Optimal PMU Placement for Enhanced System Observability: A Survey of Techniques

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***Abstract*: Phasor Measurement Units (PMUs) enable highly accurate, time-synchronized measurement of voltages and currents, transforming traditional supervisory control systems into advanced wide-area monitoring systems.PMUs with lower cost and smaller size, extend real-time monitoring to distribution networks and have shown strong results in state estimation, parameter and topology identification, and fault detection. These capabilities support improved system operation and energy management. However, despite their superior accuracy and synchronization over conventional systems, PMUs are expensive to install, making optimal placement strategies essential for achieving full system visibility efficiently.This paper emphasis on optimal PMU Placement techniques overview for Enhanced System Observability.**

Keywords—PMU, optimization, observability.

1. Introduction

A smart grid technology has developed various grades which makes it distinguished with respect to the traditional grid. The smart grid can collect digital information from all over the network and take actions. The information is circulated right from the power plants to transmission lines to smart appliances inside homes and businesses. Due to these features like automated and remote control as well as early problem detection and quick fault isolation and recovery.

Wide area measurement is one of the key concepts evolved where real time grid monitoring and protection is carried out with the use of advanced monitoring techniques i.e. Phasor Measurement Units (PMUs), to collect synchronized phasor data from various points across the power grid. These PMUs are strategically placed at key locations throughout the transmission and distribution networks to capture critical parameters such as voltage, current, frequency and phase angle.

2. The following key steps are followed for real time grid monitoring

- Positioning of the PMU's
- Transmission of the data
- Analysis of the data
- Fault detection and Isolation
- Protective Action Coordination

3.The implementation of real time grid monitoring and protection has been very beneficial, some of the findings are as follows:

- Reliability of the grid has improved
- Resilience has increased
- Faster Fault Detection
- Optimal Asset Utilization
- Support for Renewable Integration

Hence to summarize real time monitoring and protection using WAMs is one of the most demanding components of modern power systems which helps the utilities immensely to operate the grids more efficiently and persistently in case of evolving changes and challenges.

Synchro Phasor**:** A sinusoidal signal is generally represented as follows:

$$x(t) = X_m \cos(\omega t + \phi). \qquad (1)$$

The phasor representation of this expression is represented by the following:

$$X = \frac{Xm}{\sqrt{2}} e^{j\Phi} = \frac{Xm}{\sqrt{2}} (\cos\Phi + j\sin\Phi).$$
(2)

Here, Xm and ϕ are denoted as the peak value of the sinusoid and the signal's phase angle, respectively. The phase angle measurement is regarded as positive when measured in an anti-clockwise direction from the positive real axis. It relies on the frequency inherent in the phasor representation. For different signals to be represented in the same phasor diagram, they must have the same frequency. Still, input signals may not remain stationary in real-time conditions, as shown in Figure 1. A finite data window is used to consider the input signals to address this. PMUs require at least one period of the input signal's fundamental frequency in the data window [1]. However, when non-harmonic and harmonic components are present, the frequency is not necessarily the same as the fundamental frequency. Thus, PMUs use frequency tracking algorithms to separate the fundamental frequency components and estimate the fundamental frequency period before measuring the phasor.

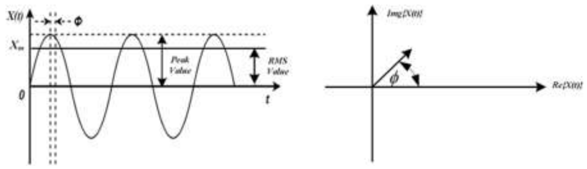

Figure 1. Synchro-phasor representation.

3.Optimal Placement of PMUs:

Using the PMUs data in state estimation (SE) equation make the SE algorithm linear which is easy to solve as compared to the nonlinear state estimation equations. Since it makes the SE algorithm linear, no iteration is required in getting the solution. Because of PMUs promising accuracy, its role is very crucial in SE algorithm. It is predicted that in the coming days SE technique will rely more on results of PMUs. However, due to expensive nature of device (Rs. 27 lacs/PMU) they cannot be installed at all the buses. Therefore, a suitable technique is required to minimize the number of PMUs with complete observability of power system. A power system is said to be completely observable when the phasor voltage of all the buses in the system can be determined uniquely either directly or indirectly [2]. Therefore, observability study in the PMUs placement problem is important before the deployment of PMUs. The block Diagram of PMU can be graphically observed in Figure 2. After assuring the complete system observability, it is necessary to find the optimal locations of the PMUs to maximize the measurement redundancy.

