



SORI applied to optimal placement of PMU for complete system observability

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Abstract—The growing world population and the increase in electricity consumption, triggered growing demand for reliable electricity. The network transmission and distribution plays an essential role in power systems for transmitting power from producers to customers. In order to avoid events such as the loss of electricity, poor quality of energy and instability in different parts of the power transmission network, it is very useful to install the PMU which provides better monitoring the power grid using measurements taken in real time in order to eliminate those events. The PMU installation at all stations can significantly improve the reliability of the electric grid. However, investment is quite high. Therefore, the optimal placement of the problem was PMU focuses on a new angle of research interest in the supply network in recent years. The proposed work determines the minimum number of PMUs and its placement, while maximizing the system observability in normal operating condition. In this paper , the concept of the System Observability Redundancy Index (SORI) will be introduced. A network with higher SORI value indicates that the monitoring system is more reliable. The simulation results were represented for the IEEE Standard 14 and 30 bus system.

Index Terms—Phasor measurement units, observability, optimal PMU placement, System Observability Redundancy Index (SORI), binary PSO, adjacent branches.

I. INTRODUCTION

Based on GPS synchronized clock, the phasor measurement unit can measuring a vast amount of network information critical power, which includes the speed of the generator, the power angle, bus voltage, current bus. By receiving information in real time measurement PMU on wide areas, operators of the central control room can monitor and analyze the quality of the distribution network under conditions of static and dynamic operation.

In 1990 Phasor Measurement Unit (PMU) has been introduced. It provides synchronized measurements in real time phasor bus voltages and branch currents. Synchronicity among PMU is achieved by simultaneously sampling the voltage and current waveforms by means of

a common synchronization signal from the global positioning system (GPS). obtaining phasors from different bus of a power system at the same space-time can improve the monitored control system performance various application areas such as state estimation and stability analysis [1]. In references [2] and [3] A description of phasor measurement technology and its present and potential future applications in the power system is well documented.

The investment approach PMU should be accomplished within the framework of two important considerations: the cost of investment and full observability of the network. Thus, the problem of optimal placement PMU (OPP) concerns where and how much PMU should be installed on a power system to achieve full network observability with minimum number of PMU, due to the fact that each box PMU measure bus voltage and currents along the lines of incident for [4] bus. the formulation of the observability analysis can be carried out by two groups of techniques: digital or topological algorithms (topological or graphical observability) . In recent years, several methods are presented to find the minimum and the optimal placement of PMUs to a power supply system completely observable as simulated annealing [5] , genetic algorithm [6], asTabu research [7] particles swarm optimization [8], combined with simulated annealing Tabu search [9]. In [10], the OPP problem was addressed by the non-dominated sorting genetic algorithm (NSGA) .A development of an optimal placement algorithm for PMU using integer programming in documents [11, 12].

This paper is organized as follows. Section II presents the proposed formulations of optimal placement of PMU.. In Section III, binary particule swarm optimization is described. Simulations results for Case studies and analysis of results are given in Section IV, and Section V concludes the paper.

II. FORMULATION OF OPTIMAL PMU PLACEMENT PROBLEM

A. PMU placement rules and measurements

A PMU is capable of measuring the voltage phasor installed bus and current phasors of some or all the lines connected to that bus. Figure 1 illustrates a wide area measurement system from phasor measurements synchronisées. The placement of PMUs may use the following rules [13], [14] :

- Rule 1: Assign one voltage measurement to a bus where a PMU is placed, including one current measurement to each branch connected to the bus itself.
- Rule 2: Assign one voltage pseudo-measurement to each bus reached by another equipped with a PMU.
- Rule 3: Assign one current pseudo-measurement to each branch connecting two buses where voltages are known. This allows interconnecting observed zones.
- Rule 4: Assign one current pseudo-measurement to each branch where current can be indirectly calculated by the Kirchhoff current law (KCL).

This rule applies when the current balance at a bus is known.

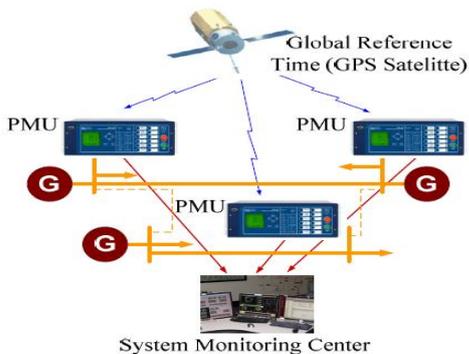


Figure.1. Wide area measurement system based on synchronized phasor measurements.[13].

