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Power System State Estimation with Optimal PMU Placement under Contingencies

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Abstract

It discusses the significance of Phasor Measurement Units (PMUs) in monitoring and protecting power systems. DC load flow method is used to analysed power flow in electrical networks, assuming certain conditions like Constant voltage magnitudes and steady state analysis. It introduces a novel algorithm for optimal PMU placement based on the maximum connectivity considering both normal and contingency conditions. Additionally, a new state estimation algorithm is presented for estimating the system states (Voltage magnitude and angle) by minimizing weighted least-square problem with respect to x. The effectiveness of the algorithms is demonstrated through testing on various bus test systems, showcasing their suitability for practical applications in power system monitoring.

Keywords: Phasor measurement Unit (PMU), Optimal Placement, DC load flow, State Estimation, Contingencies, Weighted least square

1. Introduction

Power system state estimation (PSSE) is very important in modern era for analysis, controlling, monitoring and management of the power delivery (Lital Dabush, 2023). State estimation method is used to calculate unknown system state variable (voltage magnitude and angle) on the basis of estimation. The objective is to obtain an accurate representation of the system's state in real-time, even when certain measurements may be corrupted or unavailable. In earlier this process involves data collected from Supervisory Control and Data Acquisition System (SCADA) where it contains error and less accurate (M. Shafiulla, 2016). On Aug 2003, more than 50 million people in North America faced blackout (Anon., 2003) . This biggest blackout because lack of correct data. Integration of renewable energy is difficult for reliable supply. Real time data monitoring is required to deal with fluctuations caused by renewable power supply. To provide real time data, SE needs absolute observability of the system. The measurements can be obtained through the placement of PMU technology (Phadke, jan 1994). Weighted Least Square (WLS) method is one of the various methods to estimate the state of the power system. Due to high-cost there is need for calculating minimum number and optimal placement of PMU without compromising observability of the power system. Phasor Measurement Units (PMUs) were created in the mid-1980s and rely on GPS signals for synchronizing measurements. These measurements include positive sequence voltage phasors at network buses and positive sequence current phasors in the connected lines. Several researchers have addressed the challenge of identifying optimal locations for Phasor Measurement Units (PMUs). In the work referenced as (B Xu, 2005) , the optimal PMU locations were determined using a method based on integer programming. Chakrabarty et al. (S. Chakrabarti, Aug 2008) introduced a binary search algorithm for effective PMU placement, while Hurtgen et al. (M. Hurtgen, October 2010) utilized an iterated local search approach. Dua et al. (D. Dua, October 2008) presented an optimal multi-stage scheduling method for PMU placement. Another contribution, referenced as (B.K. Saha Roy, Novemeber 2012) , proposed a greedy algorithm to ascertain the optimal PMU locations. Saha Roy et al. (Basetti Vedik, January 2017) suggested a three-stage algorithm to address the optimal placement problem. Baseti et al. (V. Jaiswal, 2016) introduced the Taguchi binary bat algorithm for optimal PMU allocation, employing a graph theory-based approach in (Tahabilder, 2017) for the same purpose. The concept of State Estimation (SE) in power systems was initially introduced by Schweppe et al. (Wildes,

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January 1970), leading to subsequent enrichments in this research domain. Sasaki et al. (H. Sasaki, August 1987) brought forth a parallel computation algorithm for SE, and Monticeli et al. (Monticelli, May 1983), in reference (Monticelli, May 1983), discussed bad data detection and identification through the largest value of normalized residual. Furthermore, Bretas et al. (Bretas, Jnauary 1989) proposed an asymmetry index-based method for discriminating between large load variations and bad data.

