

PMU Optimal Placement in Wide Area Monitoring Systems using Grey Wolf Optimization technique

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Abstract: Wide area monitoring system requires the integration of an advanced technology that provides real time synchronized phase angle measurements at all their measurement points. The phasor measurement units are the most advanced devices to achieve that. The objective of this work is first, to find the optimal placement of a minimum number of PMUs in some standardized IEEE systems. Next, the same method was applied to the Algerian 63 bus system. Two cases are taken into consideration: the minimum number of PMUs without considering the ZIB, then, considering the ZIB. The simulations are carried out using MATLAB/SIMULINK.

Keywords: Smart Grid, Wide Area Monitoring Systems (WAMS), Phasor measurement unit (PMU), optimal PMU placement (OPP), Grey-Wolf optimization.

1. INTRODUCTION

Smart Grid utilities and research institutions are looking for the best solution for PMU placement, for both the observability and fault location in wide area monitoring systems. In modern energy management system, state estimation (SE), observability and fault location are becoming crucial applications. Conventional state estimators use a set of measurements; bus voltage, real and reactive power flows, and injections, in order to estimate the bus voltage phasors in the system. These measurements were obtained, in the near past, only through the supervisory control and data acquisition (SCADA) system, which gathers the real time measurements from the remote terminal units (RTUs) installed in substations[1]. A PMU became the measurement technique of the best choice in electric power systems for Wide Area Monitoring System (WAMS) [2]. They provide positive sequence voltage and current measurements synchronized with accuracy of a microsecond. The deployment of this device can improve performances of power system protection, monitoring, and control systems [2], [3],[6]. With the increased interest in the development and deployment of Smart Grid, researches are leaning on the

use of PMUs to replace the old fault detection and observability solutions[3]. Phasor Measurement units (PMUs) can offer accurate node voltage and current phasors referring to the same time-space coordinate. They can enhance many applications such as state estimation and bad data detection [4], stability control [5], remedial action schemes [6], and disturbance monitoring [7]. PMU is a monitoring device that assures advanced protection, analysis and control in power systems. A PMU placed at a given bus is capable of measuring the voltage phasor of the bus as well as the phasor currents for all lines incident to that bus. It uses synchronization signals from the global positioning system (GPS) satellites and provides the phasors of voltage and currents measured at a given substation. PMUs provide the precise description necessary to minimize and control power outages and avoid cascading blackouts. PMU utilization is increasing not only for substation applications but also at control centers for Energy Management System (EMS) applications [8]. These devices are necessary when dealing with wide disturbances, for power system state estimation and for network protection and control. However, considering the high cost of PMUs, it is not possible to place one in each bus to make the entire system observable. As a result, the problem of optimal PMU placement (OPP) appeared to find where and how many PMUs should be implemented in a power system to achieve its

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full observability at minimum number of PMUs [9]–[11]. Using the data provided by PMUs installed in some appropriate bus nodes of a power network, one can construct a new type of measuring system to improve the observability and the precision of the power system state estimator. The observability depends on the type, the number and the geographic distribution of measurements [2]. Several researches have been conducted to reduce the number of PMUs used.

2. STATE OF THE ART

The Optimal PMU Placement (OPP) observability problem concerns the determination of the minimum number of PMUs, and their optimal placement set necessary to assure the observability of the entire power system. The authors in [1], present a state of the art of the optimization methods applied to the optimal PMU placement for observability problem. They proposed taxonomy of Optimal PMU Placement (OPP) methods describing a large number of works devoted to this topic. According to them, optimal PMU placement problems are classified into two categories: mathematical and heuristic algorithms. Several works are listed in paper [1] as mathematical algorithms which use the Linear Integer Programming (ILP) or Integer Nonlinear programming. A voltage stability based contingency ranking method is carried out in [12] to present few critical contingencies considered in the optimal PMU placement problem. A hybrid two-stage PMU placement technique is proposed in [13] which uses an ILP based approach to guarantee the system topological observability. A description of an optimal PMU placement for the overall network observability is presented in [14] taking into consideration the PMU failures and network contingencies that give rise to both topology changes and bad data measured by PMUs. A new formulation for PMU placement is developed in [15] based on ILP, the work considers the necessity of the network observability under all possible arrangements of lines connections at complex buses. The authors take also into consideration the cases of the lines outage and PMUs failure probability.

