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Research Article

Impact of Grid Integrated Energy Storage Systems with Phasor Measuring Units for Secured Data Control Using Metaheuristic

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In this article, malleable determinations have been made by integrating solar panels in the field of Power System State Estimation (PSSE) where the optimal placement using Phasor Measuring Units (PMUs) plays a major role in the integration process. This kind of integration provides a path for determining the importance of PMU and converting the grid to be smart. In preceding, methods of PSSE researchers were not able to demonstrate the smart grid process due to failure of integrating solar cells. Thus, the integrated solar cells in the proposed method can be able to detect the presence of false data and secure the identified data using a Data Management Systems (DMS). In addition, the DMS estimates a particular state during a certain period of time thus creating an external awareness about communicating devices. Moreover, the process of PSSE with solar cells and PMU placement mechanism functions effectively using a metaheuristic Ant Lion Optimization (ALO) where two fundamental scenarios are considered and simulated using MATLAB. The simulation results indicate that the proposed method provides satisfactory simulation results for about 67% when compared to existing method.

1. Introduction

In recent days, distribution networks are sprouting from passive networks to active networks. The rationale behind this development is because an enormous number of distributed generations allied with distributed networks. However, the qualities of Power System State Estimation (PSSE) get to suffer from the shortage of adequate/accurate measurements. Since PSSE delivers the start state of plentiful Data Management Systems (DMS), applications including real-time monitoring, accuracy, and reliability will have a noteworthy impact in making the grid smarter. In the future, there will be enhancement in deploying the Intelligent Electronic Devices (IEDs) for the aim of providing better operational efficiency.

According to the revelation, the IEDs are handling the challenges between the needs of the distribution system, and therefore, the interaction of the kit with the electrical system is therefore a big criterion to put Phasor Measuring Units (PMUs) at the acceptable location for not only maximizing the observability of the network but additionally to realize other desired functionalities like monitoring, reliability, and security of the networks. A primary requirement to be considered in PSSE is that the disparity of critical measurements from actual distribution systems where PSSE has the potential of generating high estimation by considering limited measurements. For PSSE, ensuring the safety of knowledge has always been given paramount importance. The information is often transferred to a different system that is placed in highly secured condition which suggests safeguarding the information from several devastating forces and forbidden operators. When a network possesses an inadequate degree of security, then, it will interrupt the system to be unprotected from severe conditions. Hence, the network should be properly designed to make sure adequate security subsists in the least time during the operation of power systems.

1.1. Existing Literatures. This section concisely articulates the recent techniques and applications in PSSE, PMU placement, and data attacks in the literature. Mixed Integer Linear programming- (MILP-) constructed channel-based optimal allocations of PMU units are proposed in [1]. But if the channel failure occurred, then, the system becomes unobservable [1]. As conferred in [2, 3], the PMUs and SCADA are installed for determining the optimal locations with the objective of ensuring maximum accuracy of the SE. The drawback of [2, 3] is the high cost because both measuring devices are implemented for achieving the system observability. Metaheuristic methods such as Binary Search Gravitational Algorithm (BSGA) [4], Taguchi Binary Bat Algorithm (TBBA) [5], Improved Particle Swarm Optimization (IPSO) algorithm [6], Exponential Binary Particle Swarm Optimization (EBPSO) [7] algorithm, fuzzified binary Artificial Bee Colony (ABC) algorithm [8], Genetic Algorithm (GA) [9, 10], Modified Binary Cuckoo Optimization Algorithm (MBCOA) [11], hybrid PSO–GSA algorithm [12], and multi-dimensional fruit fly optimization algorithm [13] are stated the optimal placement of PMU for system observability. However, these approaches are highly sensitive to control parameters and require high tuning of parameters in obtaining the solution. The authors in [14] indicated the Optimal PMU placement (OPP) using probabilistic load flows for planning purpose with high accuracy of PMU measurements, whereas additional computational burden occurred for load flows due to the complex network.

