Binary spider monkey algorithm approach for optimal siting of the phasor measurement unit for power system state estimation

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Article Info

Article history:

Received Aug 30, 2021
Revised Apr 22, 2022
Accepted May 21, 2022

Keywords:

Binaryspider monkey optimization
Complete observability
Optimal placement
Phasor measurement unit
State estimation

ABSTRACT

The phasor measurement unit (PMU) is an essential measuring device in current power systems. The advantage seems to be that the measuring system could simultaneously give voltages and currents phasor readings from widely dispersed locations in the electric power grid for state estimation and fault detection. Simulations and field experiences recommend that PMUs can reform the manner power systems are monitored and controlled. However, it is felt that expenses will limit the number of PMUs that will be put into any power system. Here, PMU placement is done using a binary spider monkey optimization (BSMO) technique that uses BSMO by simulating spider monkeys' foraging behavior. Spider monkeys have been classified as animals with a fission-fusion social structure. Animals that follow fission-fusion social systems divide into big and tiny groups, and vice versa, in response to food shortage or availability. The method under development produced the optimum placement of PMUs while keeping the network fully observable under various contingencies. In the study published in IEEE14, IEEE24, IEEE30, IEEE39, IEEE57, and IEEE118, the proposed technique was found to reduce the number of PMUs needed.

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1. INTRODUCTION

In power generation and distribution, the transmission and distribution network is crucial in transmitting electricity from power plants to customers. The power network provider must monitor and measure the different components of the power transmission network to avoid a loss of energy. Accurate measurement of the power system will provide more reliable and sustainable operation. Previously, supervisory control and data acquisition (SCADA) systems have been used to monitor the networks. The phasor measurement unit (PMU) is capable of measuring key network information including bus current, bus voltage, power angle, and generator speed, all using global position system (GPS) synchronized clocks. Operators in the control room may observe and evaluate the quality of the distribution network based on both dynamic and statistical operating circumstances by obtaining PMU measurement information from a wider area. Wide area monitoring system (WAMS) offers more advantages over SCADA in the form of better phasor measurement, increased sampling, and more precise measurement. The phasor measurement (PMUs) installation at all substations may greatly enhance the power network dependability, according to Phadke *et al.* [1], [2]. Regardless, the PMU device investment in all areas is economically undesirable owing to the high price of the device. By optimizing the quantity of PMU placement and using the full degree of observability, optimal PMU placement (OPP) is used to decrease maintenance fees and unit expenses. There are three main types of OPP algorithms, and they may be broadly classified as deterministic, heuristic, and meta-heuristic. The deterministic methods are implemented with the help of the mathematical programming method. The linear integer programming issue is the kind of problem where design variables can only take integer values. The strategic location of PMUs was addressed by Chen and Abur [3]. In Bei *et al.* the researchers suggested that PMUs be strategically placed for various budgets [4]. With respect to injection and power flow measurements, a specific form binary integer programming (BIP), a type of Integer linear programming (ILP), was employed to solve this problem. Additionally, the decision was made to sacrifice a single PMU to reduce the state estimation's susceptibility to PMU failure. Some elements of PMU installation were discussed by Dua *et al.* [5]. Two indexes, via bus observability index (BOI) and system observability redundancy index (SORI), were developed in order to rate these numerous solutions even further. The optimal placement was made possible by using the capability of bus observability and zero injection and, therefore, the placement quality was enhanced by the use of BOI and SORI. In the Indian power grid's Tamil Nadu State has benefited from the usage of ILP in determining the most advantageous PMU location, as it was demonstrated in [6]. The Chakrabarti and Kyriakides [7] suggested a binary search algorithm for determining the least quantity of PMU required.