The observability conditions that have to be met for selecting the placement of PMU sets are [13], [14],:

- Direct measurements:

Condition 1: For PMU installed at a bus, the bus voltage phasor and the current phasors of all incident branches are known.

- Pseudo-measurement

Condition 2: If one end voltage phasor and the current phasor of a branch are known, then the

voltage phasor at the other end of the branch can be calculated.

Condition 3: If voltage phasors of both ends of a branch are known, then the current phasor of this branch can be directly obtained.

- Extension-measurements

Condition 4: If there is a zero-injection bus (ZIB) without PMU and the current phasors of the incident branches are all known but one, then the current phasor of the unknown branch can be calculated using KCL.

Condition 5: If the voltage phasor of a ZIB is unknown and the voltage phasors of all adjacent buses are known, then the voltage phasor of the ZIB can be obtained through bus voltage equations.

Condition 6: If the voltage phasors of a set of adjacent ZIBs are unknown, but the voltage phasors of all the adjacent buses to that set are known, then the voltage phasors of ZIBs can be computed by bus voltage Equations.

B. System observability redundancy index SORI

The redundancy index is an important factor for representing the stability of the power network In optimal PMU placement. After applying the optimization algorithm, a multiple number of optimum solutions being available. Maximum bus observability index (MBOI)[15] will be implemented to indicate the performance on quality of optimization. In MBOI_i at bus-i, can be defined as the number of PMUs which are able to observe a given bus. Consequently, the MBOI is limited to maximum connectivity (mci) of a bus-i plus one:

$$MBOI_i \leq mci + 1 \quad (1)$$

In order to select the most favorable results from a number of optimal solutions obtained using different optimization methods, system observability redundancy index (SORI) which is defined as a measure of the sum of the bus coverage for all the implemented bus ($i = 1$ to n) in an active system. Much more SORI value indicates that the monitoring system based on PMU is more reliable. Therefore, the best method of optimization is selected based on the SORI [16]. the SORI can be calculated using Equation (1) and (2).

$$SORI = \sum_{i=1}^n MBOI_i \quad (2)$$

C. Domination set and case study

An example of a 6-bus system with domination set has been simplified in Figure.2.

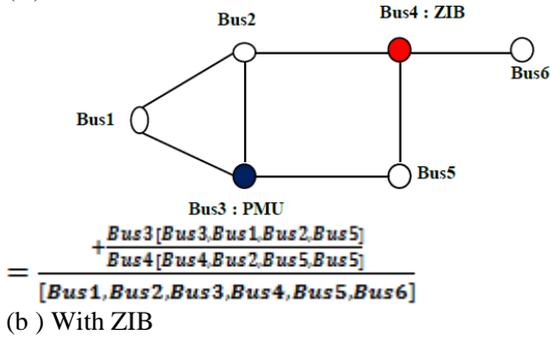
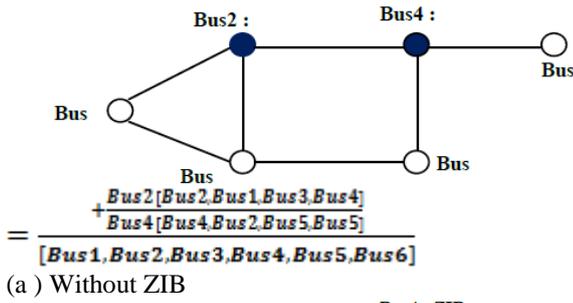


Figure .2-Bus system with network fully observed. (a) Without ZIB. (b) With ZIB

Firstly, the equation (3) shows the way of generating the connectivity matrix A, as follows:

$$a_{i,j} = \begin{cases} 1 & \text{if } i = j \text{ or } i \text{ and } j \text{ are connected} \\ 0 & \text{if otherwise} \end{cases} \quad (3)$$

$$A = \begin{bmatrix} 1 & 1 & 1 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 0 & 0 \\ 1 & 1 & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix} \quad (4)$$

The $\inf(a_{ij})=a_{64}=1$, it means that the bus 4 covers a single connection bus who is bus6.

The zero injection bus (ZIB) of this power system is :

$$ZIB = [0 \ 0 \ 0 \ 1 \ 0 \ 0] \quad (5)$$

In (5) , ‘1’ means that the corresponding bus is a zero injection bus, while ‘0’ means the other way.