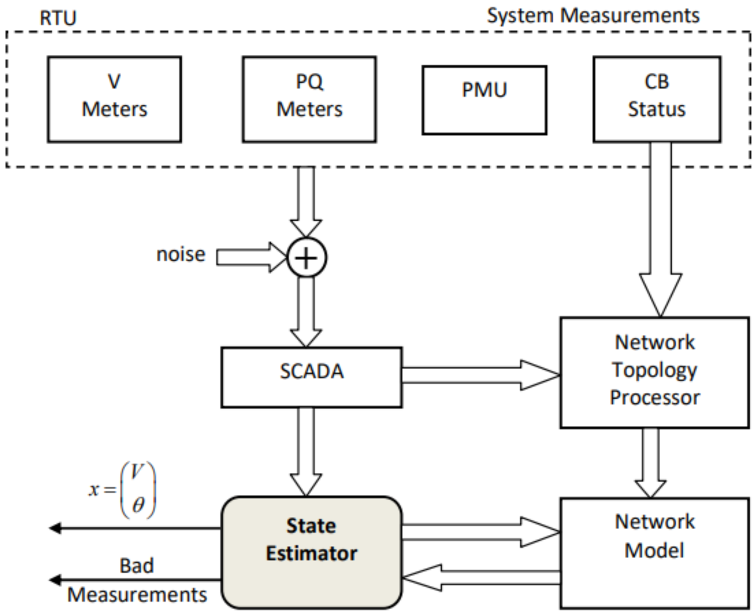

Figure 1. State Estimation Block Diagram

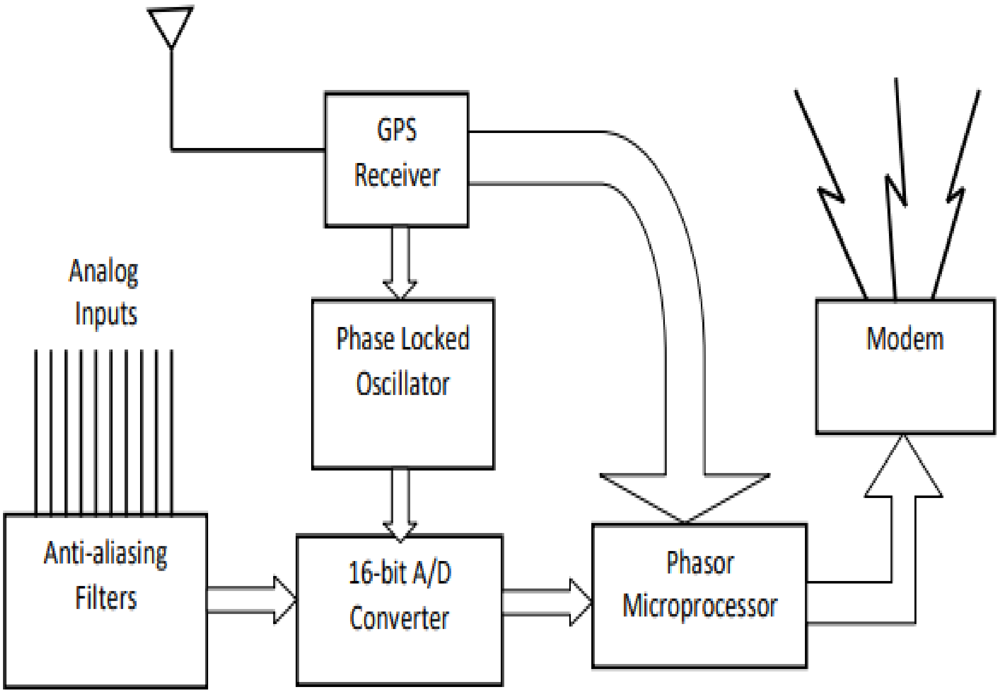

Figure 2. Block diagram of PMU

It has been found that when phasor measurements are added to the other measurements in sufficient numbers, the accuracy of the state estimate is much improved.

2. Problem Formulation

2.1 Optimal Placement of PMU

This novel algorithm relies on determining the maximum connectivity of a b us to lines. The maximum connectivity of a specific bus to lines is computed by summing each column of the binary bus matrix. In this approach, the initial bus for PMU placement is selected based on the highest connectivity among buses and lines. If multiple buses share the same maximum connectivity, the first PMU placement is randomly chosen from any of those buses with maximum connectivity (S. Kundu, 2018). Subsequently, the allocation of other PMUs is based on the maximum number of new buses that can be observed through the PMU, rather than the maximum connectivity of buses to lines. For Example: a small 7 bus system is considered.

