International Journal of Smart Grid and Clean Energy

Optimal PMU placement in a smart grid: An updated review

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Abstract

In recent years, the monitoring and control of the power grid has become an essential objective to prevent system failure. The provision of measurements generated from phasor measurement units (PMUs) can play a significant role in achieving this goal. PMUs can offer synchronized measurements and dynamically measure voltages and current phasors. The estimation of the states of each bus via the installation of PMUs at each node of the bus is not necessary and is hindered by the high cost and complexity of the installation and communication methods. Therefore, a method that reduces the total number of PMUs without affecting the maximum observability and reliability of the power grid is needed. Achieving the minimum number of installed PMUs with maximum observability is the main target of optimal PMU placement. Several techniques are available for resolving this issue, and these techniques lie in two main categories: mathematical techniques and metaheuristic approaches. In the last few years, a huge number of publications have reported different techniques that are based on the principle used and the intended application. Some comprehensive reviews have also been reported a few years ago. This area is an intensively pursued field of study, and many new techniques and important results have been reported after the publication of these reviews. Therefore, there is a need for a comprehensive review of recent research on optimal PMU placement. The present work attempts to provide a critical review of recent literature on optimal PMU placement. We expect this review to be beneficial to researchers and industries that are studying the optimal placement of PMUs in their networks.

Keywords: Synchrophasors, Phasor Measurement Unit, Smart Grid, OPP

1. Introduction

Power demand is increasing because of advacements in technology and improvements in living standards worldwide. To meet this demand, power generation needs to be increased. However, owing to factors such as limited fossil fuels, environmental concerns, and difficulties in the construction of new power plants, the efficient management of existing transmission and distribution infrastructures and the integration of renewable sources of energy into the grid are essential requirements. The deployment of accurate measurement devices with monitoring capabilities is necessary to observe the status of the system. This job has been traditionally been performed by using a supervisory control and data acquisition (SCADA) system. The most common task of SCADA is the state estimation of the power grid, which depends on unsynchronized and slow measurements [1]. Measurements that are based on SCADA have some limitations and errors, such as delays in measurement, because of its slow duty cycle and telecommunication bias. Wide-area monitoring protection and control (WAMPAC) has been proposed to solve the problems and limitations of SCADA [2] [3]. The main component of WAMPAC is the phasor measurement unit (PMU), which is a device that can facilitate the real-time computing and synchronized phasor measurement of voltage and current in a power grid [4]. PMUs can achieve precision and accuracy by using the Global Positioning System (GPS), which have precise reference timing signals. This timing is used to achieve the synchronized measurement of voltage and current phasors. PMU utilization has increased rapidly to improve the monitoring of the power grid. However, PMUs are costly devices; therefore, it is essential to optimize the number and installation location of PMUs. Instead, of installing these devices on all buses to enhance complete observability in the power system, PMUs can be installed

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doi: 10.12720/sgce.8.1.59-69

on select buses by using optimization algorithms to make the system observable with a minimum number of PMUs [5]. Therefore, optimizing the number of PMUs and the location of these units for maximum observability of the system without decreasing or causing a significant effect on observability is important. This problem is known as the optimal PMU placement (OPP) problem.

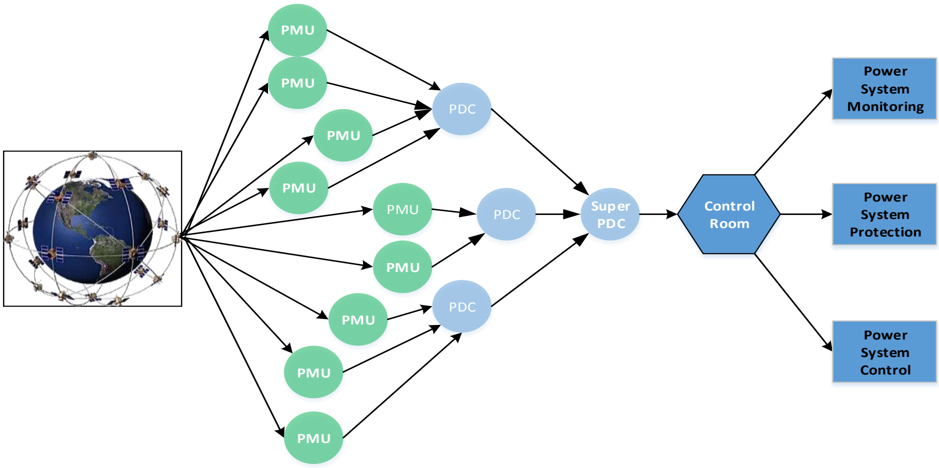

Fig. 1. Layout of a WAMPAC system with its all components.

