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Optimal placement of the phasor measurement units using differential evolution algorithm

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ABSTRACT

The increasing consumption of the electric energy aimed at develop the transmission networks and the demand for higher reliability from the network; in this regard, wide-area measurement systems using phasor measurement units (PMUs) have revolved the trend of power network management. In this paper, the optimal allocation of PMUs in order to reach the perfect observability of the network; based on a differential evolution algorithm, is proposed and it is shown that, the deployment of constraints related to the zero-injection busses (ZIB) aimed to decrease the number of PMUs and their corresponding cost. By comparing the proposed method to the other methods, its simplicity and good performance are approved.

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1. INTRODUCTION

Nowadays, talking about the importance or necessity of energy production in various financial, social, and even political aspects is clear because of the complexity of modern technology in power distribution systems. Without the need for advanced machines, the operators could control the power systems and serve the energy management aims. These controls should ensure that reliable, flexible electric power with optimal financial performance is realized. In recent years, another system has been introduced that aims to compensate for the available flaws in the wide area measurement system (WAMS). It is called the wide area monitoring system, and it has been greatly considered by the Abbasi and Seifi [1].

Phasor measurement units (PMUs) [2]–[13] were first introduced in the middle of the 1980s, as signal processing technology advanced. A large number of these PMUs have been used in advanced studies of power systems all over the world due to their capability, and their application is growing rapidly. Electric utility state estimation is critical for the best utilization, monitoring, protection, and control of power systems. Traditional estate estimation methods, on the other hand, are not precise due to their non-synchronous parameters, and reaching the final solution relies on solving a large number of nonlinear equations through repetitive methods. So, the system utilizer in the control center hasn't a good vision of dynamic condition of the system.

The optimal placement of PMUs can be find by linear and non-linear programming-based model including genetic algorithm [14], [15], binary-coded genetic algorithm (BCGA) and branch-and-bound algorithm (BBA) [16], whale optimization algorithm [17], generalized pattern search algorithm [18], semidefinite programming [19], integer-arithmetic algorithm [20], neural network [21], binary semidefinite programming [22], greedy strategies [23], recursive quadratic programming [24], integer linear programing [25] and so on. On the other hand, optimal PMU placement (OPP) problems are solved as single- or multi-objective that one of the objectives is to reduce the number of PMUs [26], increasing measurement redundancy [27], minimizing total PMU installation cost [28], enhancing the power system's measurement reliability [29], and enhanced transient stability [30]. Moreover, some papers [31]–[33] consider the different constraints including PMUs specific channel capacity, a line/PMU outage, one branch outage, and one PMU failure, that can be solved by heuristic algorithms.

In the central control room, the state estimator uses the crude phasor data to make a valid state estimation of the system. The prerequisite for using these state estimators is to install PMUs and establish suitable communication infrastructures to transfer the crude measurement data. Providing these items requires a huge investment. So, choosing the plans for optimal allocation of PMUs has a high degree of importance. As a result, these plans must be evaluated in terms of the power system's observability. Considering the advantages of the differential evolution algorithm, it is hoped that this algorithm could realize a saving in the cost of the project by enhancing the solutions to the PMU allocation problem [34]. This study presents the PMUs optimal allocation to achieve full network observability via a differential evolution technique and the deployment of constraints related to the ZIB aimed at decreasing the number of PMUs and their corresponding cost.

2. THEORY AND PREVIOUS STUDIES

2.1. Differential evolution algorithm

The differential evolution algorithm (DEA) [35]–[47] was introduced in 1995 by Storn, and Price. This algorithm is population-based and aside from some similarities to the other evolutionary algorithms, it's unique concerning the method of generating the solution. In evolutionary algorithms, the new population is generated using the crossing or mutation operators. In the DEA, firstly, the mutation operator is used to generate an experimental vector and then, this selection operator used to generate a child. In the differential evolution, the length of mutation's step is originated from the differences among the current population. Although the evolutionary difference has similarities with the other evolutionary algorithms, using the distance, and direction data correspond to the current population to succeed in the exploration operation has separated it from the other evolutionary algorithms [37]. The primary evolutionary algorithm was developed to solve the continuous space problems, then, they were developed to cope with the discrete space problems. The basic DE algorithm is shown in Figure 1. The DEA, includes: i) set the initial values for the scale factor, the cross-factor, the number of populations (NP), and the maximum number of evolutionary steps (Maxinter); ii) set the initial population count to pop; iii) implement the DE/rand/1/bin policy enforcement choices in order to create a new generation of individuals, specifically: operation of mutation; procedure of crossover; procedure of selection; and iv) until such time as the termination criteria are satisfied [37].

