Optimal Placement of Phasor Measurement Units for Transmission Grid Observability

Md Shafiullah*, Md Juel Rana, Md Shafiul Alam
Electrical Engineering Department
King Fahd University of Petroleum & Minerals
Dhahran, Saudi Arabia
*shafiullah@kfupm.edu.sa

Muhammad Athar Uddin
Department of Electrical & Electronic Engineering
International Islamic University Chittagong
Chittagong, Bangladesh
mau_iiuc@yahoo.com

Abstract—**Phasor Measurement Unit (PMU) provides both magnitude and phase information of current and voltage signals with appropriate time stamp which is very useful in controlling power system networks in real time. Consequently, PMU is considered as one of the most significant measurement devices for complete observability of the future electricity grids. But placing PMU in every bus of the network is not economically viable. This paper aims to place PMUs in different buses of electric network to ensure full network observability employing five evolutionary, colony and swarm optimization algorithms namely backtracking search algorithm (BSA), differential evolution (DE), artificial bee colony (ABC), particle swarm optimization (PSO) and invasive weed optimization (IWO). The proposed algorithms have been tested on IEEE 14-bus, 30-bus, 39-bus and 57-bus test networks. The obtained results illustrate the compatibility of the proposed schemes in compared to each other as well as in compared to available techniques in literatures.**

Keywords— Artificial Bee Colony (ABC); Backtracking Search Algorithm (BSA); Differntial Evolution (DE); Invasive Weed Optimization (IWO); Optimal PMU Placement(OPP); Particle Swarm Optimization (PSO); Phasor Measurement Unit (PMU); Power System Observability.

I. INTRODUCTION

Due to the ever increasing demand of electricity and highly competitive electricity market conditions, the modern power system network operates to their maximum capacity; thus susceptible to instability which reduces the reliability. Therefore, it is of utmost importance to estimate the health of the power system through accurate measurements and taking control actions accordingly to prevent blackouts. State estimation is an efficient means in determining the real time states of a power system network[1]. Before the advent of time synchronized measurement technology the state estimation was dependent on traditional measurement systems. The supremacy of PMU measurement system over traditional schemes lies in its ability to provide time synchronized voltage and current measurement with an accuracy of less than 1μs with the help of advanced global positioning systems (GPS) [2]. When PMU is installed on a bus it measures the current phasors of all branches connected to that bus and voltage phasor of that bus. From the measured branch current phasors and branch parameters voltage phasor of adjacent buses can also be computed [3]. The power system is said to be observable when all the system states are observable directly or indirectly. By placing PMU on all buses the system can be made directly observable. However, it is neither economically viable because of higher cost of PMUs nor possible due to lack of communication facilities in some substations [4]. This situation creates the optimal PMU placement (OPP) problem which can be defined as the placement of lowest number of PMUs without compromising the full observability. Minimum number of PMUs in the system enhances the capability of the state estimators to extract the bad data even in the situation of measurement loss [5].

In order to solve the OPP problem various mathematical and heuristic algorithms have been reported in the literatures. Integer programming has been employed for OPP in [6], numerical methods has been used in [7] for optimal placement of PMUs. In [8] Binary search algorithm was used considering single line outage. The heuristic algorithms are widely used in solving power system optimization problems [9], [10]. The application of these approaches in solving OPP problem can not only examine the observability but also capable of overcoming some drawbacks of conventional techniques like branch outage or PMU failure [11]. The heuristic algorithm employed to realize OPP problem are genetic algorithm [12], simulated annealing [13], binary integer linear programming [14], Convex Programming [15], Tabu search [16], bacterial foraging algorithm [17].

This paper aims to compare five different heuristic and swarm optimization algorithms namely invasive weed optimization (IWO), backtracking search algorithm (BSA), artificial bee colony (ABC), differential evolution (DE) and particle swarm optimization (PSO) to obtain the system observability by installing minimum number of PMUs. The effectiveness of the algorithms has been tested on different IEEE standard test transmission networks.