Graph theory and Analytical Hierarchy Process- (AHP-) based OPP for complete network observability are presented in [15]; however, the AHP has been used only for multiphasing. Hence, this method cannot provide accurate redundancy. An effective greedy algorithm based PMU placement represented in [16] ensures full network observability, and also, it provides a way of defending the network against data integrity attacks. But the prime setback of [16] is that the PMU placement cost is compromised. However, data-driven clustering technique [17] is identified for both normal and critical states. Consequently, the percentage of accuracy is not fully enhanced to identify the critical state [17]. The greedy search method [18] explains the fast dynamic response that is suitable for high sampling rate allocation. But the aforementioned method [18] focuses on allocating the PMUs based on ranking. On the contrary, the Lyapunov exponent-based OPP approach identifies the critical buses and ensures full network observability [19]. But the approach [19] does not put emphasis on detecting the bad data measurements. In [20], a mathematical study of components of uncertainty that affects the voltage profile provided by Weighted Least Square (WLS) estimators in a distribution system has been presented. Conversely, the technique [20] depends only on weight estimates. The bad data detection that is used to ensure the integrity of SE to filter faulty measurements using the principal component analysis, approximation method, and the Cumulative Sum (CUSUM) algorithm-based Generalized Likelihood Ratio (GLR) [21] for centralized and distributed cyber-attack detection has been presented in [21, 22]. But the configuration of power system introduces arbitrary errors in SE. By considering the aforementioned issues [1–22], a novel technique for handling the data attack is introduced to OPP problem and transferring the data in a secure way. There are different types data attacks present. In the proposed method, false data injections have been identified by using PMU measurements. PMU placement is preferred at the bus adjacent to the radial bus so that the voltage phasor at the radial bus can be obtained by the measurement of the current through the radial line.

Due to the penetration of distributed energy resources (DERs), the fault level in the microgrid changes significantly. Thus, for improving the resilience of the microgrid, the conventional protection philosophy needs to be modified. The protection devices (PDs) need to alter their operational settings to accommodate the system parameter changes due to changes in an operation state or network reconfiguration. With rapid development of RES, the harmonic level is becoming a serious issue to the adoption of power electronic devices [23–25].

2. Problem Formulation

The main objective of PMU placement is to diminish the required number of PMUs installed in the PSSE that makes the whole system observable under normal conditions. Observability is the ability to estimate the power system state for a given set of measurements. For an N bus system afforded with m measurements of voltage and current phasors, the linear matrix equation involving the measurements and the state vector can be defined as

$$\Delta Z = \begin{bmatrix} \Delta Z_1 \\ \Delta Z_2 \\ \cdot \\ \cdot \\ \cdot \\ \Delta Z_m \end{bmatrix} = \begin{bmatrix} h_1(x_1, x_2, \cdots..x_n) \\ h_2(x_1, x_2, \cdots..x_n) \\ \cdot \\ \cdot \\ \cdot \\ h_m(x_1, x_2, \cdots..x_n) \end{bmatrix} + \begin{bmatrix} e_1 \\ e_2 \\ \cdot \\ \cdot \\ \cdot \\ e_m \end{bmatrix} = h(x) + e. \tag{1}$$

The objective for WLS based a state estimate, such that the sum of squared measurement residuals, weighted by their corresponding error covariance minimization, is given a matrix form

$$J(x) = (\Delta Z - h(x))^T R^{-1} (\Delta Z - h(x)). \tag{2}$$

Gain matrix is formed using the measurement Jacobian R and the measurement error covariance matrix, R. The covariance matrix is assumed to be diagonal having measurement variances as its diagonal entries. Since the Gain Matrix is formed as

$$J\left(x^k\right) = H^T R^{-1} H, \quad (3)$$

where m is the number of measurements and n is the number of state variables.

$$H = \frac{\partial h(x)}{\partial x} = \begin{bmatrix} \frac{\partial h_1(\mathrm{x})}{\partial x_1} & \cdots & \frac{\partial h_1(\mathrm{x})}{\partial x_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial h_m(\mathrm{x})}{\partial x_1} & \cdots & \frac{\partial h_m(\mathrm{x})}{\partial x_n} \end{bmatrix} \quad (4)$$

is the Jacobian matrix, and R is the diagonal matrix with value σ_i^2, where

$$\begin{bmatrix} \sigma_i^2 & \cdots & . \\ \vdots & \ddots & \vdots \\ . & \cdots & \sigma_m^2 \end{bmatrix} \quad (5)$$

is the standard deviation of the error associated with ith measurement.

