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Review on Heuristic Algorithms Used In Power Grid and Its Suitability to Smart Grid

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Abstract
Smart grids are the next generation of the power grid system. The transition from power grids to smart grids is to ensure an environmental and economically efficient power system. Smart grids, unlike the traditional power grid, integrate a vast variety of generation sources of electricity into the grid. Hence the complexity of efficiently monitoring the smart grid is high. PMUs are high-speed sensors used for real-time monitoring, protecting and control of the power system. Data from PMU assists in providing reliable and continuous power supply. However, placing PMUs at all the buses of a power system is economically infeasible. Optimal PMU Placement (OPP) has been an area of high interest as it focuses on finding the minimum PMUs required without compromising on maximum system observability. Meta-Heuristic algorithms have been widely used in the OPP problem. Various algorithms of heuristic were applied in both power systems and smart grids to the OPP problem. The need to adapt to the changing environment from power grids to smart grids adds more complexity to the heuristic algorithms. This paper provides the literature review of the heuristic algorithm for OPP in power grids and smart grids. This paper reviews six well-established heuristic algorithms along with their enhanced and modified version for OPP in power grids and its suitability to smart grids applications. This review will be of interest to researchers and industries who are researching in power grids and the upcoming area of smart grids and PMU placements.

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I. Introduction

Since the invention of electricity, the world has been moving at a fast pace in all areas of technological development. In the electronic era, electricity has become a basic requirement. With the increase in power demand, the need for a highly reliable and efficient power system is the need of the hour. The traditional power grid has been undergone vast transformations. It has moved from the Centralized Power grid to the distributed power system and now has developed into the most innovative technology called the Smart Grids. Smart Grids combines the distributed power system with communication technology to provide a reliable power supply. The three main functions of the power system are generation, transformation, and distribution. The Smart grid has integrated communication technology into the power system to monitor and control all the components of the smart grid. The smart grid provides a communication network between the various power generating sources like the huge power plants, renewable energy sources, microgrids to the transmission and distribution network to smart homes and intelligent buildings. With a greater number of components being integrated into the smart grid, monitoring and

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controlling the grid has become of the main research areas in power systems.

The Smart grid has various generating sources integrated into its network. In order to build an efficient power grid, the transmission grid must be capable of monitoring the power flow i.e. the voltage and frequency. The transformation from power grids to smart grids requires sustainability. The growth from a traditional power grid to a smart grid has to be controlled and well monitored. The sustainability is achieved with three main smart components: Smart Control centres, smart network and smart sub-station [1]. Wide area monitoring protection and control (WAMPAC) is the major component used to facilitate real-time computing. WAMPAC provides synchronized phasor current and voltage measurements in the power grid [2]. Phasor Measurement Units (PMU) also known as Synchrophasor are the main components of WAMPAC [3]. PMUs monitor the voltage phasor and current phasor to detect fluctuations and discrete controls of switching in order to identify undesirable events occurring in the power system [4,5]. State estimation for monitoring and controlling the power system is provided by the PMU and this ensures optimal power flow [6]. Buses installed with PMU can be measured for synchronized measurements value of voltage phase. The current phasors of the it's adjacent bus can also be calculated. Complete System observability can be achieved if all the buses in the grid are monitored. Because of system's high cost and the installation charges, PMUs cannot be economically installed in every bus. The challenge with Optimal PMU Placement (OPP) is finding the minimum PMUs required to attain maximum system observability [7]. Different techniques of optimization for the OPP problem are discussed in the literature. Various Advanced Heuristics algorithms have been presented for the problem of OPP, which not only analyzed the observability of the system, but also many more constraints like sensitivity constraint [8], fault observability [9], inadequate communication in substation constraint [10], mean square error(MSE) [11,12] and critical measurements [13,14] are some of the other constraints thatheuristic optimization has examined.

This paper discussed the important heuristic algorithms for the problem of OPP in power grids and its suitability for smart grids. Section 2 describes the OPP problem formulation using a topological observability technique. Section 3 explains the heuristic algorithms for the OPP problem in power grids and how the algorithms are also well suited for the dynamic smart grids. Section 4 concludes the paper.