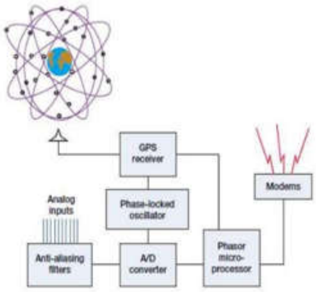

Figure 2. Block Diagram of PMU

3.1. Optimal PMU Placement Related Terminologies

There is requirement some important terminology related to the PMU placement in power system. These terminologies are explained as follows:

Observability: PMU is a specific device by which we can measure the installed bus phase voltage value and also measure the phase value of current of connected branch by the use of PMUs GPS time stamped measurement signals are fed to a Phasor Data Concentrator (PDC).

Phasor measurements are sorts and collects by the help of PDC and the conversion of PMU’s data into useful information by using signal processor that is visible on Human Machine Interface (HMI). Power system state’s information can be easily access by user. For the PMUs placement some assumptions are considered which are as follows:

Case 1: By the installation of PMU on any bus the phase voltage value and phase current value of all connected branches are become known. This type of measurement is known as “direct measurement”. With considering the function of PMU, a PMU is located in the bus P, as shown in Fig. 3.5, from this figure it is indicted that the bus voltage can be directly measured.

Case 2: If one end of branch voltage and current phasors are known, the other branch end voltage phasor can be calculated by using Kirchhoff laws. This type of measurement is called “Pseudo measurement”.

Case 3: These types of measurements are also referred to as "pseudo measurements" because they can be made immediately if the voltage phasors of any branch's voltage at both ends are known.

PMU can be installed at the scheduled buses to allow for thorough network monitoring. The PMU measures the phase values of voltage and current of lines that are linked to the same bus when it is located at any bus. With the most PMUs possible, the goal is to observe the network in its entirety.

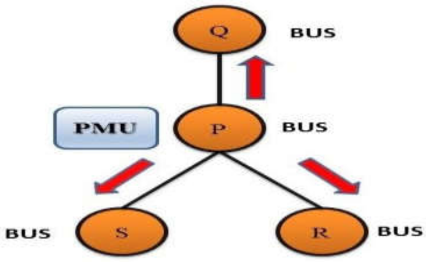

Fig. 3. Observability rules of buses

4. Optimization Techniques

Recent literature highlights various optimization techniques for PMU placement:

I. Integer Programming: Integer programming (IP) has emerged as a crucial method for optimising PMU placement due to its ability to handle complex constraints and objective functions effectively. Early work by Zhao et al. [3] laid the foundation by applying integer programming to minimise the cost of PMU installations while ensuring comprehensive system observability. Their approach involved formulating the placement problem as a binary integer program, where the decision variables represent whether a PMU is installed at a specific location. Building on this, Zhao et al. [4] introduced mixed-integer linear programming (MILP) to address larger and more intricate power grids. Their method incorporated various operational constraints and aimed to optimize both the cost and performance of PMU placements. They demonstrated that MILP could effectively balance multiple objectives, such as minimizing the total number of PMUs while ensuring all critical system elements were observable. Further advancements in Paramo et al. [5] integrated integer programming with dynamic system constraints, focusing on adapting PMU placement strategies to account for real-time operational changes and contingencies. This research developed models that considered varying load conditions and network configurations, enhancing the adaptability and robustness of PMU placements. Recent work in Parmar and Parekh [6] has extended these methods by combining integer programming with advanced heuristic approaches to improve computational efficiency and solution quality. This approach addressed the limitations of traditional integer programming by providing near-optimal solutions more rapidly.