The Chakrabarti and Kyriakides [7] suggested a binary search algorithm for determining the least quantity of PMU required. A implicit data exclusion preprocessing technique [8] and a matrix decline algorithm were applied to make the placement form and the computational time smaller work required to determine the ideal placement set. In [9] proposes a heuristics-based technique for ensuring a fully observable power system with the fewest feasible PMUs. According to Farsadi *et al.* [10], optimization techniques based on the sorting were employed to evaluate the lowest PMU required in IEEE57-bus and 14-bus systems. These graphs by Baldwin *et al.* [11] are a great way to build subgraphs that are measuring spanning measurements. The minimal spanning tree (MST) technique is adjusted depth first. By using the MST method, DFS is enhanced, which has rapid computation capabilities, and thus further enhances depth first search (DFS's) weak and complicated convergence. Cai and Ai states this [12]. A superior approach to the heuristic method is meta-heuristic. Meta-heuristic search process uses intelligent approaches to find discrete variables and non-continuous costs. In this study, we use the simulated annealing method, which has been implemented in [13], to determine the PMU location with respect to observability for the system. As it is used in [14], the modified simulated annealing (MSA) technique enables the search space to be much reduced, when compared to the simulated annealing (SA) method. The direct combination (DC) method heuristic rule is also used to decrease the searching spaces using the Tabu search technique. Simulated annealing has also been suggested by Abdelaziz *et al.* [15] for OPP. This method, which only requires a few stages, is very efficient in discovering optimum or near-optimal solutions. Genetic algorithm (GA) is a natural selection-inspired search technique. In [16], a genetic algorithm method for guaranteeing the smallest possible number and placement of PMUs involves calculating the lowest possible number of phasors measured.

It is confirmed in [17] that the non-dominated sorting algorithm (NSGA) reduces the quantity of PMUs and maximizes redundancy in measurement. Allagui *et al.* describe a method of monitoring network buses using implanted measuring devices in [18]. While flocking birds and schooling fish are social activity, Hajian *et al*. [19] statet that Drs. Eberhart and Kennedy developed particle swarm optimization (PSO) in 1995 as a socially influenced population-based stochastic optimization approach. To calculate the optimal number of PMUs needed for complete observability, Hajian *et al*. [19], Gao *et al*. [20], Hajian *et al*. [21], and Ahmadi *et al*. [22] used an adapted discrete binary version of the particle swarm optimization technique (BPSO). In [23], [24] used a similar approach like BPSO for location of PMUs in the improved binary flower pollination algorithm (IBFPA) algorithm. Binary search space only offers solutions with logic 0 or 1 values, and a new binary spider monkey optimization algorithm (BSMOA) is presented in this study based on [25]–[27]. To optimize the placement of PMUs in the power system network for security, the basic SMO algorithm's position updating equations have been altered using logical operators. This simplifies computation time, increases the robustness of the solution, and makes the solution applicable to other applications.

2. PROBLEM FORMULATION FOR OBSERVABILITY WITH OPTIMAL PMU SITING

The ultimate focus of the PMU siting issue is to use the least quantity of PMUs needed. To attain total visibility of the power system while keeping total price to a minimum. The PMU Problem with a 'm' bus system is defined as shown in (1). Which includes cost of PMU installesd.

$$f(p) = min \sum_{i=1}^{m} w_i * p_i \qquad (1)$$

Subjected to restraint

$$G(p) \geq b \quad (2)$$

where binary variable 'p' is a vector for PMU, whose entry has as shown in (3)

$$p_i = \begin{cases} 1, if a PMU placed at i^{th} bus \\ 0, else \end{cases} \quad (3)$$

where i=1,2,….n bus number, w_i is the cost of PMU sited at i^{th}bus, b is a unit vector of length n

$$b = [11111]^T \quad (4)$$

An entry in the observability restraint vector function *G(p)* is non-zero if the respective buses can be observed with regard to the specified measurement set, and zero otherwise. Vector-constraint function provides observability of all network nodes in a complete manner. In order to fulfil the constraint, it is necessary to find a solution, that is, a minimal set of p_i. In order to construct the restraint vector function, the binary connection matrix (*AA*) of the power system is used as input. It reflects the bus connection information of a power system, which may be derived from the line-data of a power system's underlying electrical network. The *n-m*thelement of matrix *AA* corresponds to bus m and bus *n* is defined as:

$$AA_{m,n} = \begin{cases} 1, if m = n \\ 1, if bus 'n' is linked to bus 'm' \\ 0, else \end{cases} \quad (5)$$

Let us consider IEEE-5 bus system as example shown in Figure 1.