II. PHASOR MEASUREMENT UNITS

Phasor measurement unit provides the magnitude and phase angle of alternating voltage or current in the power system. While extracting magnitude and phase information basic PMU assumes pure sinusoidal waveform of alternating current (AC) signals with constant frequency. The instantaneous AC signal is written as $x(t)$.

$$x(t) = |X_m| \sin(wt + \theta) \tag{1}$$

Where, $|X_m|$ and θ represent the magnitude and phase of the signal respectively. In phasor form the above signal is represented as follows:

$$\vec{X} = |\vec{X}| e^{j\theta}; \text{ Where, } |\vec{X}| = \frac{|X_m|}{\sqrt{2}} \quad (2)$$

In order to calculate the phase value of a signal at a certain power system bus k the measurement unit must possess the capability for precise measurement of zero crossing instant (t_{zck}) of AC signal as well as its reference time (T_{zcref}) [18]. The phase value of the signal with frequency f Hz is then calculated in degree as:

$$\theta_k = 360^0 f(t_{zck} - T_{zcref}) \quad (3)$$

Thanks to the high speed electronics and GPS which enables the precise measurement of zero crossing time as well as common time reference for PMU. The schematic of a basic phasor measurement unit is shown in Fig.1.

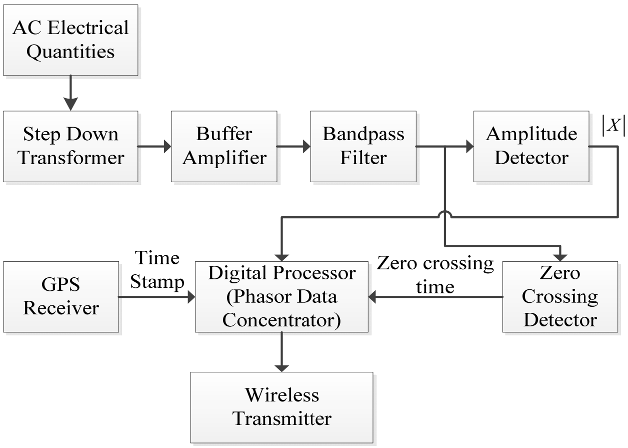

Fig.1 Schematic of PMU

The buffer amplifier along with the step down transformer is used to scale down the electrical signal as well as provide electrical isolation. All unwanted signals from the measured waveform of the signal are blocked by the band pass filter. Amplitude and zero crossing detectors provide the required information to determine the phase and magnitude of the signal. This information and the time stamp from the GPS are further processed at the phasor data concentrator to generate accurate magnitude and phase angle of the signal. Then the data are sent through wireless transmitter to system operator/central controller.

III. OPP PROBLEM FORMULATION

It is essential to have an efficient methodology which will determine minimum number of PMUs and their optimal location to make the system completely observable. For an N-bus power system the OPP problem can be formulated as follows:

$$Min\, F(x)$$

$$F(x) = \sum_{i=1}^{N} C_i n_{ij} + \sum_{i=1}^{N} W_i u_{ij} \quad (4)$$

Where, C_j is the cost for installing a PMU, n_{ij} represent binary bit for PMU installation at bus i, W_i is the penalty factor if the bus i is not observable and u_j is the binary bit to indicate bus un-observability at bus i.

Three topological observability rules have been considered for network observability analysis [5]: (i) If a PMU is installed on a bus, current phasors of all branches connected to that bus and voltage phasor of that bus are known. (ii) If voltage phasors of both ends of a branch are known then the current phasor of that branch can be obtained directly using ohm's law. (iii) If all the current phasors of the branches connected to a bus are known except one then the unknown one can be determined using Kirchhoff's current law.

