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Artificial Intelligence based Optimal Placement of Phasor Measurement Unit for Smart Grid

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Abstract

A Phasor Measurement Unit (PMU) device ensures the stability, reliability, and proper visibility of critical areas of the power grid by providing a synchro phasor measurement of both voltage and current in real-time. Since it is not practical to place them at each branch of the system, the main concern lies in achieving entire network observability either by direct or indirect measurement through an optimal set of PMUs placed at the optimal location. This gives rise to the Optimal PMU Placement Problem (OPP). In this paper, OPP is solved by an optimization technique i.e., a Genetic Algorithm. The constraints that can greatly affect obtaining optimal solutions are reviewed and the effect of including Zero Injection Bus (ZIB) on the proposed method in solving OPP is studied. The algorithm is applied to IEEE-14 and IEEE-30 bus test systems for validation purposes. Since optimal sets of solutions are obtained from the proposed method, the solutions are ranked by the system observability redundancy index to find the best one. Further, a comparative analysis of the result is done with the depth first search algorithm and other widely used algorithms.

Keywords: Artificial Intelligence, Genetic Algorithm, Phasor Measurement Unit, Zero Injection Bus, ,.

1. Introduction:

In recent years there has been remarkable development in power grids with the different challenges faced while integrating renewable to the grid. This development has led the grid to become smarter. A smart grid is prone to provide a highly reliable power system along with optimized utilization of available resources which is required for a developing country like Nepal. Better operation of power systems is provided through the development of the global positioning system (GPS), digital signal processing unit, and integrating information and communication (ICT) [1] layers which lead to the development of smarter grids. A reliable WAMS can prevent the smart grid from turning into cascade tripping and blackouts [2]. Since most of the issues related to traditional grids mainly occur due to improper system monitoring so Wide Area Monitoring System (WAMS) is considered one of the key elements in smart grid which can monitor the current status of a critical area in real time. These real data are streamed from a device known as Phasor Measurement Unit (PMU). PMUs were introduced in the 1980s and the synchronised measurement of PMU is enabled using GPS with better accuracy than one microsecond. The synchronised measurements are then further used to capture the system dynamics, which helps to study the system behavior under different conditions and build a better system model.

There are many applications under development where WAMS utilize the application of PMU [3]. PMU provides a synchronized measurement of real-time branch currents and bus voltages which is very useful for estimating many system parameters, detecting and locating the fault, optimizing power dispatch, state estimation and analysing stability and upgrading the monitoring of the power system. For real-time data, the efficiency and correctness provided through SCADA are relatively small, so the generators and loads will be disconnected earlier than indicating the grid to collapse by the time estimations. Such a condition was already faced in the northeast USA in 2003, which had led to the worst system blackout [2]. Real anticipate power concern networks require active protection, control, monitoring and fault detection in real-time, which utilize synchronized technology. Synchronized measurement of voltage phasor of the particular bus and also current phasors through all the lines are thus provided by PMU. Inspite of the supremacy of PMU over conventional measurement regarding various aspects, it is impractical to place PMU over the whole system, i.e., at each bus, because of the relatively expensive cost of PMU [4]. Therefore PMUs are required to be placed optimally over the system in such a way that the whole system gets observable through it. To solve the problem of optimization, mainly mathematical, advanced heuristic and meta-heuristic optimization techniques are used.