The techniques for solving the OPP problem are classified into three major categories: 1) conventional methods, 2) advanced heuristic techniques, and 3) modern metaheuristic approaches [6] [7]. The conventional methods that are used for optimization include dynamic programing, nonlinear programing, and linear programing, which can solve optimization problems but have drawbacks, such as in finding the local minimum or in the optimization of large-scale data and large objective function. To solve these challenges, advanced heuristic and modern metaheuristic optimization technique such as ant colony technique, genetic algorithm (GA), subbranch-like immune technique, and particle swarm [8] have been utilized.

Ref. [9] presented a methodical report of the optimization approaches applied to the OPP problem and also analyzed and categorized the present and future research trends in this field. Many methods has been reviewed and classified in a good manner to understand each method, and the most commonly utilized techniques for the OPP problem optimization are integer programing (IP) and the simulated annealing (SA) algorithm.

A comprehensive review of OPP techniques was presented in Ref. [10]. However, many new approaches and important results have been added to the literature since the publication of this review. Thus, the present work reviews the techniques and results that were reported after the publication of Ref. [10].

In this review, the reported OPP solution have been classified into two major categories: mathematical methods and heuristic algorithms. Section II presents the functional blocks and the concept of the OPP problem. Section III discusses the mathematical techniques. Section IV describes the heuristic algorithms. Section V concludes.

2. Formulation of the OPP Problem

A PMU is a device that measures the phasor value of the current and voltage of the bus on which it is installed. Figure 1 shows a WAMPAC system with its all components, such as PMUs connected to the GPS. The phasor signals, which are measured and stamped by GPS time, are sent to another unit known as a phasor data concentrator (PDC) via the PMUs. The purpose of utilizing a PDC is to collect raw phasor data and synchronize it with time to sort and generate real-time information that is time aligned. The signal processor of the system converts the phasor of PMUs into useful data. A human nachine interface can show this information to the operator, who can simply monitor and record the critical data of the power grid states to prevent hazards to the future correction of the system. In Ref. [11], the rules of PMU placement, such as the allocation of bus voltage for PMU on the located bus and the measurement of the branch current and other criteria, are addressed.

By placing PMUs at the calculated location of buses, the operator can observe the network operation completely. These PMUs can then measure the phasor value of voltage in each bus and measure the phasor value of current at each connected branch to the bus. Therefore, the objective of OPP is to increase the observability of the network or make it fully observable, i.e., not decrease the number of PMUs but rather optimize the number of installed PMUs.

Ref. [7] formulated the n-bus system OPP problem and utilized the IP technique to solve the following problem:

$$\text{Min} \sum_{i}^{n} w_i x_i \quad \text{by following } f(x) \geq \hat{1} \tag{1}$$

x = binary decision variable vector

i = bus number

$x_i = 1$ if a PMU is located at bus i

$x_i = 0$ if a PMU is not located at bus i

w_i = the cost of PMU installed at the i^{th} bus

f (x) = vector function with a nonzero entry if the corresponding bus voltage is observable

$\hat{1}$ = vector having all entries

Therefore, the problem is to determine the solution vector that consists of a minimum x_i and fulfills Equation 1. The constraint optimization function was determined via the binary connectivity matrix (matrix A). This matrix provides the bus connectivity data for the grid. The proposed matrix has been determined as follows [7]:

$$A(m,n) = 1 \; if \; bus \; m = bus \; n \tag{2}$$

$= 1;$ in case of link between two buses.

= 0; in other cases.