The approach for solving the optimal PMU placement for system observability is the Heuristic algorithms. A new method based on

Genetic Algorithm considering the Zero-Injection buses is presented in [16] to ensure the system observability.

Critical bus constrained optimal PMU location is presented in [17], where Zero Injection Bus (ZIB) is considered for the complete system observability. The authors propose to identify the critical buses that are joined to the ZIB, in order to dictate the true state of the system. Binary Integer Programming (BIP) is used to minimize the objective function designed under bus constraints for optimal PMU allocation and takes into consideration both ZIB and critical buses. The authors in [18] present a multi-objective probabilistic model, this method optimizes both the number of PMU, used for the observability, for its minimum and the maximum of system redundancy.

Two types of observability analysis are presented in [19]: numerical and topological observability. The paper studied a topology transformation method that implies a merging between a ZIB with one of its incident buses. The authors solved the problem of the right incident bus choice by proposing three rules to assure the right selection of the bus to be merged with the ZIB as well as the right PMU placement. An ILP based method is proposed in [20] under voltage stability and intensely islanding to ensure the system full observability. An additional objective is proposed which consists in a rise in the reliability of the system.

In this paper, the problem of finding the minimum number of PMUs to achieve the observability and fault detection in wide area monitoring system is presented. Grey Wolf Optimization (GWO) technique is proposed to find the optimal PMU placement to assure the observability of some standard IEEE bus systems. The Algerian network was also used as test data.

3. PROBLEM FORMULATION

PMUs are devices capable of measuring synchronous real time voltage and current phasors. They are used in power systems for several applications, one of them is to assure the observability of the transmission lines to provide a platform for the control and monitoring of Wide Area Monitoring Systems (WAMS)[21].

PMUs use the clock signal of the Global Positioning System (GPS) to provide synchronized phase angle measurements at all their measurement points, and they are

capable of measuring the 50/60 Hz sinusoidal waveforms of voltages and currents at a high sampling rate, up to 1200 samples per second and with high accuracy. A Zero Injection Bus (ZIB) is a bus which has no load or no generator or no measurement device. The sum of current flowing to a ZIB, is zero. Zero injection bus is the bus from which no current is being injected into the system [22].

The typical OPP problem concerns the determination of the minimum number of PMUs, n , and the optimal location set, $S(n)$, of the n PMUs, ensuring that the entire power system remains a single observable island. This model can be generalized to include additional constraints or contingencies. The objective function is formulated as follows [19]:

$$\min \sum_{i=1}^N x_i \quad (1)$$

Subject to

$$[A][X] \geq [b] \quad (2)$$

Where N is the number of system buses and $[A]$ is a binary connectivity matrix. Entries for matrix $[A]$ are defined as follows:

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

$[X]$ is defined as a binary decision variable vector where $[X] = [x_1, x_2, \dots, x_n]^T$ and $x_i \in \{0,1\}$.

$$x_i = \begin{cases} 1 & \text{if a PMU is installed at bus } i \\ 0 & \text{otherwise} \end{cases} \quad (4)$$

$[b]$ is a column vector $[b] = [1, 1, 1, \dots, 1]^T_{1 \times N}$. b is a vector of length N .

Each element of vector b , is set to 1. This ensures that each bus is observed by at least one PMU.

a- System Observability Redundancy Index (SORI)

In optimal PMU placement, the redundancy index is an important factor for representing the stability of the power network. Due to a multiple number of available optimum solutions after applying the optimization algorithm, Bus Observability Index (BOI) will be implemented to indicate the performance on quality of optimization. The redundancy measurement is obtained as follows [23][24]:

$$R = \sum_{i=1}^N |A_i| X_i \quad (5)$$

Where AX represents the number of times a bus i is observed by PMUs.

b- Bus Systems

In this work, we consider the Algerian network and some standardized IEEE bus system: 14, 30 and 57 bus systems. PMUs are installed in network system to measure the voltage and current samples from various location points [25]. Figure 1 shows a single line representation of IEEE 14 bus system. Table 1 shows the system description of the networks used in our tests; it includes the number of transmission lines, number of ZIB and their locations.