Mathematical methods like Integer Linear Programming (ILP) and exhaustive search has been used for solving the OPP. Since OPP is a discrete problem, ILP is suitable for solving it [5]. ILP has also been used for detecting and eliminating bad data in critical measurement pairs in [6]. In [7] the search method is used for obtaining the global optimal value while solving the OPP problem where it has been combined with other method to give an efficient result. While in cooperating exhaustive search with its own methodology, a reliable solution was obtained in [8] but for a larger system it seems to be impractical. So, the difficulties in handling the larger systems where there are constraints problems have been overcome by using Artificial Intelligence (AI) techniques. AI algorithms like heuristic techniques, including depth first search (DFS), simulated annealing, breadth first search, neural network, fuzzy logic, genetic algorithms, particle swarm optimization and ant colony optimization, etc., have also been used for solving the optimal placement problem. Along with analysing the system observability, advanced heuristic algorithms dominate some difficulties of conventional methods, such as PMU failure or branch outage [9]. The heuristic solving method, the DFS algorithm, was used in analysing the optimal location of PMU [10]. The analysis was done in IEEE-14 and 57- test bus. Also, DFS was analysed with simulated annealing and minimum spanning tree method in [11]. In [12] Power System Analysis Toolbox (PSAT) was used to find the optimal placement of PMU by DFS and compared with result obtained by ILP. The best result is obtained through a heuristic methodology rather than a mathematical. It was analysed that for complex problems and large systems, heuristic algorithms can perform better in comparison to conventional methods from [14] and [15], where a solution for the OPP problem using algorithms like GA and modified binary particle swarm optimization (BPSO) method was presented to make the system observable for utilization in linear state estimation.

The artificial intelligence based technique has been widely used in solving OPP problems but there isn’t sufficient research been done while considering Zero Injection Bus effects. In this paper, the AI-based, non-conventional meta-heuristic optimization technique, GA, has been used to solve the OPP problem while considering the case for the ZIB effect in the system. The algorithm gives an optimal number of solutions for PMU placement which are ranked using an index SORI for obtaining a reliable solution. Further, the proposed algorithm is compared with the results obtained through DFS and other widely used algorithms.

2. Observability Analysis:

For a system to be completely observable, all states in the system should be uniquely determined. If no PMUs are placed on a bus, and no measurement is possible such buses are considered unobservable buses [15]. Therefore, observability simply is a measure of how well can be internal states of a system with the knowledge of its external outputs [16]. Some important measurement constraints for observability analysis are illustrated below:

• Installation of PMU at a specific bus makes itself and buses incident to that bus observable. In Fig. 1, bus d is directly observed, whereas buses a, b and c are indirectly observed through PMU

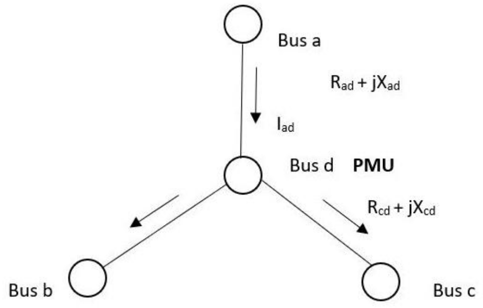

Figure 1: Direct and indirect observability rule

• Among the ZIB and buses incident to ZIB, if one bus is observable, then entire incident buses can be made observable. In Fig. 2, the current phasor of node-c and d can be determined if all branch is known except branch ’cd’ by using KCL at the zero-injection bus.

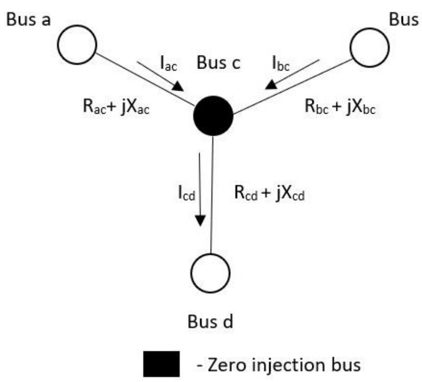

Figure 2: ZIB observability rule

• For a group of unobserved ZIB nodes with unknown voltage phasor can be made measurable through known neighboring nodes connected to a group of ZIB nodes. In Fig.3, the voltage of ZIB ’c’, ’d’ can be known through the voltages of the nodes connected to them.

2.1 Genetic Algorithm and Depth First Search for optimal placement of PMU:

GA is bio-inspired optimization technique based on natural selection. It is one of the natural selection optimization techniques to solve difficult optimization problems. It is based on the fact that "survival of the fittest one".

