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Investigating and Comparing the Simulation of Protection Networks and Their Performance Improvement in Power Systems

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Abstract

Nowadays, Phasor Measurement Units (PMUs) are used in power systems to improve the speed and accuracy of network protection and control systems. The optimal placement of these devices in the system is very important due to their high purchasing and installation costs. This study investigates the Optimal PMU Placement (OPP) problem in the system using a binary particle swarm optimization (BPSO) algorithm and MATLAB. Besides, constraints such as alternative measurement, zero-injection bus (ZIB), and traditional measurement constraint (SCADA (Supervisory Control and Data Acquisition)) are considered in the objective function of this study. This study used the system topology method to simulate the IEEE57 BUS, IEEE30 BUS, and IEEE14 BUS networks and implemented the objective function on these systems. The results showed that the entire system remained observable as a result of PMUs being installed in less than 25% of the buses. Finally, the results of this study were compared with those of similar work.

Keywords: *Phasor Measurement Unit (PMU), Network Observability, Optimal Placement*

1. Introduction and Problem Statement

Phase Monitoring Unit (PMU) has the potential to change the way you measure and control electric power systems. It can measure the voltage and current and calculate the angle between them. As a result, the phase angle of the various buses across the system can be measured in real-time. This is made possible by two advantages of PMUs, namely synchronization and time stamping. The observability of a power system generally means computing network variables to estimate the state of the system; the network will not be observable if the required data are not available for the state estimation. Network variables are commonly considered as bus voltage phasor. A PMU installed at a particular bus can measure the voltage and phase angle of that bus and also calculate the current phasor along all the branches connected to it. Consequently, the voltage and phase angle of buses connected to the PMU-equipped bus can also be calculated using the basic power laws (KVL, KCL). Therefore, PMU installed buss have direct observability (are directly observable). Buses connected to a PMU installed bus have indirect observability (are not directly observable). Moreover, buses not connected to the PMU installed bus are unobservable. The OPP problem and its constraints were modeled by a series of linear equations and solved using linear programming (Jian et al., 2006). Bei.X (2005) solved the PMU placement problem with a specific budget using binary integer programming (BIP). This paper also investigated the sensitivity of the state estimator to the elimination of a PMU number. The general formulation for the PMU placement problem was discussed using integer linear programming (ILP) for complete or partial observability with or without ZIB in Bei.G (2008). Dua et al. (2008) proposed a solution to the multi-stage PMU placement problem in a given time constraint using ILP. Antonio.A.B (2001) solved the OPP problem with a simple objective function for complete observability and minimum cost using the metal plating method. Nuqui (2005) used a metal plating method to reduce the depth of unobservability (DOU) for a practical PMU placement problem. Zhao et al. (2005) solved the OPP problem for system observability by the deployment of PMUs at sensitive buses using a metal plating method.

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2. Materials and Methods

The OPP problem is aimed to select a strategy to minimize the number of PMUs used, to ensure complete system observability by these optimal locations, as well as to provide arbitrary system replaceability conditions.

2.1. OPP Problem Formulation

A PMU installed at a bus can measure the voltage phasor of that bus as well as the current phasor of all adjacent branches of that bus. Hence, the whole system can be made observable by deploying PMUs at all buses. Nevertheless, as mentioned earlier, this is not cost-effective due to high PMU purchasing and installation costs. The PMU placement problem in this study aims to minimize the number of PMUs that makes the entire system observable as well as to maximize alternative measurement in the system.

Hypotheses and Network Bus Reduction: Some hypotheses must be considered when designing this problem. These hypotheses reduce the complexity of the problem but do not diminish its accuracy. The following are information processing methods.

Complete Observability: It is a well-known fact that the purpose of choosing a substation for PMU installation is to obtain the necessary measurements. It is assumed that all voltages and currents within the substation are measured; in general, observability means that the voltage phasor of all buses and the phasor current of all branches are specified.

Bus Reduction: Buses within a substation, connected to the same voltage, are directly connected to each other via a switch or breaker. These buses can be assembled in a similar bus with all its connections without any problems.

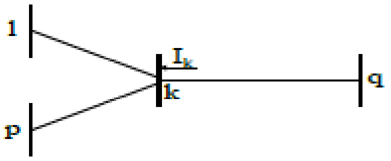
2.2. Problem Constraints

The explanation of the nonlinear constraints of the problem comes from our information on the location and deployment of measurements in the system. Complete observability means that the voltage phasors of all buses and the current phasors of the branches connected to the buses are specified. This study investigated a method for generating constraint equations based on system topology according to the following three cases:

1. Only measured by PMU
2. PMU meter and injection meter, which can be zero injection or power injection.
3. The most general case is a combination of the three above, namely the combination of PMU meter, power injection, and flow meter.

Zero-Injection Bus (ZIB): A ZIB is a bus through which no power or current is injected into the system [19]; in other words, no active or reactive load is associated with the bus. ZIBs is equivalent to the switching substations in the power system. The total number of PMUs is reduced for the observability of the power system if these buses are modeled on the PMU placement problem.

Power Injection Meter: By considering an injection meter in the *k*th bus, one unit is reduced from the observability constraints.



Power Injection Meter

It should be noted that power injection meter modeling in the OPP problem is equivalent to (or similar to) ZIB modeling in the network. As a result, the power injection meter and ZIB constraints are quite similar.

