Ybus i,e

$G_{ik} = |Y_{ik}| \cos\theta_{ik}$ and $B_{ik} = |Y_{ik}| \sin\theta_{ik}$. With these assumptions real and reactive power are calculated i,e

$$P_i^r = \sum_{k=1}^{n} (e_i^r \ (e_k^r G_{ik} - f_k^r B_{ik}) + f_i^r \ (f_k^r G_{ik} + e_k^r B_{ik}))$$

$$Q_i^r = \sum_{k=1}^{n} (f_i^r \ (e_k^r G_{ik} - f_k^r B_{ik}) - e_i^r \ (f_k^r G_{ik} + e_k^r B_{ik}))$$

where i= 1,2,3……….n.

with the above formulae the Slack power, Loss power and Line flows are calculated and to stop the iterations, it is checked with the condition i,e ($\Delta P_i^r , \Delta Q_i^r \le \epsilon$). If the condition is satisfied , iteration will stop and if not then once again jacobian matrix is calculated and the steps are repeated till the condition is satisfied. Care need to be taken such that solution should be within constraints, if voltage increases or decreases above the limit, then change of bus take place i,e PQ or PV based on which quantity has changed. Once measure is taken bus can be brought back. Solution should be feasible than observable.

3. STATE ESTIMATION WITHOUT PMU

Power system State Estimation is a process whereby telemetered data from network measuring points to a central computer, can be formed into a set of reliable data for control and recording purposes. Different methods are used for State Estimation. In this we will be using weighted least square method(WLS) to estimate the state of the system. With the help of WLS method, the Mean Squared Error(MSE) is obtained and based on MSE the results are obtained and the graphs are plotted. We consider two power system networks i,e 14-bus and 30-bus system. Initially measurements received from SCADA system are of size'm', the vector 'z' can be given as $z = [z_1, z_2.......z_n]^T$. The state vector is denoted by x. Since the power system is a complex network, state estimation follows a non-linear function

i,e $h(x) = [h_1(x_1, x_2..... x_n)……… h_m(x_1, x_2..... x_n)]^T$, where 'n' is state variable. Calculated estimate from h(x) will deviate from the actual value with an unknown error $e = [e_1, e_2……e_m]^T$.

In this paper we use the standard DC power flow model which results in a linear approximation of the model as

$$z = Hx + e$$

In order to solve the state estimation problem using WLS method ,an objective function should be minimized. The jacobian matrix given as $J(x) = \sum_{i=1}^{m} \frac{(e^* e)}{Ri}$. Here 'R' is a covariance matrix. To minimize objective function partial derivative of J(x) wrt to state variable is obtained i,e $\frac{\partial J(X)}{\partial x}$ =g(x) and $\frac{\partial h(X)}{\partial x}$ =H(x). Equation given as

$$g(x) = - H^T(x)\, R^{-1} [z - h(x)] = 0$$

Expanding g(x) into Taylors series leads to an expression $x^{k+1} = x^k + G(x^k)^{-1} g(x^k)$. Gain matrix is calculated which is a sparse matrix. Thus with this we can obtain the value of $\Delta x = (x^{k+1} - x^k)$. Repeat the procedure until the values of x^{k+1} and x^k are within certain pre-assigned threshold value 'ϵ'.

4. STATE ESTIMATION WITH PMU

State Estimation with the insertion of Phasor Measurement Unit increases the efficiency of the system by reducing the errors. PMU convert the system's critical measurements intoredundant ones, thus to render it fully observable. The critical measurements, as opposed to the redundant measurements, are those measurements whose removal in the system results in the system being unobservable and an erroneous critical measurement cannot be detected by the statistical tests based on measurement residual unless it is converted into a redundant measurement

Algorithm of PMU

1. Initialise the function E3
2. Assign the values of magnitude ,angle, length.
3. Call the Index of voltage and current measurement.
4. Form Measurement vector.
5. Form new Jacobian matrix.
6. Finding out the rotation matrix by obtaining voltage and current phasors.
7. Findout W2 matrix.
8. Findout W matrix i,e $W = diag[W1, W2]^T$
9. Findout new covariance matrix R.
10. State vector using rectangular and polar coordinates are obtained.

11. Bus voltages and Angles using PMU is obtained.
12. Display function is called.
13. END

5. SIMULATION RESULTS

In this section, we present the simulation results by using two IEEE bus configurations. The simulations are performed by using MATLAB 2014 software.In the simulation we have considered the standard IEEE-14 bus and IEEE-30 bus data and performed the load flow analysis and state estimation.

