Optimal PMU placements using sea lion optimization for adaptable distribution system

Thamaraiselvi Arivazhagan[1], Subramanian Srikrishna[2], Naveenkumar Kaliyan[3], Ganesan Sivarajan[4]

[1, 2]Department of Electrical Engineering, Annamalai University, Chidambaram, 608002, Tamilnadu, India
[3]Department of Instrumentation and Control Engineering, Sri Manakula Vinayagar Engineering College, Pondicherry, India
[4]Department of Electrical and Electronics Engineering, Government College of Engineering, Salem, 636011, Tamilnadu, India
[1]Corresponding author
E-mail: [1]*thamaraiphdau@gmail.com*, [2]*dr_smani@yahoo.co.in*, [3]*naveenk.aueee@gmail.com*, [4]*ganeshshriraj@gmail.com*

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Abstract. The technological advancements and policy reformations make the electric power distribution system an active network. The modern power system operational regulations encourage coordinated network operations among various entities and customer participation. Unlike traditional operational environments, real-time monitoring has become a mandate for secure and reliable operations. Phasor Measurement Units (PMU) is the most reliable data acquisition tool, and their application for State Estimation (SE) has already been proven. This work extends the application of PMUs for the distribution system. A multi-objective optimization framework is proposed considering the optimal placement of PMU, network reconfiguration, and topology expansion. A novel optimization tool, the sea lion optimizer has been chosen to address the developed optimization problem. The proposed operational model is employed in IEEE RBTS-2 bus system, IEEE 33 node system and 69 node radial distribution network. Numerical results provide new insights into PMUs role in enhancing distribution network operations. The statistical indices confirm that the intended optimizer performs well in the chosen highly constrained optimization environment.

Keywords: distribution system, state estimation, reconfiguration, topology expansion, sea lion optimization, PMU placement.

1. Introduction

The motive of state estimation in the power system can be an exposure to bad measurement data, reduction in small errors, detection of wrong switch statuses, network parameters estimation, wide-area monitoring, and situational awareness, fault finding, protective relaying, islanding detection, and other several applications [1], [2]. Distribution System State Estimation [DSSE] plays a vital role while implementing the features of smart grids as the inclusion of renewable energy sources, distribution generation, and demand-side management. State estimation based on PMU placements in the distribution system is gradually sprouting. PMU gives configurable alerts to take immediate action. Hence placing PMU in the distribution system will make the total system observable.

1.1. Challenges in DSSE considering adaptability

As technology develops and the population in the world increases, the need for electricity is also increasing. For this reason, expansion in the topology is essential to satisfy the demand. Distribution networks are complex due to the interconnection of renewable energy sources, distribution grid integration, and increasing end-users. To face the expected load increase in the

near future, topology expansion in the distribution systems plays a vital role. The purpose of topology extension as in distribution system is to improve the system's performance. Conversely, it has many challenges, including power quality issues like harmonics, frequency and voltage fluctuation, integration of renewable energy sources in the distribution network, electric vehicle, new client demands, operation management under island mode, and voltage stability problems. To overcome these problems, real-time monitoring is mandatory and can be easily achieved by deploying PMU at appropriate nodes in the distribution network.

1.2. State of the art methods

To make the Indian power grid reliable and efficient, moving towards a smart grid is crucial [3], [4]. It can be achieved by installing PMU in the power systems. The Indian power grid's southern area is taken into account when determining the geographical location of PMU placements in [5]. Conversely, [6] developed a model for controlled islanding mode and normal operating conditions in the Tamilnadu power grid for PMU placement.

The changes of configuration in the distribution system under normal operation and contingency modes have a huge impact on finding the best location of PMUs. Hence [7] suggested a novel elucidation method to identify the best feasible location for PMUs. This method ensures full framework observability in all distribution network activity operation settings by calculating only one configuration. Further, the observability of the network considering topology changes is detailed [8].

On the other hand, a method has been proposed for collecting a minimal number of critical measures with high overall redundancy [9]. To enhance the measurement redundancy in the distribution system, Optimal PMU search space reduction techniques were presented [10], which provided a feasible solution with a reduced number of PMUs. An integer nonlinear programming mechanism was proposed to mitigate the effective PMU location problem, where the measurement redundancy is maximized to measure the redundancy for every bus [11]. In contrast, probabilistic percentage error was proposed to handle the impacts of failure probability and transmitting faulty data, probability in distribution network estimation problem to accomplish preset probabilistic error percentage in magnitude and angle [12]. Modified Greedy Algorithm [13] was used to solve the tri objective optimization problem; however, [14] suggested a technique for assigning metering equipment in electrical distribution systems and strives to provide candidate solutions that represent strong trading between two competing objectives. The Non-Dominated Sorting Genetic Algorithm [15] was also used for solving optimal PMU placement problems. Besides that, the tactic of pre-assigned PMUs enables significantly to reduces the number of possible candidates for PMU placement, allowing consideration to be given to other PMU placements in the power system [16]. A technique for different conditions, namely, normal condition, loss of single PMU, the effect of unequal PMU cost, lack of communication infrastructure, presence of conventional power flow measurements, the effect of channel limitation, and effect of zero injection buses proposed in [17]. The exponential binary particle swarm optimization [18] was implemented to provide multiple solutions for various practical problems like single PMU outages and single line outages. Data traffic was handled in [19] using the Hybrid Algorithm of Genetic Algorithm and Minimum Spanning Tree.