If the rank of Jacobian Matrix is equal to that of the state vector, then, the solution will be unique and the network is observable. The objective for the OPP problem is expressed as a nonlinear WLS minimization model and is given as follows:

$$W_x = \min \sum_{i=1}^{N} W_i * X_i. \quad (6)$$

2.1. SMRI Calculation. In OPP, it is possible that multiple solutions having the same number of PMUs exist. In this study, two indices are projected to assess the quality of these solutions, the bus observability index (BOI) and the SMRI. In BOI, βi is defined as the times that bus i is observed and is equal to the number of PMUs observing bus i. If the maximum bus observability index is limited to maximum connectivity ηi of a bus plus one, which happens only when all adjacent buses and the bus itself are equipped with PMUs.

$$\beta i \leq \eta i + 1. \quad (7)$$

SMRI can be obtained by simply adding up BOI at all buses in the system. Higher SMRI value indicates that the PMU-based monitoring system is more reliable. The SMRI can be calculated by the following equation:

$$\mathrm{SMRI}_{\max} = \frac{1}{n} \sum_{j=1}^{N} \beta i, \quad (8)$$

where n is the number of network buses and βi is the number of times that bus j is observable (by direct, indirect, and pseudomeasurements) considering PMUs are installed at certain buses. The PMUs are allocated in primacy at critical buses which are identified with more branches forming complete observability.

2.2. Constraints. From equation (6), the optimal allocation of PMU under normal condition in PSSE is subjected to the following constraint:

$$\sum_{i=1}^{N} X_i \geq 1. \quad (9)$$

Accordingly, equation (9) ensures that all the buses are observed at least one PMU. Therefore, single PMU can observe the intact system and maintain the system parameters within the restrictions, and it will avoid the voltage imbalance and blackout of the system.

$$X_i = \begin{cases} 1, & \text{if PMU is installed at bus } i, \\ 0, & \text{otherwise.} \end{cases} \quad (10)$$

From equation (6), the optimal allocation of secured PMU with maximum redundancy in PSSE subjected to the constraint is as follows: all the buses must be observed at least twice by PMU in the case of single PMU outage. Hence, equation (9) can be modified into

$$\sum_{i=1}^{N} X_i \geq 2. \quad (11)$$

From equation (11), it can be seen that a single PMU outage cannot affect the full system observability. If buses are also present in the system, the value of $\sum_{i=1}^{N} X_i = 1$. If buses are not present in the system, then, $\sum_{i=1}^{N} X_i = 0$. Accordingly, $\sum_{i=1}^{N} X_i \geq 2$ indicates that all the buses are observed at least twice by a PMU. While the number of PMU increased in the contingency condition for secure data transfer, maintain the system limits within in the parameter. In order to afford maximum measurement redundancy for desired system, the method has three resources such as unallocated channels of existing PMUs, new Flow Measurement (FM), and new PMUs/channels. The optimal approach depends on the cost burden on the resources. Unallocated channels of existing PMUs may provide a more cost-effective way for measurement redundancy. However, new FMs may also not be able to provide measurement redundancy due to diverse reasons such as the existence of FM on the branch. As a result, the problem chooses the least cost solution to provide measurement redundancy. This method used new PMUs for all maximum measurement redundancy demands and does not save channels in unwanted locations. Therefore, the increased PMU conceals the maximum redundancy.

3. Metaheuristic Algorithm

ALO may be a population-based algorithm, so local optimal avoidance is intrinsically high. Ant lions relocate to the position of the simplest ants during optimization, so promising areas of search spaces are saved. Therefore, the ALO algorithm is proficient of solving the optimization problems with mimicking the hunting behavior of ant lions and performing a strong search of an answer space. In earlier reports, some optimization techniques like TBBA [5], IPSO algorithm [6], GA [9, 10], and MBCOA [11] are used to find the solution of OPP. However, multiple iterations and requirements of huge memory space demand considerable execution time, which restricts these methods to use in complex networks. The varied placement criteria for full observability and maximum measurement redundancy are not possible to satisfy across all conditions. Conversely, the location of PMUs with Integer applied mathematics (ILP) cannot guarantee maximum redundancy; hence, the multistage placement counting on the results of ILP may cause significant information deficiency. Therefore, the ALO algorithm is in a position to beat the aforementioned drawbacks. Additionally, the projected algorithm is capable to approximate the worldwide optimum of optimization problems for the subsequent reasons; for example, the search space is guaranteed by the random selection of ant lions, and random walks of ants around them and exploitation of the search space are guaranteed by the adaptive shrinking boundaries of ant lion traps. There is a high probability of resolving local optima stagnation for utilizing random walks and roulette wheel.