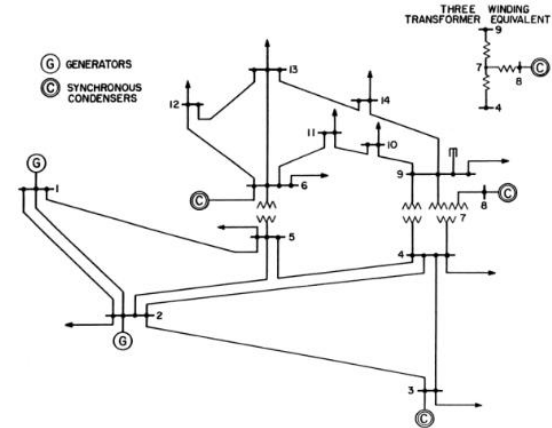


Fig. 1: Single line IEEE 14 bus system

Table 1 IEEE bus systems description

	N. of lines	N of ZIB	ZIB locations
14 bus	20	1	7
30 bus	41	6	6, 9, 22, 25, 27, 28
57 bus	80	15	4, 7, 11, 21, 22, 24, 26, 34, 36, 37, 39, 40, 45, 46, 48.
Algerian Network	96	9	3, 13, 15, 16, 21, 38, 46, 54, 55.

4. GREY WOLF OPTIMIZATION

Grey Wolf Optimizer (GWO) is a new meta-heuristic optimizer, developed by Seyedali Mirjalili in [26]. Inspired by nature, GWO mimics the leadership hierarchy and hunting mechanisms of grey wolves in nature. Four types of grey wolves are involved (alpha, beta, delta, and omega) for simulating the leadership hierarchy. In addition, the three main steps of hunting are implemented; searching for prey, encircling prey, and attacking prey [26].

The mathematical modeling of the social hierarchy for solving any optimization problem involves classification of the fittest or

best solution as the alpha (α), the second and third best solutions as beta (β) and delta (δ) respectively. All other solutions are classified as omega (ω)[27].

The hunting behavior is loosely modeled by the following operators:

a) Searching for the prey

Grey wolves mostly search according to the position of the alpha, beta, and delta. They diverge from each other to search for prey and converge to attack prey.

b) Encircling the prey

Grey wolves encircle prey during the hunt. In order to mathematically model encircling behavior the following equations are proposed:

$$\vec{D} = |\vec{C} \otimes \vec{X}_p - X(t)| \quad (6)$$

$$\vec{X}(t+1) = \vec{X}(t) - \vec{A} \otimes \vec{D} \quad (7)$$

Where t indicates the current iteration, $\vec{A}$ and $\vec{C}$ are coefficient vectors, $\vec{X}_p$ is the position vector of the prey. And $\vec{X}$ indicates the positions vector of a grey wolf.

The vectors $\vec{A}$ and $\vec{C}$ are calculated as follows:

$$\vec{A} = a(2\vec{r}_1 - 1) \quad (8)$$

$$\vec{C} = 2 \cdot \vec{r}_2 \quad (9)$$

Where components of a are linearly decreased from 2 to 0 over the course of iterations and $\vec{r}_1$, $\vec{r}_2$ are vectors of random numbers in the range [0, 1], in the same dimensions as vectors $\vec{X}_p$ and $\vec{X}$. The $\otimes$ between $\vec{A}$ and $\vec{D}$ (also $\vec{C}$ and $\vec{X}_p(t)$) means corresponding component wise multiplication[26], [27].

c) Attacking the prey

Grey wolves have the ability to recognize the location of prey and encircle them. The hunt is usually guided by the α wolf. The β and δ might also participate in hunting.

In order to mathematically simulate the hunting behavior, the α (best candidate solution) β , and δ are supposed to have better knowledge about the potential location of prey. Therefore, they take the first three best solutions obtained, and the other search agents (including the ω) are obliged to update their positions according to the position of the best search agent. The following formulas are proposed in this regard[26]:

$$\vec{D}_\alpha = |\vec{C}_1 \otimes \vec{X}_\alpha - \vec{X}|,$$

$$\vec{D}_\beta = |\vec{C}_2 \otimes \vec{X}_\beta - \vec{X}|, \quad (10)$$

$$\vec{D}_\delta = |\vec{C}_3 \otimes \vec{X}_\delta - \vec{X}|$$

These distances are used to find the new position of wolf $\vec{X}(t+1)$ using the following equations:

$$\vec{X}(t+1) = \frac{\vec{X}_1 + \vec{X}_2 + \vec{X}_3}{3} \quad (11)$$

Repeating the functions of encircling and hunting, the prey (best solution) is reached [26], [27].