Fig. 1 shows the Voltage and Angle at different buses ,after performing the load flow analysis using Newton Raphson method. Fig. 2 and Fig. 3 gives the values of voltage and angle at different buses after performing State Estimation i,e with and without insertion of PMUs and from those Figures we can clearly visualize that with the insertion of PMU, the voltage deflection is almost negligible i,e it remains same as the initial. There by increasing the efficiency of the systems. Fig. 4 and Fig. 6 demonstrates the percentage of voltage angle error and voltage magnitude error of IEEE-14 bus and IEEE-30 bus system respectively. And from the respective graphs we can visualize, that the percentage error reduces quite lower with the insertion of PMUs there by increasing the stability of the system.

Newton Raphson Loadflow Analysis

Bus No	V pu	Angle Degree
1	1.0600	0.0000
2	1.0450	-4.9891
3	1.0100	-12.7492
4	1.0132	-10.2420
5	1.0166	-8.7601
6	1.0700	-14.4469
7	1.0457	-13.2368
8	1.0800	-13.2368
9	1.0305	-14.8201
10	1.0299	-15.0360
11	1.0461	-14.8581
12	1.0533	-15.2973

Fig. 1. The load flow analysis of IEEE-14 bus system using NR method.

State Estimation Without PMUs

Bus No	V pu	Angle Degree
1	1.0068	0.0000
2	0.9899	-5.5265
3	0.9518	-14.2039
4	0.9579	-11.4146
5	0.9615	-9.7583
6	1.0185	-16.0798
7	0.9919	-14.7510
8	1.0287	-14.7500
9	0.9763	-16.5125
10	0.9758	-16.7476
11	0.9932	-16.5397
12	1.0009	-17.0203

Fig. 2. The state estimation of IEEE-14 bus system without using PMU

State Estimation with PMUs

Bus No	V pu	Angle Degree
1	1.0584	0.0000
2	1.0451	-5.0258
3	1.0046	-12.7546
4	1.0083	-10.2142
5	1.0118	-8.7264
6	1.0700	-14.4443
7	1.0457	-13.2372
8	1.0800	-13.2371
9	1.0305	-14.8206
10	1.0299	-15.0364
11	1.0461	-14.8553
12	1.0533	-15.2946

Fig. 3. The state estimation of IEEE-14 bus system using PMU

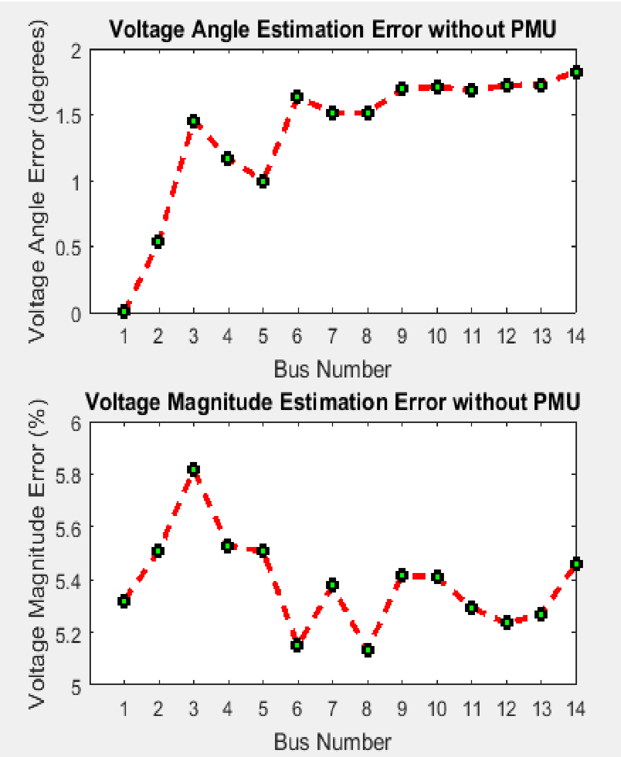

Fig. 4(a). The voltage angle error and voltage magnitude error without PMU for IEEE-14 bus system