Table 1.Maximum connectivity (mc) of 6-bus system

Bus	mc	Buses connected
1	2	Bus2, bus3
2	3	Bus1, bus3,bus4
3	3	Bus1, bus2,bus5
4	3	Bus2, bus5,bus6
5	2	Bus3, bus4
6	1	bus4

Table 2.Infomation of 6-bus system

System	Branch number Nb	ZIB number	Location ZIB
6-bus	7	1	4

Table 3.optimum PMU and placement with and without ZIB

	Syst em	ZIB	SORI	N _{PMUs}	PMUs Location
With ZIB	6-b		8	2	2,4
Without ZIB	us	4	4	1	3

III. BINARY PARTICLE SWARM OPTIMIZATION

A. Particule swarm optimization(PSO)

PSO was inspired by the behaviour of bird blocks and fish Schools, and it was first developed by Kennedy and Eberhart in 1995. PSO covers a swarm of particles that fly through hyperspace problem solution. Each particle in the swarm implies a location matrix and a speed matrix. The position array is a possible solution to this problem, while the speed array is used to adjust the position of matrix in each iteration, and the speed itself is also adjusted in each iteration. Equations (6) and (7) show the mechanism of conventional iterative PSO.

$$V_i(t + 1) = w \times V_i(t) + c_1 \times ran_1 \times (p_i - X_i(t)) + c_2 \times ran_2 \times (p_g - X_i(t)) \quad (6)$$

$$X_i(t + 1) = X_i(t) + V_i(t + 1) \quad (7)$$

In (6) and (7) V is the velocity array, X is the position array, i is particle number, t is iteration number, c₁ and c₂ are acceleration coefficients, ran₁ and ran₂ are stochastic numbers arranged between 0 and 1, p_i is the historical best position of particle i, p_g is the historical best position of the whole swarm. In each iteration, constraint conditions are assessed for each particle and the objective function is calculated for those satisfying particles. The best positions p_i and p_g here are derived according to this calculation. When a new position that can minimize the objective function better than p_i is derived by particle i, p_i should be replaced with that position. Similarly, if a new position that can minimize the objective function better than p_g is derived by any particle in the swarm, p_g should be replaced with that position. In this iterative method, the movement of each particle in the solution hyperspace evolves to an optimal or near-optimal solution [17],[18].

B. Binary Particule Swarm Optimization (BPSO)

For the PMU placement problem, the table of a position X particles PSO algorithm gives PMU information installation location. This is a set of binary bits of the lengthn the number of buses in the target power system. Value '1' a bit means an installation of PMU to the corresponding bus, while the value "0" means no installation of the PMU corresponding bus. In this case, instead of conventional PSO, a the version of the binary PSO algorithm must be used, which is interpreted by (8) and (9) [18],[19]

$$V_{ij}(t + 1) = w \times V_{ij}(t) + c_1 \times ran_1 \times (p_{ij} - X_{ij}(t))$$

$$+c_2 \times \text{ran}_2 \times (p_{gj} - X_{ij}(t)) \tag{8}$$

$$X_{ij}(t+1) = \begin{cases} 1, & \text{if } f(x) = A * x \geq \hat{I} \\ 0, & \text{if otherwise} \end{cases} \tag{9}$$

where:

f(x): is a vector function, whose entries are non-zero if the corresponding bus voltage is solvable using the given PMU placement set and zero otherwise.

The entries of binary connectivity matrix A are defined in equation (3).

\hat{I} , is a vector whose entries are all equal to one.

Here j denotes the number of the element in an array, which is as well the number of the bus in the target power system.