II Advanced techniques:

1. Metaheuristic Algorithms: An In-Depth Survey Metaheuristic algorithm have become increasingly prominent in solving the complex optimization problems associated with PMU placement. Over the past decade, researchers have developed and refined various metaheuristic approaches to address the unique challenges posed by power system monitoring. This section reviews significant contributions and advancements in metaheuristic algorithms for PMU placement.

2. Genetic Algorithms (GAs) Gas has been extensively used in PMU placement due to its robustness in exploring large solution spaces. Early work in Patel et al. [7] applied Genetic Algorithms to optimize PMU placement by encoding potential solutions into chromosomes and using evolutionary operations, such as selection, crossover, and mutation, to explore feasible configurations. Their work demonstrated that Gas could effectively balance cost, observability, and redundancy in PMU deployment. Later, Zhao et al. [8] extended this approach by introducing a multi-objective GA, which simultaneously optimized several criteria, including installation cost and system reliability. They employed Pareto optimality to provide a set of trade-off solutions, allowing decision-makers to choose configurations that best fit their specific needs.

3. Particle Swarm Optimization (PSO) PSO has been another popular choice for PMU placement. Early work by Zhao et al. [9] demonstrated the effectiveness of PSO in obtaining high-quality solutions for PMU placement problems. PSO mimics social behaviour, where particles (potential solutions) adjust their positions based on individual and group experiences. Their study highlighted PSO's fast convergence and adaptability to varying system conditions. Later, Esmaili et al. [10] further refined PSO by integrating a local search mechanism to enhance solution accuracy. Their hybrid PSO approach combined global exploration with local exploitation, improving the algorithm's performance in complex power systems with dynamic constraints.

4. Ant Colony Optimization (ACO) Ant Colony Optimization (ACO) has also been applied to the placement of PMUs. Early work in Shahriar et al. [11] developed an ACO algorithm tailored for PMU deployment, incorporating pheromone-based search strategies to guide the optimization process. Their approach improved convergence rates and solution quality compared to traditional ACO methods. Later, Khorram and Jelodar [12] introduced a modified ACO that included dynamic pheromone updating and heuristic guidance. This modification aimed to overcome ACO's limitations, such as slow convergence and sensitivity to parameter settings, thereby enhancing its applicability to large-scale problems involving PMU placement.

5. Hybrid Metaheuristic Approaches Hybrid approaches combining multiple metaheuristic algorithms have gained traction in recent years. In Singh and Singh [13], a hybrid algorithm combining Gas and PSO was proposed to leverage the strengths of both techniques. This hybrid approach enhanced solution accuracy and computational efficiency by using Gas for global search and PSO for local refinement. Later, Basetti and Chandel [14] developed a hybrid PSO-GA algorithm with an adaptive mechanism that dynamically adjusts the balance between exploration and exploitation. Their method showed promising results in solving complex PMU placement problems, providing high-quality solutions while maintaining computational efficiency.

6. Other Metaheuristic Methods In addition to widely used metaheuristics, Saleh et al. [15] explored Simulated Annealing (SA) for the placement of PMUs. SA, known for its ability to escape local optima, provided a complementary approach to traditional metaheuristics. Their study demonstrated that SA could be effective in finding competitive solutions for PMU placement problems. Later, Zhang et al. [16] investigated the use of Differential Evolution (DE) in the placement of PMUs. DE, with its mutation and crossover operations, offered a robust alternative for optimizing PMU configurations, particularly in scenarios with complex objective functions and constraints.

5. Observability and Redundancy:

Ensuring complete observability and redundancy in power systems through the placement of PMUs is crucial for maintaining system reliability and performance. Over the past decade, several key studies have addressed these aspects:

1. Observability Enhancements in Ghosh et al. [17], methods were proposed to enhance system observability by strategically placing PMUs to cover critical nodes and branches, ensuring comprehensive monitoring. Their approach utilised optimisation techniques to maximise the observability of system states. Later, Maji and Acharjee [18] developed algorithms to enhance observability by integrating PMU placement with network topology optimisation. Their study emphasized ensuring that all critical system states were observable with minimal PMU

deployment. Further advancements in Yang et al. [19] introduced an approach integrating PMU placement with state estimation techniques to enhance observability. They demonstrated that combining these methods could significantly improve the accuracy of system state estimation.