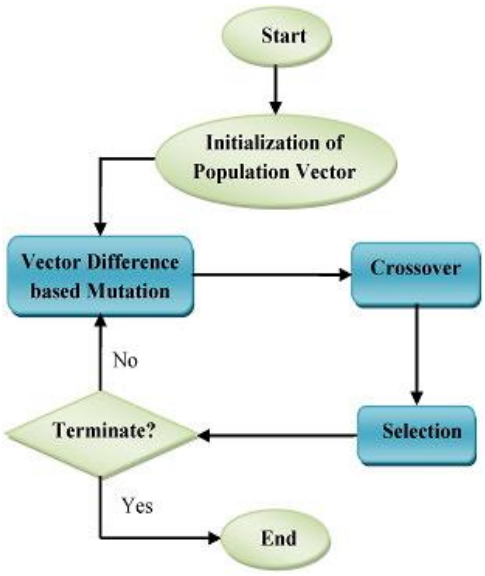


Figure 1. Flowchart of difference evaluation algorithm

2.1.1. Mutation

The mutation operator (in the DEA) generates an experimental vector by introducing mutations into any member of the population individually, the objective vector, and a weighted difference. For example, $X_i(t)$ is generated for a child as: an objective vector $X_{i1}(t)$ is selected from the population, so that, $i_1 \neq 1$, then two individuals $X_{i2}(t)$and $\mathrm{X}_{\mathrm{i}3}(\mathrm{t})$are selected, haphazardly; so that, $i \neq i_1 \neq i_2 \neq i_3$ and also $i_1, i_2, i_3 \sim \mathrm{U}(1, \mathrm{n_s})$. The experimental vector will be generated using these particular individuals so that (according to Figure 2) [48].

$$\overrightarrow{u_\iota} = X_{i1}(t) + \beta(X_{i2}(t) - X_{i3}(t)) \quad (1)$$

Where $\beta \in (0, \infty)$ is a scale factor which controls the effect of difference [49].

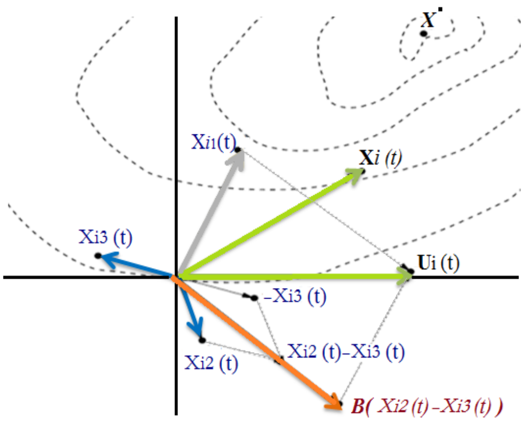


Figure 2. The mutation operator in the differential evolution algorithm (DEA)

2.1.2. Crossover

A discrete combination of the experimental vector $\mathrm{U_i(t)}$ is accomplished through the use of the crossover operator, and the father vector $X_i(t)$ for generating the $X_i'(t)$ child. The selection is employed as (as in Figure 3) [50].

$$X_{ij}'(t) = \begin{cases} U_{ij}(t), & if\ j \in J \\ X_{ij}(t) & otherwise \end{cases} \quad (2)$$

Where $\mathrm{x_{ij}}(\mathrm{t})$ is assigned to the $\mathrm{j^{th}}$ element of $X_i(t)$. In other words, *j* is a collection of indexes that will change. It is a collection of the selected words.