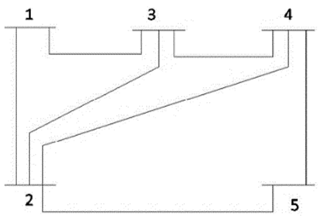

Figure 1. IEEE 5 bus test system

Binary connectivity matrix (*AA*) for IEEE-5 bus test system is

$$AA = \begin{pmatrix} 11100 \\ 11111 \\ 11110 \\ 01111 \\ 01011 \end{pmatrix} \quad (6)$$

For the system shown in Figure 1, the restraint vector task for the IEEE-5 bus test system was accomplished to achieve complete observability by (7)

$$G(p) = [G1G2G3G4G5]^T = A * P \quad (7)$$

where for buses

$$\left.\begin{array}{c} Bus1: p_5 + p_1 + p_2 \geq 1 \\ Bus2: p_5 + p_4 + p_2 + p_3 + p_1 \geq 1 \\ Bus3: p_4 + p_2 + p_3 \geq 1 \\ Bus4: p_9 + p_7 + p_4 + p_5 + p_3 + p_2 \geq 1 \\ Bus5: p_5 + p_2 + p_4 + p_1 \geq 1 \end{array}\right\} \quad (8)$$

In (8) '+' works as logical operator 'OR'. It can be stated from (8) that, to make bus-1 observable of the 5-bus test system, at least one PMU must be located at any of the buses (1, 2 or 3), if (8) is satisfied. Then the test system shown in Figure 1 is completely observable.

3. BINARY SPIDER MONKEY OPTIMIZATION ALGORITHM (BSMOA)

A newly developed swarm intelligence meta-heuristic algorithm, BSMOA [25], [26], it created to find the balance among local and global search abilities in order to achieve improved solution optimization [27]. As a result of the early stagnation, convergence and lack of investigation and development in prior algorithms, this method is designed to solve these issues and more. Each step of the SMO is: For binary optimization issues, BSMO is suggested, which is a generalization of the SMO method [25], [26]. Improved IBPSO algorithm described by Yuan *et al.* [28]–[32] is the motivation for this method. They programmed IBPSO with the help of alogical operator, and utilised PSO’s velocity equations to implement it. Algorithm BSMO operates in binary space by applying logical operators to its basic equations. This method generates a random binary solution. This equation may be used to assist construct it:

$$p_{i,j} = \begin{cases} 0, r < 0.5 \\ 1, otherwise \end{cases} \quad (9)$$

where $p_{i,j}$is the i^{th} spider monkey of j^{th} dimension, *0.5* is our probability value, and ‘r’ is a random value in the choice of [1,0]. A random value between 0.5 and 1 is used to determine the dimension. A dimension with a random number less than 0.5 will be set to 0, and vice versa. Spider monkeys' position calculations occur after initialization and use AND, OR, and XOR operations. The following updated equations are provided.

3.1. Local leader phase

The final positions of the spider monkey p modules are dependent on the knowledge acquired by the leader and group members’ experience in the local leader phase. When you acquire a new position, you compute the fitness value of that position. The employee’s new job offers a greater fitness value than his previous one, and so the employee changes his location. The location revise equation for i^{th} p (which is a element of k^{th} local group) in this phase i.

$$p_{n_{i,j}} = \begin{cases} p_{i,j} \oplus ((b \otimes (ll_{k,j} \oplus)) + \\ (d \otimes (p_{r,j} \oplus p_{i,j}))), if rand \geq pr \\ p_{i,j,} otherwise \end{cases} \quad (10)$$

3.2. Global leader phase

All Solutions keep their locations update by accounting for group member knowledge and data from global leaders. According to the (11), the positions are always updated as

$$P_i = 0.9 \times \frac{(fitness_i)}{min\_fitness} + 0.1 \quad (11)$$

where P_i denotes the probability, $fitness_i$ denotes the fitness of the i^{th} p, and min_fitness is the group’s minimum fitness. For this phase, if the $P_i$less than random value then the position update equation is

$$p_{n_{i,j}} = \begin{cases} p_{i,j} \oplus ((b \otimes (gl_j \oplus)) \\ +(d \otimes (p_{r,j} \oplus p_{i,j}))) \end{cases} \quad (12)$$