IV. PROPOSED TECHNIQUES

In this paper, five well known evolutionary and swarm optimization techniques (OT) namely invasive weed optimization (IWO), backtracking search algorithm (BSA), artificial bee colony (ABC), differential evolution (DE) and particle swarm optimization (PSO) have been employed to solve OPP problem. Evolutionary algorithms (EA) work on the principle of natural biological evolution. In order to achieve better solutions EA operates on the potential populations of solutions based on the principle of survival of the fittest. The optimization starts with the randomly chosen initial population of solutions and at each generation new set of populations are generated according to their fitness in the associated problem domain. This process causes the evolution of individuals having better characteristics than their previous generation. Thus improved approximation of the solutions is obtained. The flow chart of the EA is shown in Fig. 2. The target here is to find the strategic bus location for PMUs which will minimize the objective function formulated in equation (3). The rest part of this section briefly describes the used optimization techniques.

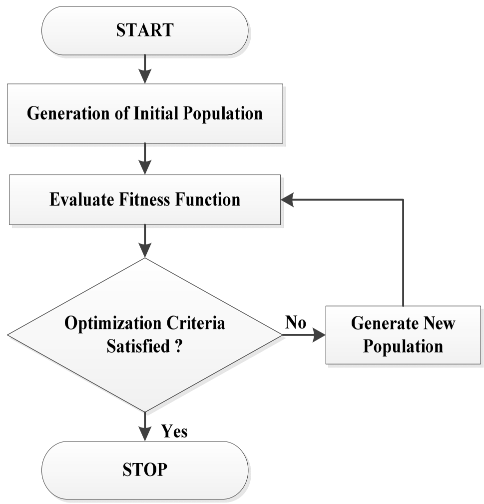

Fig.2 Flow Chart of Evolutionary Algorithm

A. *Backtracking Search Algorithm (BSA)*

BSA is a population based higher level iterative evolutionary algorithm for combinatorial optimization problems. Pinar Civicioglu proposed the algorithm in its present form in 2013 by optimizing benchmark mathematical problems[19].

Initialization of population, selection-I, mutation, crossover and selection-II are the major steps of BSA. Though BSA has huge similarity with famous optimization algorithm like GA, DE but the mutation and crossover and boundary control mechanisms are different. Details about BSA can be found in [20], [21].

B. Differential Evolution (DE)

It is an effective optimization technique for realizing all kinds of non-linear as well as multimodal functions. It was first presented by Rainer Storn and Kenneth Price in 1995. The main operators used by this method are initialization of population, mutation, crossover and selection. Strength of this optimization method lies in its fast convergence, parallel computation and easy usage [22]. Details about differential evolution can be found in [23], [24].

C. Artificial Bee Colony (ABC)

ABC is basically based on unique behavior of honey bees in searching nectar and transferring the information of availability of honey resources via waggle dance. The main parts of the algorithm are food resources, employed as well as unemployed foragers. The deciding factors for recruitment of nectar source by the bees depend on the direction, distance and quality of nectar resources. This method is capable of solving unimodal and multi-modal numerical optimization problems [25], [26].

D. Invasive Weed Optimization (IWO)

IWO is a bio-inspired stochastic optimization algorithm that mimics the natural actions of weeds in finding and settling appropriate and better places for growth and reproduction. Compared to other evolutionary algorithm IWO has its distinctive features of reproduction, spatial dispersal and competitive exclusion [27], [28].

E. Particle Swarm Optimization (PSO)

PSO is a population based technique which is based on social behavior of bird flocking. The particle denotes the individual hovered through multidimensional search space. The optimum location of an individual particle is achieved by the best solution generated by itself and its neighboring particles. Each particle moves with an primary location and velocity where velocities are bounded by the overflowing forbiddance and for not flying in the unusable fields [28], [29].

V. SIMULATION RESULTS AND DISCUSSIONS

The proposed techniques have been applied in IEEE-14, 30, 39 and 57 bus networks. Full observability of the network under normal operating condition has been considered for the simulation. The techniques have been developed in the MATLAB programming environment. Fig. 3 shows the one-line diagram of IEEE standard 14-bus test network for better understanding of the OPP problem. Optimal locations and number of PMUs required for full system observability of IEEE-14 bus system is presented in Table I for normal operating condition without any contingency. Although different algorithm provides different optimum locations after solving the OPP problem but all the algorithm give same number of PMUs for full observability of the system which is same as the existing results presented in [3].

