Optimal Placement of Phasor Measurement Units in Khorasan Network Using a Hybrid Intelligent Technique

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Abstract

In this paper, an efficient and comprehensive hybrid intelligent technique for the optimal placement of phasor measurement units (PMUs) is proposed to minimize the number of PMU installation subjected to full network observability. Three main purposes of PMUs output synchronous measurements are monitoring, control, and protection of power system. We have combined Binary Imperialistic Competition Algorithm (BICA) and Genetic Algorithm (GA) for assuring complete observability under normal and single PMU loss or single line outage cases. Zero-injected buses which are transfer buses in the power system network are considered to obtain the best performance. They have capability to reduce the number of required PMUs for full observation of the power system network. The effectiveness of the proposed method is verified via 400 kV Khorasan network using MATLAB software environment. Experimental results show that minimum number of required PMUs and maximum bus observations can be achieved by the proposed method.

Keywords—Genetic algorithm, Phasor Measurement Units, Binary Imperialistic Competition Algorithm.

I. INTRODUCTION

Modern and restructured power systems are operated close to their unstable condition to use their maximum capacity. This is mainly due to rapidly increasing demand for electricity and competitive energy market conditions [1].

PMUs are commonly installed with the major goal of power system full observability to more effectively perform the monitoring, control, and protection scenarios of power system using their output synchronous measurements [2].

Phasor measurement units (PMUs) provide time-synchronized (real-time) phasor measurements in power systems [3]. This is available with the Global Positioning System (GPS) [4]. PMUs, which are synchronized with clock signals from GPS satellites, are able to provide synchronized measurements. The ability to calculate synchronized phasors makes PMU one of the most important measuring devices in future of power system monitoring and control. When these units are installed on a system bus, the phasor of the bus voltage can be measured as well as the phasor of the line currents emanating from that bus. Hence, the voltage phasor of adjacent buses can be calculated using Kirchhoff's laws in the steady-state condition. Therefore, it is not necessary to install these units on all of the system buses to control or estimate the system states [5], [6].

The measurement data can be used for wide area monitoring; real time dynamics and stability monitor-ring; dynamic system ratings; and improvements in state estimation, protection, and control.

A bus or a line is observable if at least one of following rules is satisfied [7], [8]:

1. A bus to which a PMU is allocated is directly observable. In this case, voltage phasor of the bus and current phasors of connected branches are directly available.
2. Any transmission line for which the voltage and current phasors are available at one end, using the line parameters, voltage phasor at the other end is calculated.
3. If in a zero-injected bus, current phasors of all connected branches are available except one, the current phasor of unavailable line can be calculated using KCL equations.
4. A zero injected bus with unknown voltage is observable if voltage phasors of all adjacent buses are available, using node equations.
5. If voltage phasors at both ends of a line are known, current phasor of the line is calculated using the line parameters.
6. If there is a group of adjacent zero-injected buses, and all the adjacent buses to this group are observable, then the zero-injected buses phasors are computable, using KVL and KCL equations for these buses.

Installation of the PMUs on all of the system buses is impossible because of their high cost and the lack of communication facilities [9]. Thus, the main goal is therefore to minimize the number of required PMUs to be installed in the power system while maintaining full observability of the system.

Optimal placement of PMUs in power systems to enhance state estimation is a problem needed to be

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solved. In recent years, there has been a significant research activity in finding the minimum number of PMUs and their optimal locations. Some previous efforts are based on evolutionary algorithms including Genetic Algorithm [10-12], Tabu Search Algorithm [13], Differential Evolution Algorithm [14], Decision Tree [15], Particle Swarm Optimization Algorithm [16] and Binary Imperialistic Competition Algorithm [7].

This paper proposes an exhaustive search approach to determine the minimum number and optimal placement of PMUs for state estimation in single branch outages. It is also possible to use this approach to ensure observability for single PMU outages. An exhaustive search method (BICA-GA) is implemented in this paper to determine the minimum number of PMUs needed to make the 400 kV Khorasan network observable. Due to its exhaustive nature, the method gives the global optimal solution.