2. Redundancy and Reliability In Almalawi et al. [30], a focus was placed on the trade-off between cost and redundancy in PMU placement. A model was developed to ensure sufficient redundancy while minimizing deployment costs, balancing these often-conflicting objectives. Later, Naveenkumar et al. [20] explored redundancy strategies by analyzing the impact of redundant PMUs on system reliability. Their work demonstrated that strategically placed redundant PMUs could enhance system fault tolerance and reliability. Finally, Naveenkumar et al. [21] proposed a method to optimize PMU placement considering both observability and redundancy. Their approach aimed to provide robust solutions that ensured full observability while incorporating redundancy to handle potential PMU failures.

3. Hybrid Approaches In Arivazhagan et al. [22], combined optimization techniques with redundancy considerations were used to develop a hybrid approach for PMU placement. Their study showed that integrating these aspects could lead to more resilient and reliable power system monitoring solutions. Later, Arul Jeyaraj et al. [23] utilized a hybrid optimization approach to address both observability and redundancy. Their method incorporated various optimization algorithms to strike a balance between comprehensive system coverage and reliability.

4. Advanced Techniques in Müller and Castro [24], advanced techniques for enhancing observability and redundancy were explored by integrating machine learning algorithms with traditional optimization methods. Their study highlighted the potential for these advanced techniques to enhance PMU placement strategies. Additionally, Zhao et al. [25] explored the application of network theory to optimize PMU placement for enhanced observability and redundancy. Their research provided insights into leveraging network metrics to improve placement strategies. Figure 4 illustrates the study of PMU placement using various optimization and heuristic techniques.

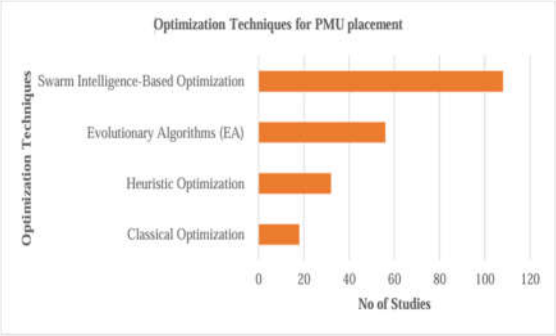

Figure 4: Optimization techniques for PMU placement

6. Challenges in PMU Placement and Utilization:

PMUs offer significant advantages in real-time monitoring and control of power systems. However, their deployment and integration come with a set of complex challenges that need to be addressed to fully leverage their capabilities. This section outlines the major challenges faced in PMU placement and utilization, encompassing technical, economic, and operational aspects. Optimisation Complexity: One of the primary challenges in PMU placement is the computational complexity involved in solving the optimisation problems associated with their deployment. The PMU placement problem is often formulated as a combinatorial optimization problem, which is known to be NP-hard. As grid sizes increase and constraints become more complex, the computational effort required to find optimal or near-optimal solutions grows exponentially. Scaling optimization algorithms for large and complex power systems presents significant challenges.

7. Advance optimization techniques:

This paper [26] proposes a strategic OPP approach based on two parameters: Degree of Connectivity (DOC) and Shortest Path Distance (SPD). The method prioritizes installation locations and determines an efficient sequence for PMU deployment, reducing communication line length and overall cost. The approach is validated on IEEE 14- and 30-bus systems, demonstrating improvements in system observability, reliability, and efficiency for smart grid applications. The research [27] proposes a methodology for optimally placing Phasor Measurement Units (PMUs) in power systems while ensuring full (100%) observability, redundancy, and adaptability to network changes caused by transmission expansion planning (TEP). Starting with IEEE 14, 30, and 118 bus systems, the study considers a 20-year horizon with increasing load demand. Based on this growth, new transmission lines are identified using TEP, creating evolving system topologies. For each expansion scenario, PMU placement is optimized using mixed-integer linear programming to determine not just where, but also in what order PMUs should be installed over time. Although PMU placement is inherently a multi-objective problem (maximizing observability while minimizing the number of PMUs), the methodology simplifies it by treating observability as a strict constraint and minimizing PMU count. This approach yields reliable results and supports practical, time-phased PMU deployment planning in expanding power systems.