1.3. Research gap and motivation

The summary of the research works in the field of PMU placements is presented in Table 1. The following points are observed from the literature survey. Numerous research works were done on PMU placements in the transmission systems, but a few have been commenced for distribution systems; most of the research articles focused on network reconfiguration for loss minimization; the topology expansion is focused only on the transmission systems. To develop a realistic operational mode, a multi-objective model is developed to ensure highly reliable and complete

observable distribution network operations using PMU. This research's main aim is to determine the best PMU site considering network reconfiguration, loss minimization, and topology expansion. To the author's best knowledge, this realistic model is presented for the first time in the distribution system.

Table 1. Consolidated literature survey

Year	Author	Algorithm / Approaches	Objectives		
			Min OPP	Reconfiguration	Topology expansion in distribution system
2008	Prasad et al. [21]	Genetic algorithm	+		
2013	Gopakumar et al. [5]	Integer linear programming	+		
2014	Abdelsalam et al. [27]	Ant colony optimization	+		
2015	Alvarez et al. [9]	Lower critical measurement with high redundancy	+		
2017	Mabaning et al. [10]	OPP Search space reduction	+		
2018	Zhang et al. [22]	Mixed-integer nonlinear programming	+		Research Gap No reports
2019	Arefi et al. [12]	Binary particle swarm optimization	+		
2019	Souifi et al. [23]	Genetic algorithm-based graph theory		+	
2020	Chen et al. [11]	Integer linear programming	+	+	
2020	Tiwari and Kumar [24]	Hybrid Taguchi and binary particle swarm optimization	+	+	
2021	Duque et al. [14]	Modified monkey search	+	+	
Proposed		Sealion optimization algorithm	+	+	+

1.4. Objectives

The objectives of the proposed work are as follows:

1) Optimal PMU placement in the distribution system to make the system observable and keep away from system failures. This can be achieved by placing PMU in nodes.

2) Network reconfiguration will minimize the losses and load balancing in the distribution system.

3) Expansion of the topology will give an idea to expand the topology in real-time in case there is any need for topology extension.

2. Problem formulation

A multi-objective optimization problem is performed to discover the least number of PMUs while minimizing losses. Fig. 1. depicts a diagrammatic illustration of a multi-objective prototype. It's described as follows:

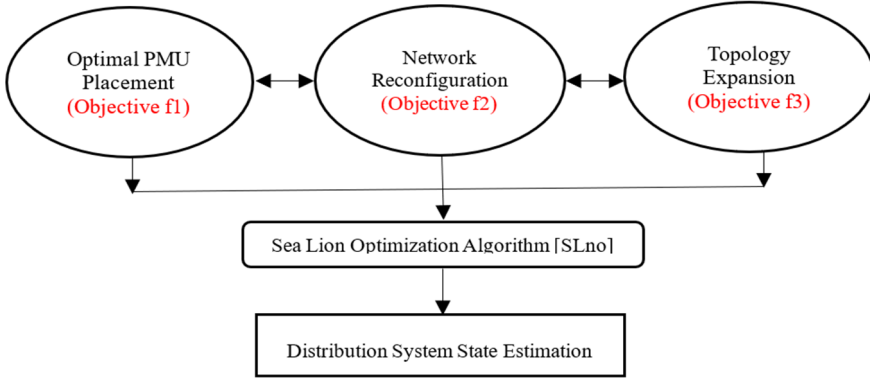$$Obj\ function = Min\ (f_1, f_2, f_3).\tag{1}$$

Fig. 1. Multi objective prototypical for PMU placement

2.1. PMU placement in the adaptable distribution system

The OPP's primary goal is to determine the least number of PMU required for complete system observability [10]. It is stated as follow:

$$f_1 = Min \sum_{i=1}^{n} w_i x_i, \tag{2}$$

where w_i is the cost for simplicity, the cost w_i is assumed as constant, x_i is binary decision variable of installing PMU at bus i (1 to install, 0 otherwise), n number of network buses.

The measurements are taken with the system consent to calculate the magnitude of the bus voltage and the angle to each bus of the network, aimed at comprehensive system observability. This indicates each bus in the network should be seen at least once. As a result, various constraints developed cannot be applied to a system with minimum $O_{min} = 1$ bus observability:

$$O_i = \sum_{i=1}^{n} A_{ij} x_i, \quad i = 1,2,\dots,n, \tag{3}$$

$$A_{ij} = \begin{cases} 1, & \text{bus } i = \text{bus } j, \\ 1, & \text{bus } i \text{ is adjacent with bus } j, \\ 0, & \text{otherwise}, \end{cases} \tag{4}$$

where $O_1 \geq O_{min}$ is the number of PMUs observing bus i, A_{ij} is the binary connectivity coefficient between bus i and bus j.