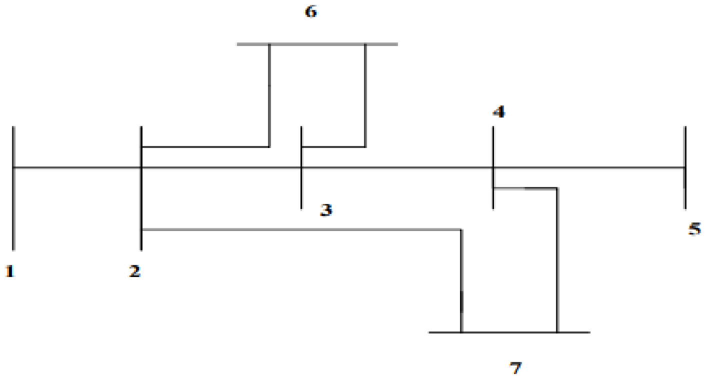

Figure 3. 7 bus system

Examining the bus connectivity matrix reveals that bus 2 exhibits the highest connectivity, total 5. Consequently, the initial PMU is assigned to bus 2. Placing a PMU at bus 2 enables the observation of five buses, namely, bus 1, 2, 3, 6, and 7. Notably, buses 3 and 4 share an identical maximum connectivity of 4. Despite this, the decision is made to allocate the PMU to bus 4 instead of bus 3. Selecting bus 3 for PMU placement would only result in observing one new bus (bus 4) since buses 2, 3, and 6 are already observable. On the other hand, by allocating the PMU to bus 4, two new buses are observed (bus 4 and 5). Consequently, the optimal solution is determined to be {2, 4}. With PMUs placed at bus 2 and bus 4, all seven buses become observable.

2.2 DC Power Flow

Direct Current (DC) power flow in transmission lines is a simplified method used to analysis and simulate the transmission of electrical power from one point to another. Unlike Alternating Current (AC) power flow, which involves the consideration of both magnitude and phase angle, DC power flow primarily focuses on the active power component and neglects reactive power. The DC power flow (Equations provide a simplified representation of power flow in a transmission network, considering only the active power (real power) component and neglecting reactive power (Garcia-Valle, December 2007) (B Venkateswara Rao, 2011) (Greimann, 1988). The DC power flow (Equations are derived from Ohm's Law and are useful for analysing power transmission over long distances. Here are the key (Equations for DC power flow:

$$P_{ij} = \frac{V_i - V_j}{X_{ij}} \qquad \text{(Equation 1)}$$

Where: P_{ij} is the active power flow from bus i to j , V_i and V_j are the voltage magnitudes at bus I and j respectively, X_{ij} is the reactance of the transmission line between bus i and bus j. For multiple buses:

$$P = B \,.\Delta\theta \qquad \text{(Equation 2)}$$

Where, P is the vector of active power injections at each bus, B is the bus admittance matrix, $\Delta\theta$ is the vector of voltage angle differences.

2.2.1 Newton-Raphson Iteration

The DC power flow (Equations are typically solved iteratively using the Newton-Raphson's method. The iteration updates for voltage angles $\Delta\theta$ are given by:

$$\Delta\theta = B^{-1}.P \qquad \text{(Equation 3)}$$

2.3 Weighted Least Square State Estimation in Power System

WLS method is used to assign a value to an unknown system parameter with some criteria. The principle is minimizing the sum of squares of the differences between the calculated and true value of the function. All types of measurements can be expressed in terms of system state using (Equation 1.

$$Z = h(X) + e \qquad \text{(Equation 4)}$$

Where Z is measured value, X is state vector, h(X) is non-linear function, and e is the error of measurement.

The state of the system estimated by minimizing WLS problem with respect to x is used as objective function:

$$J(x) = [z - h(X)]^T R^{-1} [Z - h(X)] \qquad \text{(Equation 5)}$$

The optimization problem is to minimize J(X), i.e.

$$\frac{\partial J(X)}{\partial x} = 0 \qquad \text{(Equation 6)}$$

Using Taylor's series method and neglecting higher order derivative

$$h[X^{(K+1)}] = h(X^{(K)}) + \frac{\partial h(X)}{\partial x}|_{X=X^{(K)}} \Delta X \qquad \text{(Equation 7)}$$