Flowmeter: If a flowmeter is deployed on the *j-i* line, if one bus is observable, the other becomes observable too. So, we can write:

Flowmeter

This means that the observability of buses i and j are determined by this meter and the observability of other network buses must be covered by the OPP.

2.1. Observability with Regard to Injection and Flow Meters

For a system consisting of injection and power meters, the most general case is to perform PMU placement until we have complete observability of the system. Injection meters, either a power injection meter or a zero-injection meter, are treated similarly. There are two different ways to bring injection meters into computation, namely topological transformation, and nonlinear constraint functions. This thesis uses the topological transformation method. In this method, the bus containing injection measurements can be merged with one of the buses around it. It should be noted that PMUs can be deployed at either or both PMUs on both buses if the solution chooses the merged bus (i.e., the combination of two buses) (Ahmadi, 2011).

The OPP problem does not have a single solution using the basic objective function. The optimization algorithm may achieve different solutions by minimizing the number of similar PMUs. For this reason, the Total System Observability Redundancy Index (TSORI) or the total system observability index, and alternative measurements, are used as constraints to solve the OPP problem. A bus is called observable if it has been measured at least once directly or indirectly through PMUs.

2.2. Selecting the Objective Function of the Problem

We define the objective function of the problem so as to satisfy the following objectives:

$$\min\,[n_{\mathrm{PMU}}] \tag{1}$$

$$\max\,[\mathbf{b}\,,\mathrm{TSORI}] \tag{2}$$

Given the constraints above in the equation:

where:

b: Number of buses with an alternative measurement index of 1 or more.

TSORI: Total System Observability Index.

n_{PMU}**:** Number of PMUs installed on the system.

Given the above, the cost function used in this study is defined as follows:

$$F(X) = w_2 * X^T * X - w_1 * b - C * Z \tag{3}$$

$$Z = \sum_{i=1}^{n} AX \tag{4}$$

where:

Z: Total System Observability Index (TSORI).

The more Z and b are maximized, the more minimized the objective function becomes.

b is the number of buses with an alternative measurement index of 1 or more. For example, if you have a BOI (Bus Observability Index) as follows:

$$BOI = [0\quad 1\quad 0\quad 2\quad 1\quad 3\quad 0] \Rightarrow$$

$$measuremen\,redundanc\,y(X) = [0\quad 0\quad 0\quad 1\quad 0\quad 2\quad 0] = BOI - 1$$

$$b = 2$$

The more b is maximized, the more minimized the objective function becomes.

The first term, $X^T * X$, is equal to n_{PMU}, aiming to minimize n_{PMU}.

Notice that X is our solution matrix. If PMU is installed at bus *i*, it is 1 and otherwise, it is 0.

Figure 1 shows the flowchart of the PMU placement optimization problem using the proposed BPSO algorithm.

Table 1 shows the values selected for the parameters of the BPSO algorithm. It should be noted that these values are selected after running the program several times, taking into account the best solutions, and the least runtime.

Table 1. BPSO Parameters and Objective Function

Parameter	**Value**
Population Size	$5*N_{bus}$
Personal Learning Factor (C_1)	6.66
Social Learning Factor (C_2)	20
Number of Iterations (itmax)	500
W_1, W_2, C (objective function coefficients)	0.01, 1, 0.001

3. Results and Findings

The OPP suggested in this study is coded by MATLAB R2013a using the BPSO algorithm. The system used to run the above program has the following specifications:
Processor: Intel(R) Core (TM) 2Duo T8100 @ 2.1GHz
Installed Memory (RAM): 4GB
Windows Edition: Windows 7 Ultimate

The proposed objective function and the tested BPSO algorithm are deployed and run on standard IEEE 14 bus, IEEE 30 bus, and IEEE 57 bus systems.

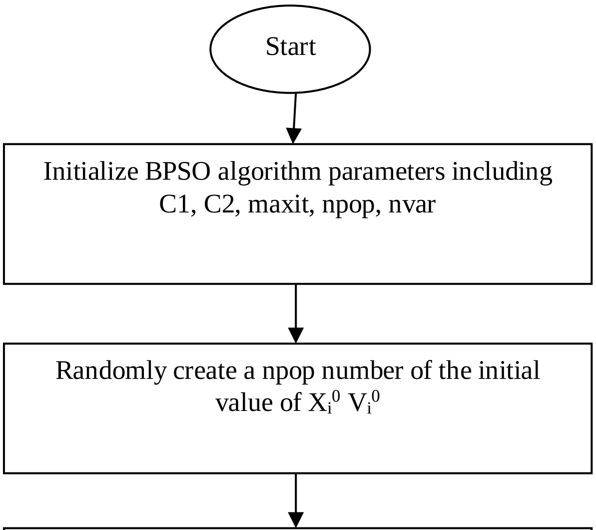
Table 2. Three Scenarios Examined

First Case	Investigating the proposed objective function using BPSO algorithm in normal network mode without ZIB and meters on IEEE 14 bus, IEEE 30 bus, and IEEE 57 bus systems
Second Case	Investigating the proposed objective function using the BPSO algorithm, considering ZIB, and comparing the first case on IEEE 14 bus, IEEE 30 bus, and IEEE 57 bus systems

Figures 1, 2, 3 show the standard IEEE 14 bus, IEEE 30 bus, and IEEE 57 bus networks, respectively.