A_{ij} is determined by the PMU's ability to measure the bus voltage from bus i and bus j using ohm's law, presuming that line impedance is specified. Assuming that the line impedance is known.

The set of constraints may also be written in terms of vectors and matrices as:

$$Ax \geq b, \tag{5}$$

$$A = \begin{bmatrix} A_{11} & A_{12} & \cdots & A_{1n} \\ \vdots & \vdots & \vdots & \vdots \\ A_{n1} & A_{n1} & \cdots & A_{nn} \end{bmatrix}_{n \times n}, \tag{6}$$

$$x = [x_1 \quad \cdots \quad x_n]_{1 \times n}^{T}, \tag{7}$$

$$b = [O_{min} \quad \cdots \quad O_{min}]_{1 \times n}^{T}, \tag{8}$$

where A is the binary connectivity matrix, x is the binary decision variable in installing PMUs, b is the minimum bus observability required for each bus.

2.2. Radial distribution network reconfiguration

For a radial topology, minimization of network power losses while meeting operational constraints [21]-[22] can be stated as follows:

$$f_2 = Min\, P_{losses} \sum_{i=1}^{NR} R_j |I_j|^2, \tag{9}$$

where R_j is the resistance of the branch j, I_j is the magnitude of the current flowing through the branch j, NR is the total number of branches in the system.

2.3. Topology expansion

Topology expansion in the distribution system for full system observability is achieved using Eq. (10). Subsequently, the topology expansion [28] problem becomes:

$$f_3 = Min \sum_{i=1}^{n} N_i \geq 1, \tag{10}$$

$$cov = Max \sum_{i=1}^{n} N_i \geq 1. \tag{11}$$

Subject to the minimum true value of error $(N_1, N_2, N_3,\ldots, N_n)$, where N_i is decision variable that corresponds to the placement of PMU at ith bus = 1, if a PMU placed at ith bus = 0, otherwise.

2.4. Constraints

– Radial system constraint:
From an operational point of view, the distribution network should be made up of radial structures [27].
– Bus voltage magnitude:
The magnitude and angle of state variables at each node should be within their acceptable limits to sustain power quality:

$$V_{min} \leq V_i \leq V_{max}, \quad \forall\, i \in Nb, \tag{12}$$

$$\delta_i - \delta_j | \leq ||\delta_i - \delta_i|_{max}, \quad i \in [1,2,\ldots\ldots n], \tag{13}$$

where V_i is the voltage on bus i, V_{min} and V_{max} are minimum and maximum bus voltage limits, respectively.

The reasonable minimum voltage is 0.95 volts and also the maximum voltage is 1.05 volts (5 %). The construction process starts with the initial population.
– Current constraints:
Each branch's current magnitude (feeder, laterals, and switches) must be within its authorized ranges:

$$I_j \leq I_{j,max}, \quad \forall j \in NR, \tag{14}$$

where I_j max is maximum current limit of branch j.
– Feeder capability limits:

$$|I_k| \leq I_k^{max}, \quad k \in \{1,2,3,\ldots l\}. \tag{15}$$

3. DSSE considering network reconfiguration and topology expansion

3.1. Need for optimization algorithm

In 2019 [29], a new bio-inspired algorithm was introduced to solve the optimization problem named Sea lion Optimization algorithm. It is verified that it has superior performance and high convergence compared to the others presented in the literature.

For solving a wide area problem like optimal PMU placement in the distribution system the metaheuristic algorithm named sea lion optimization is used. SLnO is a population-based method used to determine the quality of a solution by applying fitness principles [30]. The proposed methodology proceeds by generating a population of various search agents in this manner. The fitness function of an effective solution based on the largest value is generated for each search agent in order to evaluate them. The best search agent $\overline{SL}$ with the fittest individuals among some of the group of feasible solutions is established at that moment, and all associated locations belonging towards the other search agents should be adjusted simultaneously in accordance with this modification. The hunting behaviours of sea lions [29] are shown in Fig. 2.

The main phases of the hunting behaviour of sea lions are as follows:

1) Using their whiskers to track and chase the prey.

2) Asking additional individuals of their subgroup to join them in chasing and surrounding the prey.

3) Make an attack on the prey.

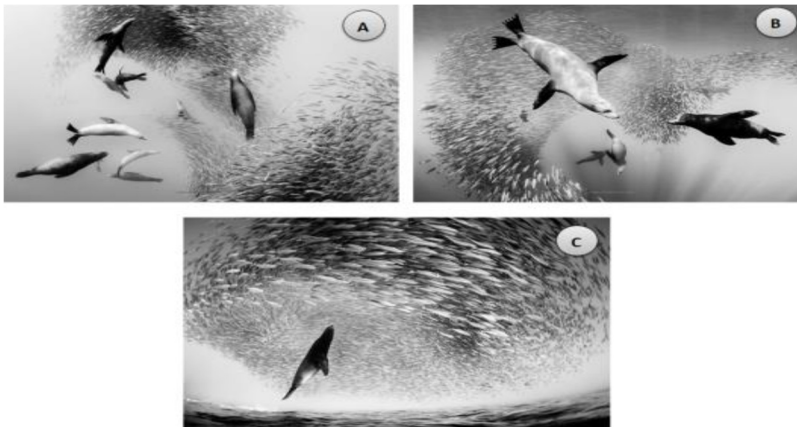This work mathematically models the sea lion's hunting technique to develop the SLnO algorithm and optimize it.