3.3. Local leader decision phase

In local leader decision phase deals random solution $p_{n_{i,j}}$ is the j^{th} dimension of i^{th} new position of p. Here $p_{i,j}$ is the previous dimension of j^{th} p in the i^{th} position. And gl_j is the global best in the j^{th} element. Solution $ll_{k,j}$ represent the local best of the j^{th} dimension in the k^{th} group, b and d are logical random numbers in the choice [1,0] and [1,-1] respectively, and $+, \oplus, \otimes$ are logical OR, AND, and XOR operators.

$$p_{n_{i,j}} = \begin{cases} p_{i,j} \oplus ((b \otimes (ll_{k,j} \oplus p_{i,j})) + \\ (b \otimes (gl_j \oplus p_{i,j}))), rand \geq pr \\ useequation(9), otherwise \end{cases} \quad (13)$$

3.4. Binary spider monkey algorithm

- Step 1: During the initialization phase, the population size, global-leader limit, and local-leader limit, the most number of groups and rank of perturbation (pr) are all established. Generate random solutions using (9). Using this calculate fitness values and determine global and local leaders by comparison.
- Step 2: During the local leader phase, based on (10), generate a new solution. Calculate the best solution among the present and previous on the basis of the fitness.

- Step 3: Phase of global leadership, based on the (11), compute probabilities. Create a new population based on the (12). Determine the new solution fitness and choose the superior option based on the fitness of the new and old solutions. Update the position of the local and global leaders.
- Step 4: In decision phase for the local-leader; if the local-leader is not modified, divert all members to forage using (13).
- Step 5: If the global leader is not updated, then divide into two groups and increased, if the most number of groups is reached, combine all groups into one. Local leader should be updated.

If the convergence condition is met, the iterations are terminated.

4. RESULTS AND DISCUSSION

This technique was tested on IEEE 14, 24, 30, 39, 57, and 118 bus test systems and was also simulated for five different use cases. i) OPP without considering zero injections, ii) OPP considering zero injections, iii) OPP without considering zero injections and one PMU loss, iv) OPP considering zero injections and one PMU loss, and v) OPP considering zero injections and one PMU loss and a line outage. Proposed technique was simulated using MATLAB software. Table 1 showsthat number of zero-injection buses and radial buses, for the six test systems [19], [28].

Using the aforementioned values, it can be deduced to the basic scenario, the necessary quantity of PMUs for attaining full observability is about 1/3rd of the network dimension. This figure almost doubles when the scenario in which a single PMU outage or loss causes it is taken into consideration. It is expected that minimum of 2 PMUs will be in possession of each bus in a power system in order to maintain the power system observable.

4.1. Case 1: OPP without considering zero injections

The information shown in Table 2 details the ideal number of PMUs needed for various systems. It also gives the places where they are required. 2, 6, 7, and 9 are necessary for placement in an IEEE 14-bus system, and without taking into consideration zero injection buses (ZIBs). In order to achieve full observability, 33 PMUs are needed for the 118-bus system. Number of PMUs required increases with system.

4.2. Case 2: OPP considering zero injections

The findings for the number and placement of the buses for system observability considering zero injection buses, provided in Table 3. Three PMUs are required to implement an IEEE 14 bus system, and bus numbers are 2, 6, and 9. The number of PMUs is reduced considering zero injections compare with case 1. The cost of PMUs also reduced compare with case 1.

4.3. Case 3: OPP without considering zero injections and one PMU loss

Table 4 illustrates the quantity of PMUs needed for various systems and their bus positions. It also shows the maximum quantity of PMUs required when they are deployed under single PMU loss conditions when ZIBs are not enabled. For the IEEE 14bus system, nine PMUs are necessary. In this case number of PMUs is increased compare with base case.