3.1. First Case

In this case, the OPP problem is resolved an investigated without considering ZIB constraints as well as traditional meters. Table 3 shows the problem-solving for the IEEE 14 bus network. After 15 times running the program, all runs resulted in a single solution, which is shown in Table 3. As discussed in Chapter 3, the concept of alternative measurement is the number of times each bus is observed more than once whose results are presented in Table 4. In the cost function, we use the number of buses with an alternative measurement equal to 1 and more.



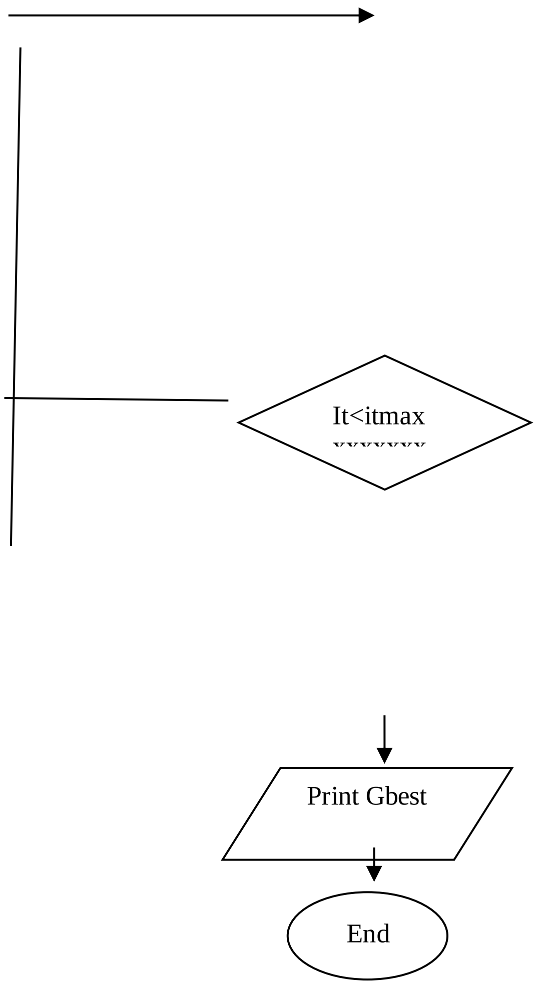


Diagram 1. OPP Flowchart Using BPSO

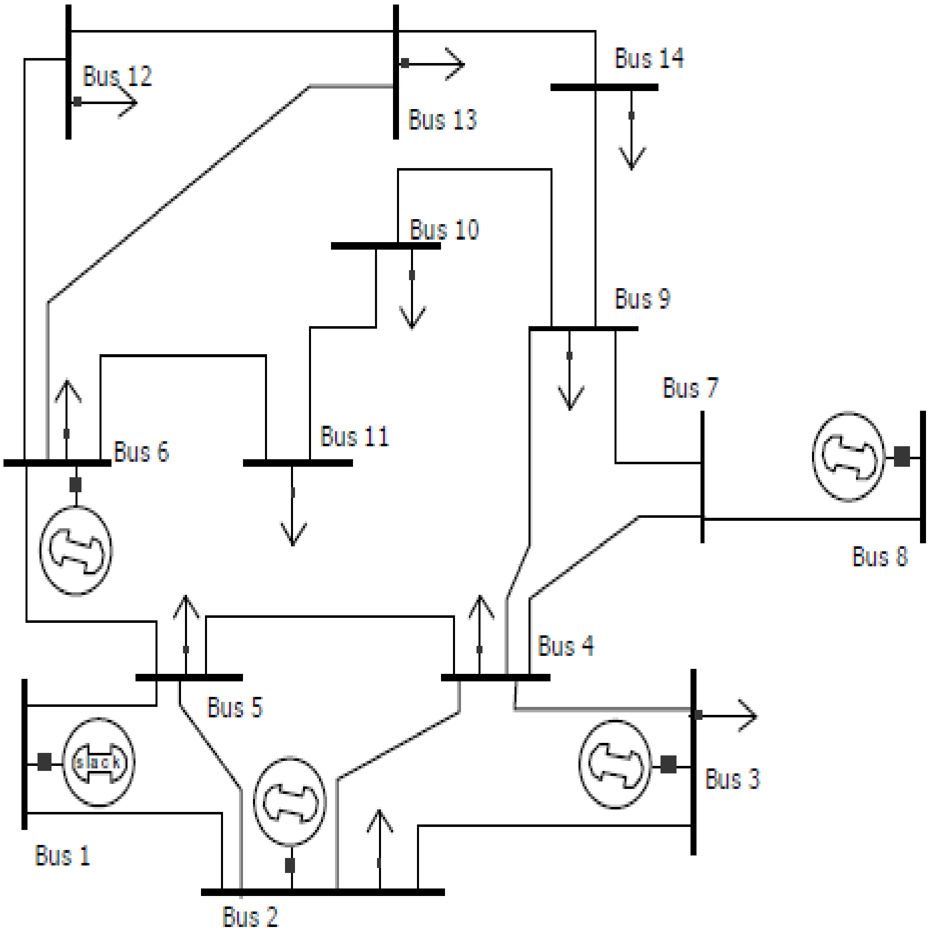


Figure 1. Standard IEEE 14 Bus Network

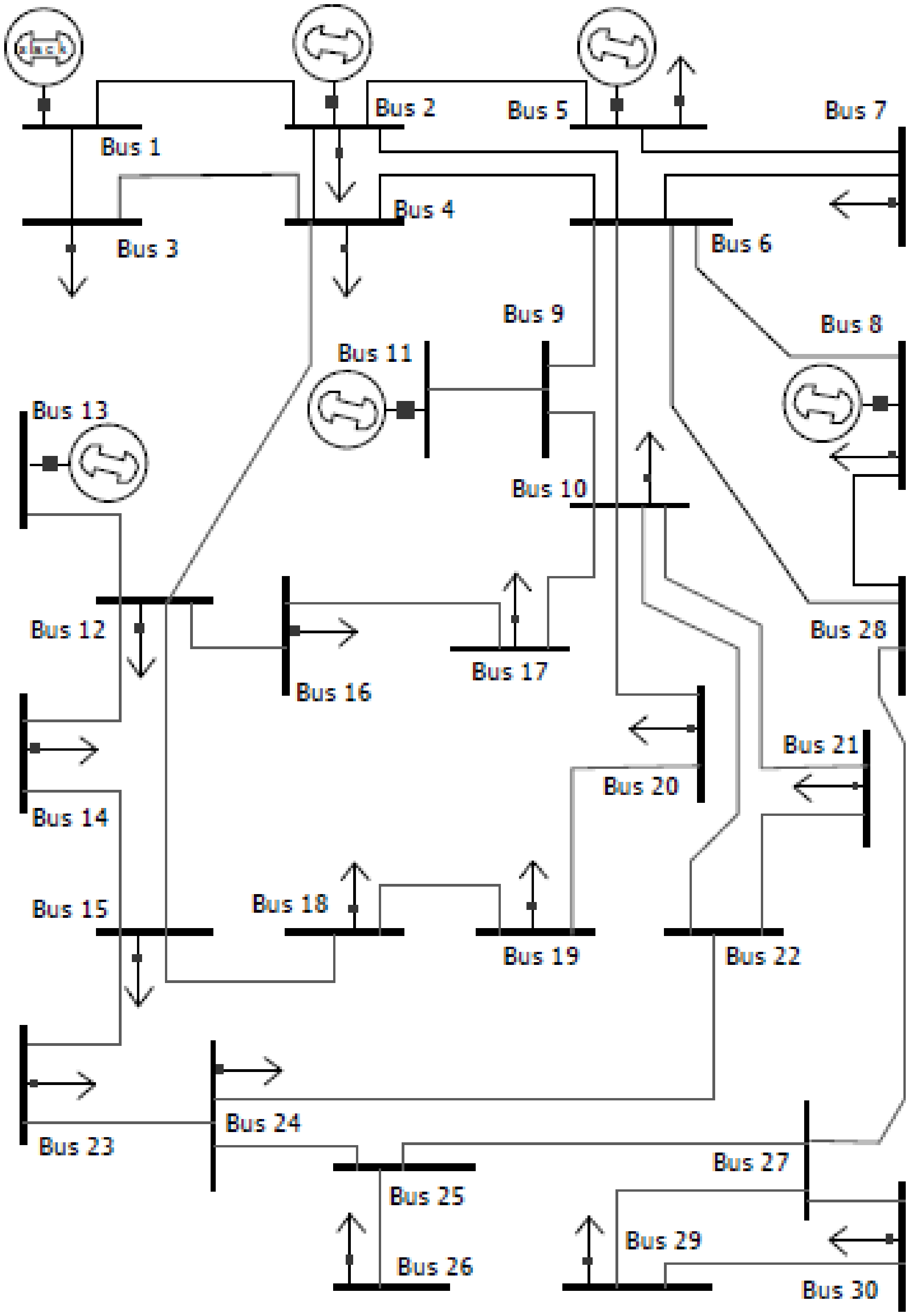


Figure 2. Standard IEEE 30 Bus Network

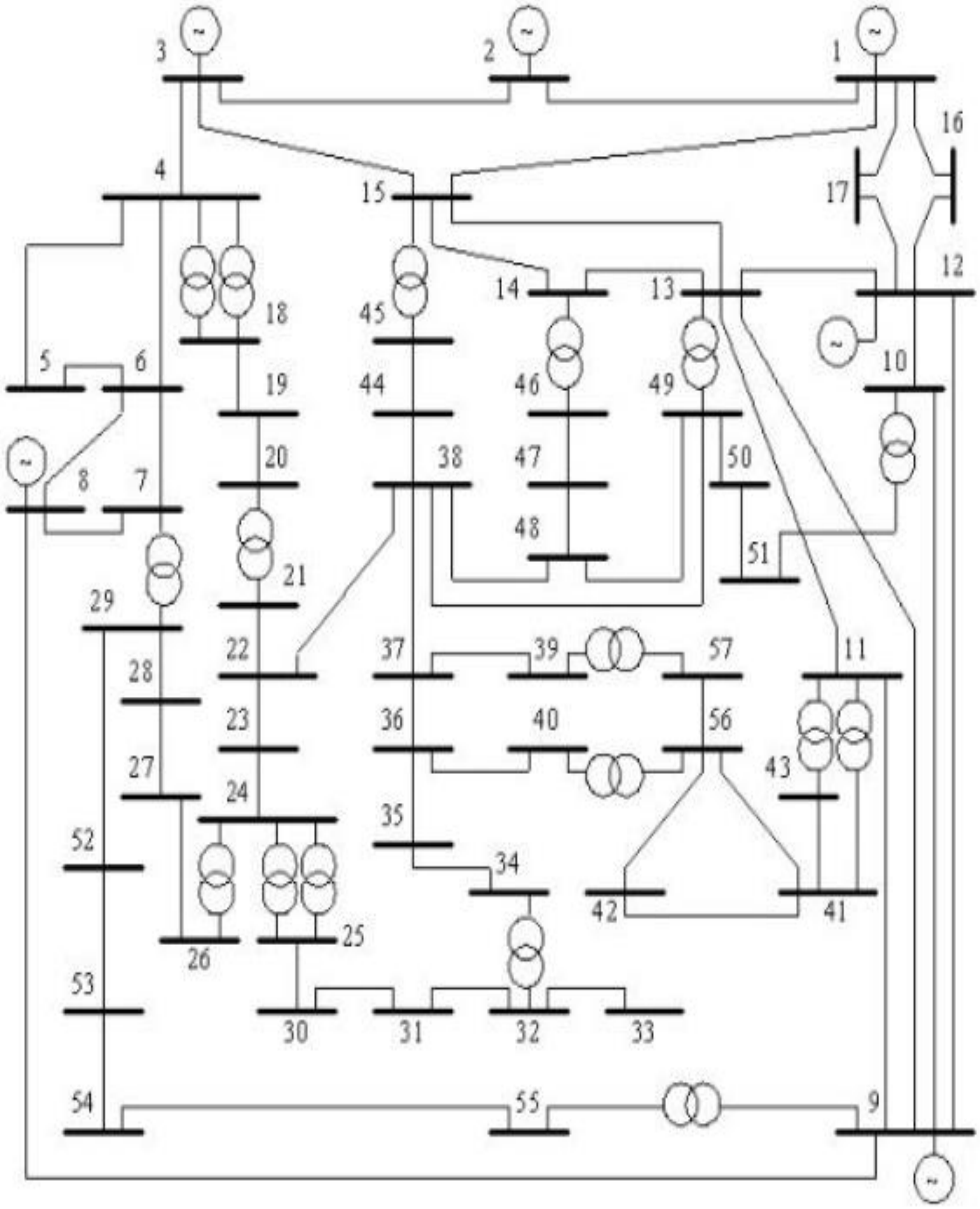