Fig. 2. Hunting behaviour of Sea Lions: a) chasing, approaching, and tracking prey,
b) encircling, c) Stationary situation and attack

3.2. Multiobjective optimization based on SLnO considering network reconfiguration and topology expansion

The following is the staging process trying to implement Multiobjective PMU placement and distribution system reconfiguration: The flowchart of multi objective sea lion optimization algorithm in shown in Fig. 3.

Step 1: Read data of the test bus systems.

Step 2: Set the initial value for the SLnO parameter's population.

Step 3: Make a population of 'n' sea lions as a starting point.

Step 4: Develop a multi-objective strategy to reach the objective.

Step 5: Evaluate each search agent's fitness function.

Step 6: Compare the fitness of each sea lion and update the position of the search agents.
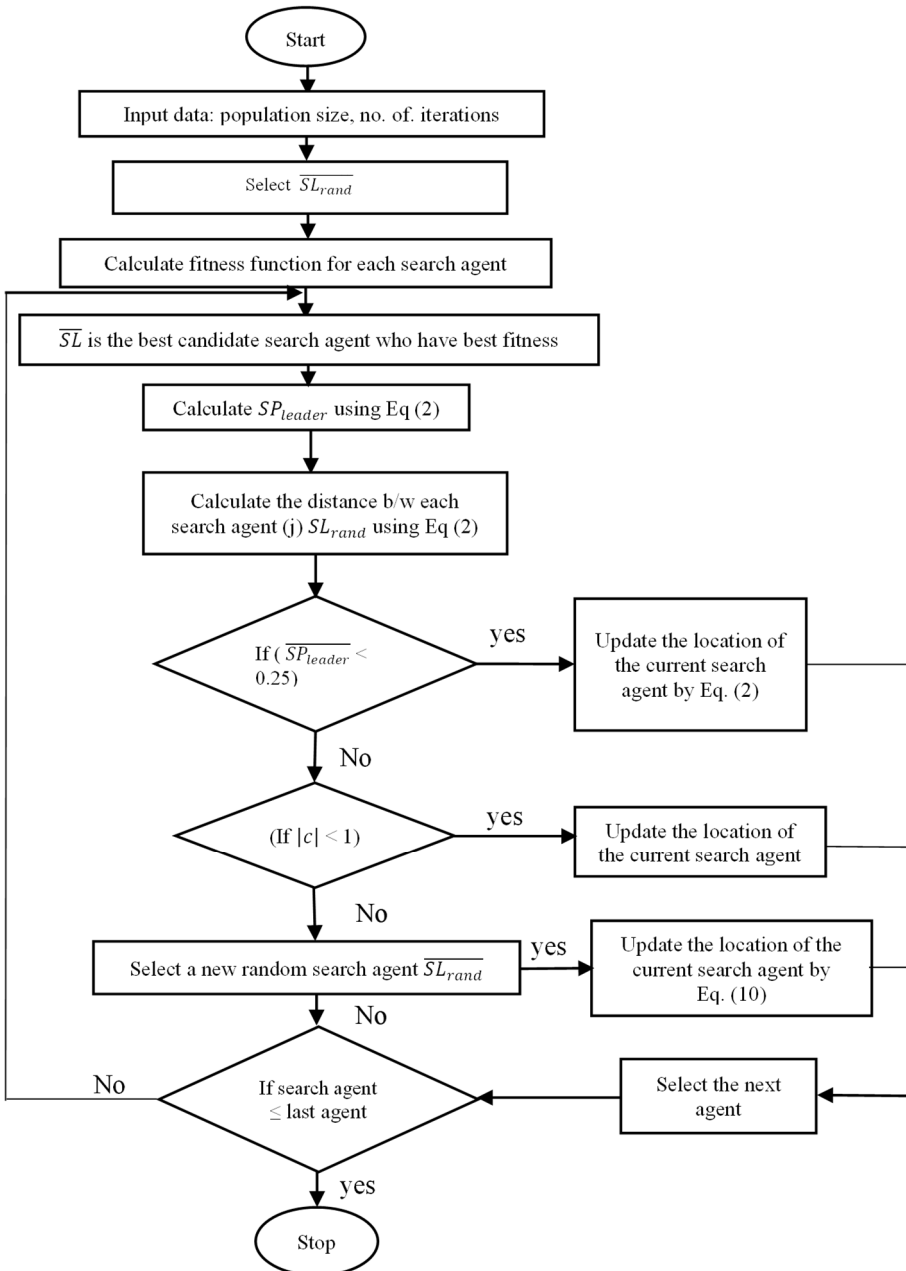
Step 7: Stop when the best solution is met.

