Optimal Identification and selection of Phasor Measurement Units- A Methodology

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***Abstract*—The Phasor measurement unit (PMU) is becoming an important tool for monitoring, controlling and protecting the electric networks. Hence its deployment for the present and future power system networks has become a great challenge for the planning engineers. The optimal PMU placement (OPP) is quite important strategy for deploying the PMUs optimally. Since the optimization techniques yield multiple solutions, it has become an important task again for the engineers to select the best set out of all the available solutions of results. This paper, after presenting the literature on various optimization methods used for solving OPP problem, suggests Multiple Criteria Decision Making (MCDM) methods to select the suitable solution based on the criteria.**

Keywords— PMU; Observability; OPP; optimization; constraints; MADM; Alternatives; Attributes;

I. INTRODUCTION

The invention of Phasor Measuring Unit (PMU) has inroduced the backup protection schemes[1], adaptive protection schemes [2-8], model analysis based network redesigning and highly secured power networks [9-10]. Starting from the introduction of optimal PMU placement, many authors have suggested many algorithms to answer the optimal PMU placement. Most of these placements were purely based on observability constraints. And, their results are different from author to author even though their number is different. But, the power utilities are not clear about which set of PMUs should be considered and which set will serve the most of their purpose. To answer this problem, this paper suggests the Multi-Attribute Decision Making methods to be used for selecting the best solution for their desired criteria.

This article is sectionalized as follows: section I introduces PMU and the problem of OPP. Sections II-V List out the mathematical, topological and heuristic algorithms used for solving OPP problem. Section-VI introduces to MCDM techniques and explains TOPSIS method. After discussing the results in section IV, it concludes the work in section V.

A. Phasor Measurement Unit

The Phasor Measurement Unit (PMU) is capable of measuring various synchronized parameters from the power system. To achieve synchronism, it uses synchronizing signals from Global Positioning Satellite (GPS). This has made the PMU the most prominent tool for various power system strategies.

The observability of a bus can be referred as its ability of being measured either directly or indirectly by the PMU placed either to itself or its incidence bus.

II. MATHEMATICAL ALGORITHMS

A. Integer Linear Programming (ILP)

An Integer Linear Programming (ILP) is deterministic strategy in which all the design parameters would take only integer values. An integer linear programming (ILP) based optimal PMU placement for system observability was introduced in [11] where it considers the locations of conventional measurements. The algorithm [12] extends to incorporate conventional measurements to identify the optimal PMU locations. This scheme also gives the PMU locations under any desired level of redundancy. An ILP based multi-stage PMU placement is suggested in [13]. It models zero-injection constraints as linear.

B. Integer Quadratic Programming (IQP)

It deals with the optimization of a quadratic objective function subjected to linear constraints. It assures integer values to all the design variables. In [14], a PMU placement technique was suggested using integer quadratic programming, but, with no including zero-injection effect. It considers both normal as well as the outage of a transmission line or PMU conditions. Paper [15] suggests another IQP approach that uses the network connectivity matrix to determine optimal PMU locations.

III. TOPOLOGICAL ALGORITHMS

A. Depth First Search (DFS)

The Depth First Search algorithm is a recursive algorithm used for traversing network. It searches the vertices of network based on the criteria called backtracking. This algorithm continues visiting all the nodes until the unvisited nodes have been visited. Authors have used DFS algorithm to solve the OPP problem. As the DFS criterion is rigid and unitary, the solution may not be optimum. So, it is failed in finding optimum solution even though it is computationally faster.

B. Minimal Spanning Tree (MST)

It is nothing but the modified DFS method. This modification makes the MST algorithm faster, and improves the complexity and convergence.The PMU placement strategies using this approach are implemented.

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IV. Heuristic Algorithms

A. Simulated Annealing (SA)

In [16], a pioneering research on PMU placement is proposed using simulated annealing (SA). A rule based OPP considering unobservable buses is presented in [17]. Later, authors [18] have proposed a graph theoretic approach using SA to solve the pragmatic communication-constrained PMU placement problem. Sensitivity constrained OPP method to ensure the dynamic data of power system by observing the system completely is suggested in [19].