3.1. Successive Placements of PMU with Solar Cells. The need for PSSE is becoming popular because of the necessity of the latest system modeling and operation practices related to the integration of distributed energy resources, and therefore, the adoption of advanced technologies within the distribution network has been affected. Some initiatives are deployed by a digital relay, IEDs, automated feeder switches and voltage regulators, smart inverters, and PMUs for improving the system observability and transferring the information in a secure way. The value of putting in measurement devices could also be higher, and careful selection of the latest measurement location is vital. Also, information is present regarding various data where the system might not be ready to transfer the data during a safe mode. To handle the abovementioned case, uncertainty of PSSE results is often taken into account within the PMU placement to solve the problem of network observability and transfer the information securely. Within the power grid, if any malfunction happens due to the road outages, communication failure, PMU outage, and external/internal faults of the system will not maintain entire observability.

In such cases, the system could not transfer the information in a secured way. Therefore, the secured PMU placement for shielding data attacks is projected during this method. PMU tries to maximize the probability of accuracy of receiving data from measurements. In case of redundant measurements, the PMU is capable to identify errors from measurements and provide state of system with suitable accuracy by using equation (10). Figure 1 illustrates the flow chart for successive PMU placements in securing and normal operating condition. The metaheuristic technique (ALO) is used for solving the OPP problem because of the nature of the search space, where the decision variables are defined on the bounded set {0, 1}. With the advantages such as very few parameters, fast convergence, and rapid discovery of good solutions, the ALO algorithm is preferred as a key optimization tool to solve the PMU placement problem.

4. Demonstrations and Discussions

The placement of secured PMU has been incorporated with an algorithm referred to as ALO and it's been tested on various systems to validate the effectiveness of the proposed model. To calculate the ability of the presented formulations with solar cells, OPP for the above-mentioned systems has been performed to meet the subsequent two scenarios:

(i) Scenario 1: maximum coverage with PMU placements in PSSE

(ii) Scenario 2: PMU placements considering data attacks

All the simulation work has been developed in MATLAB platform and is executed on PC configured with Intel (R) Core (TM) i3-5005U processor, 2.00 GHz, 4 GB RAM, and 64-bit operating systems.

4.1. Scenario 1. In PSSE, the PMU has been placed for system observability with maximum measurement redundancy. The chosen standard IEEE systems are low configured buses so that it can be treated as in distribution systems. In this scenario, the main objective is placing the minimum PMUs to attain the complete observability with maximum redundancy under normal operating conditions in PSSE. In addition, it shows the multiple locations of PMU for IEEE 14 bus, IEEE 30 bus, IEEE 57 bus, and IEEE 118 bus with different SMRI presented in Table 1. Based on the SMRI values, the set of PMUs which covers the maximum value is chosen and its optimal locations are highlighted. The SMRI value for the IEEE 14 bus system is 19 compared with the value of SMRI [4, 8, 11] which is much lesser [11] or equal to [4, 8] the proposed methods for the system observability. In a similar way, the SMRI value of the IEEE 30 bus is 52 which is compared with [4, 8, 11]; the value of redundancy coverage is much lesser so that the proposed model gives maximum redundancy and complete observability.

In the case of IEEE 57 bus system, the redundancy value is 69 which is compared with [8, 11]; it seems to be a lesser value against the proposed method. In the IEEE 118 bus system, the proposed method has the SMRI value of 157 which is much lesser [4] or equal to that of [11] the existing method. For IEEE 300 bus, the proposed method achieved the SMRI value of 282 for complete observability. Table 2 shows the comparison of the proposed results with other techniques based on SMRI values. Apparently, the proposed model provides the feasible solution as compared to earlier reports [4, 8, 11].