Where K is the iteration index, $X^{(K)}$ is the solution vector at Kth iteration. Here H(X) = $\frac{\partial h(X)}{\partial x}$ can be named as Jacobian matrix and it can be expressed as in equation 8 below:

$$H(X) = \frac{\partial h(X)}{\partial x} = \begin{bmatrix} \frac{\partial h_1(X)}{\partial x_1} & \frac{\partial h_1(X)}{\partial x_1} & \cdots & \frac{\partial h_1(X)}{\partial x_1} \\ \frac{\partial h_1(X)}{\partial x_1} & \frac{\partial h_1(X)}{\partial x_1} & \cdots & \frac{\partial h_1(X)}{\partial x_1} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial h_1(X)}{\partial x_1} & \frac{\partial h_1(X)}{\partial x_1} & \cdots & \frac{\partial h_1(X)}{\partial x_1} \end{bmatrix} \qquad \text{(Equation 8)}$$

Using Newton Raphson iterative method and substituting (Equation the linear (Equation is:

$$H^T[z - h(X^K) - H\Delta(X^K)]^T R^{-1} = 0 \qquad \text{(Equation 9)}$$

The state of the system is updated by using following (Equation:

$$X^{K+1} = X^K + [{H_K}^T R^{-1} H_K]^{-1} {H_K}^T R^{-1}(z - h(X^K) = 0 \qquad \text{(Equation 10)}$$

2.4 Description of the Matlab Code.

The main Matlab programs call 5 sub-programs

1. **Opt.m –** optimal placement of PMU.
2. **Nrlf.m** – To obtain the true state vector from NRLF method.

3. **Wls**.m – Returns estimated state vector and the covariance matrix from traditional measurement.
4. **Pmu**.m – Estimate state vector from WLS output and phasor measurements.
5. **Errorstate.m** – Calculate the errors in estimates and plots the voltage magnitude and angle estimation errors at every bus.

3. Simulation Results

A simulation was conducted employing the aforementioned state estimation algorithm on IEEE-30 bus systems. The foundational assumption was that the load flow solution served as the starting point for generating measurements, incorporating appropriate measurement errors. The base case load flow was utilized as the initial reference. Traditional state estimation measurements encompassed active and reactive power flows, power injections, and voltage magnitudes, while phasor measurements involved voltage and current phasors. The distribution of measurements was uniform across the entire system. The load flow solution was considered to represent the true state vector, and errors were introduced to the measured quantities using a normal random number generator with an appropriate standard deviation. Each PMU was assumed to measure bus voltage and line currents for all lines originating from that bus. Phasor angles were adjusted to adhere to the convention that the swing bus angle is 0°

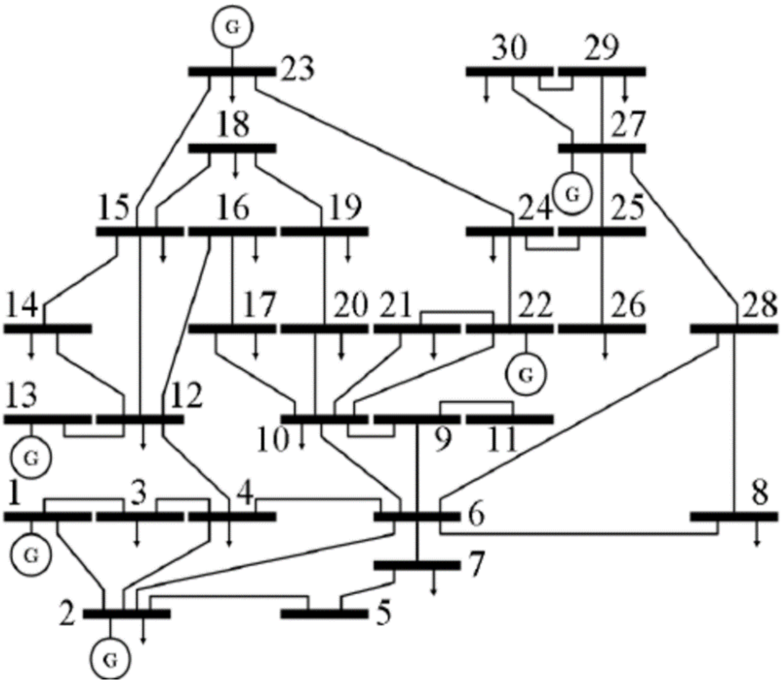

Figure 4. IEEE 30 Bus system line diagram

The simulation results are depicted in the following figures:

Figure 5 illustrates Voltage magnitude comparison between actual data, state estimation with and without phasor measurements respectively, for IEEE-30 bus system.

Figure 6 showcase voltage angle comparison between actual data, state estimation with PMU and without PMU.

