Improved BPSO for Optimal PMU Placement

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***Abstract*-Optimal phasor measurement unit (PMU) placement involves the process of minimizing the number of PMU needed while ensuring entire power system network completely observable. This paper presents the improved binary particle swarm (IBPSO) method that converges faster and also manage to maximize the measurement redundancy compared to the existing BPSO method. This method is applied to IEEE-30 bus system for the case of considering zero-injection bus and its effectiveness is verified by the simulation results done by using MATLAB software.**

***Index Terms*-- binary, measurement redundancy, particle swarm optimization, phasor measurement unit**

I. INTRODUCTION

Phasor measurement unit (PMU) is a measurement device that has became popular because of its measurement ability that can provide synchronized phasor measurements. This ability allows one to measure the state of the system in real-time, which most electric utility companies cannot get it through state estimation that is currently deployed. The real time data it provides is extremely accurate since the PMU itself is equipped with a GPS receiver. Thus, every data it gets are time-stamped down to microseconds which encourage better monitoring of power system operational state. Furthermore, it allows the operator engineer to detect, anticipate and correct problems during irregular system conditions. These advantages could prevent the biggest blackout in North American history, which one of the causes was by the lack of real-time data that allowed the operator engineer to correctly execute contingency plans they had. Hence, the idea of having a power system being monitor by PMU is seen as an attractive solution.

However, PMU itself comes with an expensive price tag. It is not an economy savvy solution to have it installed at every bus in the power system. In spite of that fact, thorough studies that have been made in recent years, have proven that a power system can be made observable with a small number of PMUs depending on the size of the power system. Hence, the objective of PMU placement is mainly focuses on finding the minimum number of PMUs required and its placement in a power system that can achieve full observability of the network.

There were so many studies that have been made in recent years that investigated various algorithms to utilize PMU measurements in a power system. Simulated Annealing (SA) method was used to solve the pragmatic communication constrained PMU placement problem. Reference [1] combined SA method and graph theory to develop an algorithm that managed to minimize the size of the PMU set and ensured the observability of the system. Integer Linear Programming (ILP) method is one of the methods that has been extensively researched over the years. Reference [2], easy analysis of network observability for mixed measurement sets based on conventional measurement was proposed by adapting the ILP approach. After, it was enhanced in [3] by topology transformation concept based on the merging process of zero-injection bus and one of its neighbors. Apart from finding the minimum number of PMUs required, some studies have expanded their research by considering the single PMU loss and also maximum measurement redundancy. Reference [4] considered maximum measurement redundancy and also extended it to consider a practical limitation on the maximum number of PMU channels. Meanwhile, a case of considering the single PMU loss was overcome in [5] by multiplying the inequality for every constraint with two which ensure every bus will be monitored by at least two PMUs.

Particle swarm optimization (PSO) method is also increasingly popular in recent years due to its simplicity to implement. In a case of PMU placement problem, a binary version of PSO (BPSO) was successfully used in many studies to address the optimization problem. In [6] [7], BPSO was used to minimize the number of PMU required and maximize the measurement redundancy. An improved BPSO method was proposed by [8] to avoid pre-mature convergence and also increased chances of better exploration of the search space. Reference [9] combined SA and BPSO method to improve particles' search speed and also its convergence rate. Reference [10] proposed a new rule that was added into a modified PSO algorithm and managed to further reduced the number of PMUs required by incorporating zero-injection bus in its study.

This paper proposes an improvement to the existing BPSO method that converges faster while maximizing the measurement redundancy to its solution. This paper is organized into six sections including this section. Section II explains the rules that are used to deal with PMU placement. Section III describes the PSO and BPSO method including equations used in the proposed method. The proposed improvement for IBPSO is presented in Section IV while Section V demonstrates the proposed method on IEEE-30 bus system. Section VI concludes this paper by highlighting the key elements and also the contribution of this paper.

II. PMU PLACEMENT RULES

For power system to achieve full observability, the voltage phasor of all its buses must be known. A bus in the power system is identified as observable if its voltage can be directly measured or calculated by using other known bus voltage and branch currents. Voltage phasor and all adjacent branch currents of a bus that has PMU installed can be directly measured by the PMU. Meanwhile, by using indirect measurements, bus that neighbour to PMU installed bus can have its voltage phasor and branch currents value known through calculation by using Ohm's law and Kirchoff's Current Law (KCL).