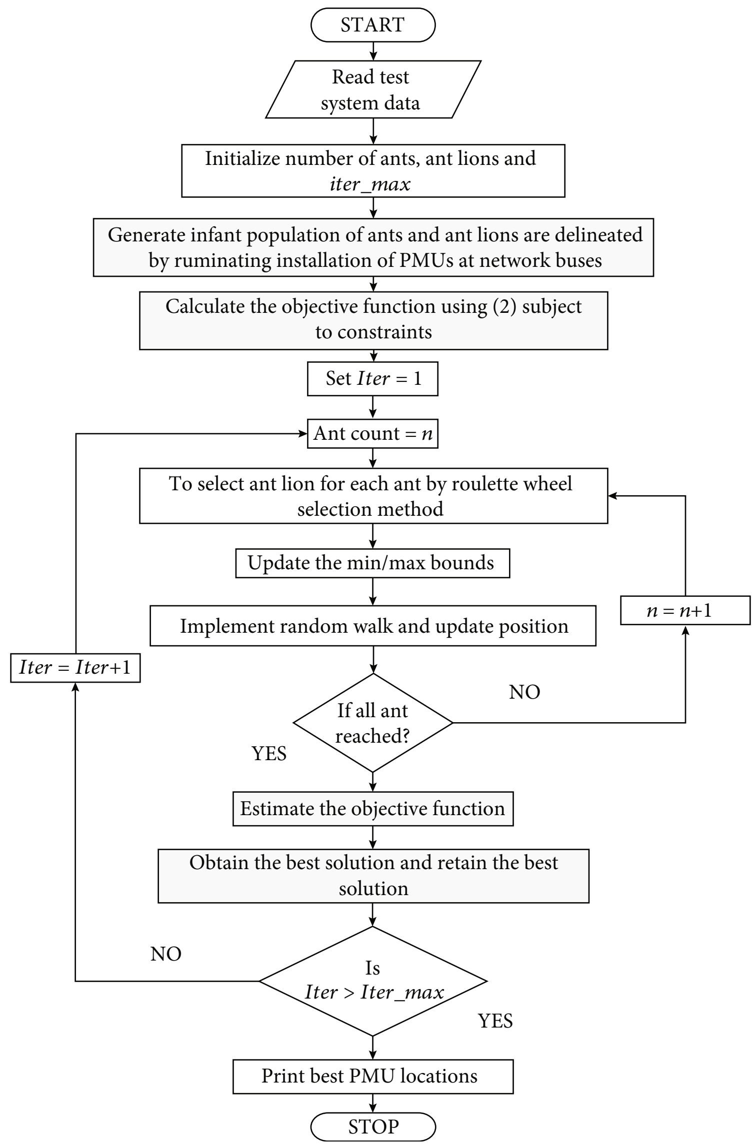

Figure 1: Flow chart for successive PMU placements.

Table 1: Optimal placement of PMUs under normal operation.

Test system	No. of PMUs	Maximum coverage with PMU locations	SMRI	Computational time in sec
IEEE 14	4	2, 6, 7, 9	19	15
IEEE 30	10	2, 4, 6, 9, 10, 12, 15, 20, 25, 27	52	29
IEEE 57	17	1, 5, 9, 15, 19, 22, 26, 29, 30, 32, 36, 38, 41, 47, 51, 54, 57	69	40
IEEE 118	32	3, 7, 9, 11, 12, 17, 21, 25, 28, 34, 37, 41, 45, 49, 53, 56, 62, 63, 68, 70, 71, 76, 79, 85, 86, 89, 92, 96, 100, 105, 110, 115	157	85
IEEE 300	72	1, 2, 3, 11, 15, 17, 21 23, 24, 26, 37, 41, 43, 44, 49, 55, 57, 61, 63, 70, 71, 72, 77, 81, 89, 102, 104, 105, 108, 109, 114, 119, 122, 130, 137, 139 140, 145, 153, 155, 159 166, 173, 178, 183, 184, 188, 198, 205, 210, 211, 214, 217, 223, 225, 229, 231, 232, 234, 237, 238, 240, 245, 249, 9002, 9003, 9004, 9005, 9007, 9021, 9023, 9053	282	120

4.2. Scenario 2. The secured PMU placement in PSSE has been implemented for an IEEE test system by means of fragmenting the single network into multiple areas. Therefore, each fragmented area is considered the distribution system. In each network, the OPP has been instigated which makes the system observable with the minimum number of PMUs and

Table 2: Comparison of the results with the existing techniques.

Methods	IEEE 14 bus		IEEE 30 bus		IEEE 57 bus		IEEE 118 bus		IEEE 300 bus	
	No. of PMU	SMRI	No. of PMU	SMRI	No. of PMU	SMRI	No. of PMU	SMRI	No. of PMU	SMRI
BGSA [4]	4	19	10	52	—	—	32	164	—	—
FABCA [8]	4	19	10	50	17	72	—	—	—	—
MBCOA [11]	4	16	10	42	17	63	32	157	—	—
NLP and ILP	4	19	—	—	—	—	—	—	—	—
Proposed ALO	4	19	10	52	17	69	32	157	72	282

Table 3: Secured placement of PMU for standard IEEE test systems.