- The GA starts with initializing a population that is randomly generated, and its fitness is tested
- "Reproduction" is for quickly searching for minima/maxima if there are many variables
- "Crossover" is applied for making the data near to local minima/maxima
- "Mutation" avoids being trapped into the local minima/maxima point, so it diverges some offspring from the point

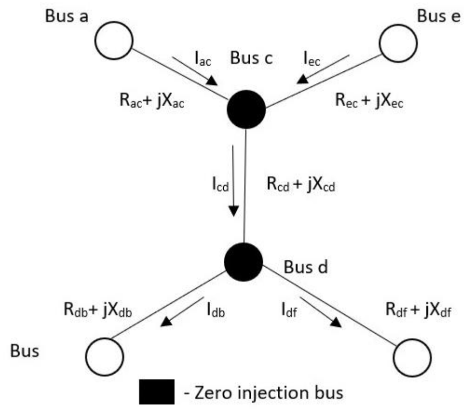

Figure 3: ZIB observability rule

GA for optimal placement of OPP vary from other technique as:

i GA does not follow a fixed point. It follows an arrangement of design

ii GA upgrades the capacity of estimation rather than its alternative data

iii GA utilize probabilistic move governs [17].

GA can be used as the main algorithm for solving the optimal placement problem. In [2] the algorithm has been used for reliability placement of PMUs in the smart grid for IEEE-2382 bus system which other reliable based approaches failed to obtain. Using GA, various typical full observability along with partial observability can also be analysed. Multiple papers have used different approaches to solve the OPP based on the objective, constraints, and key features of the problem. Some constraints include the process of considering power flow measurement, ZIBs, PMU outage and multistage placement. Using GA considering these constraints have resulted in an effective solution for finding optimal PMU in the system. In [10] optimal number and location of PMU were obtained, resulting into full network observability while considering the effect of ZIB. Including ZIB has significantly resulted in a reduced number of PMU for providing full observability. Similarly in [18] one line/ one PMU outage was considered for obtaining optimal solution and placing those optimal number of PMUs for getting maximum redundancy.

Whereas, DFS searches for a tree or graph structures. The initial stage of the DFS algorithm is at the root of the tree or graph or node. The algorithm explores as far as possible along each branch of the nodes. So basically the DFS algorithm starts from the marked root and moves its search toward the adjacent unmarked nodes. This loop continues to operate until all of the nodes are marked as searched. Then the process of backtracking will continue for checking unmarked nodes and transverse them. The nodes in the path are finally taken to complete the search.

3. Methodology:

3.1. OPP formulation:

The objective function is to minimize the number of PMUs used and the constraint will be that all system buses should be observable with the PMU employed so that branch phasors are measurable. The objective function of optimal placement of PMU (OPP) is mathematically expressed as:

$$x_i = \begin{cases} 1 & if\ \ PMU\ installation\ at\ bus\ i \\ 0 & otherwise \end{cases} \quad (1)$$

$$Obj.Function = minimize \sum_{i=1}^{N} W_i x_i \quad (2)$$

Subject to the constraint:

$$A_{ij}.f(x) \geq 1 \quad (3)$$

Where Eq. 1 is the objective function, and the cost factor of specific PMU installed at bus i is given by w_i considered to be the same for each PMU. N is the total no of system buses, and x_i is the decision variable given by either 0 or 1. Furthermore, A_{ij} denotes the binary connectivity matrix whose elements are given by

$$A_{ij} = \begin{cases} 1 & \text{if i = j} \\ 1 & \text{if i and j are interconnected} \\ 0 & \text{otherwise} \end{cases} \quad (4)$$

In order to explain the formulation process in detail, let us consider the IEEE 7 bus system Fig. 4. The connectivity matrix of the system will be given by Eq. 5.