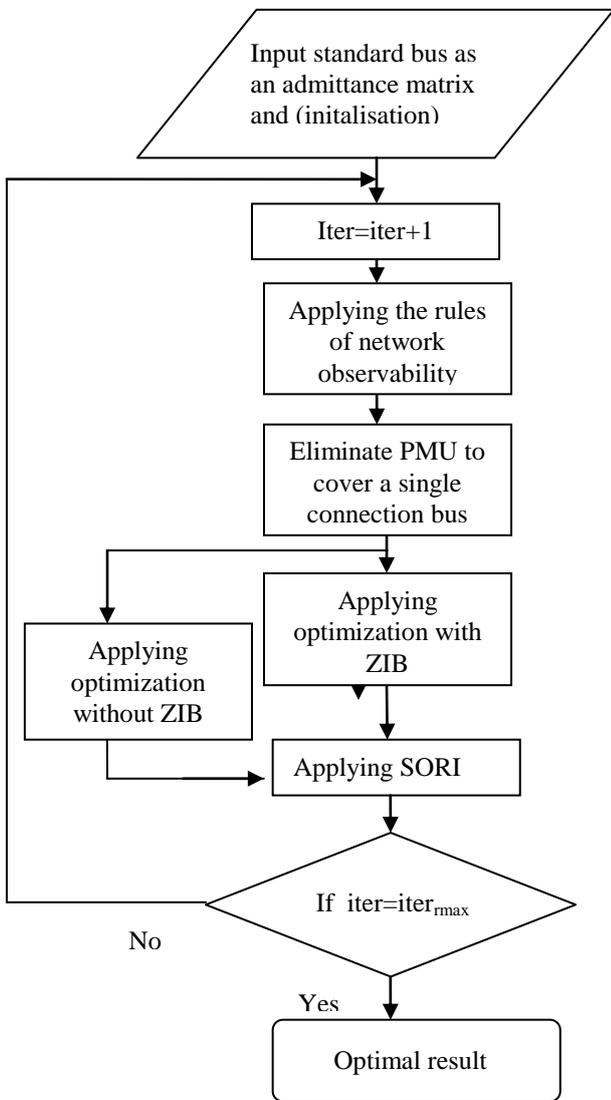


Figure 3. Flowchart of the binary PSO

Thus the placement of multi-objective model PMU formulated with two main objectives. The main raw objective is the maximization of reliability observability of the system. The second main objective is the minimization of the number of PMU. The PMU assumed to be identical; so minimizing the number of PMUs will result in cost minimization. Therefore, the objectives of PMU minimization and reliability of observability maximization are in conflict. To resolve the conflict, relative weights to be assigned to each objective combine two contradictory objectives functions in one programming model objective function . The objective function in binary PSO algorithm is defined as:

$$\text{Max } w_1(SORI_j) + w_2(\sum_{i=1}^n x_{ij})^{-1} \tag{10}$$

Where SORI is given in (2), n is the total number of buses to be placed in the system and wi defines the weight associated to each objective and sum of wi is equal to one.

IV. SIMULATION RESULTS

The proposed PMU placement method is applied to the IEEE 14-bus and 30-bus systems [20]. The single-line diagrams of the test systems are shown in Figs. 4 and 5.

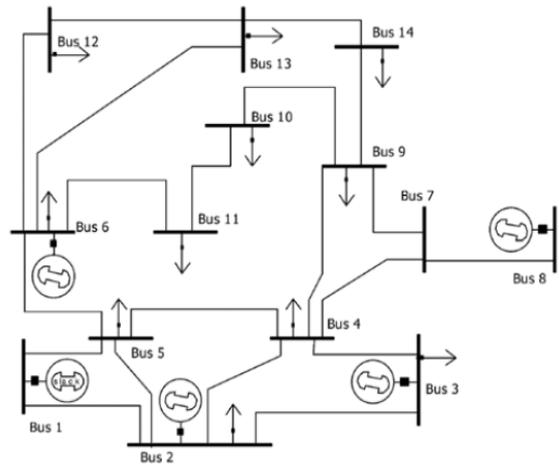


Figure 4. IEEE 14-bus test system [20]

Table 4. Information of 14-bus system

System	Branch number Nb	ZIB number	Location ZIB
14-bus	20	1	7

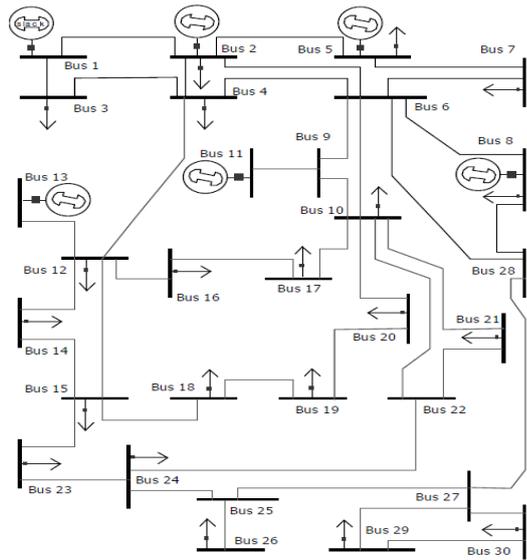


Figure 5.. IEEE 30-bus test system [20]

Table 5. Infomation of 30-bus system

System	Branch number Nb	ZIB number	Location ZIB
30-bus	41	5	6,9,11,25,28

With maximum iteration number set to 200 and swarm size set to 100, feasible solutions of the proposed PMU placement method, with consideration of the System Observability Redundancy Index (SORI), are shown in table 6 and table 7 for IEEE 14-Bus and IEEE 30-Bus respectively.