8. Conclusion and future scope:

PMUs have become indispensable tools for modern power system monitoring and control, offering high-resolution, real-time data that enhances system reliability, efficiency, and resilience. As power systems become increasingly complex and dynamic, the strategic placement and utilization of PMUs are critical for ensuring robust grid performance and stability. Research conducted over the past decade has demonstrated the significant benefits of PMUs in enhancing grid observability, improving fault detection, and facilitating real-time system management.

However, the deployment and integration of PMUs present several challenges, including computational complexity, cost considerations, data management, cybersecurity concerns, and issues with system integration. Addressing these challenges requires ongoing research and innovation. Future research directions include the development of advanced optimization techniques, such as hybrid and machine learning-based algorithms, to enhance PMU placement strategies. Real-time adaptive placement methods and integration with smart grid technologies are also crucial for improving system responsiveness and efficiency. Additionally, advancements in cybersecurity and data privacy are crucial for protecting PMU systems from emerging threats and ensuring the integrity of data.

9. References:

[1] Cruz, M.A.; Rocha, H.R.; Paiva, M.H.; Segatto, M.E.; Camby, E.; Caporossi, G. An algorithm for cost optimization of PMU and communication infrastructure in WAMS. Int. J. Electr. Power Energy Syst. 2019, 106, 96–104. [CrossRef]

[2] D. Saxena, Senior Member, IEEE, SayakBhaumik, and S. N. Singh, Senior Member, IEEE.” Identification of Multiple Harmonic Sources in Power System Using Optimally Placed Voltage Measurement Devices”, IEEE Transactions On Industrial Electronics, VOL. 61, NO. 5, MAY 2014,pp-24832593.

[3]. X. Zhao, L. Yang, and B. Xu, “Optimization models for phasor measurement unit placement,” IEEE Transactions on Power Systems, vol. 29, no. 2, pp. 576–586, 2014.

[4]. Y. Zhao, M. Li, and X. Wu, “Data validation and error correction techniques for PMU systems,” Journal of Electrical Engineering and Automation, vol. 8, no. 6, pp. 211–223, 2017.

[5]. G. Paramo, A. Bretas, and S. Meyn, “Research Trends and Applications of PMUs,” Energies, vol. 15, no. 15, p. 5329, 2022.

[6]. J. Parmar and C. K. Parekh, “A comprehensive review on optimal PMU deployment: Challenges, developments, and future directions in wide-area power system monitoring,” Int. J. Environ. Sci., vol. 11, no. s23, pp. 7620–7640, 2025.

[7]. D. Patel, S. Kumar, and Y. Miao, “Quantum computing for solving complex PMU placement problems,” J. Quantum Comput. Res., vol. 5, no. 3, pp. 144–158, 2024.

[8]. X. Zhao, Y. Liu, and M. Zhang, “Optimization and cost analysis of PMU deployment in smart grids,” IEEE Trans. Smart Grid, vol. 15, no. 1, pp. 98–109, 2024.

[9]. M. Esmaili, M. Ghamsari-Yazdel, and R. Sharifi, “Enhancing observability in MILP-based optimal joint allocation of PMU channels and conventional measurements with new security concepts,” Energy Syst., vol. 10, no. 4, pp. 791819, 2019.

[10]. M. S. Shahriar, I. O. Habiballah, and H. Hussein, “Optimization of phasor measurement unit (PMU) placement in supervisory control and data acquisition (SCADA)-based power system for better state estimation performance,” Energies, vol. 11, no. 3, p. 570, 2018.

[11]. E. Khorram and M. T. Jelodar, “PMU placement considering various arrangements of line connections at complex buses,” Int. J. Electr. Power Energy Syst., vol. 94, no. 1, pp. 97–103, 2018.