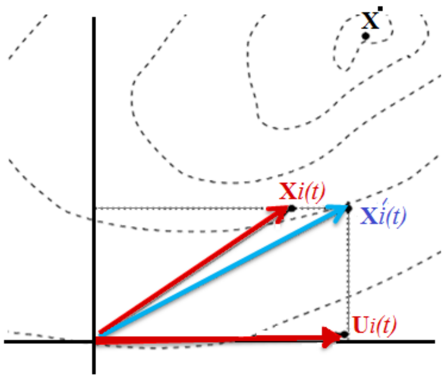


Figure 3. The crossover in DE algorithm

2.1.3. Selection

The selection operator is used in two ways. First, in order to determine a person who should be used in mutation to generate an experimental vector. Second, in order to assign which father or child will go to the next stage random selection usually is used to compute the differential vectors. In most DEA implementations, the objective vector is chosen at random or by using the best individual. In the DEA to generate the next generation, the exact selection method is used. In this condition, the child will replace their father if he will be better than him, otherwise, the father will become a part of the subsequent generation. This action guarantees that, the function the average value of the population will not become worse [51].

2.2. Evaluation of the implemented methods

To address the issue of PMU allocation in recent years, different methods have been evaluated in various papers. In an endeavor to decrease the extension cost, which will save the system's cost, a bunch of these researchers have tried to enhance the solutions by implementing evolutionary optimization problems. The previous research done in this field includes: simulated annealing (SA) [52]–[67], binary imperialistic competition algorithm (BICA) [68], chemical reaction optimization (CRO) [69], recursive tabu search (RTS) [35], [70], [71], genetic algorithm (GA) [72], and so on.

3. METHOD

In general, power system observability refers to the process of computing network variables in order to provide an approximation of the system's state. The network will not be observable, and it may be possible to divide it numerically as well as topologically [73]. This is due to the fact that the data required for the state estimation will not be available.

3.1. The numerical method of analyzing the observability

In the numerical method, in order to reach a mathematical definition for the observability, the mathematical model of the system should be concluded. In most of the references, the linear model of the system is used which is defined as:

$$Z = HX + e(3) \quad (3)$$

the Z vector in this model comprises m measurements of bus voltage and line current. X is the N-dimensional state vector and H denotes the measurements' constant Jacobean matrix and e denotes the measurement error vector. Considering the previous formula, if the Jacobean matrix H will be of a full degree, the network is observable and the state estimation is practical. Due to the inherent limitations of the numerical technique when used to big power systems (because of the high scattering of matrixes), the alternative method of topological analysis of observability is proposed [73].

3.2. The topological method of observability

In this method of evaluating the observability of a uniform graph, based on the whole electric laws and condition of power distribution, according to these four laws is done:

- Law 1: there is no ambiguity in the voltage and current phasors of any of the edges that are connected to the vertex in which the PMU has been put (as in Figure 4) [74].

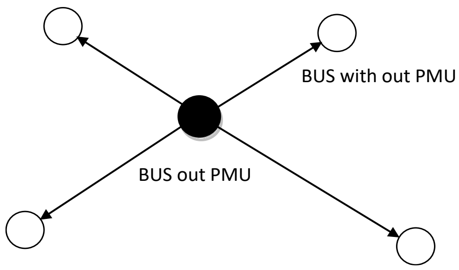


Figure 4. The first law in the topologic evaluation of the observability

- Law 2: if a vertex's voltage phasor and the current of one of the edges connected to it are both clear, the voltage phasor of the other vertex connected to that edge is concluded (as in Figure 5).