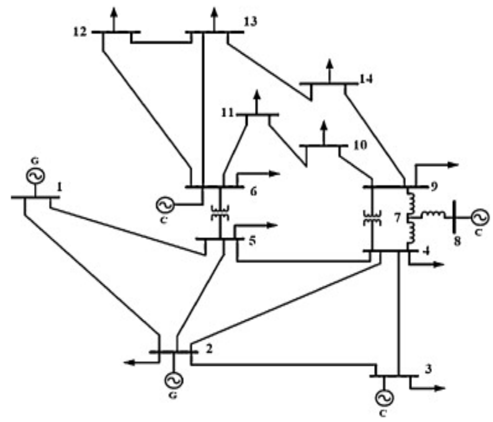

Fig. 3 IEEE-14 bus test system

Table I: IEEE-14 Bus Network

Techniques	Buses to Place PMU	Number of PMUs
BSA	2,6,7, 9	*4*
DE	2,7, 11, 13	*4*
ABC	2, 8, 10,13	*4*
IWO	2,7, 11, 13	*4*
PSO	2, 8, 10, 13	*4*
[3]	2,6,7, 9	*4*
[14]	2,6,7,9	*4*

Table II: IEEE-30 Bus Network

Techniques	Buses to Place PMU	Number of PMUs
BSA	3,5,8,10,11,12,15,18,25,27	10
DE	3,5,6,9,10,12,18,24,25,30	10
ABC	2,4,6,9,10,12,18,24,26,27	10
IWO	3,5,8,10, 11,12,19,24,25,29	10
PSO	1,6,7,10,11,12,19,24,25,30	10
[3]	2,3,6,9,10,12,15,19,25,27	10
[14]	1,7,9,10,12,18,24,25,27,28	10

Table III: IEEE-39 Bus Network

Techniques	Buses to Place PMU	Number of PMUs
BSA	2,6,9,13,14,17,19,20,22,23,29,32,37	13
DE	2,6,9,10,12,14,17,1922,23,29,34,37	13
ABC	2,6,9,10,12,14,17,1922,23,25,29,34	13
IWO	2,6,9,10,12,14,17,19,20,22,23,25,29	13
PSO	2,6,9,10,12,14,17,1922,23,25,29,34	13
[3]	2,6,9,10,12,14,17,19,20,22,23,25,29	13
[15]	2,6,9,10,13,14,17,19,20,22,23,25,29	13

Table IV: IEEE-57 Bus Network

Techniques	Buses to Place PMU	Number of PMUs
BSA	2,6,12,15,19,22,26,29,30, 32,36,38,39,41,47,50,54	17
DE	1,4,9,10,20,23,25,26,29, 32,36,41,45,46,49,53,57	17
ABC	1,4,9,19,22,25,26,29,32, 36,38,41,45,46,50,53,57	17
IWO	1,4,9,19,22,25,26,29,32, 36,38,41,45,46,50,53,57	17
PSO	2,6,12,15,19,22,26,29,30, 32,36,38,39,41,47,50,54	17
[3]	1,4,9,20,24,27,29,30,32, 36,38,39,41,45,46,51,54	17
[14]	1,4,6,10,20,23,25,27,29,32, 36,39,41,45,46,49,54	17

The optimization techniques have also been applied to solve OPP problem for IEEE-30 bus test system and the results obtained is presented in Table II. In this case the optimum number of PMUs required for system observability is 10 which matches with the results of [3] and all the algorithms give almost same optimum locations with identical number of PMUs. For IEEE-39 bus system the optimum number of PMUs is 13 as shown in Table III. Similarly, for IEEE-57 bus the optimum PMU numbers are 17 and locations for different optimization techniques are summarized in Table IV.