II. DESIGN AND IMPLEMENTATION OF ALGORITHM

A. Optimal PMU Placement Problem

It is neither economical nor necessary to install a PMU at each bus of a wide-area power network. As a result, the problem of optimal PMU placement (OPP) concerns with where and how many PMUs should be implemented in a power system to achieve full observability at minimum number of PMUs. For N bus system, optimal placement problem is defined as follows [17]:

$$x_i = \begin{cases} 1 & if \quad PMU \quad is \quad installed \\ 0 & otherwise \end{cases} \tag{1}$$

Connectivity matrix is an n×n matrix whose ijth element represents the connection of the ith bus to the jth bus defined as follows:

$$A_{i,j} = \begin{cases} 1 & i = j \\ 1 & if \quad bus \quad i \quad connected\,to \quad j \\ 0 & otherwise \end{cases} \tag{2}$$

The objective functions of the problem are defined as follows:

$$Min : \sum x_i \tag{3}$$

$$Max : eAx \tag{4}$$

$$s.t \qquad Ax \geq 1 \tag{5}$$

where parameter e is the unit vector in the above equation.

To ensure system observability under failure of a PMU in a single line outage, the right-hand side of the constraint is multiplied by 2. If two PMUs are observing a bus, then a related line outage and failure of a PMU will not affect the node observability [18].

B. Hybrid Optimization Algorithms (BICA-GA)

The purpose of Optimization is finding the best solution according to constraints and requirements of the problem.

Genetic algorithm is inspired by the biological process and Imperialistic Competition algorithm was inspired of human, social, cultural and political phenomena. Binary Imperialistic Competition Algorithm (BICA) has been proposed in [7]. Like other evolutionary algorithms, ICA starts with an initial population. Each element of the population is called a country.

$$country = [x_1, x_2, \ldots, x_N] \tag{6}$$

Some of the powerful countries are selected as initial imperialists which establish their empires. Other countries which have less power become the colonies of these imperialists. The colonies are divided among the imperialists based on their position and power. The cost of each country is calculated as follows:

$$cost = \sum_{i=1}^{N} x_i \tag{7}$$

The colonies assimilate toward their pertinent imperialist to obtain a better position. After colonies movement toward imperialist, they may reach better positions with more power. In such case, the mentioned colony becomes the new imperialist. In the next step, the imperialistic competition begins among imperialists. The imperialistic competition will progressively go on toward the increase in the power of powerful empires and the decrease in the power of weaker ones. By this competition, the weak empires lose their colonies and become weaker and, eventually, eliminated after losing all relevant colonies. These competitions among the empires will cause the countries to converge to a condition in which there is only one Superpower Empire in the world and all the other countries are colonies of this empire [19].

The total power is mainly affected by imperialist power. However, colonies have minor effect on the total power. Total power is calculated as follows:

$$TC_n = Cost(imperialist_n) + \xi mean\{Cost(coloniesofempire_n)\} \tag{8}$$

Where ξ is a positive factor which is assumed to be 0.02 in [6]. In fact, ξ depicts the role of colonies in calculating the absolute power of an empire. Imperialistic Competition algorithm has many advantages, Including:

- Novelty idea.
- Based on human social behavior that smarter biological behavior.

- Speed up convergence.
- The ability to optimize a function with variable number immense.

But it has shortcomings, Including:

- Weakness in the complete search area when the problem size is very large.
- The algorithm is very fast approaching the optimal local and therefore must be re-run again.
- Sometimes when a situation changes by the operator algorithms (the displacement between the Empire) takes place in a closed loop and can be repeated many times and the only solution to this algorithm will be executed again.