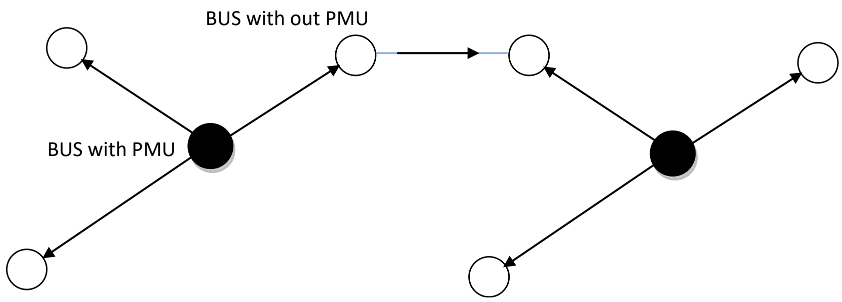


Figure 5. The second and third law in the topologic evaluation of the observability

- Law 3: if the voltages of both vertexes connected to one edge are clear, its currents will be clear, too.
- Law 4: if the current of the whole edges connected to a vertex with zero injective current except in one of them will be clear, the current of the other edge will be clear (Figure 6).

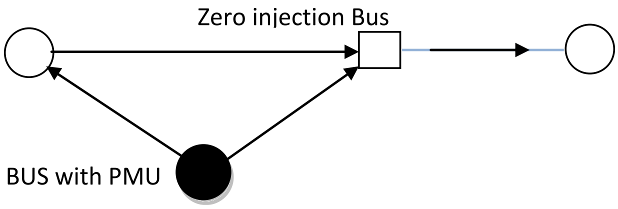


Figure 6. The fourth law in the topologic evaluation of the observability

- Law 5: using the allocation laws, one could reach the result that if every single bus that is connected to the ZIB will be observed in some way, then the ZIB itself is observable, so that bus could be merged with one of the side buses and conclude the new crossover matrix (as in Figure 7).

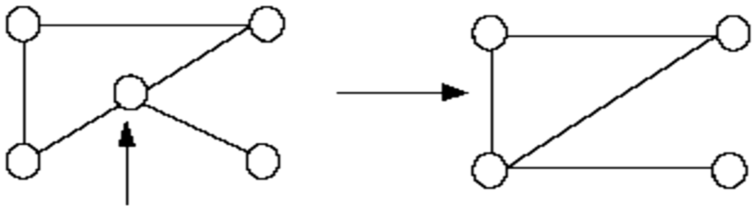


Figure 7. The fifth law in the topologic evaluation of the observability

3.3. The formulation of the PMUs allocation problem

Installed on a bus, a PMU has the ability to compute both the voltage phasor of the bus itself as well as the current phasor of all of the branches that are attached to it. So, by installing PMU at strategic spots of the network, the prerequisite data needed for evaluating its observability could be gained. The optimal allocation problem [74] for an n-bus system is written as:

$$\min \sum_{i=1}^{n} W_i X_i \tag{4}$$

$$X_i = \begin{cases} 1 & PMU\ installed\ in\ bus\ i \\ 0 & otherwise \end{cases}$$

$$\text{s.t. } f_i \geq 1, \forall\, i \in B \tag{5}$$

$$f = AX \tag{6}$$

W_i is considered to be the cost of installation for any PMU in bus i^{th} and $f(x)$ is a function that shows the constraints of observability for any bus of the network. In this paper, in order to grow the pace of calculations, the topological method has been used to formulate the constraints of the problem. The constraints of the problem are analyzed in two stages according to the strategy that has been proposed: i) without taking into consideration the ZIB and ii) taking into consideration the ZIB.

4. RESULTS AND DISCUSSION

An optimization problem has been developed for IEEE-standard power systems with 14, 30, 57, or 118 buses. A software was created in MATLAB R2019a on a PC with a Core i7 3.90 GHz Intel CPU and 16 GB of random-access memory (RAM) to solve the problem for each network.

4.1. Optimal placement of PMUs aimed at full observability of network without considering the zero - injection bus

Table 1 summarizes the evaluation outcomes. Any of the evaluated test systems with the corresponding number of PMUs, as stated in Table 2, have become fully observable, according to the program's output results. Table 2 shows the location of the PMU installation for standard power system observability and the simulation computation time.