Thus, Equation 1 is written by considering three critical cases [11]: (1) only PMU measurement, (2) PMU only measurement plus injection bus (e.g., zero injection bus), and (3) PMU only measurements.

Current flows and the placement problem of injection PMUs can be formulated with further constraints and limitations on the optimization function, and some of these constraints have been addressed in the following works: zero injection buses effects [12], conventional measurements effects [12][13], single or multiple PMU loss contingencies [14], single branch outage [15], contingency of single-line disconnection [16], effect of PMU channel limitation [17], and single-PMU loss [18].

3. Mathematical Programming Methods

One of the most popular numerical programing techniques is IP, which is also known as mathematical programing. This method has been utilized to solve problems with integer design elements, and has been divided to integer linear programing (ILP), integer nonlinear programing, and integer quadratic programing (IQP) on the basis of linear, nonlinear, or quadratic factor design elements, respectively [19].

3.1. Integer linear programming

Ref. [20] implemented ILP for OPP to enhance full observability in the power grid. Zero injection restrictions has been modeled on the basis of the ILP structure. The results specify the following: (1) OPP for the complete observability of power systems can be calculated effectively. (2) A modification method based on the connectivity matrix is efficient in a computational manner and is easy to implement for systems that have zero injection buses. (3) By considering single-line outage, the number of PMU is increased. On a MATLAB environment, the ILP algorithm was tested for IEEE standard-bus [20].

3.2. Binary semidefinite programming

An integrated binary semidefinite programing model that uses binary decision elements was utilized in Ref. [21], and this paper influenced the current unadventurous measurements and synchronized phasor measurements of system efficiency. Ref. [21] also considered the limited channel capacity of PMUs in the reliability and accuracy of the measurements. The suggested approach with an outer approximation pattern is solved on the basis of binary ILP. The developed technique is simulated by using the IEEE 14, 57, and 118 bus system; therefore, the reliability and validity of the suggested method have been verified [21].

In some cases, the combination of two or three mathematical algorithms can be used to achieve a better solution and efficient optimization. In Ref. [22], the authors derived a state estimator for all buses by using a greedy algorithm to improve OPP, obtain the best state estimation efficiency, and achieve the optimal results for the three-phase-network IP optimization approach. The reliability of this method is evaluated by using transmission and distribution test systems [22].

3.3. Integer quadratic programming

Ref. [23] applied the IQP method to decrease the total number of PMU and increase measurement efficiency in the power grid. In this approach, conventional measurement can also be utilized in the proposed OPP technique. The proposed optimization algorithm has been simulated and tested in MATLAB by employing IEEE 14-bus and 30-bus standard test systems, which proved the complete observability of systems under normal conditions and single-line (or single-PMU) operation conditions [23].

3.4. Exhaustive search

Another method that can be used is the exhaustive search optimization method [24] [11], which is a common optimization procedure. This method systematically computes all conceivable solutions to achieve the best result. It also indicates the solution that satisfies the limitations by optimizing an objective function. This method is not appropriate for a large-scale search space or a large system but guarantees the discovery of the global optimum in a small system.

Ref. [25] offers a new equivalent ILP method (EILPM) that is based on the exhaustive search of PMU placement. In the suggested EILPM, an additional constraint for observability protection can simply be executed by following a single-PMU constraint. Furthermore, the communication channel constraint involves the conversion of nonlinear conditions into linear conditions. This technique has been tested by utilizing standard test systems, such as IEEE 118 bus, and by comparing them to EILPM and other methods of PMU placement optimization. The comparison shows that this approach is more efficient than other approaches. Additionally, the application of the EILPM method to the Iran power grid proves that this method can be used in real power grid conditions [25].