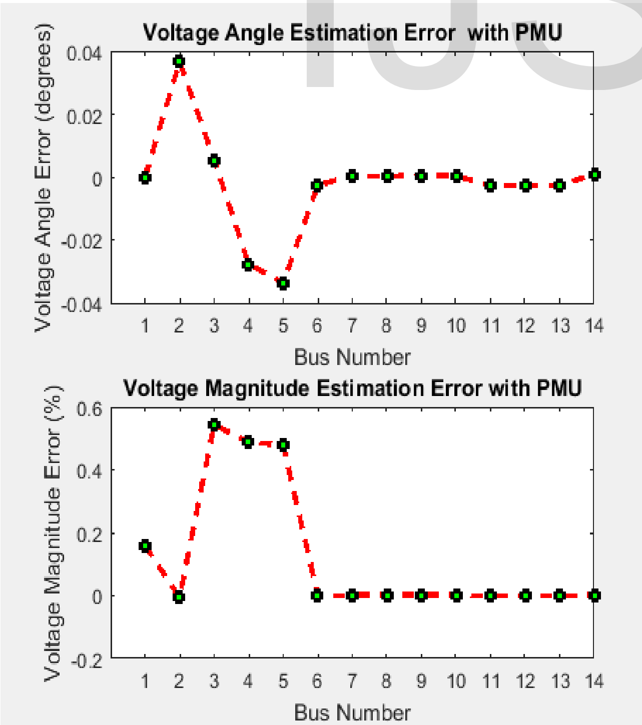

Fig. 4(b). The voltage angle error and voltage magnitude error with PMU for IEEE-14 bus system

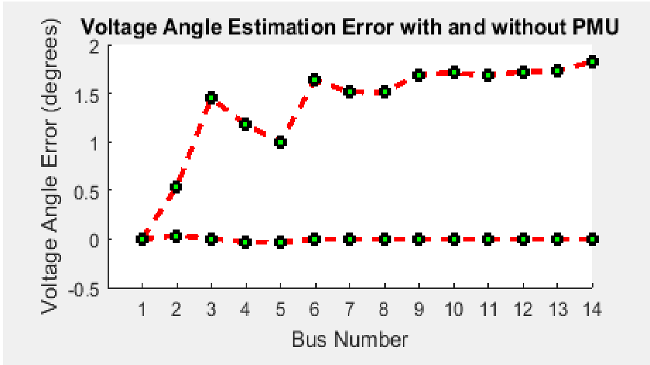

Fig. 5(a). Combined graph of voltage angle error and voltage magnitude error without PMU for IEEE-14 bus system

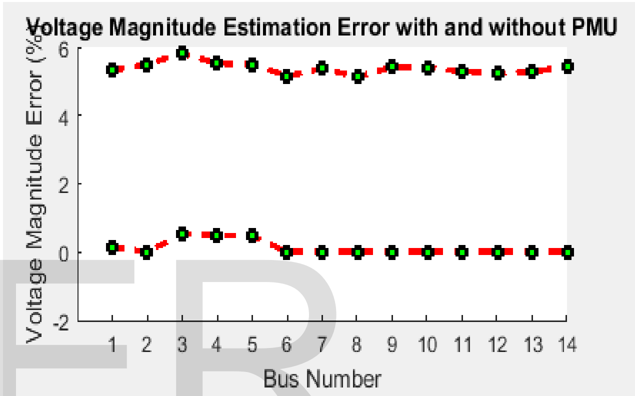

Fig. 5(b). Combined graph of voltage angle error and voltage magnitude error with PMU for IEEE-14 bus system

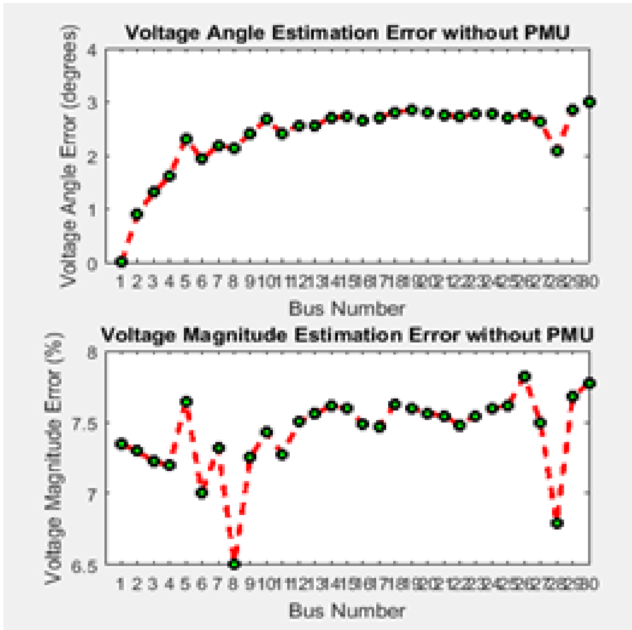

Fig. 6(a). The voltage angle error and voltage magnitude error without PMU for IEEE-30 bus system