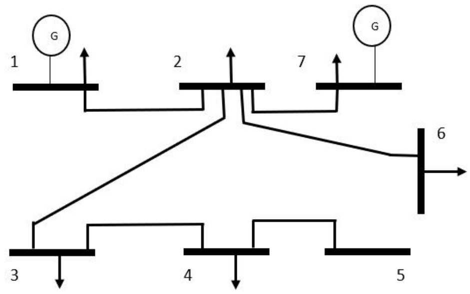

Figure 4: IEEE-7 bus test system

$$\boldsymbol{A_{ij}} = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 0 & 0 & 1 & 1 \\ 0 & 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad (5)$$

Now the constraint function for the system is given by Eq. 6.

$$f(x) = \begin{bmatrix} f_1 = x_1 + x_2 \\ f_2 = x_1 + x_2 + x_3 + x_6 + x_7 \\ f_3 = x_2 + x_3 + x_4 \\ f_4 = x_3 + x_4 + x_5 \\ f_5 = x_4 + x_5 \\ f_6 = x_2 + x_6 \\ f_7 = x_2 + x_7 \end{bmatrix} \geq 1 \quad (6)$$

The operator '+' denotes the logical 'OR' and aleast one of the variables appearing in the sum should be non-zero. In a similar way, the connectivity matrix and constraints for IEEE-14 and 30 bus systems are determined and the objective function is solved by using the GA toolbox.

3.2. GA for solving OPP:

GA can provide multiple solutions to OPP with different measurement redundancies. The measurement redundancies can be adjusted using 'GA solver' options like population size, generations and many others to get the result. Here in this paper, the GA is selected as an optimization algorithm and for solving the OPP problem, a genetic algorithm graphical user interface toolbox is utilized through MATLAB software. The basic procedure of GA for OPP problem formulation is shown in Fig.5 where the initial stage to solve the OPP problem is to take the input data, which are bus test system data and form the connectivity matrix. The second step is to find the radial bus of the system given in Table 1. And initialize PMUs to those buses. The condition for ZIB is checked further and the merging of the buses is done according to the observability rules, as discussed earlier. The objective function given by Eq. 2 is to be minimized using the GA toolbox. The options provided by the toolbox, like population, mutation, crossoverand reproduction, are adjusted so that we can obtain the best solution. The stopping criteria for the algorithm are given by Eq. 3. When the resultant number of PMUs makes the whole system measurable through it, then the criteria are fulfilled.

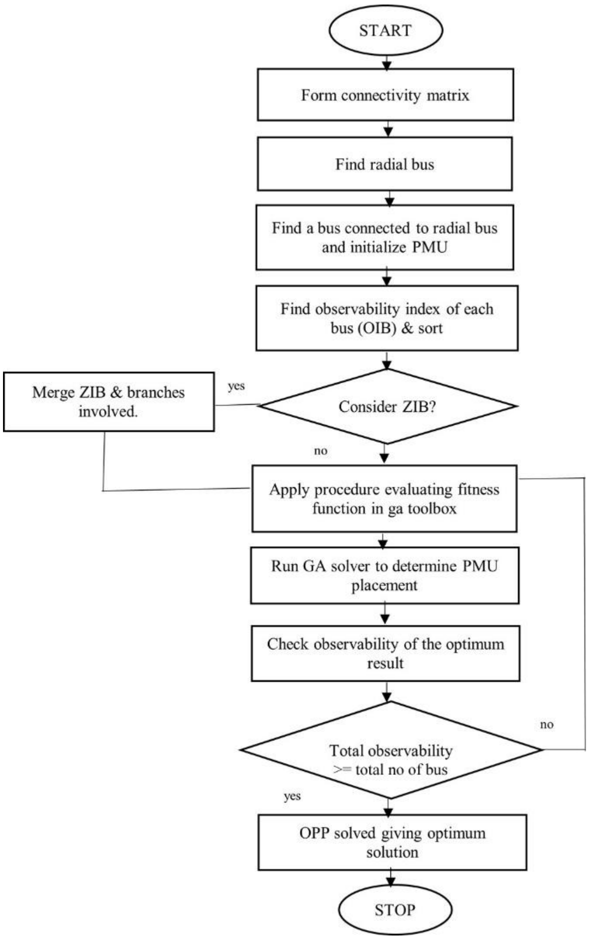

Figure 5: Flowchart for finding OPP solution

3.3. DFS for solving OPP:

In order to compare the results of the proposed algorithm with another artificial intelligence based algorithm, the depth first algorithm is used further. The test system is modeled and simulated using Power System Analysis Toolbox (PSAT). The simulink models of the test systems are loaded as a data file and, the power flow analysis is done using the Newton-Raphson method [19]. The PMU placement tool is selected where the OPP is solved using the DFS algorithm for applying the DFS algorithm to the test system. Fig.6 shows the flow chart for implementing the DFS algorithm to solve OPP in PSAT MATLAB.