4. Heuristic Algorithms

4.1. Genetic algorithm

One of the most common heuristic algorithms is GA, which is an adaptive search technique with the capability of repeating the natural evolution process to find the solution. This process has been utilized to achieve the optimal result for search and optimization problems. Therefore, GA can be used in engineering to solve major problems; therefore, this method has stimulated the interest of scholars and specialists in various areas such as systems engineering, management sciences, and operations engineering research [26]. Ref. [27] combines GA with the map reduce model, i.e., the map reduce GA (MRGA), which can perform parallel computing. Furthermore, MRGA allows better fitness convergence and scalability and is usually applied on computing clusters of Hadoop to find the OPP. This achievability and the performance of MRGA has been verified by various test systems, such as the IEEE 14-node system, IEEE118-node system, and Wp 2383-node system. The results show MRGA has major advantages in case of the number of installed PMU, the multiplicity of the solution, the accuracy and precision, and the feasibility.

4.2. Tabu search

This method presents a recursive tabu search (RTS) procedure to find the best location of PMU installation. In this method, the ordinary tabu search (TS) technique is performed several times, but the optimum solution obtained from earlier executions is utilized at the initialization of each TS iteration as the initial point of the RTS. On the basis of the considered success rate of the TS method, RTS is the best method among three alternative TS initialization schemes [28]. The suggested RTS algorithm results have been verified on the various IEEE standard test systems such as 14-, 30-, 57-, and 118-bus systems. Furthermore, the results of RTS has been compared with the results of other OPP algorithms, and the result shows that the proposed RTS algorithm would minimize the total number of installed PMUs in the power grid compared with previous techniques, which might find the same or rather higher number of PMUs [28].

4.3. Pollination algorithm

Ref. [29] presents a novel optimization method called the flower pollination algorithm (FPA) to solve the optimal placement problem. The FPA was developed by Yang [30], who was inspired by the pollination process of flowering plants. FPA has been extended to multiobjective optimization with promising results. This problem aims to minimize the number of PMUs to achieve full system observability and maximize measurement redundancy at system buses. This method has been tested on the IEEE 14-, 30-, 57-, and 118-bus test systems; New England 39-bus test system; Canal Network 49-bus test system; and Western Delta Network 52-bus test system in Egypt. The results obtained by the proposed method are compared with other optimization methods such as binary particle swarm optimization (BPSO) method, greedy algorithm, single vertex, and binary ILP.

4.4. Simulated annealing

To achieve full observability by following preinstalled measurement system, Ref. [16] utilized an innovative two-step optimization algorithm for OPP. The optimization problem has been formulated under the condition of a preinstalled PMU and a normal operation situation in a power system to increase the observability of a power system. Thereafter, single-line power failure and single-bus power failure plus other possible practical situation are considered to improve the reliability of this method.

To ensure that the minimum number of PMUs are installed, convex programing with minimization model is applied as the first step. At the next phase, SA was utilized to optimize the redundancy of the measurement [31]. Additionally, the influence of zero injection bus on system visibility is also considered to decrease the number of installed PMUs without a significant effect on full observability. To validate the consistency, efficiency, and effectiveness of the suggested technique, various IEEE standard-bus systems have been examined [31].

In the another research, a multistage SA method is utilized [32] to provide the optimal joint placement of PMUs with current regular measurement units. This method is faster than other conventional SA algorithms and can find the optimal point faster than other methods on the basis of uphill movements throughout different steps, thus enabling it to find the best solution [32].

4.5. Differential evolution

The differential evolution (DE) method is suggested to solve the joint placement issue of the phasor measurements [19] of PMU devices with power flow measurements that specify the state variables in a power grid. Therefore, a joint placement problem was formulated to optimize PMU measurement redundancy and to decrease the number of measurement devices by following full network observability.

This problem solved is by utilizing the maximum system observability redundancy index and by considering the existence of an optimized solution for formulated problems. The DE algorithm has been used to solve the nonlinear IP problem of the system and to find an optimal solution by satisfying the practical problems of the electrical power grid. This technique has been approved for several standard test systems in MATLAB environment such as IEEE 7- and 14-bus test systems, and the reliability of this technique was validated with/without injection buses [33].