Figure 3. Standard IEEE 57 Bus Network

The greater the alternative measurement, the more reliable the network is, meaning that, if a PMU is lost, a larger portion of the network remains observable.

Table 3. The Solution to the OPP Problem for the IEEE14 Bus Without Zero Bus

No. of PMUs	Location of PMUs	No. of times each bus is observed by PMUs (BOI)														TSORI	No. of buses observed more than once
		1	2	3	4	5	6	7	8	9	10	11	12	13	14		
4	2, 6, 7, 9	1	1	1	3	2	1	2	1	2	1	1	1	1	1	19	4

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Table 4. Alternative Measurement Analysis for the IEEE14 Bus Without Zero Bus

No. of PMUs	Location of PMUs	Alternative Measurement														No. of buses observed more than once
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	
4	2, 6, 7, 9	0	0	0	2	1	0	1	0	1	0	0	0	0	0	4

Figure 4 shows the best cost in different iterations without ZIB.

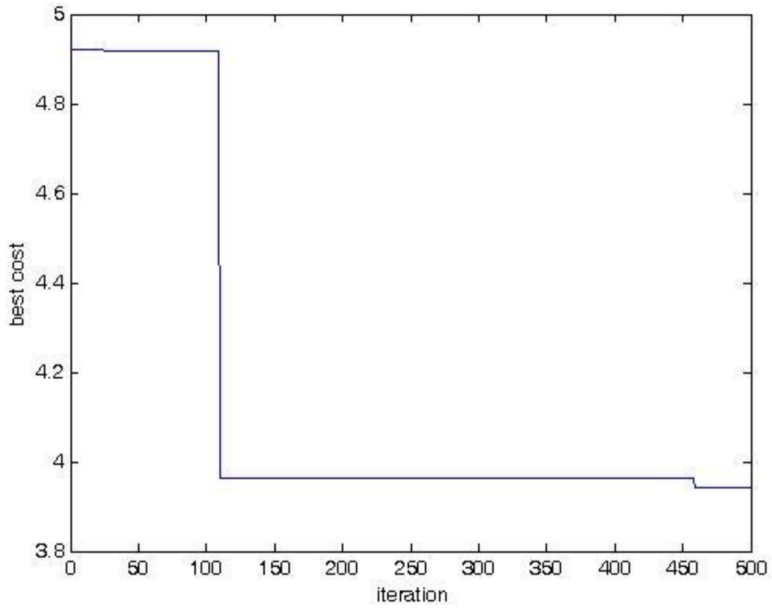

Figure 4. The Best Cost in Different Iterations for the IEEE14 Bus Network

Table 5 shows the problem-solving method for the IEEE 30 bus and its results. As can be seen, the two groups have the same TSORT solution as well as the same number of buses more than once observed. These two solution groups can be used depending on the network needs and in terms of system exploitation. For example, the designer has to decide whether he/she wants to have an equal alternative measurement at bus 2 and 4 (i.e., first case), or whether bus 4 is very important and he/she wants to have an alternative measurement equal to 3 and bus 2 has an alternative measurement equal to 1. Table 6 shows the alternative measurement index for each bus.