Table 1. IEEE bus system data with no. of branches, zero injection buses and radial buses details

Bus System	No. of branches	Total no. of Zero Injection	Zero Injection Bus numbers	Total no. of Radial Buses	Radial Bus Numbers
IEEE14	20	1	7	1	8
IEEE24	38	4	11, 12, 17, 24	1	7
IEEE30	41	6	6, 9, 22, 25, 27,28	3	11, 13, 26
IEEE39	46	12	1, 2, 5, 6, 9, 10, 11, 13, 14, 17,19, 22	9	30, 31, 32, 33, 34, 35, 36, 37, 38
IEEE57	78	15	4, 7, 11, 21, 22, 24, 26, 34, 36, 37, 39, 40, 45, 46, 48	1	33
IEEE118	179	10	5, 9, 30, 37, 38, 63, 64, 68, 71, 81	5	19, 73, 87, 111, 112

Table 2. No. of PMU's required without considering zero injections for IEEE 14-bus system

Bus System	Optimum no. of PMU's needed	Bus position of the PMU's
IEEE14	4	2, 6, 7, 9
IEEE24	7	2, 3, 8, 10, 16, 21, 23
IEEE30	10	2, 4, 6, 9, 10, 12, 15, 19, 25, 27
IEEE39	13	2, 6, 9, 10, 13, 14, 17, 19,20, 22, 23, 25, 29
IEEE57	17	1, 4, 6, 9, 15, 20, 24, 28, 30, 32, 36, 38, 41, 47,51,53,57
EEE118	32	3, 5, 9, 12, 15, 17, 21, 25, 28, 34, 37, 40, 45, 49, 52, 56, 62, 64, 68, 70,71, 76, 79, 85, 86, 89, 92,96, 100, 105, 110, 114

4.4. Case 4: OPP considering zero injections and one PMU loss

Table 5 illustrates the quantity of PMUs needed for various systems and their bus positions. It also shows the maximum quantity of PMUs required when they are deployed under single PMU loss conditions when ZIBs are enabled. For the IEEE 14 bus system, seven PMUs are necessary. In this case number of PMUs is decreased compare with previous case because considering zero injections.

4.5. Case 5: OPP considering zero injections and one PMU loss or a line outage

The Table 6 illustrates the total number of PMUs desired for various systems. It also shows the various bus locations and the different situations where full observability maintained when one PMU fails or when the power line goes out. It is essential for IEEE14-bus structure 8 PMUs, and the bus information 2, 4, 5, 6, 8, 9, 11, and 13 are important for placing. The findings in Table 7 illustrate how many PMUs are needed for various systems, with their associated algorithms, and show the effectiveness of the proposed approach to find out the least quantity of PMU's installations to attain a power system completely observable considering different algorithms.

Table 3. No. of PMU's required considering zero injections for IEEE 14-bus system

Bus System	Optimum no. of PMU needed	Bus position of the PMU's
IEEE14	3	2, 6, 9
IEEE24	6	2, 8, 10, 15, 20, 21
IEEE30	7	2, 4, 10, 12, 15, 19, 27
IEEE39	8	3, 8, 13, 16, 20, 23, 25, 29
IEEE57	11	1, 6, 13, 19, 25,29, 32, 38, 51, 54, 56
IEEE118	28	3, 8, 11, 12, 17, 21, 27, 31,32, 34, 37,40, 45, 49, 52, 56, 62, 72, 75, 77, 80, 85, 86, 90, 94, 102, 105, 110

Table 4. No. of PMU's required considering zero injections and one PMU loss

Bus System	Optimum no. of PMU required	Bus position of the PMUs
IEEE14	9	2, 4, 5, 6, 7, 8, 9, 10, 13
IEEE24	14	1, 2, 3, 7, 8, 9, 10, 11, 15, 16, 17, 20, 21, 23
IEEE30	21	2, 3, 4, 6, 7, 9, 10, 11, 12, 13, 15, 16, 18, 20, 22, 24, 25, 26, 27, 28, 30
IEEE39	28	2, 3, 6, 8, 9, 10, 11, 13, 14, 16, 17, 19, 20, 22, 23, 25, 26, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39
IEEE57	33	1, 3, 4, 6, 9, 11, 12, 15, 19, 20, 22, 24, 25, 26, 28, 29, 30, 32, 33, 34, 36, 37, 38, 41, 45, 46, 47, 50, 51, 53, 54, 56, 57
IEEE118	68	2, 3, 5, 6, 9, 10, 11, 12, 15, 17, 19, 21, 22, 24, 25, 27, 29, 30, 31, 32, 34, 35, 37, 40, 42, 43, 45, 46, 49, 51, 52, 54, 56, 57, 59, 61, 62, 64, 66, 68, 70, 71, 73, 75, 76, 77, 79, 80, 83, 85, 86, 87, 89, 90, 92, 94, 96, 100, 101, 105, 106, 108, 110, 111, 112, 114, 116, 117