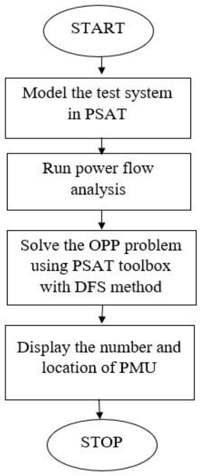

Figure 6: Basic procedure for using DFS in PSAT

3.4. SORI and BOI:

In order to have the best placement among many obtained results, the bus observability index (BOI) and system observability redundancy index (SORI) have been enforced. For a given number of bus 'i', the BOI is defined as (b_i). The maximum value of b_i as the number of PMUs capable of observing a given bus 'i' is limited to the maximum connection of the particular bus 'i', i.e., n_i plus one, as shown in Eq. 7, which happens only when the bus itself and the buses adjacent to the particular bus is equipped with PMUs.

$$b_i \leq n_i + 1 \tag{7}$$

Whereas SORI is used for selecting the most favorable output from a number of optimal solutions obtained while using an optimization algorithm.

$$\gamma = \sum_{i=1}^{n} b_i \tag{8}$$

SORI is defined as a measurement of the sum of bus coverage for all the implemented buses (i = 1 to n) in an active system [20]. Basically, SORI is the summation of the bus observability index of all buses 'n' in the given system. So, higher the value of SORI, more reliable is PMU based system.

4. Results and Discussion:

The OPP problem is simulated in MATLAB R2018a. GA is used as optimization solver and tested for the IEEE 14 and 30 test bus system to implement the objective.

Table 1: Data of standard 14 and 30 bus test system

Test bus	No. of branches	No. of ZIB	ZIB location	No. of radial bus	Radial bus
14- bus	20	01	7	01	8
30- bus	41	06	6, 9, 22, 25, 27, 28	03	11, 13, 26

Table 2: SORI of Optimal set of PMU for 14- bus system

Test System	Sets of Optimal Placement	SORI
	2, 6, 7, 9	**19**
	2, 7, 11, 13	16
14-bus	2, 7, 10, 13	16
	2, 8, 10, 13	14
	2, 6, 8, 9	17

Table 1 shows the number of ZIBs for 14 and 30 buses. Table 2 gives the optimal sets of placement during normal operation. Since the set 2,6,7,9 has the highest SORI value, it is an optimal solution.

Table 3: SORI of Optimal set of PMU for 30- bus system

Test System	Sets of Optimal Placement	SORI	Redundancy
	1, 2, 6, 10, 11, 12, 18, 21, 25, 30	44	3
	1, 6, 7, 9, 10, 12, 18, 24, 26, 30	43	4
	1, 6, 7, 10, 11, 12, 18, 23, 25, 27	45	3
	1, 6, 7, 9, 10, 12, 19, 24, 25, 27	47	4
	2, 3, 6, 9, 10, 12, 19, 23, 25, 29	47	4
	2, 4, 6, 9, 10, 12, 19, 24, 25, 29	49	5
30-bus	2, 3, 6, 10, 11, 12, 19, 24, 26, 27	45	4
	2, 3, 6, 10, 11, 12, 15, 19, 25, 27	48	4
	1, 6, 7, 10, 11, 12, 15, 18, 25, 29	44	3
	2, 4, 6, 10, 11, 12, 18, 21, 25, 27	48	4
	1, 7, 8, 9, 10, 12, 19, 23, 26, 27	47	4
	2, 4, 6, 9, 10, 12, 15, 19, 25, 27	**52**	**5**
	1, 2, 6, 10, 11, 12, 15, 19, 25, 27	48	3
	2, 4, 6, 10, 11, 12, 15, 18, 25, 27	50	4
	2, 4, 6 ,9 ,10, 12, 19, 23, 25, 30	49	5

Similarly, Table 3 shows the results obtained for the IEEE-30 bus system. Set 2, 4, 6, 9, 10, 12, 15, 19, 25 and 27 have the highest value of SORI. Table 4 shows that by considering the ZIB effect in the systems the number of PMUs which are required to make the system observable is considerably reduced i.e, reduced to 3 and 7 no. of PMUs for 14 and 30 bus system respectively.