Table 1. Results of PMUs placement, without considering the ZIB

System	The number of the ZIB	The number of PMUs, without taking into account the ZIB
IEEE 14-bus	1	4
IEEE 30-bus	5	10
IEEE 57-bus	15	17
IEEE 118-bus	10	32

Table 2. The locus of PMUs, without considering the zero-injection busses

System	Location of PMUs in allocation without the ZIB	Simulation time (s)
IEEE 14-bus	9, 7, 6, 2	0.291
IEEE 30-bus	27, 25, 18, 15, 12, 10, 9, 6, 4, 2	0.318
IEEE 57-bus	57, 53, 51, 47, 41, 38, 36, 32, 28, 25, 22, 19, 15, 9, 6, 1	0.436
IEEE 118-bus	114, 110, 105, 102, 94, 91, 86, 85, 80, 77, 75, 71, 70, 68, 63, 62, 56, 53, 49, 45, 42, 37, 34, 29, 25, 21, 17, 15, 12, 9, 5, 2	0.679

4.2. Optimal placement of PMUs aimed to full observability of network with considering the ZIB

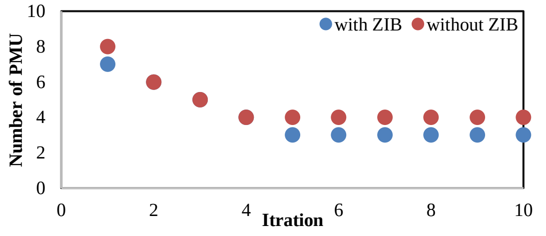
Considering the ZIB in the PMUs allocation problem cause saving in cost and decreases the number of PMUs needed to realize the full-observable network. The allocation problem is resolved, considering the ZIB. The loci of ZIB in standard networks are listed in Table 3. The simulation calculation time and the location of installation of PMUs have been tabulated in Table 4. The comparison of results of solving allocation problem considering the effect of the ZIB revealed a 10% to 30% decrease in the number of PMUs, concerning the case in which ZIB is ignored. Eventually, proposed results considering the effect of the ZIB prove that solving the PMUs allocation problem considering the effect of the ZIB decreases the number of PMUs aimed for the full-observability operation of the network, consequently reducing the costs. Despite the similar results of differential evolution to the binary particle swarm optimization (BPSO) algorithm, because of the higher pace in converging to the objective point and its powerful performance not to trap in local optimum, the final results of the differential evolution algorithm are preferred to the other algorithms. Figure 8 shows convergence properties of OPP optimization in various test systems with and without ZIB. Where 14-bus network is shown in Figure 8(a), 30-bus network is shown in Figure 8(b), the 57-bus system is shown in Figure 8(c) and 118-bus system is shown in Figure 8(d).

Table 3. The locus of the ZIBses in standard test networks

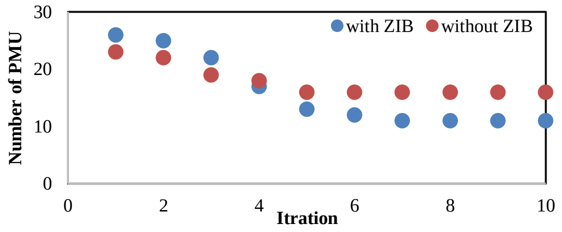
System	The number of the ZIB	Location of the ZIB
IEEE 14-bus	1	7
IEEE 30-bus	5	29, 25, 11, 9, 6
IEEE 57-bus	15	22, 19, 17, 14, 13, 11, 10, 9, 6, 5, 2, 1
IEEE 118-bus	10	81, 71, 67, 64, 63, 38, 37, 30, 9, 5

Table 4. The locus of PMUs, with considering the ZIBses

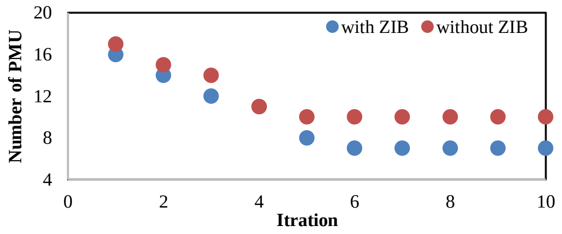
System	Location of PMUs in allocation with the ZIB	Simulation time (s)
IEEE 14-bus	9, 6, 2	0.371
IEEE 30-bus	29, 18, 15, 12, 10, 5, 1	0.443
IEEE 57-bus	54, 51, 41, 38, 32, 26, 25, 19, 13, 5, 1	0.571
IEEE 118-bus	110, 105, 102, 94, 90, 86, 85, 80, 77, 75,72, 62, 53, 49, 45, 40, 37, 34, 32, 31, 27, 21, 17, 12, 11, 8, 3	0.809