5. RESULTS AND DISCUSSIONS

In our work, two case studies have been taken into consideration: first, we did not consider the effect of the ZIB. Second, we took into consideration their effect. The results obtained for the IEEE bus systems are represented in tables 2 and 3, respectively.

a) Without considering the ZIB

SORI: Summation of Redundancy Index.

Table 2 Results without considering the ZIB

	Min. PMU	PMU placement	SORI	Percentage of use
14 bus	4	2 6 7 9	19	28.6%
30 bus	10	2 4 6 9 10 12 15 18 25 27	52	33.3%
57 bus	17	1 4 9 15 20 24 27 29 31 32 36 38 39 41 47 50 54	71	29.8%

b) Considering the ZIB

Table 3 Results considering the ZIB

	Minimum PMU	PMU placement	SORI	Percentage of use
14 bus system	3	2 6 9	16	21.43%
30 bus system	7	2 4 10 12 15 20 27	41	20%
57 bus system	11	1 9 15 18 29 31 32 41 47 51 53	67	19.3%

c) Results for the Algerian network

We applied the same objective function and the same optimization technique to the Algerian network and the results are presented in table 4.

Table 4 Results for the Algerian Network

Algerian network	Min. PMU	PMU placement	SORI	Percentage of use
Without ZIB	18	4 10 13 15 16 18 19 26 27 32 36 38 43 45 46 54 58 62	82	28.5%
With ZIB	14	1 4 13 18 19 26 29 32 36 43 45 51 58 62	79	22.22%

From the previous tables, we notice that: the number of PMUs required to achieve the full observability of the transmission line system is at minimum if we consider the effect of ZIB.

d) A Comparative study

Table 5 shows a comparison between our proposed optimization method and the previous methods provided in literature. It concerns the optimal number of PMUs found to assure the observability of some IEEE standard systems.

Another comparison is performed, in table 6, between our proposed method and the methods used in state of the art, and this comparison deals with the obtained system redundancy.

Table 5 Optimal PMU number comparison

Algorithms	Ref.	14 bus	30 bus	57 bus
This work- GWO method		3	7	11
PSO-MFO	[24]	3	7	11
GA	[16]	3	7	11
MICA	[28]	3	7	13
BinaryIntegerprogramming	[22]	3	7	N/A
Topology transformation method	[19]	3	7	11
Modified BPSO	[21]	3	7	12
IntegerLinearProgramming	[23]	3	N/A	14
Taguchi bat	[29]	3	7	N/A
GreedyModified	[30]	3	7	11
Graph Theory	[31]	4	10	N/A
Tabusearch	[32]	3	N/A	13
BICA	[33]	3	7	11
IntegerProgramming	[34]	3	7	N/A
Binarycuckoo optimisation	[35]	3	7	11

BICA (Binary Imperialistic Competition Algorithm)

Table 6 Redundancycomparison

	Ref.	14 bus	30 bus	57 bus
Proposed GWO		16	41	67
MICA	[28]	16	39	N/A
PSO-MFO	[24]	16	41	67
BinaryIntegerprogramming	[22]	15	36	N/A
Topology	[19]	N/A	N/A	60
BICA	[33]	16	41	59
IntegerProgramming	[34]	15	36	N/A
Binarycuckoo optimisation	[35]	16	42	63

6. CONCLUSIONS

The objective of this work was to find the optimal number of PMUs to achieve the observability of some IEEE bus systems. The optimization technique used to achieve this objective is the Grey Wolf Optimization. The advantage of this application is to monitor the transmission line systems. Two cases have been taken into consideration, in the first case we neglect the effect of Zero Injection Buses, however in the second case we take it into consideration. We notice that the complexity on the system is proportional to the number of buses in the system.

We tested also our work on the Algerian Network that consists of 63 bus systems. The number of PMUs required is reduced to 14 PMUs with a redundancy of 78.

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