II. Formulation of the OPP Problem.

The OPP problem can be formulated using the topological technique. This technique is used by most heuristic algorithms. The three main objectives of the OPP problem are to calculated the minimum number of PMUs required, maximum system observability and maximum data redundancy. Heuristic algorithms formulate the power gird topologically to examine the search space. System observability of the grid can also be depicted topologically with a complete rank spanning tree. There are six efficient rules that explain a topological analysis of a power grid. The rules are illustrated below (Known values are green color-coded and the calculated value is red color-coded):

1. *Direct Measurements:* The Bus with PMU

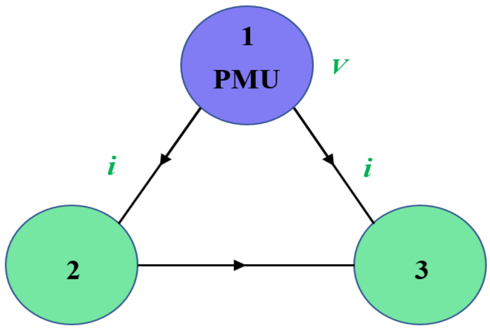

Fig.1. System Observability with Direct Measurement.

installed has its voltage phasor (V)measured. Alsothe current phasors (i) of all adjust lines of the bus are available. Fig.1. illustrates the V and i that are measured from bus-1 which is PMU Equipped.

2. *Pseudo-Measurements(V):* The voltage phasor (V) of one end can be calculated if the voltage phasor and current phasor of the other end is known. Fig.2. illustrates the V of bus 2 can be calculated when V of bus-1 and i of the line between bus 1,2 are

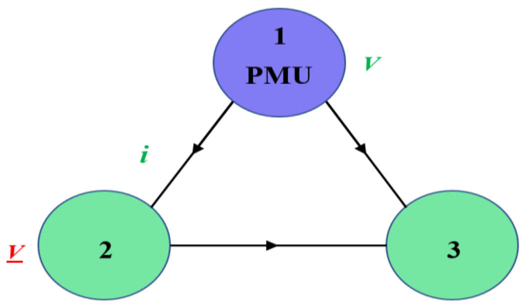

Fig.2. System Observability with Pseudo-Measurement.

known.

3. *Pseudo-Measurements (i):* The current phasor *(i)* of a line can be calculated if the voltage phasor of both ends is known.

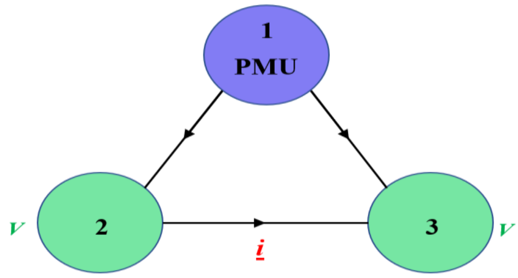

Fig.3. System Observability with Pseudo-Measurement (*i*).

Fig.3. illustrates the i of the line between bus 2,3 can be calculated when both V of buses-2,3 is known.

4. *KCL Equations for Zero-injection bus:* Knowing all the current phasor of the joint line except one in a zero- injection bus, the unknown line current phasor can be

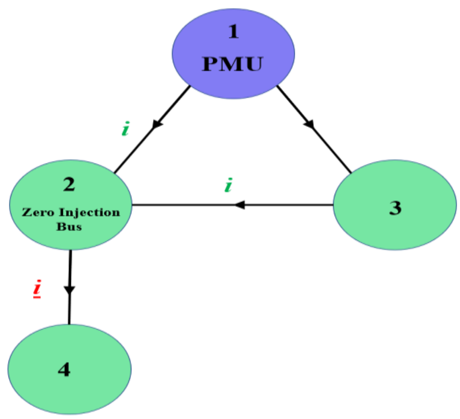

Fig.4. System Observability of ZI buses using KCL equations.

calculated. Fig.4. illustrates ZI bus-2 with known i between bus-1,2 and bus-2,3 can be used to calculate the line current phasor between bus-2,4.

5. *Node Equations for Zero-injection bus:* Voltage Phasor of a zero- injection bus can be calculated if the voltage phasor of all the adjacent buses are known. Fig.5 illustrates the V of ZI bus-2 can be calculated if all adjacent bus1,3,4- V values are known.

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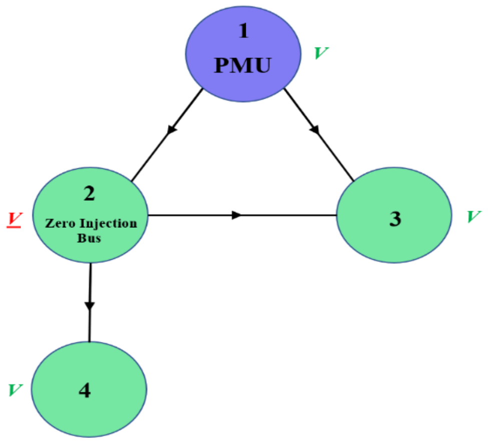

Fig.5. System Observability of ZI buses using Node equations.