GA was inspired by the natural evolution of species. In natural evolution, each species searches for beneficial adaptations in an ever-changing environment. As species evolve, new genetic information is encoded in the chromosomes. This information changes by the exchange of chromosomal material during breeding (crossover) and also mutation [20]. From the engineering standpoint, if we have two solutions with good approximation for a given problem, their combination might lead to a better solution. So, GA pertains to the search algorithms with an iteration of generation-and-test [21]. Genetic algorithm generates a very large set of possible solutions to solve a problem. Each of these solutions is evaluated using a fitness function. Some solutions with highest fitness score are combined to geather to generate the next solution. Thus, the search space will evolve in a direction that reaches the optimal solution. This algorithm is used for discrete optimization and its local minimum entrapment is lower than other methods. However, genetic algorithm is computationally expensive, and there is no guarantee to reach the optimal solution.

In this algorithm N chromosomes will be generated. Two chromosomes are selected based on fitness-score for offspring production. Due to the crossover rate, bits in the two chromosomes moving in random manner. In the selected chromosomes, some bits are reversed with respect to the mutation rate. These steps will be repeated until the new populations with N chromosomes are obtained [12].

As noted before, ICA search space is weak. If the main operator of GA (crossovere), and ICA (assimilation) performed concurrently, search is much more complete. Crossovere operator cause to increase standard deviation in each empire. Furthermore, such combination leads to more complete search and lower convergence rate. Mutation operator, randomly select an empire and placed in another empire, also reduces convergence rate. The mutation operator can be used to led the algorithm to escape from local minima. Fig. 1 shows the flowchart of the proposed algorithm.

III. CASE STUDIES AND SIMULATIONRESULT

To make the details clear, simulations are carried out on the 400 kV Khorasan network. This network has 13-bus and a zero-injection bus (bus 11) which is shown in Fig. 2.

Name of buses are as follows:

1- Shirvan *2*- Ferdos *3*- Toos *4*- Abotaleb
5- Esfarayen *6*- Sarbedaran *7*- Nishaboor
8- Foolade Khorasan *9*- Modares *10*- Torbatjam
11- Shadmehr *12*- ShahidKaveh *13*- Birjand

According to Table I, in the current network with 4 PMUs, buses 4, 8 and 13 are not observed.

By the proposed method, number of PMUs is decreased for full observation. This case study is reported by "with considering zero-injection bus" and

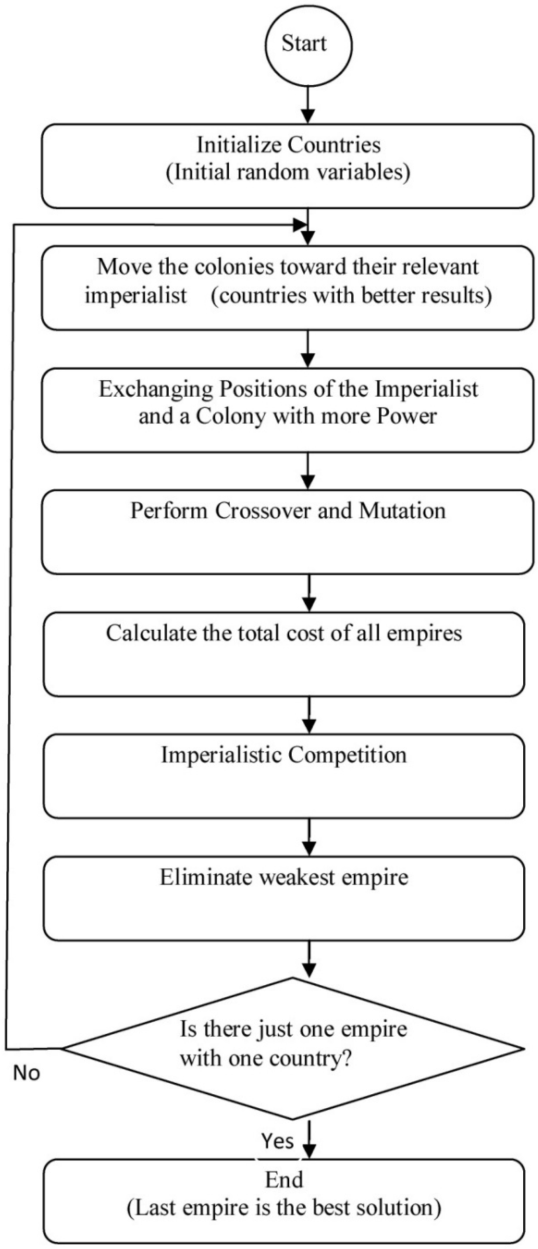

Fig. 1. Flow chart of proposed method.