VI. Conclusions

This paper employs five evolutionary, colony and swarm optimization algorithms such as backtracking search algorithm (BSA), differential evolution (DE), artificial bee colony (ABC), invasive weed optimization (IWO) and particle swarm optimization (PSO) in order to make observable different power system networks. Though all the techniques do not end up with same bus numbers but give same number of PMUs to be installed for complete observability. Additionally, the available literatures also give exactly same number of PMUs are required to make the specified power networks to be observable. Furthermore, from the obtained results it could be concluded that the proposed techniques are capable enough to come up with satisfactory solutions for big or small networks.

References

[1] A. G. Phadke, "Synchronized phasor measurements in power systems," *IEEE Comput. Appl. Power*, vol. 6, no. 2, Apr. 1993.

[2] J. Bertsch, C. Carnal, D. Karlson, and J. McDaniel, "Wide-Area Protection and Power System Utilization," *Proc. IEEE*, vol. 93, no. 5, pp. 997–1003, May 2005.

[3] B. K. Saha Roy, A. K. Sinha, and A. K. Pradhan, "An optimal PMU placement technique for power system observability," *Int. J. Electr. Power Energy Syst.*, vol. 42, no. 1, pp. 71–77, Nov. 2012.

[4] F. Aminifar, C. Lucas, A. Khodaei, and M. Fotuhi-Firuzabad, "Optimal Placement of Phasor Measurement Units Using Immunity Genetic Algorithm," *IEEE Trans. Power Deliv.*, vol. 24, no. 3, pp. 1014–1020, Jul. 2009.

[5] S. A. Taher, H. Mahmoodi, and H. Aghaamouei, "Optimal PMU location in power systems using MICA," *Alex. Engr. J.*, Dec. 2015.

[6] A. Abur, "Observability analysis and measurement placement for systems with PMUs," *IEEE PES Power Systems Conference and Exposition, 2004.* IEEE, pp. 1472–1475, 2004.

[7] A. Abur, "Improved bad data processing via strategic placement of PMUs," *IEEE Power Engineering Society General Meeting, 2005*. IEEE, pp. 2759–2763, 2005.

[8] S. Chakrabarti and E. Kyriakides, "Optimal Placement of Phasor Measurement Units for Power System Observability," *IEEE Trans. Power Syst.*, vol. 23, no. 3, pp. 1433–1440, Aug. 2008.

[9] M. Shafiullah, M. S. Alam, M. I. Hossain, and M. N. Hasan, "Transient performance improvement of power system by optimal design of SVC controller employing genetic algorithm," *8th International Conference on Electrical and Computer Engineering*. IEEE, pp. 540–543, Dec-2014.

[10] M. S. Alam, M. Shafiullah, M. I. Hossain, and M. N. Hasan, "Enhancement of power system damping employing TCSC with genetic algorithm based controller design," *International Conference on Electrical Engineering and Information Communication Tech. (ICEEICT)*. IEEE, pp. 1–5, May-2015.

[11] M. Nazari-Heris and B. Mohammadi-Ivatloo, "Application of heuristic algorithms to optimal PMU placement in electric power systems: An updated review," *Renew. Sustain. Energy Rev.*, vol. 50, pp. 214–228, Oct. 2015.

[12] P. P. Bedekar, S. R. Bhide, and V. S. Kale, "Optimum PMU placement considering one Line/ One PMU outage and maximum redundancy using genetic algorithm," *The 8th Electrical Engineering/ Electronics, Computer, Telecommunications and Information Technology (ECTI) Association of Thailand - Conference 2011*. IEEE, pp. 688–691, May-2011.

[13] R. F. Nuqui and A. G. Phadke, "Phasor Measurement Unit Placement Techniques for Complete and Incomplete Observability," *IEEE Trans. Power Deliv.*, vol. 20, no. 4, pp. 2381–2388, Oct. 2005.

[14] S. Billakanti and C. Venkaiah, "An effective binary integer linear programmed approach for optimal placement of PMUs in power systems," *Smart Electr. Grid (ISEG), 2014 Int. Conf.*, pp. 1–8, 2014.