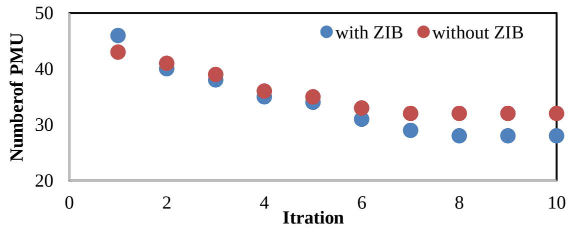
(a)



(b)



(c)



(d)

Figure 8. Convergence properties of OPP optimization in various test systems with and without ZIB (a) 14 bus, (b) 30 bus, (c) 57 bus, and (d) 118 bus

4.3. Algorithms comparison for OPP optimization from various points of views

This section compares the suggested approach findings to other methods that have already been published in the literature in order to better understand the OPP optimization problem. Several configurations to minimize the number of PMUs is displayed in various articles. Table 5 compares optimal PMU placement of several optimization strategies to minimize the number of PMUs for IEEE 14-, 30-, 57-, and 118-bus test systems with and without ZIB. Table 6 shows the minimal number of PMUs required to produce a fully observable system as well as the proportion of PMUs put in buses for the aforementioned test systems under both with and without ZIB conditions.

Table 5. The comparison between results of allocation problem with the other references

Test system	Bus no. (PMU placements)	Reference
	Without ZIB	
IEEE 14-bus	9, 7, 6, 2	Proposed method (PM) [26], [69]
	13, 11, 7, 2	Mousavian and Feizollahi [75]
	13, 10, 7, 2	Jamuna and Swarup [76]
	13,10, 8, 2	Al-Mohammed *et al*. [46]
IEEE 30-bus	27, 25, 19, 15, 12, 10, 9, 6, 4, 2	Jamuna and Swarup [76], (PM)
	29, 25, 18, 15, 12, 10, 9, 6, 5, 1	Jamuna and Swarup [77]
	27, 25, 24, 19, 12, 10, 9, 8, 5, 1	Al-Mohammed *et al*. [46]
	29, 25, 20, 15, 12, 11, 10, 7, 6, 3	Mousavian and Feizollahi [75]
IEEE 57-bus	57, 53, 51, 47, 41, 38, 36, 32, 28, 25, 22, 19, 15, 9, 6, 1	[69], [72], (PM)
	57,54, 50, 47, 46, 45, 41, 36, 32, 30, 29, 26, 22, 19, 9, 4,1	Mousavian and Feizollahi [75]
	55, 52, 50, 47, 45, 41, 39, 36, 32, 27, 25, 22, 19, 15, 12, 6, 3	Venkateswaran and Kala [47]
IEEE 118-bus	114, 110, 105, 102, 94, 91, 86, 85, 80, 77, 75, 71, 70, 68, 63, 62, 56, 53,	Ivatloo [72] (PM)
	49, 45, 42, 37, 34, 29, 25, 21, 17, 15, 12, 9, 5, 2	Mousavian and Feizollahi [75]
	114, 110,105,101, 94, 91, 86, 85, 80, 75, 71, 68, 64, 62, 57, 54, 51, 46,	Ivatloo [72]
	44, 40, 36, 30, 28, 23, 21, 17, 15, 12, 9, 5, 3	
	114, 110, 105, 101, 94, 91, 86, 85, 80, 75, 71, 68, 64, 62, 57, 54, 51, 46,	
	44, 40, 36, 30, 28, 23, 21, 17, 15, 12, 9, 5, 3	
IEEE 14-bus	9, 6, 2	Proposed method [69], [70], [75], [77]
IEEE 30-bus	29, 18, 15, 12, 10, 5, 1	Hurtgen and Maun [77], (PM)
	27, 23, 18, 12, 10, 5, 1	Koutsoukis *et al*. [70]
	27, 23, 19, 12, 10, 7, 1	Xu *et al*. [69]
	30, 24, 19, 17, 12, 7, 1	Mousavian and Feizollahi [75]
IEEE 57-bus	54, 51, 41, 38, 32, 26, 25, 19, 13, 5, 1	Ivatloo [72], (PM)
	56, 54, 51, 38, 32, 29, 25, 20, 13, 4, 1	Koutsoukis *et al*. [70]
	56, 54, 51, 38, 32, 29, 25, 19, 13, 6, 1	Mousavian and Feizollahi [75]
	54, 51, 41, 38, 32, 29, 25, 19, 13, 5, 1	Mahari and Seyedi [68]
IEEE 118-bus	110, 105, 102, 94, 90, 86, 85, 80, 77, 75,72, 62, 53, 49, 45, 40, 37, 34,	Koutsoukis *et al*. [70], (PM)
	32, 31, 27, 21, 17, 12, 11, 8, 3	Hajian *et al*. [78]
	114, 110,105, 101, 94, 90, 86, 85, 80, 77, 75, 72, 62, 56, 52, 49, 45, 40,	Mahari and Seyedi [68]
	34, 33, 28, 25, 21, 17, 12, 11, 8, 2	Mousavian and Feizollahi [75]
	110, 105, 102, 94, 90, 86, 85, 80, 77, 75, 72, 62, 56, 53, 49, 45, 40, 37,	
	34, 32, 31, 27, 21, 17, 12, 11, 8, 3	
	114, 110, 105, 101,94, 90, 86, 85, 80, 77, 75, 62, 56, 53, 49, 45, 40, 34,	
	29,25, 21, 17, 15, 12, 8, 6, 1	