Figure 7 display Voltage angle and magnitude estimations error using state estimation method without PMU and with PMU

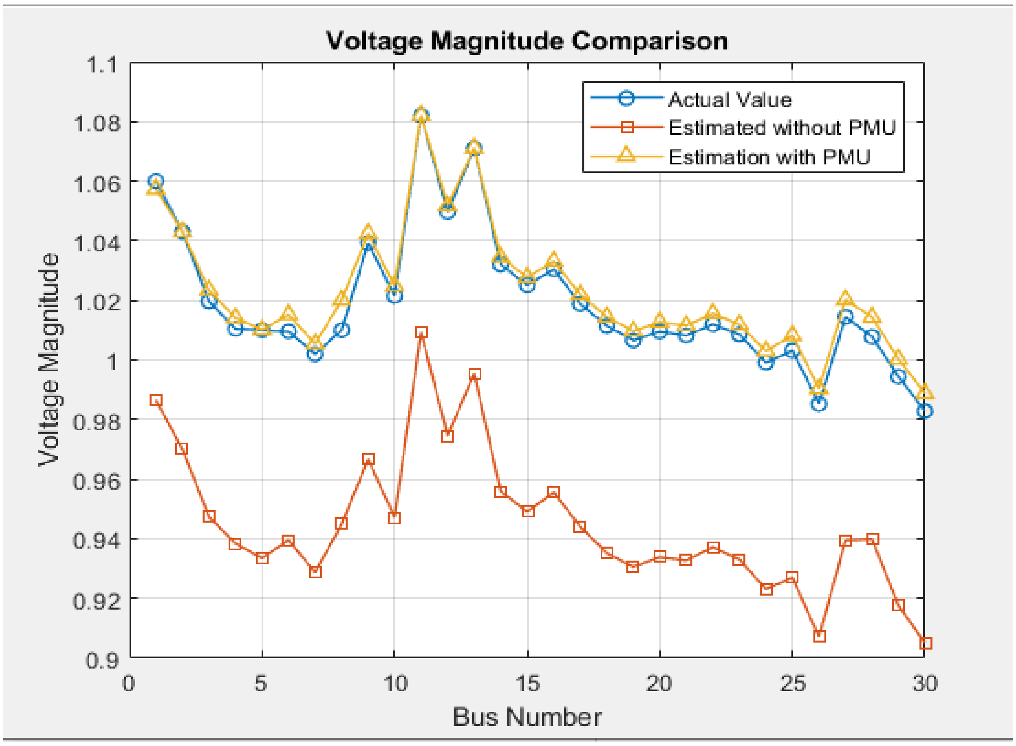

Figure 5. Voltage magnitude comparison

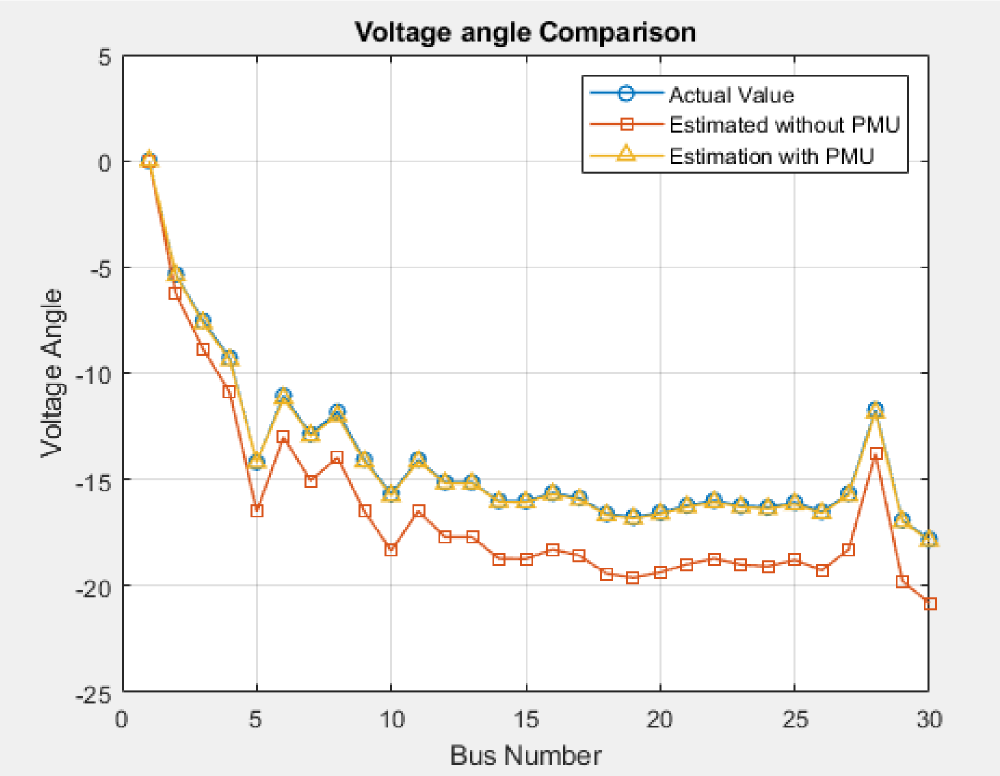

Figure 6. Voltage angle Comparison

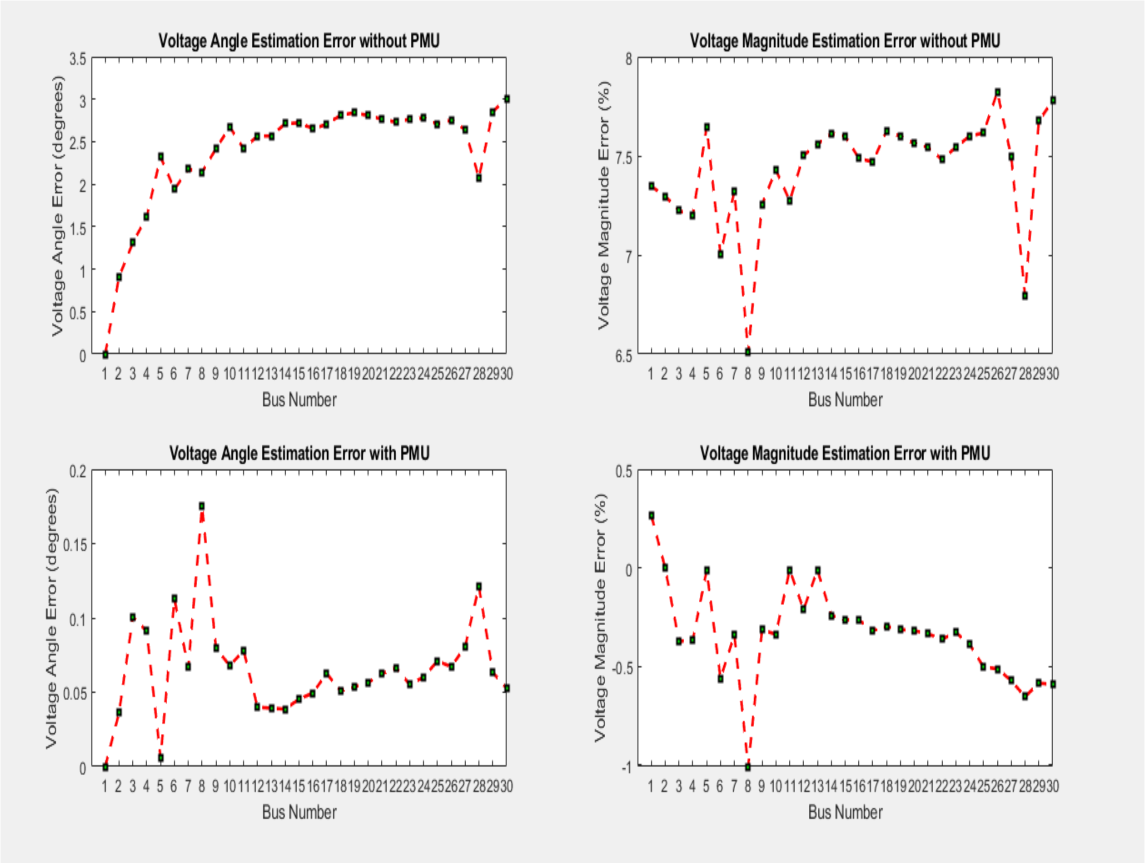

Figure 7. Error Comparison without PMU and with PMU

4. Conclusion

This paper provides an effective approach for power system state estimation utilizing WLS method and incorporating PMU units. The utilization of PMUs results in significantly reduced estimation errors, indicating higher accuracy compared to estimations conducted without PMUs. The outcomes demonstrate that angle measurements play a pivotal role in enhancing the performance of the state estimation algorithm. Traditional state estimation involves a non-linear relationship between the measurement vector and the state vector, necessitating iterative methods and, consequently, increased computational time. The introduction of phasor measurements in the post-processing step requires no alterations to the traditional Energy Management System (EMS) software, making it a swift and additional application software implementation. The study also reveals that as the power system expands, accuracy of estimation decreases.