Test system	No. of PMUs	Secured PMU location	SMRI
IEEE 14	8	2, 4, 5, 8, 9, 11, 12, 14	33
IEEE 30	20	1, 3, 5, 6, 9, 10, 11, 12, 13, 15, 17, 18, 19, 22, 24, 25, 26, 27, 28, 30	78
IEEE 57	33	1, 3, 4, 6, 9, 12, 15, 19, 20, 22, 24, 26, 28, 29, 30, 31, 32, 33, 35, 36, 38, 39, 41, 43, 45, 46, 47, 50, 51, 53 54, 56, 57	127
IEEE 118	68	1, 3, 5, 7, 9, 10, 11, 12, 15, 17, 19, 21, 22, 24, 25, 26, 27, 29, 31, 32, 34, 36, 37, 40, 42, 44, 45, 46, 49, 52, 53, 56, 57, 58, 59, 62, 64, 65, 67, 68, 70, 71, 73, 75, 77, 79, 80, 84, 85, 86, 87, 89, 91, 92, 94, 96, 100, 102, 105, 107, 109, 110, 111, 112, 115, 116, 117, 118	299
IEEE 300	172	1, 3, 6, 7, 8, 13, 14, 15, 17, 19, 21, 26, 27, 33, 34, 36, 41, 42, 43, 44, 46, 47, 49, 51, 53, 54, 57, 58, 63, 64, 69, 70, 71, 72, 74, 76, 78, 79, 80, 81, 85, 86, 87, 88, 94, 97, 98, 99, 100, 103, 104, 105, 107, 108, 109, 114, 115, 116, 117, 118, 119, 120, 121, 125, 126, 127, 128, 129, 135, 136, 137, 138, 139, 140, 141, 143, 144, 145, 147, 148, 149, 155, 156, 157, 158, 159, 160, 161, 163, 164, 165, 166, 167, 168, 169, 170, 172, 173, 174, 175, 177, 179, 184, 185, 186, 189, 190, 192, 194, 198, 199, 201, 203, 208, 209, 210, 211, 214, 219, 220, 221, 222, 223, 232, 233, 234, 236, 237, 242, 243, 244, 245, 246, 248, 249, 281, 319, 320, 322, 323, 528, 531, 552, 609, 1190, 1200, 7011, 7012, 7017, 7049, 7055, 7130, 7139, 7166, 9004, 9005, 9007, 9012, 9021, 9026, 9031, 9035, 9036, 9038, 9041, 9042, 9043, 9044, 9053, 9054, 9055, 9533	712

maximized coverage redundancy. The secured PMU placement (simulation of data attacks) calculated from equation (3) should satisfy the constraint given in equation (8), where the decision variable should be greater than or equal to 2. Therefore, if the above condition is achieved, then, the data can be transferred in a secure manner. In scenario 2, there is no consistent work carried out in the secured placement of PMU in PSSE. The secured PMU placement has been tested in standard IEEE test systems (IEEE-14, IEEE-30, IEEE-57, IEEE-118, and IEEE-300) to make the network highly secured while transferring the data to another system without attack. Table 3 shows the required number of PMU and the location of secured PMU for detecting the above-mentioned data attacks and prevents the system from external attack. The constraint to ensure the observability and appropriate redundancy to bad data process is given in equation (8). Based on the constraints, the proposed method is formulated and implemented in test case systems.

For proving the importance of the proposed method, two scenarios are considered with standard IEEE test systems and the results are also simulated using MATLAB. It can be clearly observed from Tables 1–3 many algorithms are compared with the proposed one where the primary importance is given to the coverage range of PMUs and corresponding computational time. After finding optimal PMU placements, the next subsequent scenario is analysed for securing the placement methods, and in this case, also, conventional techniques do not guarantee full load security conditions whereas the projected method ensures safety location of PMUs. Further, the same technique is also analysed in large scale test systems where outcomes are much effective in terms of all parametric values.

5. Conclusions

The use of DMS with PMU and solar cells to improve data quality in PSSE is proposed in this research. The proposed technology is unique in that it incorporates solar cells inside PMUs for PSSE, allowing for increased security and efficient data transfer without the risk of external hacking. In addition, the test system's partition has been acknowledged for data attacks. Furthermore, most SE approaches have only been used in transmission systems. However, the benefits of secure data transfer can be determined in the future by initiating the assignment of PMUs in PSSE. The suggested approach's simulation results with a standard IEEE test system show that this method is capable of producing improved outcomes. The focus of a future work will be on dealing with external sources of uncertainty with safety margins. According to the experimental data, the proposed ALO outperforms BGSA the average values and the convergence speeds.

5.1. Policy Implications. The proposed applications of phasor measurements will provide the real-time operating staff with previously unavailable yet greatly needed tools to avoid voltage and dynamic instability and monitor generator response to abnormal significant system frequency excursions. The PMU application has been adopted by the Power Grid corporation. Many PMUs are implemented in India.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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