"without considering zero-injection bus". Table II, shows the minimum number of PMUs that are used to make the system observable at normal operating conditions using BICA-GA hybrid algorithm.

Table III, is showing the minimum number of PMUs that are used to make the system observable at one PMU failure and single branch outages conditions by BICA-GA hybrid algorithm.

Table IV, presents a comparison of proposed algorithm with other methods at normal operation mode.

Table V, presents a comparison of proposed algorithm with other methods at one PMU failure and single branch outages conditions.

In all cases the results of new method are either better than other methods or identical.

At zero injection busses, no current is injected into the system. Therefore, if zero injection busses are also modeled in the PMU placement problem, the total number of PMUs can be further reduced.

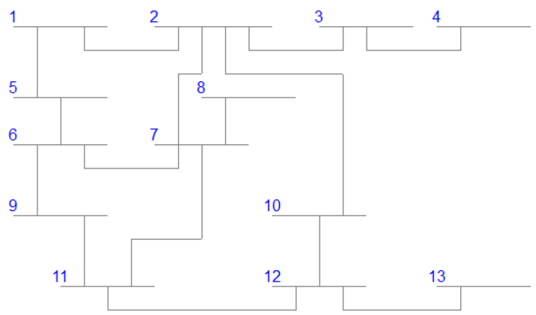

Fig. 2. 400 kV Khorasan network

TABLE I

Current network (400 kV Khorasan network)

Number of PMU	4
location	2-5-10-11
Measurement redundancy (total)	15
Measurement redundancy (each bus)	2-2-1-0-1-1-2-0-1-2-1-2-0

TABLE II

Minimum number of PMUs that are used to make the system observable at normal operating conditions

BICA-GA hybrid algorithm	without considering zero-injection	with considering zero-injection
Number of PMU	5	4
Best location	1-3-6-7-12	1-3-7-12
Measurement redundancy (total)	19	16
Measurement redundancy (each bus)	1-3-1-1-2-2-2-1-1-1-2-1-1	1-3-1-1-1-1-1-1-1-1-2-1-1
CPU run time (s)	0.0793	0.0757

TABLE III

Minimum number of PMUs that are used to make the system observable at one PMU failure and single branch outages conditions

BICA-GA hybrid algorithm	without considering zero-injection	with considering zero-injection
Number of PMU	8	7
Best location	1-2-3-6-7-9-10-12	1-2-3-6-7-10-12
Measurement redundancy (total)	30	29
Measurement redundancy (each bus)	2-5-2-1-2-3-3-1-2-3-3-2-1	2-5-2-1-2-2-3-1-2-3-3-2-1
CPU run time (s)	0.0453	0.0441

TABLE IV

Comparison of the number of PMUs of proposed algorithm with other methods at normal operation mode

System	without considering zero-injection	with considering zero-injection
BICA-GA hybrid algorithm	5	4
BICA	6	5
GA	6	5
BPSO	6	5
Tabu Search	7	6

TABLE V

Comparison of the number of PMUs of proposed algorithm with other methods atone PMU failure and single branch outages conditions.

System	without considering zero-injection	with considering zero-injection
BICA-GA hybrid algorithm	8	7
BICA	9	8
GA	9	8
BPSO	9	8
Tabu Search	10	9

IV. CONCLUSION

In this paper, a new method based on the BICA-GA is introduced. The optimal placement of PMUs to obtain full network observability by maximum measurement redundancy, and considering the impact of zero injection buses has been solved.

The algorithm was applied to 400 kV Khorasan network under normal operation mode, single line outage and one PMU failure. Results depict that BICA-GA produces the best solution include fast convergence, small run time, and capability of finding global optimum.

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