Table 6. Optimum PMU and placement with and without ZIB for IEEE 14-bus system

	ZIB	SORI	N _{PMUs}	PMUs Location
With ZIB		19	4	2,6,7,9
		16	4	2,7,10,9
		16	4	2,7,11,13
Without ZIB	7	12	3	2,6,9

Table 7. Optimum PMU and placement with and without ZIB for IEEE 30-bus system

	ZIB	SORI	N _{PMUs}	PMUs Location
With ZIB		51	10	2,4,6,9,10,12,15,18, 25,27
		51		2,4,6,9,10,12,15,19, 25,27
		44		1,4,5,9,10,12,15,18, 25,27
		49		2,3,6,9,10,12,15,18, 25,27
		51		2,4,6,9,10,12,15,20, 25,27
Without ZIB	6,9,1 1,25, 28	33	7	2,4,10,12,20,24,29
		33		2,4,10,12,20,24,30
		33		2,4,10,12,19,24,29

	33	2,4,10,12,19,24,30
	33	2,4,10,12,20,24,29

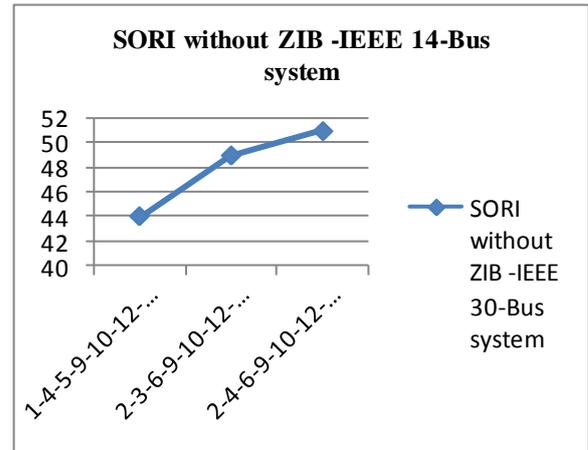


Figure 6. .SORI without ZIB for IEEE 14-Bus system.

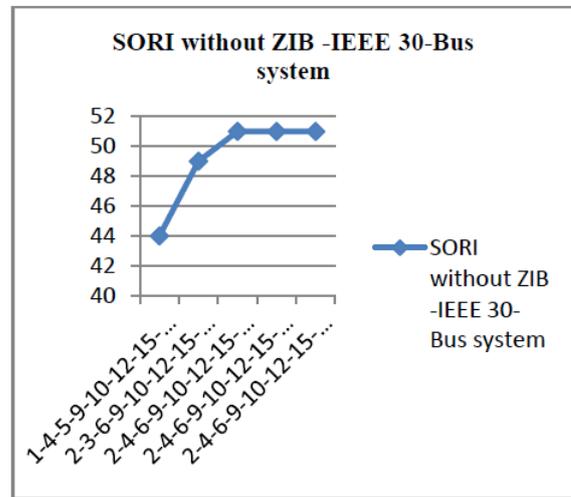


Figure 7. .SORI without ZIB for IEEE 30-Bus system

Figures 6 and 7 show the variation OUT according to the different locations of PMUs. they show the best placements corresponding to the maximum values of SORI for full observability of IEEE 14-bus system and IEEE 30-Bus without ZIB.

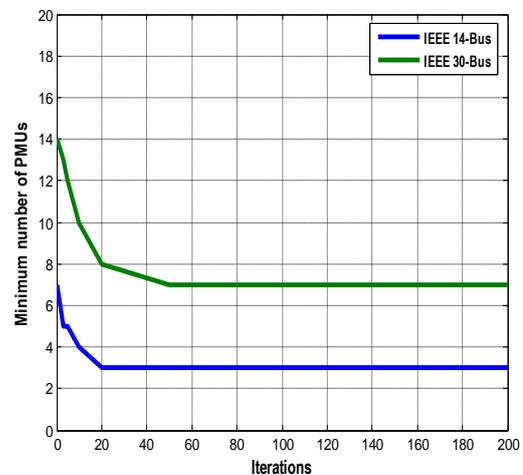


Figure 8 .Convergence achieved by PSO with ZIB

Figure 8 illustrates the optimal number of obtained PMU, which is 3 and 7 for the two systems considered IEEE 14-Bus 30 and IEEE-bus respectively with consideration of ZIB.

V. CONCLUSION

Due to the increasing development of power systems, control and protection systems requirements are more complex. In recent years, the theory of synchronized measurement of phase angle verified that brings a profound advantage in real-time protection network. Moreover, with the device of the phasor measurement unit, these applications will improve, in reality, power monitoring, control and protection. In this paper, we tried to ensure that the number of PMU needed to oversee the electrical network is minimal with complete observability of the electrical network, the installation on less than PMU can be transferred into the combinatorial optimization problems. BPSO was introduced. To summarize, it was found that this method of optimization is able to successfully deal with the optimal PMU placement problem.

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