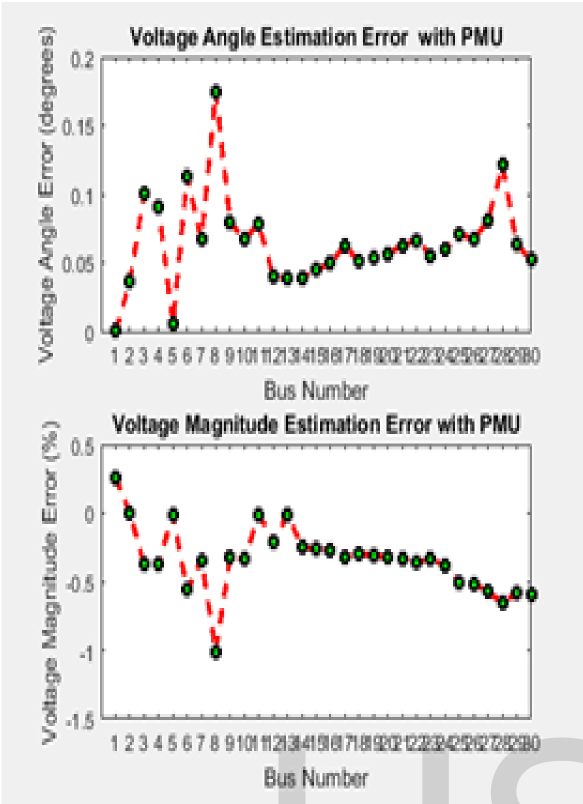

Fig. 6(b). The voltage angle error and voltage magnitude error with PMU for IEEE-30 bus system

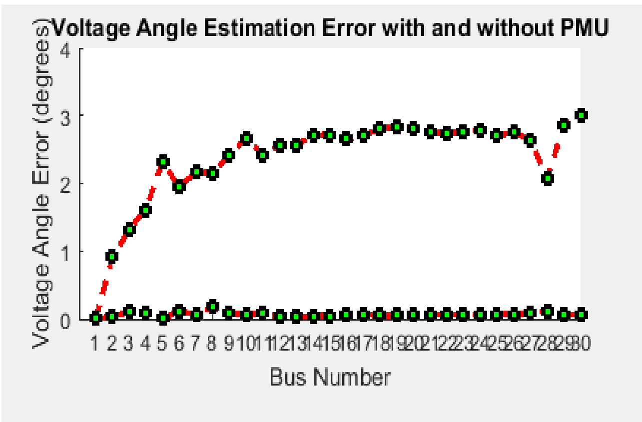

Fig. 7(a). Combined graph of voltage angle error and voltage magnitude error without PMU for IEEE-30 bus system

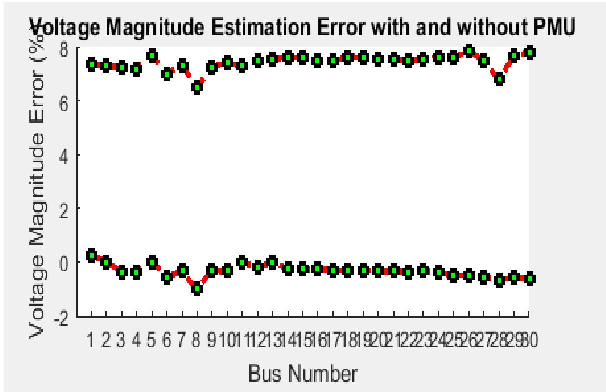

Fig. 7(b). Combined graph of voltage angle error and voltage magnitude error with PMU for IEEE-30 bus system

The comparision of the state estimation at bus 6 in both the systems are estimated and measured data areconsidered. The comparision before and after using PMU is shown in the Table I. With the observations made in the table we can say that, errors gets reduced with the insertion of PMUs, as a result efficiency and stability of the system increases.

TABLE I
COMPARISION OF REAL-TIME STATE ESTIMATION AT BUS-6 IN IEEE 14-BUS AND IEEE 30-BUS SYSTEM WITH AND WITHOUT USING PMU

Criteria	Bus6 Voltage Angle Error(degrees) Without PMU	Bus6 Voltage Angle Error(degrees) With PMU	Bus6 Voltage Magnitude Error(percentage) Without PMU	Bus6 Voltage Magnitude Error(percentage) With PMU
14-Bus	1.7	0	5.1	0
30-Bus	2	0.13	7	-0.5

6. CONCLUSION

Real –time state estimation is performed using WLS method using MATLAB . It is tested on IEEE 14-bus system and IEEE 30-bus system with and without insertion of PMUs. From the observation, one can say that the errors gets reduced with the insertion of PMUs, as a result the efficiency, reliability and accuracy of the system increases. But as the PMUs are not cost effective, so one should take care of it's placement, as we cannot place them at all the buses in the system. The optimal placement of PMU is very much needed.

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