6. *KVL Equations for Zero-injection bus:* Two adjust zero-injection buses with unknown voltage phasor can be observable if the voltage phasor of all adjacent buses is known. Fig.6 illustrates the V of ZI buses-2,3 can be calculated if all adjacent bus1,4,5-V values are known.

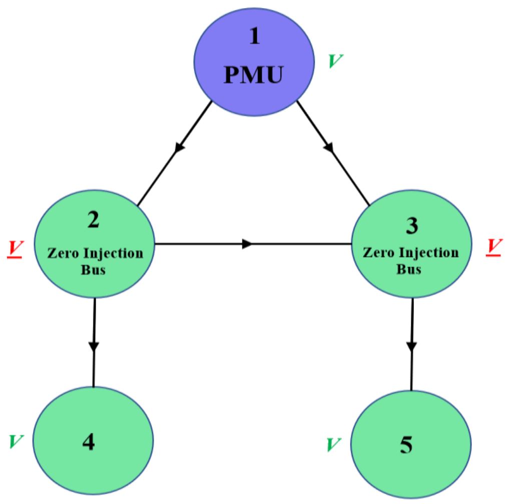

Fig.6. System Observability of ZI buses with KCL and KVL.

3. Heuristic algorithms Applied for Optimal Placement of PMU

Heuristic algorithms with multi-objective functionalities are better suited to the OPP problem. Heuristic algorithms have mainly aimed at reducing the number of PMUs. Cost reduction is the focus. However, this objective is subject to constraints such as maximizing measurement redundancy, handling one line/PMU outage or one PMU failure. The emphasis is on reducing the amount of PMUs required and optimizing the power system observability.

A. Genetic algorithm

Genetic algorithm (GA) is an adaptive and repetitive search technique that is modeled from the natural evolution process. GA for the OPP problem is a well-suited algorithm due to the following characteristics of the algorithm (i) GA is a major repetitive functionality that does not lead to a derivative secondary function. (ii) GA has a good probability of local optimum avoidance. (iii) The iterative process takes the results from the previous iteration. The OPP problem is basically a search problem with a search area that has to be completely processed to find the buses for PMU installation. Non-dominated sorting genetic-based algorithm (NSGA) is one method which combines the genetic Algorithm with the concept of graphtheory [15]. This method resulted in Pareto-optimal solutions. Pareto optimal solution arrives when all objective functions reach a point which cannot be improved without degrading a few objective values. NSGA solution provided the minimum requirement of PMUs to be installed in a power system. NSGA is a multi-objective algorithm that focused on the minimization of PMUs installed along with maximizing the power gird's measurement redundancy. The Pareto-optimal solutions with steps like crossover, mutation, and population is well suited for NSGA parameters. In [16], the problem of OPP was a formulation with a topology-based GA algorithm along with zero injection buses was considered to solve the problem. GA is able to achieve complete system observability in [17], which considered two key objectives including (i) maximum redundancy in system-observability and (ii) one PMU/branch interruption. The maximized redundancy objective led to an increased number of PMUs when a branch/PMU failure occurred to ensure device observability.

GA performed parallel computing in combination with map-reduce model (MRGA) [18], which improved the fitness convergence and scalability. MRGA applied to clusters of Hadoop soled the OPP problem. The Wp 2383-node and 14 and 118-node IEEE systems verified the performance of MRGA. The results show that MRGA has significant advantages with regard to the number of installed PMUs, the solution's multiplicity, viability and the accuracy and precision.

Marin.F et al provided a procedure based on genetic algorithm to achieve maximum system observable for linear state estimation [19]. The smart grid has both centralized, decentralized power systems along with microgrids. Monitoring the Smart Grid is a multi-objective task. The GA and its enhanced versions for the OPP problem are well suited for the Smart Grid's environment for OPP. The iterative process along with the multi-objective algorithm which works with topology-based algorithms and also with Map reduce algorithm to make these heuristic algorithms suitable for the dynamic smart grid.

B. Simulated annealing

A metaheuristic algorithm, simulated annealing (SA), provides globally optimized large and discrete search space. The base logic of SA is that the new solution is the worse shift with a decreased probability as the computation proceeds. SA is applicable to the OPP problem with its characteristics of to find and obtain the optimal or almost optimal solution for a large-scale system [20]. Kerdchuen.et al proposed a method for achieving maximum system observability by taking into account the revelation of bad data using the Simulated Annealing method [21]. Kerdchuen.et al also proposed a stochastic concept of simulated annealing (SSA) [22]. To solve the problem of OPP, a new method incorporating simulated annealing and genetic algorithm known as the HGS method has been used.A system can be observed without any critical measurement in its normal condition.Whereas a different system that lacks any branch does not affect the power system's observability. Optimally installed PMU achieved complete System observability by considering particular PMU measurements and highly vulnerable system data access [23].