Table 5. The Solution to the Placement Problem for the IEEE30 Bus Without Zero Bus

No. of PMUs	Location of PMUs	No. of times each bus is observed by PMUs (BOI)										TSORI	No. of buses observed more than once
10	1, 2, 6, 9, 10, 12, 15, 19, 25, 27											50	14
10												50	14

	2, 3, 6, 9, 10, 12, 15, 19, 25, 27			

Table 6. Alternative Measurement Analysis for the IEEE30 Bus Without Zero Bus

No. of PMUs	Location of PMUs	Alternative Measurement	No. of buses observed more than once
10	1, 2, 6, 9, 10, 12, 15, 19, 25, 27		14
10	2, 3, 6, 9, 10, 12, 15, 19, 25, 27		14

Figure 5 shows the best cost in different iterations without ZIB for the IEEE30 bus network.

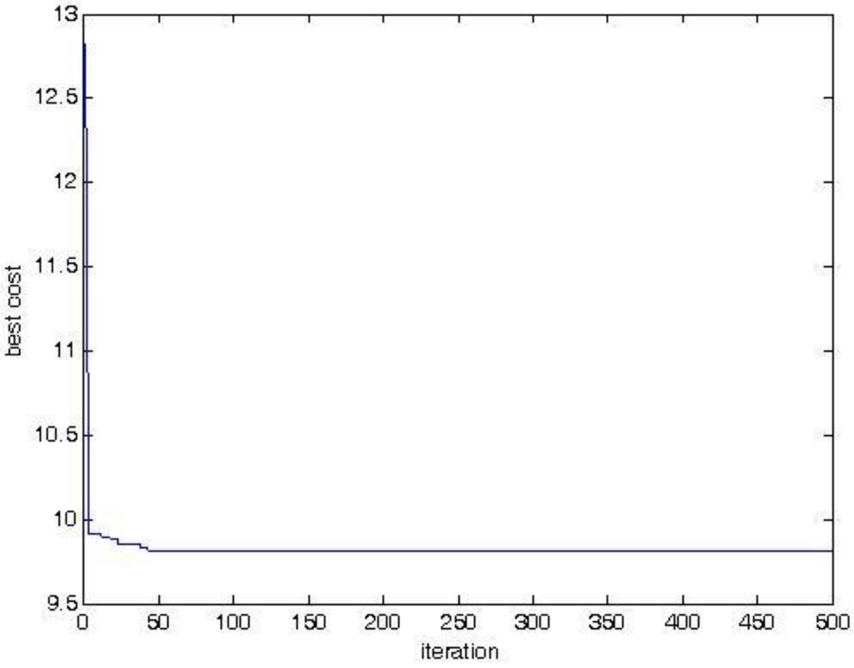

Figure 5. The Best Cost in Different Iterations for the IEEE30 Bus Network

The OPP problem was solved for the IEEE 57 bus network whose results are presented in Table 7. As can be seen, after 15 runs, 9 solution sets were selected which were better than the other runs. As can be seen, the first and second rows are the best solutions with TSORI equal to 72, the number of alternative measurements 1 and above equal to 15.

Table 7. The solution to the Placement Problem for the IEEE57 Bus Without Zero Bus

No. of PMUs	Location of PMUs	TSORI	No. of buses observed more than once
17	1, 4, 6, 9, 15, 20, 24, 30, 28, 32, 36, 38, 41, 46, 50, 53, 57	72	15
17	1, 4, 6, 9, 15, 20, 24, 30, 28, 32, 36, 38, 41, 46, 50, 53, 57	72	15
17	1, 4, 6, 9, 15, 20, 24, 30, 28, 32, 36, 38, 41, 47, 51, 53, 57	71	14
17	1, 4, 7, 9, 15, 20, 24, 27, 30, 32, 36, 38, 41, 46, 51, 53, 57	71	14
17	1, 4, 9, 15, 20, 24, 28, 29, 31, 32, 36, 38, 41, 46, 50, 54, 57	71	14
17	1, 6, 9, 15, 19, 22, 24, 28, 30, 32, 36, 38, 41, 47, 51, 53, 57	71	14
17	1, 4, 9, 15, 20, 22, 26, 29, 30, 32, 36, 38, 41, 46, 51, 53, 57	71	14
17	1, 4, 7, 9, 15, 20, 24, 25, 27, 32, 36, 38, 41, 47, 51, 53, 57	71	14
17	1, 4, 9, 15, 19, 22, 26, 30, 29, 32, 36, 38, 41, 46, 50, 53, 57	71	14

Figure 6 shows the best cost in different iterations without ZIB for the IEEE57 bus.