4.6. Particle swarm optimization

This technique has been classified as a population-based stochastic optimization technique that was established according to the social activities of flocking (behavior shown by a group of birds flying) [33]. Ref. [34] proposes a particle swarm optimization (PSO)-based algorithm to solve the OPP problem in a specific electrical power grid topology. This technique has been tested and successfully validated on IEEE 14-, 30-, and 68-bus systems. To further check the feasibility of this technique, it has been implemented in a substantial part of the Brazilian power grid. The improved PSO technique (IPSO) is described in Ref. [35]. In IPSO, the features of GA and SA are incorporated into PSO to overcome the limitations of PSO. Furthermore, this algorithm can reduce the time and placement costs by identifying the local optimum point.

Multiple solutions can increase the viability of the OPP problem in a practical environment; therefore, the combination of two methods can provide a better solution. The exponential binary PSO (EBPSO) technique has been suggested in Ref. [36] with the goal of overcoming the optimization problem and achieving maximum observability in a power system. Zero injection, single-PMU outage, and different practical possibilities are considered, along with the usual operating situation, in the proposed technique. To dynamically upgrade the position of each element in the binary procedure, a sigmoid function is used [36].

4.7. Immune genetic algorithm

A novel algorithm based on GA has been utilized in Ref. [37], namely, immune GA (IGA). IGA combines the features of the artificial immune system algorithm with GA and relies on the vaccination and immune options, which are the two phases of this method that protects against bacteria and viruses. In Ref. [38], IGA has been used to solve the OPP by utilizing three effective vaccines to reach maximum observability by considering the topological issue on the power grid implementation. The combination of local data and previous data of the OPP problem is applied to a vaccination scenario. Two factors are considered in IGA to reach an optimal result, namely, the crossover and mutation of variables; the results show that this algorithm increased the rate and efficiency of convergence [38].

4.8. Spanning tree search

In Ref. [39], the spanning tree method and tree search algorithm has been combined to optimize the solution of the OPP issue by considering least channel and multichannel PMUs for optimal observability, which is also known as spanning tree search. This paper addresses the effect of observability depth on the total number of installed PMUs in the power grid. By utilizing the spanning tree approach, electricity grid graphs were created, and the tree search technique was applied to detect the optimized location of PMUs. Furthermore, the same approach was improved to identify the minimum number of PMU channels. This technique was verified by IEEE standard-bus test systems in a MATLAB environment to satisfy the objective of the problem [39].

4.9. Greedy Algorithm

Ref. [40] utilized a greedy algorithm to reduce the PMU placement costs, and it achieved near $(1 - 1/e)$ for the PMU installation cost. This unique performance makes the greedy algorithm more attractive than other methods in a practical case with multistage configurations and limited resources. The simulation results of this technique show that its performance is close to the optimal efficiency of the modified algorithm.

Ref. [41] uses the system reconfiguration approach for OPP in the distribution network to achieve system reconfiguration, and the ant colony algorithm has been applied as an optimization tool to minimize energy losses. In the next phase, a greedy algorithm is utilized to find the PMU placement location by minimizing the number of PMUs with consideration to the maximum observability of the system [41].

Ref. [42] enhanced a method to develop an effective greedy algorithm for OPP to defend against data integrity attacks (also known as false data injection attacks). The least-effort attack model computes the minimum number of sensors that must be compromised to manipulate a given number of states. Regarding the least-effort attack model, it proved the existence of the smallest set of sensors. Concerning the defense strategy, an effective PMU-based greedy algorithm was applied, and this algorithm not only defends against data integrity attacks but also ensures system observability with low overhead.

4.10. Recursive security algorithm

The recursive security algorithm *(RSA)* is based on the spanning tree search algorithm, which has multiple solution structures. RSA utilizes different starting points to find a better result. By applying the recursive spanning tree algorithm of the Power System Analysis Toolbox, the PMU placement location was minimized for all buses by optimizing the observability of the system. The reliability of this algorithm was proved by applying the IEEE 14-, 30-, and 80-bus systems [43].

4.11. Teaching–learning-based optimization technique

This technique can be utilized for OPP problems with and withou considering zero injection measurements. The obtained results of this algorithm differ from other optimization techniques such as GA and BPSO, and it has a higher efficiency than other methods [44]. Furthermore, in GA and BPSO, several constraint settings are required, thus affecting the efficiency of the procedure. Compared with the other optimization methods, the proposed teaching–learning-based optimization (TLBO) method does not need excessive modifications in terms of its settings and variables. Therefore, the execution of the proposed TLBO technique is simpler than GA and BPSO, and the results of this algorithm show that its convergence speed is faster than other methods [45].