Fig. 3. Flowchart for multi-objective sea lion optimization algorithm

3.3. Fitness calculation

The supremacy of each potential position is resolved through fitness function practice. As a result, the smooth selection of the fitness value seems to have an effect on the candidate solution recruitment process as well as the actual evaluation phase in recognizing the features of solutions based on their efficiency level. Consequently, in any new trial, each of the search agent's fitness values must be re-calculated [30]. Therefore, the best search mediator (SL) was picked, and the

placements of the other search mediator's positions should be altered accordingly. Through using its unique vocalization to alert them to the presence of the prey, $\overline{SL}_{rand}$, sends a vocal communication to other sea lions on the coast or under the ocean by using its particular vocalization to tell them about the prey. As a result, all sea lions who have heard their leader's vocalization will flock together as one and form a cluster, depending on the value of $(|c|)$, will update their locations toward the SL_{rand} position.

4. Optimal PMU placements result and discussion

The details of the test bus system, together with line and bus data, are extracted from [20-27]. All simulations were created using MATLAB, then executed on a personal computer with an Intel Core i3 – 5005U processor running at 2.00 GHz, 8 GB of RAM, and a 64-bit operating system.

The Sea lion algorithm has been used to put the encrypted PMU. It has been tested on many systems, including standard IEEE systems, to authenticate the usefulness of the proposed prototype. In calculating the feasibility of the system formulation, OPP was done for the objectives mentioned above to satisfy the following scenarios.

Scenario 1. PMU placements in DSSE.

Scenario 2. Reconfiguration with PMU placement

Scenario 3. Optimizing PMU with Expansion topology

The following test systems were used for each of the aforementioned scenarios.

Test Case 1: IEEE RBTS-2.

Test Case 2: IEEE 33.

Test Case 3: IEEE 69.

4.1. PMU placements in DSSE

The results showed that the proposed technique could discover the optimum option for complete redundancy in a system. For IEEE RBTS-2, IEEE 33, and IEEE 69 bus distribution systems, this study proposes a simple and effective PMU placement method. The PMU placement in several IEEE test systems is shown in Table 2. From the table, it can be easily understood that the proposed algorithm obtained the optimal locations with a better coverage value. The computational time for the program execution in each test system is obtained as shown in Table 2. Many locations are obtained for each test system with different coverage values. The proposed algorithm chooses the optimal locations based on the high coverage values. For example, in the IEEE RBTS-2 Test System, 9 PMUs are essential to examine the entire system, and the ideal positions are 1, 4, 7, 10, 13, 16, 19, 21, 23. The System Measurement Redundancy Index (SMRI) is sum of the Bus Observability Index (BOI). The BOI for each bus is calculated by using the bus connectivity matrix. The SMRI value for the above places is determined as 24, which is greater than the other locations.

Table 2. PMU placements in DSSE with computational time

Test system	No. of PMUs	PMU location	SMRI	Computational time in sec
IEEE RBTS-2	9	1, 4, 7, 10, 13, 16, 19, 21, 23	24	0.060
IEEE 33	11	2, 5, 8, 11, 14, 17, 21, 24, 26, 29, 33	34	0.082
IEEE 69	23	1, 3, 5, 8, 12, 15, 18, 21, 24, 27, 30, 33, 38, 41, 44, 48, 50, 52, 55, 58, 61, 64, 69	81	0.164

4.2. Reconfiguration with PMU placement

For full framework discernibility, the issue with Optimal PMU Placement was fully resolved on the transmission network. Changing the configuration in normal and emergency modes in a

distribution network, on the other hand, has a substantial impact on locating PMUs on the network. Some solutions have been proposed; however, the researchers had to work very hard to calculate the system data in all network configurations. In this study, a novel method for determining the best position for PMUs that ensures entire system observability in all distribution network operation configurations while only calculating one configuration. The condition of sectionalizing switches and tie switches determines the distribution network configuration. Proposed algorithms define the position of these switches and their status under various operating scenarios. If the number of tie switches in the distribution network is m, there will be up to $3m$ configurations. When m is a large number, determining the exact position of PMUs from each configuration but then combining them all into one is impracticable; thus, another solution is required.
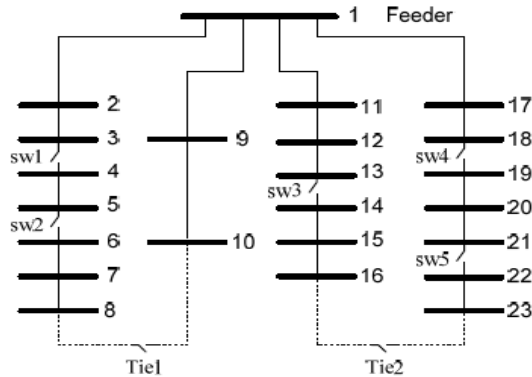

Fig. 4. Diagram of IEEE RBTS-2 bus distribution system

Fig. 4 shows a single-line diagram of the IEEE RBTS-2 bus distribution system. Table 3 illustrates the PMU placement after utilizing the proposed technique on this network, which has 22 load buses, 5 sectionalizing switches, and 2 tie switches. During the configurations, 11 PMUs are required to monitor the entire system, and their locations are 1, 3, 5, 7, 10, 12, 14, 16, 18, 20, 22, respectively. The SMRI is found as 32 and is determined based on the location.