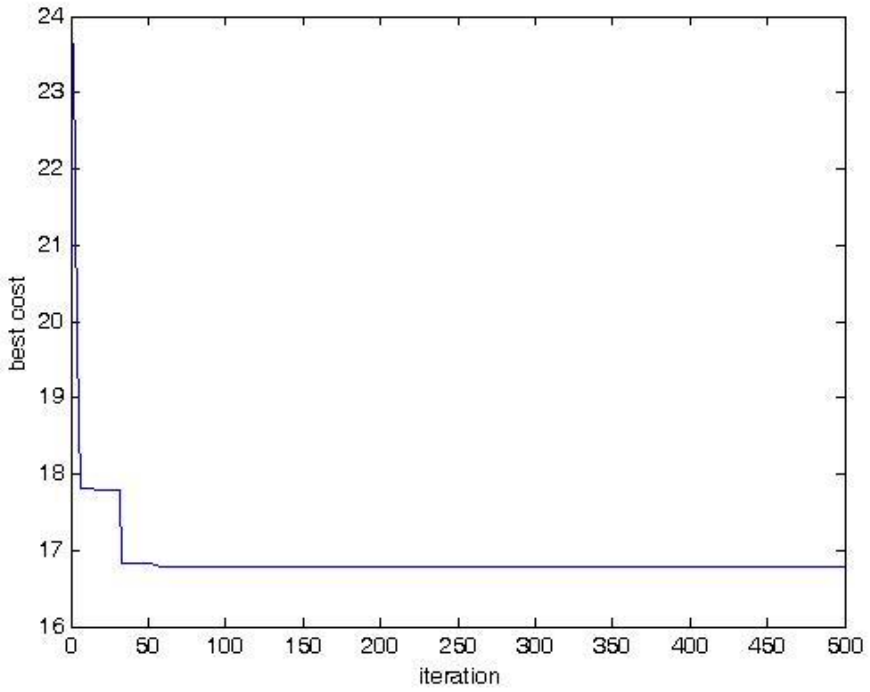

Figure 6. The Best Cost in Different Iterations Without ZIB for the IEEE57 Bus Network

Table 8 shows the optimal solutions altogether.

Table 8. Optimal Solutions for the Tested Networks Without ZIB

IEEE Network	Minimum PMU Value	Location of PMUs	TSORI
14 bus	4	2, 6, 7, 9	19
30 bus	10	2, 1, 6, 9, 10, 12, 15, 19, 25, 27	50
57 bus	17	1, 4, 6, 9, 15, 20, 24, 25, 28, 32, 36, 38, 41, 47, 51, 53, 57	72

Table 9 shows a comparison between the results of previous work and those of the proposed method in this study.

Table 9. A Comparison Between Previous Methods and the Proposed Method Without ZIB

Algorithm	Tested Network		
	14 bus	30 bus	57 bus
Proposed Method	4	10	17
Genetic Algorithm (GA) [30]	4	10	16
BPSO [13]	4	10	17
Differential Evolution (DE) [31]	4	10	17

3.2. Second Case

In this case, the placement problem is solved and investigated with zero-injection constraints. Table 10 shows the solution to the placement problem for the IEEE 14 bus network. It reaches a single solution after 15 runs. Comparing with Table 3, we can see that the number of PMUs has decreased from 4 to 3 with ZIB constraint.

Table 10. The Solution to the Placement Problem for the IEEE14 Bus

No. of	Location of PMUs	No. of times each bus is observed by PMUs (BOI)														TSORI	No. of buses observed more than once
		1	2	3	4	5	6	7	8	9	10	11	12	13	14		
3	2, 6, 9	1	1	1	2	2	1	1	1	1	1	1	1	1	1	16	2

Figure 7 shows the best cost in different iterations with ZIB for the IEEE14 bus.

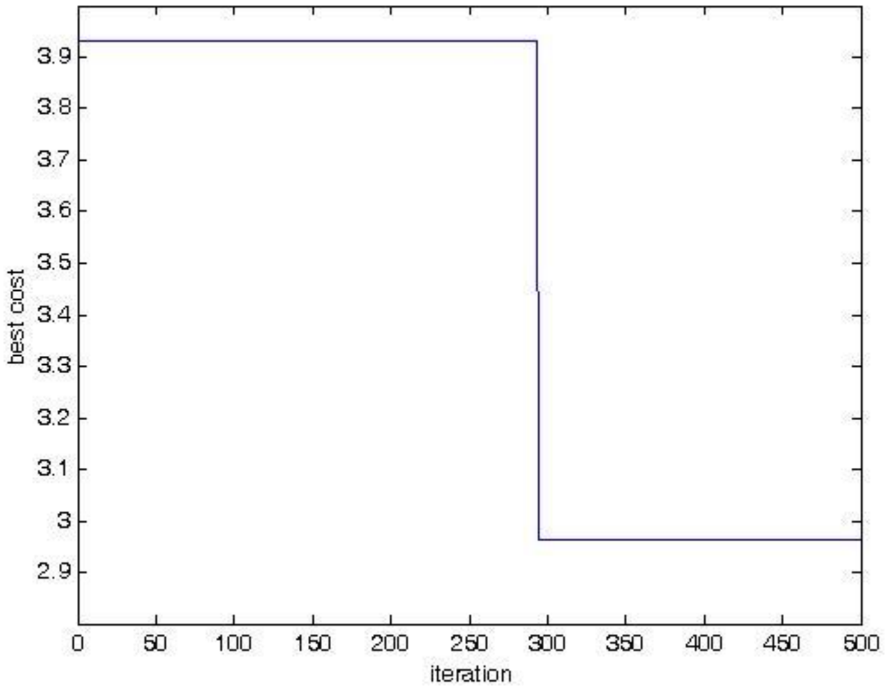

Figure 7. The Best Cost in Different Iterations with ZIB for the IEEE14 Bus Network

The placement problem is solved with ZIB for the standard IEEE 30 bus network whose results are presented in Table 11. As can be seen, we obtained 2 solutions after 15 runs that are the same for TSORI and the number of buses with alternative measurements equal to 1. Thus, choosing each solution depends on the designer's view and the constraints such as the cost per substation, the importance of each substation, and the importance of line observability, despite the loss of a PMU.