[12]. S. P. Singh and S. P. Singh, “A multi-objective PMU placement method in power system via binary gravitational search algorithm,” Electr. Power Compon. Syst., vol. 45, no. 16, pp. 1832–1845, 2017.

[13]. V. Basetti and A. K. Chandel, “Optimal PMU placement for power system observability using Taguchi binary bat algorithm,” Measurement, vol. 95, no. 1, pp. 8–20, 2017.

[14]. A. A. Saleh, A. S. Adail, and A. A. Wadoud, “Optimal phasor measurement units placement for full observability of power systems using improved particle swarm optimization,” IET Gener. Transm. Distrib., vol. 11, no. 7, pp. 17941800, 2017.

[15]. C. Zhang, Y. Jia, Z. Xu, L. L. Lai, and K. P. Wong, “Optimal PMU placement considering state estimation uncertainty and voltage controllability,” IET Gener. Transm. Distrib., vol. 11, no. 18, pp. 4465–4475, 2017.

[16]. P. K. Ghosh, S. Chatterjee, and B. K. S. Roy, “Optimal PMU placement solution: Graph theory and MCDM-based approach,” IET Gener. Transm. Distrib., vol. 11, no. 13, pp. 3371–3380, 2017.

[17]. T. K. Maji and P. Acharjee, “Multiple solutions of optimal PMU placement using exponential binary PSO algorithm for smart grid applications,” IEEE Trans. Ind. Appl., vol. 53, no. 3, pp. 2550–2559, 2017.

[18]. Q. Yang, D. An, R. Min, W. Yu, X. Yang, and W. Zhao, “On optimal PMU placement-based defense against data integrity attacks in smart grids,” IEEE Trans. Inf. Forensics Secur., vol. 12, no. 7, pp. 1735–1750, 2017.

[19]. A. Almalawi, A. Fahad, Z. Tari, A. Alamri, R. Alghamdi, and A. Y. Zomaya, “An efficient data-driven clustering technique to detect attacks in SCADA systems,” IEEE Trans. Inf. Forensics Secur., vol. 11, no. 5, pp. 893–906, 2015.

[20]. K. Naveenkumar, R. Kannan, S. Ganesan, and S. Subramanian, “Distribution system state estimation with stability assessment using bio-inspired computing,” IET Sci. Meas. Technol., vol. 14, no. 10, pp. 1003–1013, 2020.

[21]. K. Naveenkumar, R. Kannan, S. Ganesan, S. Subramanian, and M. Hariprasath, “Distribution system state estimation with elegant PMU placements using a novel metaheuristic,” Int. J. Smart Grid Green Commun., vol. 2, no. 1, pp. 3859, 2020.

[22]. T. Arivazhagan, S. Subramanian, N. Kaliyan, and G. Sivarajan, “Optimal PMU placements using sea lion optimization for adaptable distribution system,”J.Measurements Eng., vol. 10, no. 1, pp. 38–53,2022.

[23]. K. Arul Jeyaraj, V. Rajasekaran, S. K. N. Kumar, and K. Chandrasekaran, "A multi-objective placement of phasor measurement units using fuzzified artificial bee colony algorithm, considering system observability and voltage stability," J. Exp. Theor. Artif. Intell., vol. 28, no. 1-2, pp. 113-136, 2016.

[24]. H. H. Müller and C. A. Castro, "Genetic algorithm-based phasor measurement unit placement method considering observability and security criteria," IET Gener. Transm. Distrib., vol. 10, no. 1, pp. 270–280, 2016.

[25]. J. Zhao, G. Zhang, Z. Y. Dong, and K. P. Wong, "Forecasting aided imperfect false data injection attacks against power system nonlinear state estimation," IEEE Trans. Smart Grid, vol. 7, no. 1, pp. 6–8, 2016.

[26] S. Yu et al., "Comprehensive review of PMU applications in smart grid: enhancing grid reliability and efficiency", *Chinese Journal of Electrical Engineering*, pp. 1-41, 2025.

[27] Gandhi Carvajal, "Planning Scheme for Optimal PMU Location Considering Power System Expansion", Energies 2025, 18(13),
3283; https://doi.org/10.3390/en18133283