References

Anon., 2003. s.l.: www.cbca.ca/archives/the-great-north-america-blackout-of-2003-1.4683696.

B Venkateswara Rao, G. N. K. R. L. K. a. N. R., 2011. Optimization of a power system with interior point method. *International Conference on Power and Energy Systems IEEE,* pp. 1-6.

B Xu, a. A. A., 2005. *Optimal placement of phasor measurement units for state estimation,* s.l.: PSERC.

B.K. Saha Roy, A. S. a. A. P., Novemeber 2012. An optimal PMU placement technique for power system observability. *International Journal of Electrical Power and Energy System,* 42(1), pp. 71-77.

Basetti Vedik, a. A. K. C., January 2017. Optimal PMU placement for power system observability using Taguchi binary bat algorithm. *Measurement,* Volume 95, pp. 8-20.

Bretas, N., Jnauary 1989. An iterative dynamic state estimation and bad data processing. *International Journal of Electrical Power and Energy System,* 11(1), pp. 70-74.

D. Dua, S. D. R. K. G. a. S. A. S., October 2008. Optimal Multistage Scheduling of PMU Placement: An ILP Approach. *IEEE Transactions on Power Delivery,* 23(4), pp. 1812-1820.

Garcia-Valle, R. J., December 2007. *Dynamic modelling and simulation of electric power systems using the newton Raphson method.* s.l.:s.n.

Greimann, H. G. a. L. F., 1988. Newton Raphson procedure for the sensitivity analysis of nonlinear structural behavior. *Computers & structures,* Volume 6, pp. 1263-1273.

H. Sasaki, K. A. a. R. Y., August 1987. A Parallel Computation Algorithm for Static State Estimation by Means of Matrix Inversion Lemma. *IEEE Transactions on Power Systems,* 2(3), pp. 624-631.

Lital Dabush, A. K. a. T. R., 2023. State Estimation in Partially Observable Power Systems via Graph Signal Processing Tools. *www.mdpi.com/journal/sensors,* Issue https://doi.org/10.3390/s23031387, p. 1387.

M. Hurtgen, a. J. M., October 2010. Optimal PMU placement using iterated local search. *International Journal of Electrical Power and Energy System,* 32(8), pp. 857-860.

M. Shafiulla, M. R. M. A. a. M. U., 2016. Optimal placement of phasor measurement units for transmission grid observability. *International Conference on Innovations in Science, Engineering and Technology (ICISET).*

Monticelli, A., May 1983. Reliable Bad Data Processing for Real-Time State Estimation. *IEEE Power Engineering,* PER-3(5\), pp. 31-32.

Phadke, A., jan 1994. Synchronized sampling and phasor measurements for relaying and control. *IEEE Transactions on Power Delivery,* 9(1), pp. 442-452.

S. Chakrabarti, a. E. K., Aug 2008. Optimal placement of phasor measurement units for power system observability. *IEEE Transactions on Power Systems,* 23(3), pp. 1433-1440.

S. Kundu, M. A. a. S. T., 2018. State estimation with optimal PMU placement considering various contingencies. *IEEE,* Issue 978-1-5386-7339-3/18/$31.00.

Tahabilder, P. K. G. a. A., 2017. Optimal PMU placement for complete system observability and fault observability using graph theory. *2017 International Electrical Engineering Congress (IEECON),* Issue 1, pp. 1-4.

V. Jaiswal, S. S. T. a. B. M., 2016. Optimal placement of PMUs using Greedy Algorithm and state estimation. *IEEE 1st International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES),* pp. 1-5.

Wildes, F. C. S. a. J., January 1970. Power System Static-State Estimation. *IEEE Transactions on Power Apparatus and Systems,* PAS-89(1), pp. 120-125.