Table 3 shows the numerous different types of reconfigurations. For the experiment, only three combinations are investigated. The outcomes are shown in Tables 3 and 4.

Table 3. Placement of PMU on IEEE RBTS-2 bus system

Test system	Parameters	Achieved results
IEEE RBTS-2 bus system	Number of Tie switch	2
	Number of configurations	9
	Number of PMU	11
	PMU location	1, 3, 5, 7, 10, 12, 14, 16, 18, 20, 22
	SMRI	32

Table 4. Three configurations of RBTS-2 bus system

Switches	Config. 1	Config. 2	Config. 3
Switch (S1)	Close	Close	Close
Switch (S2)	Close	Open	Close
Switch (S3)	Close	Close	Close
Switch (S4)	Close	Close	Close
Switch (S5)	Close	Open	Close
Tie Switch (T1)	Open	Close	Close
Tie Switch (T2)	Open	Close	Close
Comment	Normal operation	Load balancing	Lines 6-7 and 15-16 outage

The state of the sectionalizing switches and tie switches is cleared, as shown in Table 4.

Normal/Base case operating circumstances is the default setup. The second and third configurations are a mix of the first two. Table 5 illustrates the three PMU optimum locations and their accompanying coverage values for the three setups. The final combination of three configurations results in superior placement in all other configuration combinations. 1, 2, 3, 4, 5, 6, 7, 9, 11, 12, 13, 15, 16, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, If the distribution system may be reconfigured, the PMU at the above location monitors the entire system.

Table 5. Placement of PMU for different configurations of IEEE RBTS-2 bus system

Configuration	No of PMU	PMU locations	SMRI
Base case	9	1, 4, 7, 10, 13, 16, 19, 21, 23	24
Conf 1	8	1, 4, 7, 10, 13, 16, 19, 22	22
Conf 2	9	2, 5, 6, 10, 12, 15, 18, 21, 22	26
Conf 3	9	3, 4, 7, 9, 12, 15, 18, 20, 23	26
Merging	19	1, 2, 3, 4, 5, 6, 7, 9, 11, 12, 13, 15,16, 18, 19, 20, 21, 22, 23	55

Table 6. Placement of PMU

Parameters	IEEE 33 Bus	IEEE 69 Bus
Number of Tie switch	5	5
Number of Configuration	243	243
Number of PMU	17	27
PMU location	1, 2, 3, 5, 7, 8, 9, 11, 13, 14, 17, 21, 24, 25, 26, 29, 33	1, 3, 4, 5, 8, 10, 12, 15, 18, 21, 24, 27, 30, 33, 38, 41, 44, 48, 50, 52, 55, 58, 61, 63, 64, 68, 69
SMRI	52	92

The simulation runs on 33 and 69 bus distribution systems and illustrates the effect of the proposed approach. Table 6 shows the number of tie switches, configurations, and minimum number of PMU required to observe the entire system, as well as their related locations. Tables 7 and 8 show the results of the simulation. On the network, 17 and 27 PMUs are required to ensure the entire system observability. As an outcome of this PMU placement, each bus is covered through at least two separate PMUs, except PMU buses, ensuring reliable entire system observability in all configurations.

Table 7. PMU placements with corresponding SMRI

Configuration	No of PMU	PMU locations	SMRI
Base Case	11	2, 5, 8, 11, 14, 17, 21, 24, 26, 29, 33	34
Conf 1	12	1, 3, 5, 7, 9, 11, 14, 17, 21, 25, 26, 29	36
Conf 2	13	2, 3, 5, 7, 8, 11, 14, 17, 24, 25, 26, 29, 33	39
Conf 3	13	1, 3, 5, 7, 8, 13, 14, 17, 24, 25, 26, 29, 33	40
Merging	17	1, 2, 3, 5, 7, 8, 9, 11, 13, 14, 17, 21, 24, 25, 26, 29, 33	52

Table 8. Configuration of PMU placements in DSSE

Configuration	No of PMU	PMU locations	SMRI
Base case	23	1, 3, 5, 8, 12, 15, 18, 21, 24, 27, 30, 33, 38, 41, 44, 48, 50, 52, 55, 58, 61, 64, 69	81
Conf 1	24	1, 3, 5, 8, 12, 15, 18, 21, 24, 27, 30, 33, 38, 41, 44, 48, 50, 52, 55, 58, 61, 64, 68, 69	84
Conf 2	25	1, 3, 4, 5, 8, 12, 15, 18, 21, 24, 27, 30, 33, 38, 41, 44, 48, 50, 52, 55, 58, 61, 64, 68, 69	86
Conf 3	25	1, 3, 5, 8, 10, 12, 15, 18, 21, 24, 27, 30, 33, 38, 41, 44, 48, 50, 52, 55, 58, 61, 64, 68, 69	88
Merging	27	1, 3, 4, 5, 8, 10, 12, 15, 18, 21, 24, 27, 30, 33, 38, 41, 44, 48, 50, 52, 55, 58, 61, 63, 64, 68, 69	92

Compared to previous strategies, the reconfiguration techniques discover an optimal solution to the placement problem while also reducing the computational time required to get ideal PMU locations. Even though the number of locations obtained by both methods is comparable, the suggested technique takes much less time (about half) than the existing method.