Table 11. Results of IEEE30 Bus Problem Solving with Zero Injection

No. of PMUs	Location of PMUs	No. of times each bus is observed by PMUs (BOI)										TSORI	No. of buses observed more than once
7	2, 4, 10, 12, 19, 24, 27											39	7
7	2, 4, 10, 12, 18, 24, 27											39	7

Figure 8 shows the best cost in different iterations with ZIB for the IEEE30 bus network.

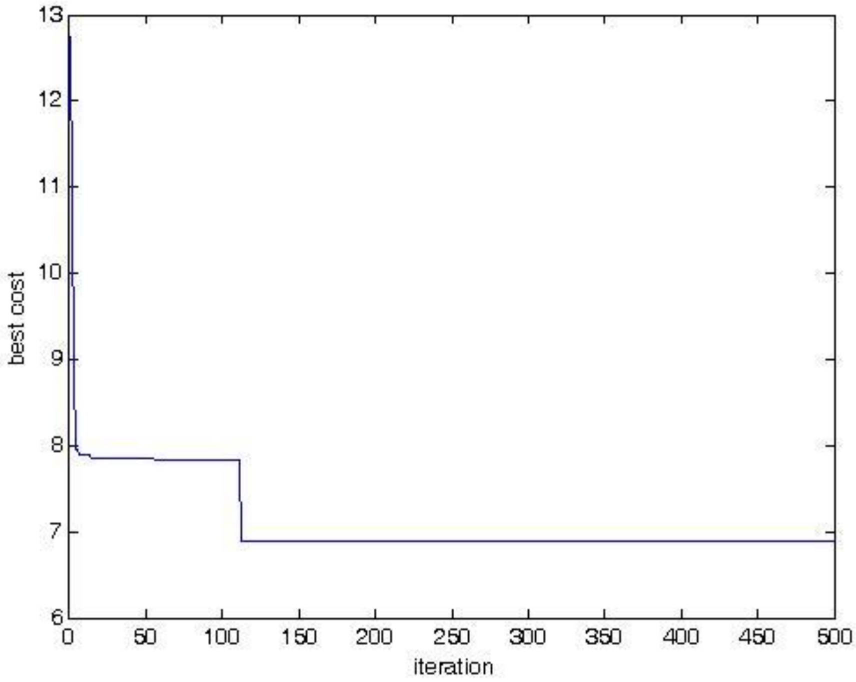

Figure 8. The Best Cost in Different Iterations with ZIB for the IEEE30 Bus Network

Table 12 solved the OPP problem for the standard IEEE 57 bus network. As can be seen, the first and fifth rows contain the number of PMUs, TSORI, and the number of buses with alternative measurements equal to 1 and more. Each of the two solutions can be selected according to the network user needs and design requirements.

Table 12. Results of IEEE57 Bus Problem Solving with Zero Injection

No. of PMUs	Location of PMUs	TSORI	No. of buses observed more than once
12	1, 3, 9, 10, 15, 20, 28, 30, 32, 49, 53, 56	68	9
12	1, 3, 9, 14, 20, 28, 30, 32, 38, 50, 53, 56	63	5
12	1, 6, 9, 10, 15, 19, 27, 30, 32, 49, 53, 56	66	8
12	1, 3, 9, 14, 19, 27, 30, 32, 38, 51, 53, 56	62	5
12	3, 9, 12, 15, 20, 28, 30, 32, 49, 50, 53, 56	68	9
12	1, 3, 9, 10, 15, 19, 25, 28, 32, 49, 53, 56	67	8

Table 13 shows the best solutions with and without ZIB, and Table 14 shows the locations of PMUs for the best solutions obtained with and without ZIB.

Table 13. Optimal Solutions for the Tested Networks with ZIB

IEEE Network	Minimum PMU Value	Location of PMUs	TSORI
14 bus	3	2,6,9	16
30 bus	7	2, 4, 10, 12, 19, 24, 27	39
57 bus	12	1, 3, 9, 10, 15, 20, 28, 30, 32, 49, 53, 56	68

Table 14. A Comparison Between Previous Methods and the Proposed Method with ZIB

Algorithm	Tested Network		
	14 bus	30 bus	57 bus
Proposed Method	3	7	12
Genetic Algorithm (GA) [30]	3	7	12
BPSO [13]	3	7	13
Matrix Reduction [32]	3	8	12
Integer Linear Programming (ILP) [1]	3	7	14

4. Discussion and Conclusion

The meta-subjective methods are very useful for solving the PMU placement problem. For this reason, it was decided to use its binary type, one of the most popular ones, i.e., the Particle Swarm Optimization (PSO) method. The advantages of the PSO method include simplicity, ease of use, insensitivity to the objective function, less independence from the basic parameters, higher speed, and more efficient computation than other algorithms. Nonetheless, some of the serious problems with such methods include high computational time, increased computation with an increasing number of solutions (i.e., number of buses), and complexity of constraints. MATLAB was used to solve OPP problems. This study first considered the ZIB constraint that was observed to reduce the number of PMUs in the selected standard networks because PMUs are installed for a variety of reasons, including cost and operating constraints at different times and overtime. The next constraint considered was the traditional measurement constraint in the system. The OPP problem was solved by this constraint for the standard IEEE57 network. As expected, the number of PMUs also declined due to this constraint.

Acknowledgments
All that I am or ever hope to be, I owe to my angel mother and sisters

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