Table 6. Comparison between different algorithms and test systems for the minimum number of PMUs and the percentage of buses equipped with PMU

Test systems	14-bus		30-bus		57-bus		118-bus	
Method	A	B	A	B	A	B	A	B
without ZIB								
Iterated local search (ILS) [79]	4	28.57	-	-	17	29.83	32	27.12
Binary particle swarm optimization (BPSO) [26]	4	28.57	10	33.33	17	29.83	32	27.12
Genetic algorithm (GA) [72]	4	28.57	10	33.33	16	28.07	32	27.12
Proposed method	4	28.57	10	33.33	16	28.07	32	27.12
with ZIB								
Simulated annealing (SA) [52]	3	21.43	7	23.33	13	22.81	29	24.58
Binary imperialistic competition algorithm[68]	3	21.43	7	23.33	11	19.30	28	23.73
Chemical reaction optimization (CRO) [69]	3	21.43	7	23.33	14	24.56	29	24.58
Matrix reduction [49]	3	21.43	8	26.67	12	21.05	29	24.58
Recursive tabu search (RTS) [70]	3	21.43	7	23.33	11	19.30	-	-
Genetic algorithm (GA) [72]	3	21.43	7	23.33	12	21.05	29	24.58
Proposed method	3	21.43	7	23.33	11	19.30	28	23.73

A: Minimum number of PMUs B: Percentage of buses equipped with PMU

5. CONCLUSION

This paper proposes a new strategy for optimizing PMU allocation with the end goal of achieving full network observability and assessing network topological observability. The optimization problem and associated restrictions, such as the condition needed to accomplish full observability of the network, are presented in the form of a differential evolution optimization problem. The topic of PMU allocation was then explored, taking into account the influence of zero-injection buses (ZIB) on the objective function. The problem has been solved using MATLAB software. It has been demonstrated that incorporating ZIB (switching station) limitations into the PMU allocation problem reduces the number of PMUs necessary to provide full-observability performance of the network, thereby lowering costs. When compared to existing strategies for solving various optimization issues, the proposed method performs well. It is hoped that using this method to solve more complex allocation problems, such as multi-stage allocation of PMUs, and the allocation problems including additional constraints like the PMUs allocation problem aimed at more observability, will lead to good results.

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