Table 9. Comparison of results with existing methods for IEEE 33 bus system

Method	Switches	Losses
Initial	33, 34, 35, 36, 37	203.673
Proposed method (SLnO)	7, 9, 14, 32, 37	134.80
HAS	7, 10, 14, 28, 36	146.39
ITS	7, 9, 14, 36, 37	145.11
FWA	7, 9, 14, 28, 32	140.98
GA	7, 9, 14, 32, 37	140.55
RGA	7, 9,14,32, 37	139.55
ALO	7, 9, 14, 32, 37	139.54
CGA	7, 9, 14, 32, 37	138.87
PSO	7, 9, 14, 32, 37	138.87

The comparison of findings with existing approaches is shown in Table 9 and 10. It demonstrates that the suggested method has the most negligible losses compared to other strategies. It is possible to conclude that the proposed method is further qualified than the existing approach since it can effectively address the computational burden and long processing time for large-scale distribution systems in practice.

Table 10. Comparison of results with existing methods for IEEE 69 bus system

METHOD	SWITCHES	LOSSES
Initial	69, 70, 71, 72, 73	224.93
CSA	14, 57, 61, 69, 70	98.56
PSO	14, 57, 61, 69, 70	98.56
CGA	14, 57, 61, 69, 70	98.56
FWA	14, 56, 61, 69, 70	98.59
HAS	13, 18, 56, 61, 69	99.3
IAICA	14, 57, 61, 69, 70	98.57
Proposed algorithm	14, 57, 61, 69, 70	97.48

4.3. Optimizing PMU placement considering topology expansion

One of the most critical aspects of PMU deployment is the topology expansion of a relevant network. This section goes in-depth on extending the topology of different test systems and cramming information into it. In practice, there are still no well-defined topologies. The size, the design of the system, choice of relevant sites, and expense problems must be considered while extending the topology.

Table 11. Feasible PMU placements for topology expansion

Test system (Topology extension)	Minimum number of PMUs	Coverage
IEEE 33 Bus	2, 5, 8, 11, 14, 17, 21, 24, 26, 29, 33, 35,38,41, 44, 47,50, 54, 57, 59, 62, 66	68
IEEE 69 Bus	1, 3, 5, 8, 12, 15, 18, 21, 24, 27, 30, 33, 38, 41, 44, 48, 50, 52, 55, 58, 61, 64, 69, 70, 72, 77, 77, 81, 84, 87, 90, 93, 96, 99, 102, 107, 110, 113, 117, 119, 121, 124, 127, 130, 133, 138	162

A probabilistic method can be used to generate the notion of topology extension, in which each bus selects a binary number at random (1 or 0) – considering the IEEE 33 and IEEE 69 bus systems in Table 11, where 11 and 23 PMUs are required in normal operation without regard for topology

extension to ensure entire network observability. While identical test systems were naturally extended ($n*2$), however, a least between 22 and 46 PMUs are put at the equivalent bus, which would not guarantee complete system observability. Furthermore, the respective PMUs will provide substantial coverage.

5. Performance evaluation of algorithm

5.1. Effect of search mediators

The number of sea lions created in each generation is calculated by sacrificing a more extensive search zone exploration while increasing computing difficulty. Every generation adds more sea lions, increasing the size of the search area and the computing load. The Search Agent (SA) size in the SLnO algorithm must be properly chosen. The SA is a number that varies from 10 to 40. Table 12 illustrates the SA's selection parameter.

Table 12. Statistical measures of SLnO for various test systems considering the total cost

Test system	Search agent	Best	Average	Worst
IEEE 33 Bus	10	144.5	148.25	152.3
	20	139.2	144.35	149.5
	30	134.8	140.575	146.35
	40	136.4	142.1	147.8
IEEE 69 Bus	10	104.8	109.55	114.3
	20	102.6	107.7	112.8
	30	97.48	103.28	109.28
	40	98.9	104.7	110.5

Table 13. Statistical measures of SLnO for various test systems considering the total cost

Indices	IEEE 33 Bus	IEEE 69 Bus
Best	134.8	97.48
Worst	146.35	109.28
Average	140.575	103.38
Standard Deviation	±4.715	±4.817
Epsilon	142	108
Iter	30	40
Sol_Iter	24	36

The goal function is not minimized in SA 10 and 20. As a result, the SA is increased to 30, which provides the best results. Only when SA = 30 is used to compare the SA values of 10, 20, 30, and 40, the overall losses are minimized. Finally, 30 SA is chosen as the optimal number. The overall power loss in the IEEE 33 and 69 bus systems is 134.8 and 97.48 kw, respectively, when SA is set to 30.