Following are the observability rules that explore the indirect measurement circuit theory used in this paper to identify bus as observable.

1. If the voltage phasor at one end and current phasor of a branch is known, the voltage phasor at the other end can be calculated.
2. If the voltage phasor of both ends are known, the current phasor of a branch can be calculated.
3. In case of zero-injection bus, if all current phasor of branches that adjacent to zero-injection bus are known except one, then the current phasor of the unknown branch can be computed using KCL.
4. If the voltage phasor of zero-injection bus is unknown, it can be calculated using node voltage equations if the voltage phasor of all adjacent buses to it are known.
5. The value of voltage phasor for a set of adjacent zero-injection bus can be calculated if voltage phasor of all buses that incident to the set are known by using node voltage equations.

Zero-injection bus mentioned in rules 4 and 5 above is a bus that has no injection current injected into it. Thus, by applying KCL at zero-injection bus, the current phasor that entered a zero-injection bus is exactly the same with the current phasor leaving it.

III. PARTICLE SWARM OPTIMIZATION (PSO)

PSO is a population based optimization method that was inspired by social behavior of bird flocking or fish schooling [11]. The individuals (particles) in this group (swarm) will be flying across the search space to find the optimal solution for the problem under consideration. The particles will adjust their positions based on their own experience and also the experience of neighboring particles over the time they are moving. The experience for each particle is based on the previous location and velocity they had before moving to a better position. Each particle changed their position in continuous PSO based on (1) below:

$$x_{ij}^{t+1} = x_{ij}^{t} + v_{ij}^{t+1} \tag{1}$$

x_{ij}(t) and x_{ij}(t+1) are the position vectors of i^{th} particle in j^{th} dimension at time t and t+1 respectively while v_{ij}(t+1) indicates the velocity vector of the particle.

The velocity vector in (1) is computed based on the experience of individual particles and also other particles within the swarm. Equation (2) is used to update the velocity vector for continuous PSO.

$$v_{ij}^{t+1} = \omega v_{ij}^{t} + c_1 r_1 \left(pbest_{ij}^{t} - x_{ij}^{t}\right) + c_2 r_2 \left(gbest^{t} - x_{ij}^{t}\right) \tag{2}$$

ω is the inertia weight, c_1 and c_2 are the learning rate of which the particle converge at its own best and global best particle respectively. r_1 and r_2 are two random values that is uniformly distribute in the range 0 to 1. The value of *pbest* and *gbest* are evaluated based on fitness function that will be explained later, *pbest* indicates the best position of particle i^{th} that it has found so far at iteration *t* while *gbest* is based on the best position of all particles' best position. The value of ω used in this paper was linearly decreased for each iteration to create balance between local and global exploration which is a common practice. Equation (3) is used to calculate the value of inertia weight in this paper.

$$\omega = (\omega_1 - \omega_2) \times \frac{(t_{max} - t)}{t_{max}} + \omega_2 \tag{3}$$

ω_1 and ω_2 will hold maximum and minimum inertia value which is 0.9 and 0.4 respectively. t_{max} is the number of maximum iterations and *t* is current iteration. Equation (3) ensures the optimization process starts with global search and towards the end will settle to local search.

The binary PSO approach that was introduced in [12] will be used to solve the optimization problem. In BPSO, position vector *x* can only accept one (PMU is installed) or zero (PMU is not installed) to indicate PMU placement at respective bus. With the help of sigmoid function, the position vector *x* is updated by using (4) which will decide based on the value of velocity vector of each particle for each iteration. Following is the equation that will replace (1) to update position vector *x*:

$$x_{ij}^{t+1} = \begin{cases} 1 & if\ r_{ij} < sig(v_{ij}) \\ 0 & otherwise \end{cases} \tag{4}$$

r_{ij} is random number between [0,1] while $sig(v_{ij})$ is a sigmoid function defined as follows:

$$sig(v_{ij}) = \frac{1}{1 + e^{-v_{ij}}} \tag{5}$$

In this paper, the fitness function in [13] will be used to find a minimal number of PMUs that guarantees full observability of the power system and maximum measurement redundancy. The fitness function, *J(x),* is formulated as follows:

$$J(x) = \left(w_1 \times \sum_{k=1}^{N} f_i\right) + (w_2 \times N_{PMU}) + (C \times j_1) \tag{6}$$