The evolution from the power grid to smart grid takes place over an already existing system. Mazhari et.al utilized atwo-step innovative OPP optimization algorithm to achieve complete observability in a pre-installed PMU power system [24]. This paper also considers other constraints to improve reliability such as single-bus power failure and single-line power failure. This method is implemented in two phases: (i) convex programming with a model of minimization is applied to calculate the least PMUs required. (ii) SA was used to optimize the measurement redundancy [25]. The papers also considered zero injection bus effect on system visibility to reduce the number of PMUs installed without compromising system observability. A multistage SA method achieved faster results than other conventional SA algorithms [26]. In various steps, this approach used uphill motions, allowing it to find the best solution.This improved SA is used to provide existing standard measurement units with the optimum joint placement of PMUs.

C. Tabu Search (TS)

Tabu Search (TS) is a global optimization, meta-heuristic algorithm that restricts the embedded heuristic algorithm from re-entering search spaces already processed. The TS has a Tabu List of recently visited states and unwanted states. Specific changes of recent moves within the search space are recorded to avoid reversing the changes. Three major elements such as aspiration, diversification, and definition of a state and its surrounding areas ensure that the search moves towards promising areas. The TS is rest when it does not converge [27]. Recursive Tabu Search (RTS) is an observability analysis technique that uses a topological method to find the optimum location to install PMUs. This technique performs the TS many times and the best solution is calculated by utilizing the solutions from the earlier executions. This result is then used as the RTS' initial point to initialize each of the TS iterations [28]. The results obtained were verified on standard IEEE test systems like 14, 30, 57 and 118-bus systems. A comparison of the obtained results with the results of other similar OPP algorithms show that this algorithm has been able to provide a better solution for the minimization functionality for the OPP problem [28].

D Particle swarm optimization

Particle swarm optimization (PSO) is a stochastic optimization technique based on population that iteratively enhances a candidate solution [29]. PSO for the OPP problem was proposed for a particular topology of electrical power gird [30]. The PSO was improved and modified into various algorithms to solve the problem of OPP. The various PSO based algorithms have solved the OPP problem with different objectives that makes these algorithms suitable for the smart grid environment. The different algorithms based on PSO for the OPP problem are tabulated in Table 1.

Table 1. Various PSO Based Algorithms for the OPP of PMUs.

Algorithm	Method	Objective Achieved	Additional Constraints
Improved PSO (IPSO) [31]	PSO+GA+SA	Reduced time and placement cost	-
binary particle swarm optimization (BPSO) [32],[33]	Variables take only two values: 0,1	Complete system observability	(i) To Observeset of zero-injection buses. (ii) Difference in PMU costs
Exponential Binary PSO (EBPSO) [34]	Developed an adaptive exponentially decaying inertia weight coefficient to provide Multiple Solutions	Reduced Placement cost and Maximised System Observability	Zero Injection, Single PMU Outage
Fault-Tolerant placement of PMU using PSO [35]	This algorithm is based on control reconfigurability criterion for PMU loss	Minimized the number of PMUs required.	-

E. Differential evolution (DE)

Differential evolution (DE) approach repeatedly improves the given measure of quality of the candidate solution. In the OPP problem, DE solves the issue of joint positioning of phasor measurements of PMU devices [36]. The measure of quality considered is the state estimate variables in the power gird. DE approaches the OPP problem by considering the joint placement problem. The main objective of the problem of the join placement is to optimize redundancy of PMU measurements and to identify the minimal PMU number required to achieve comprehensive network observability. The two major objectives

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considered for this problem are (i) to obtain Maximum system observability, (ii) redundancy index.

The OPP problem is formulated due to the fact it is not economically viable to install a PMU in every bus. The DE concept has been proposed to be used in various functions of cost problem. Principle operators such as mutation, crossover, and selection are used to attain a global optimization. Additional factors such as Parallel computation and excellent convergence properties that help reduce local optima make this heuristic algorithm well suited for the OPP problem for both power grids and smart grids [37]. The transition to smart grids from power grids has converted the two- objective OPP problem into a multi-objective problem. Non-dominated sorting differential evolution (NSDE) [38] algorithm integrates non-dominated Pareto sorting operation and algorithm for differential evolution. This integrated algorithm is used to formulate a multi-objective OPP.