5.2. Statistical measures

The disparity of objective functions for 40 trials of the algorithm is analyzed to check the validity of the acquired results. The traditional statistical indices such as finest, worse, mean, and difference Between the values calculated for every trial are shown in Table 13. The total losses for all test systems are evidently towards the ideal values. This demonstrates the desired algorithm's consistency in locating the best possible answer, and the intended technique has demonstrated its high success rate. Furthermore, the Iter and Sol Iter values improve SLnO algorithm convergence properties. Fig. 5 represents the characteristic convergence curves of the IEEE 33 and 69 bus system for the different optimization algorithms.
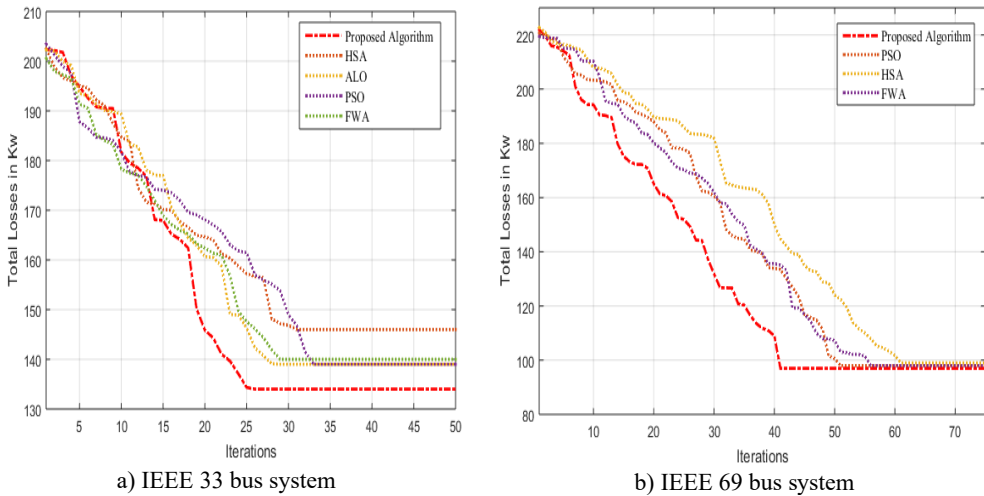
a) IEEE 33 bus system   b) IEEE 69 bus system

Fig. 5. Convergence characteristic curve

6. Conclusions

6.1. Contributions

This research proposes a sea lion optimization strategy for tackling an optimal PMU Placement problem that includes network reconfiguration and topology enlargement. The proposed prototype assures that now the system is entirely observed. Losses in the distribution network are decreased by providing network reconfiguration as an optimization objective. The results specify that the location of PMUs changes as the network is reconfigured. PMUs should be placed at nearly all nodes to avoid observability difficulties during network reconfiguration. The IEEE RBTS-2 bus system, IEEE 33, and 69 node feeder results are examples. The results of SLnO are compared to those of prevailing approaches, and the study determines that the suggested methodology is superior and trustworthy. Future research will focus on the resilience power networks.

6.2. Policy implication

The proposed technique minimizes the power losses and gives situational awareness about the status of the distribution network. As a result, it may be utilized in various typical power industry applications, such as decision-making, security, and creating the groundwork for smart grids.

Acknowledgements

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Thamaraiselvi Arivazhagan completed her B.E. degree in electrical and electronics engineering and M.E power systems from Annamalai University in 2017 and 2019, respectively. She is currently working towards her Ph.D. degree. Her research interest includes state estimation in power systems.

Subramanian Srikrishna completed his B.E., degree in electrical and electronics engineering and M.E power systems from Thiagarajar College of Engineering (TCE), Madurai Kamaraj University, Tamil Nadu, India, in 1989 and 1990, respectively. He completed his maiden Ph.D. degree in electrical engineering from Annamalai University, Tamil Nadu, India in 2001. He worked in various positions at Annamalai University, Chidambaram and became a Full professor in the year 2006. He has over 30 years of Teaching experience and more than 25 years of research experience. He is currently working as Professor and Head, Department of Electrical Engineering, Annamalai University, Tamil Nadu, India.

Naveenkumar Kaliyan completed his B.E degree in electrical and electronics engineering and M.E power systems from Annamalai University. He completed his Ph.D. degree from Annamalai University in the year 2021. He is currently working as an Assistant Professor in Sri Manakula Vinayagar Engineering College, Puducherry. He has over eight years of teaching experience. His research interest includes distribution system state estimation.

Ganesan Sivarajan a Senior Member in IEEE and a Member in Institution of Engineers (India). He has published 100 research articles which include 30 Web of Science articles and international conferences. He has authored 2 books and 4 book chapters, which include IET, Springer, and IGI global Publishers. He has guided 5 Ph.D. scholars and 10 Post-Graduate Thesis. Currently, he is working as an Associate Professor in the Department of Electrical and Electronics Engineering, Government Engineering College Salem, Tamilnadu.