Parameter w_1, w_2 and C are three weights value. $\sum_{k=1}^{N} f_i$ represents the number of observable bus, N_{PMU} is the total number of PMUs and j_1 is the measurement redundancy. N_{PMU} and j_1 can be defined as follows:

$$N_{PMU} = X^T X \tag{7}$$
$$j_1 = (M - AX)^T (M - AX) \tag{8}$$

M is the target value for measurement redundancy. If the target value for measurement redundancy is 2, the vector M will be set to 3.

IV. PROPOSED IMPROVEMENT FOR IBPSO

This paper proposed improvement that can be applied to BPSO method that is explained in Section III to get quick convergence while maintaining power system full observability and having maximum measurement redundancy. The improvement that can be considered is by reducing the search space for the particle to fly. Since the initialization was made randomly as defined in (4), it would be better to reduce the search space to encourage more feasible solutions to be found during the initialization process. Excluding radial bus from the potential solutions and pre-assigned PMU at its neighbor are two great ways to encourage more feasible solutions to be found during the initialization. Buses that are adjacent to pre-assigned PMU are guarantee observed according to the PMU placement rules described in Section II earlier, hence those buses will also be excluded from the candidate solutions of PMU placement. Radial bus is a bus that has only one bus connected to it. Consider Fig. 1 below, bus 5 is a radial bus because it only connects to one bus, which is bus 4. In this case, PMU will be pre-assigned at bus 4. Next, bus that adjacent to bus 4 which is bus 3 and bus 5 will be excluded from the potential PMU placement.

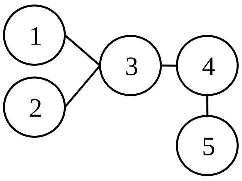

Fig 1 Modelling radial bus and proposed improvement

V. CASE STUDY

The improvement for IBPSO explained in this paper was applied to IEEE-30 bus system shows in Fig. 2. Table I shows the value of each parameter used to run the simulations.

As can be seen from Fig. 3, IBPSO converges faster than BPSO to the optimal solution during simulation. IBPSO converges at iteration 13 compared to BPSO which converges at iteration 37.

TABLE I PARAMETERS USED FOR BPSO

Parameters	Value
Number of particles	$10{*}N_{\text{bus}}$
Individual acceleration constant (c_1)	2
Social acceleration constant (c_2)	2
Maximum number of iterations, t_{max}	$5{*}N_{\text{bus}}$
Maximum inertia weight, ω_1	0.9
Minimum inertia weight, ω_2	0.4
C	0.01
w_1	-2
w_2	1
M	3

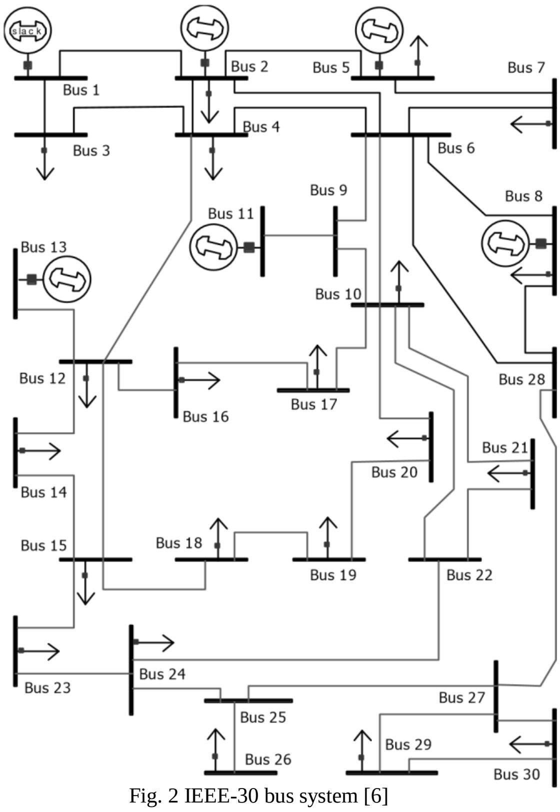

Fig. 2 IEEE-30 bus system [6]