Table 4: Optimal number and location of PMU with and without ZIB

Test System	Optimal number of PMU	Optimal location of PMU
Without ZIB		
14-bus	4	2, 6, 7, 9
30- bus	10	2, 4, 6, 9, 10, 12, 15, 19, 25, 27
With ZIB		
14-bus	3	2, 6, 9
30- bus	7	1, 2, 10, 12, 19, 23, 27

Further, the comparative analysis is done with DFS as shown in Table 5. The simulation period was faster but the number of PMUs required was found to be more than GA. Also, Table 6 gives the SORI comparison of the optimal placement results obtained by different methods. The best outcome is found in the placements resulting through GA.

Table 5: Comparative analysis of GA with DFS technique for solving OPP

AI Algorithms	Test System	Optimal number of PMU	Optimal placement
GA	14- bus	4	2, 6, 7, 9
	30- bus	10	2, 4, 6, 9, 10, 12, 15, 19, 25, 27
DFS	14-bus	6	1, 4, 6, 8, 10, 14
	30-bus	12	3, 5, 6, 11, 12, 17, 18, 20, 21, 24, 26, 27

Table 6: Comparision of SORI of the proposed method with other methods

Test bus	Optimal no. of PMU	Optimal placement	SORI
intlinprog			
14- bus	4	2, 8, 10, 13	13
30- bus	10	1, 5, 8, 10, 11, 12,	35
bintprog			
14- bus	4	2, 6, 7, 9	19
30- bus	10	1, 5, 8, 10, 11, 12,	35
ABC			
14- bus	4	2, 6, 7, 9	19
30- bus	10	2, 3, 8, 9, 12, 14,	50
fmincon solver			
14- bus	4	2, 6, 7, 9	19
30- bus	10	2, 4, 6, 10, 11, 12, 15,	48
GA			
14- bus	4	2, 6, 7, 9	19
30- bus	10	2, 4, 6, 9, 10, 12, 15,	52

5. Conclusion and Future scope:

In this paper, using the proposed algorithm, GA, new results are obtained for full observability. The problem formulated while considering the ZIB effect resulted in a reduced number of PMUs in IEEE-14 and 30 standard bus systems. The multiple sets of results are obtained by adjusting the GA solver like population size, selection operators, crossover fraction, elite count, etc, so they are ranked by the BOI and SORI indices. Also the comparative analysis with different techniques and algorithms is presented. Comparatively, the proposed method, GA's solution, is expected to give a higher SORI value than the other algorithms.

The proposed method, can be extended by many constraints and considerations in itself, like by considering the conventional measurements and current branch limit cases. The study can be further explored considering the cases where there is an islanding system, line outages, or obtaining the observability in the condition of faults and device failure. Inspite the objective of finding optimal solution is fulfilled but the cost of PMUs is not considered as an analysing factor. So a methodology for determining the minimum number of PMUs with the least cost factor might be further implemented. In the study, the computational time for GA simulation is found to be slow because of the factors like population size, ZIB cases, size of the system, etc. Such affecting factors should be determined and can be minimized by using advanced algorithms or hybrid algorithms. The algorithms can be combined with one another to form a strong methodology so that the drawback of one can be overcome through the other. Further, through improved analysis of the GA solver operators, one can get better solutions by modifying them to suit better the constraints like population size, number of mutations and crossover. Also, in the future, the optimal placement problems for PMU placement should be implemented in real networks so that we can analyse whether or not the optimal placement of PMU qualifies the proposed methodology through its performance.

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