A TLBO algorithm is utilized in Ref. [46] to satisfy the multiobjective problems of OPP. The nondominated sorting notion and crowding distance computation mechanism are implemented in this paper to resolve the OPP issue. The efficiency of the suggested technique is studied on standard problems and practical challenges, and the results show that this method cannot efficiently find a proper solution for

OPP issues.

4.12. Improved binary particle swarm optimization

This paper demonstrates the PSO and BPSO technique with their equation, and the proposed improved BPSO (IBPSO) algorithm was explained on the basis of the described equation. IBPSO increases convergence speed while maintaining the full observability of the power system by obtaining optimal measurement redundancy compared with BPSO. To consider the influence of the practical issue and zero injection bus effect on the proposed algorithm, it is simulated in MATLAB software on an IEEE 30-bus system to verify the effectiveness and validity of the proposed IBPSO algorithm [47].

4.13. Best-first search algorithm

Ref. [48] used the best-first search (BFS) algorithm to achieve the OPP with full observability in normal functioning conditions. A pruning technique was applied to reduce the measurement redundancy of systems made by BFS and to reduce the total number of measurement devices already determined by BFS. The suggested method is tested in an IEEE test system, such as IEEE 14- and 30-bus systems. It was also tested in a 246-bus Indian power grid, and the results show that this method is better than existing methods, such as ILP. The proposed method can achieve full observability and minimum PMU placement [48].

The intelligent search method in two phases is proposed to find the OPP in Ref. [49]. The first step involves determining the suboptimal placement of PMUs by utilizing the BFS algorithm. In the next step, the pruning algorithm was used to identify and eliminate redundant PMU positions. This technique has been effectively applied to IEEE test systems by following normal functioning conditions and practical contingency conditions. The simulation results suggested that the technique is more operational than other existing approaches, particularly for large-scale systems. The suggested technique is also computationally efficient and well organized; therefore, the execution time for any case is less than or equal to two seconds [49].

4.14. Mixed heuristic/metaheuristic method

Ref. [19] used the new technique in substations by applying the two-level state estimation method. To specify the optimal place and total number of PMUs, a mixed heuristic/metaheuristic technique was implemented. The suggested technique is able to prepare precise measurement data to ensure the observability of the power grid. Furthermore, it is able to earmark further PMUs/measurement units to provide full observability, and the method is based on a GA with a unique performance function. The analysis of the results shows that the suggested algorithm provides a significant and reliable solution for the OPP problem in electrical grids [19].

4.15. Modified binary cuckoo optimization algorithm

The modified binary cuckoo optimization algorithm (MBCOA) is an evolutionary algorithm that was applied in Ref. [50] to solve the OPP problem. MBCOA is classified as a topological technique and is based on the lifestyle of a cuckoo birds, which are parasitic birds. This type of bird emigrates to find enough food and appropriate nests to lay eggs. This binary structure is a novel method that has not been applied for OPP thus far. OPP was established on several test networks such as IEEE 14-, 30-, 57-, and 118-bus test systems during the regular operation of a system and during single-PMU failure condition; single-line outage has also been considered. Furthermore, it was tested on 2383- and 2746-bus test systems, and the capability of this algorith for handling large electrical power grid has been verified [50].

5. Conclusion

One of the most important issues to be addressed in the transition of power grids to smart grids is ensuring the full observability of the whole system or at least the maximum observability by utilizing synchrophasor measurements. Therefore, given the system constraints, finding the best solution for installing the optimal number of PMUs is the objective of many types of research. This paper reviewed the existing solutions for the OPP problem and then classified them into two major categories: conventional mathematical methods and heuristic algorithms. Each category has been divided into subcategories and general features of each subcategory. Furthermore, some significant features of the method was shown. The findings of this study show that the combination of two or three algorithms can increase the efficiency of OPP techniques.

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