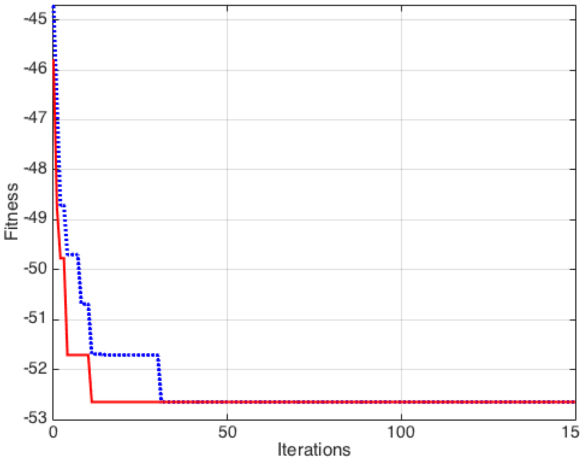

Fig 2 Comparison of convergence rates between IBPSO (solid line-red) and BPSO (dotted line-blue)

TABLE II BPSO PMU PLACEMENT SETS

No. of PMUs	PMUs Location	BOI	SORI
7	1,5,10,12,19, 23,27	1,2,1,1,1,1,1,1,1,1,1,1,1,1,2,1,1, 1,1,2,1,1,1,1,1,1,1,1,1,1	33
7	1,5,10,12,18, 24,27	1,2,1,1,1,1,1,1,1,1,1,1,1,1,2,1,1, 1,1,1,1,2,1,1,2,1,1,1,1,1	34
7	3,5,10,12,18,24, 27	1,1,1,2,1,1,1,1,1,1,1,1,1,1,2,1,1, 1,1,1,1,2,1,1,2,1,1,1,1,1	34

TABLE III IBPSO PMU PLACEMENT SETS

No. of PMUs	PMUs Location	BOI	SORI
7	3,5,10,12,19, 24,27	1,1,1,2,1,1,1,1,1,1,1,1,1,1,1,1,1, 1,1,2,1,2,1,1,2,1,1,1, 1,1	34
7	1,5,10,12,19, 24,27	1,2,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1, 1,1,2,1,2,1,1,2,1,1,1,1,1	34
7	1,2,10,12,18, 24,27	2,2,1,2,1,2,1,1,1,1,1,1,1,1,2,1,1, 1,1,1,1,2,1,1,2,1,1,1,1,1	37

Table II and Table III show three PMU placement sets including their Bus Observability Index (BOI) and also Summation of Redundancy Index (SORI) for BPSO and IBPSO respectively. BOI shows the number of times the buses in IEEE-30 bus system are observed by PMU. Meanwhile, SORI shows the sum of BOI for a system. Large value signifies the quality of the PMU placement set. All PMU placement sets are obtained by minimizing the number of PMUs required for full observability of power system while also maximizing the measurement redundancy.

The optimal PMUs placement set for BPSO is either {3,5,10,12,18,24,27} or {1,5,10,12,18,24,27} since the value of SORI for both placement set are the same and have maximum value among the three PMU placement set which is 34. Meanwhile, the optimal PMU placement for IBPSO is {1,2,10,12,18,24,27} since it holds the maximum value of SORI which is 37. Thus, the proposed improvement holds the best optimal solution since it converges faster and carries the largest value of SORI compared to BPSO.

VI. CONCLUSION

This paper shows that reducing the search space helps the particles to converge faster and managed to give the optimal number of PMUs needed while maintaining the power system observability. The high value of measurement redundancy (SORI) proves the effectiveness of this method. The exclusion of radial bus and pre-assigning a PMU to its neighbor helps to achieve the objective of this paper. In a nutshell, the main contribution of this paper lies during the initialization phase since it manages to reduce the search space for particles to explore hence accelerates convergence.

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