Table 5. No. of PMU's required considering zero injections and one PMU loss

Bus System	Optimum no. of PMU required	Bus position of the PMUs
IEEE14	7	2, 4, 5, 6, 9, 10, 13
IEEE24	11	1, 2, 7, 8, 9, 10, 16, 18, 20, 21, 23
IEEE30	12	2, 3, 4, 7, 10, 12, 13, 15, 16, 19, 20, 24
IEEE39	14	3, 12,15, 16, 20, 23, 25, 26, 29, 34, 35,36, 37, 38
IEEE57	21	1, 3, 9, 12, 14, 15, 18, 20, 25, 28, 29, 30, 32, 33, 38, 41, 50, 51, 53, 54, 56
IEEE118	64	1, 2, 5, 6, 8, 9, 11, 12, 15, 17, 19, 20, 21, 23, 25, 27, 28, 29, 32, 34, 35, 37, 40, 41, 43, 45, 46, 49, 50, 51, 52, 53, 56, 59, 62, 66, 68, 70, 71, 72, 75, 76, 77, 78, 80, 83, 85, 86, 87, 89, 90, 92, 94, 96, 100, 101, 105, 106, 108, 110, 111, 112, 114, 117

Table 6. No. of PMU's required considering zero injections and one PMU loss and a line outage

Bus System	Optimum no. of PMU required	Bus position of the PMU's
IEEE14	8	2, 4, 5, 6, 8, 9, 11, 13
IEEE24	11	1, 2, 7, 8, 9, 10, 16, 18, 20, 21, 23
IEEE30	13	1, 3, 5, 7, 10, 12, 13, 15, 16,17, 19, 20, 24
IEEE39	19	3, 6, 8, 13, 16, 20, 23, 25, 26, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38
IEEE57	23	1, 3, 6, 9, 12, 14, 15, 18, 20, 25, 27, 29, 30, 32, 33, 36, 38, 41, 50, 51, 53, 54, 56
IEEE118	65	1, 3, 5, 7, 8, 10, 11, 12, 15, 17, 19, 21, 22, 24, 25, 27, 28, 29, 32, 34, 35, 37, 40, 41, 44, 45, 46, 49, 50, 51, 52, 54, 56, 59, 62, 66, 68, 72, 73, 74, 75, 76, 77, 78, 80, 83, 85, 86, 87, 89, 90, 92, 94, 96, 100, 101, 105, 107, 109, 110, 111, 112, 115, 116, 117

Table 7. Assessment of PMU placements in IEEE bus system using BSMO algorithm with existing methods

Bus System	Optimal No. of PMUs for different systems			
	GA [18]	Modified binary PSO (MBPSO) [22]	IBFPA [23]	Proposed method
IEEE14	-	3	3	3
IEEE24	6	6	6	6
IEEE30	7	7	7	7
IEEE39	-	-	-	8
IEEE57	-	13	13	11
IEEE118	29	29	29	28

5. CONCLUSION

This article presented a novel method called BSMO based on binary search space. Logic operators have been considered as the vital component of moving on to binary search room. In BSMO, the location of every spider monkey consists of 1 and 0 logic values, and these logical decision values are applied for optimal placement of PMUs in power system, which gives test systems a means of being topologically observable under consideration of ZIB, one PMU loss, and contingency of one line. The test results determined the effectiveness of the proposed approach to find out the least quantity of PMUs installations to attain a power system completely observable considering different operational aspects of the power system when compared to the GA, MBPSO and BFPA methods. This indicated that the proposed method is applicable for large systems.

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