F. Grey Wolf Optimizer (GWO)

Grey Wolf Optimizer is a new meta-heuristic optimization algorithm introduced by S. Mirjalili et al. [39]. This algorithm imitates the grey wolf's system of leadership and pack-hunting techniques. The grey wolfs are of four different types within the pack: the alpha, beta, delta, and omega. GWO simulates this hierarchy for the search process. The grey wolfs encircle the prey before they go for the kill. This encircling method is simulated in the algorithm to move in the search space. The problem of OPP was solved by using this algorithm. The algorithm primarily focuses on high system observability.Power networkingsystems for example, the Algerian’s 114-bus, 14 and 30-bus IEEEpower systemswere taken for the study [40]. This simulation was performed with/without zero-injection bus consideration. The results tabulated in Table 2 show that the minimum PMUs were achieved when zero-injection buses were taken into considerations.

IEEE Bus	No. of PMUs without ZIB	No. of PMUs with ZIB	Percentage of saving PMUs With ZIB
14	4	3	25%
30	10	7	30%

Table 2. Comparison of GWO OPP PMUs

The GWO for smart grids will be able to handle the microgrids and generating sources that are almost equivalent to the ZIB and the minimum required number of PMUs is calculated. The Swarm Intelligence aspect and the multiple solution candidates that are selected based on the search area makes this algorithm more suitable for handling the multiple constraint OPP problems.

4. Suitability of Heuristic Algorithms for OPP in Smart Grids

Integrating Renewable Energy Sources (RES), microgrids and PEVs into the power systems increases the importance of complete system observability and measurement redundancies. The transition from the distributed electric grid to smart gird requires a high quality of measurements and control of the state estimation of the systems. System observability becomes more complex with microgrids that operate more frequently at island mode. Heuristic algorithms are better at handling the ZIB constraints. This approach can be applied for handling microgrids that are trivial for PMU observation. The OPP problem in smart grids is a multi-objective problem. Minimum PMUs with maximum data redundancy still form the base of the OPP problem in the smart grid. The algorithm that formulates the minimum PMU problem over an already existing power system is the key requirement in terms of practical applications.

Table 3 lists the heuristic algorithms and the multiple constraints that are incorporated into the algorithm to make them more suitable for smart grids.

Table 3. Objectives and Additional Constraints of the analysed papers

Algorithm	Method	Objective Achieved	Additional Constraints
Genetic Algorithm (GA)			
GA for OPP	Adaptive +Repetitive	Minimum PMUs Maximum Redundancy	i. NSGA – Pareto Optimum
			ii. Observing a group of zero-injection buses.
			iii. MRGA -Parallel Computing with multiple solutions.
Simulated Annealing (SA)			
SA for OPP	Repetitive + decreasing probability	Maximum System Observability	SSA and HGS- A hybrid method to handle incomplete observability
			2-Step Optimization: Considered power grid with preinstalled PMUs and ZIBs
Tabu Search (TS)			
TS for OPP	Linear State estimator model	Maximum System Observability	RTS: Topological method that initializes based on previous iteration.
Particle Swarm Optimization (PSO)			
Improved PSO (IPSO) [31]	PSO+GA+SA	Reduced time and placement cost	-
Binary particle swarm optimization (BPSO) [32],[33]	Variables take only two values: 0,1	Complete system observability	(iii) Observing a group of zero-injection buses. (iv) Difference in PMU costs
Exponential Binary PSO (EBPSO) [34]	Developed an adaptive exponentially decaying inertia weight coefficient to provide Multiple Solutions	Reduced Placement cost and Maximised System Observability	Zero Injection, Single PMU Outage
Fault-Tolerant placement of PMU using PSO [35]	Considered PMU loss built on control reconfigurability.	Calculated the Minimum count of additional PMUs required.	-
Differential evolution (DE)			
DE for OPP	Pareto non-dominating sorting + DE	Minimum PMUs	Joint PMU issue, Power Flow, Cost Functions
Grey Wolf Optimizer (GWO)			

GWO for OPP	Mimics Pack hunting Technique of Grey wolves	Minimum PMUs	Zero- Injection Buses

III. .Conclusion:

The evolution of smart grids is the most innovative technological development of this era. Reliability is one of the core objectives of smart grids. The state estimation from PMU makes the smart grids reliable and provides control over the grids. Optimal Placement of PMUs is an essential research area and the complexity of this problem is high due to the dynamic nature of the smart grid. Hence meta-heuristic and advance heuristic algorithms that are formulated to work on the already existing power grids are well suited for the Optimal PMU Placement problem in smart grids. This paper reviewed the most well established meta-heuristic algorithms and the different modified algorithms that focus on the multi-objective OPP problems for smart grids.

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