[15] S. Akhlaghi, "Optimal PMU placement considering contingency-constraints for power system observability and measurement redundancy," *2016 IEEE Power and Energy Conference at Illinois (PECI)*. IEEE, pp. 1–7, Feb-2016.

[16] G. N. Korres, P. S. Georgilakis, N. C. Koutsoukis, and N. M. Manousakis, "Numerical observability method for optimal phasor measurement units placement using recursive Tabu search method," *IET Gener. Transm. Distrib.*, vol. 7, no. 4, pp. 347–356, Apr. 2013.

[17] K. Mazlumi and H. Vahedi, "Optimal placement of PMUs in power systems based on bacterial foraging algorithm," *18th Iranian Conference on Electrical Eng.* IEEE, pp. 885–888, May-2010.

[18] A. S. Deese, T. Nugent, and S. Coppi, "A comparative study of optimal PMU placement algorithms for cost minimization," *2014 IEEE PES General Meeting*. IEEE, pp. 1–5, Jul-2014.

[19] P. Civicioglu, "Backtracking Search Optimization Algorithm for numerical optimization problems," *Appl. Math. Comput.*, vol. 219, no. 15, pp. 8121–8144, Apr. 2013.

[20] M. S. Shahriar, M. Shafiullah, M. A. Asif, M. M. Hasan, and M. Rafiuzzaman, "Design of multi-objective UPFC employing backtracking search algorithm for enhancement of power system stability," *18th International Conference on Computer and Information Technology (ICCIT)*. IEEE, pp. 323–328, 2015.

[21] M. Shafiullah, M. A. Abido, and L. S. Coelho, "Design of robust PSS in multimachine power systems using backtracking search algorithm," *2015 18th International Conference on Intelligent System Application to Power Systems (ISAP), Proceedings of the Conference on*. pp. 1–6, Sep-2015.

[22] R. Storn and K. Price, "Differential Evolution – A Simple and Efficient Heuristic for global Optimization over Continuous Spaces," *J. Glob. Optim.*, vol. 11, no. 4, pp. 341–359, 1997.

[23] M. Ijaz, M. Shafiullah, and M. A. Abido, "Classification of power quality disturbances using Wavelet Transform and Optimized ANN," *2015 18th International Conference on Intelligent System Application to Power Systems (ISAP), Proceedings of the Conference on*. IEEE, pp. 1–6, Sep-2015.

[24] M. A. Zamee, K. K. Islam, A. Ahmed, and K. R. Zafreen, "Differential evolution algorithm based load frequency control in a two-area conventional and renewable energy based nonlinear power system," *4th International Conference on the Development in the in Renewable Energy Technology*. IEEE, pp. 1–6, Jan-2016.

[25] D. Karaboga and B. Basturk, "On the performance of artificial bee colony (ABC) algorithm," *Appl. Soft Comput.*, vol. 8, no. 1, pp. 687–697, Jan. 2008.

[26] A. H. M. A. Rahim and M. A. Ali, "Tuning of PID SSSC controller using artificial bee colony optimization technique," *2014 IEEE 11th International Multi-Conference on Systems, Signals & Devices (SSD14)*. IEEE, pp. 1–6, Feb-2014.

[27] A. R. Mehrabian and C. Lucas, "A novel numerical optimization algorithm inspired from weed colonization," *Ecol. Inform.*, vol. 1, no. 4, pp. 355–366, Dec. 2006.

[28] M. S. Shahriar, M. Shafiullah, M. Asif, Afzal, M. M. Hasan, and A. Ishaque, "Comparison of Invasive Weed Optimization (IWO) and Particle Swarm Optimization (PSO) in Improving Power System Stability by UPFC Controller Employing a Multi-Objective Approach," in *1st International Conference on Advanced Information and Communication Technology*, 2016.

[29] R. Eberhart and J. Kennedy, "A new optimizer using particle swarm theory," *MHS'95. Proceedings of the Sixth International Symposium on Micro Machine and Human Science*. IEEE, pp. 39–43, 1995.