B. Genetic Algorithm (GA)

For system complete observability, to solve the OPP problem, GA is applied in [20]. Later, authors have proposed a non-dominated sorting GA (NSGA) to find the best tradeoffs between PMU minimization and redundancy maximization in [NSGA]. In [21], an immunity genetic algorithm (IGA) is applied to identify the PMU locations for system complete observability.

C. Particle Swarm Optimization (PSO)

A binary PSO based optimal PMU placement considering line/PMU outage is proposed in [22, 23]. In the presence of conventional measurements, authors have proposed another PMU placement strategy using binary PSO in [24]. It considers zero-injection effect.

Later, the meta-heuristic methods like Ant colony optimization, bat algorithm, cuckoo search, harmony search, bee algorithm, fire-fly algorithm, flower pollination algorithm and so on, have come-up with the new searching-strategies called intensification and diversification. Since these strategies assure promising solutions with a search focused with diversified solutions, they have surpassed the earlier heuristic techniques in finding the optimal solutions.

Interestingly, to benefit the advantages of the individual algorithms, the researchers are suggested to combine the two or more algorithms to develop a new and hybrid algorithm. But, one must be careful that this hybridization should achieves better results, otherwise it would drive us into a challenge of finding a new algorithm which is still an open problem.

V. Other PMU Placement Strategies

In [25], a Tabu Search (TS) which is a gradient-descent optimization method is applied to solve the OPP for complete observability. On integrating the Differential evolution (DE) with the Pareto non-dominated sorting, a PMU placement technique has been proposed in [26]. Iterated local search (ILS) based PMU placement is suggested in [27] based on the assumption that a PMU installed bus could estimate the current phasors leaving that particular bus. Based on Greedy algorithm, a secure PMU placement against data injection attacks is developed in [28].

A. Constraint-based PMU Placement

To make the wide area measurement system reliable, the contingencies for conventional meters, single contingency and measurement redundancies can also be considered. But, they are expensive.

While placing PMUs considering the critical contingencies, it is essential to implement a policy that considers both the lines and buses based on their role in driving the system to system blackout. In [29], critical elements are identified based on their transient behaviour using fuzzy classification. But, the definition of fuzzy variables has made it more complicated. Later, paper [30] has identified critical buses based on their bus connectivity their operating voltage levels. Similarly, paper [31] presents an OPP problem taking a single contingency into account. But, nowhere, they have considered critical transmission lines/buses outage that could lead to the system blackout. So, obviously, the resultant optimal placement would never assure a secured wide-area protection system.

Importantly, here, the research can be extended by optimizing the number of PMUs by considering installation cost, redundancy, communication reliability, uncertainty, metering accuracy, phase angle range limitations, and other considerable constraints, or both.

Besides that, all these techniques and strategies produce multiple solutions, and it has become a great challenge for the planning engineers to differentiate each solution from the rest. To select the suitable solution, this paper suggests MCDM techniques as follows.

VI. Multiple Criteria Decision Making

Multiple criteria decision making (MCDM) helps the decision makers taking decisions in the presence of multiple criteria. The MCDM is classified into two types such as Multiple Attribute Decision Making (MADM) and Multiple Objective Decision Making (MODM). MADM helps the decision maker in the process of evaluation whereas MODM which helps them in designing. The most common aspects in MADM are described below [32]:

- *Alternatives:* These are the choices available for the decision maker in taking a decision. These are supposed to be prioritized and ranked ultimately. In the case of OPP problem, the multiple solutions mean the alternatives.
- *Attributes:* Aattributes can be referred as goals or decision criteria. Even though alternatives can be viewed from the attributes, they may conflict with each other. For example, the cost may conflict with efficiency. The decision maker may also determine the weights of the relative importance of criteria. Referring to OPP, one can consider the percentage of system observability, observability of critical elements, and observability of a particular region of interest as the attributes. In order to prioritize the criteria, MADM methods assign criteria with the weights of importance.
- *Decision matrix:* It is a m×n matrix whose element d_{ij} represents the performance of i^{th} alternative with respect to j^{th} criteria. The hierarchy of MADM is shown in Fig. 1 given below:

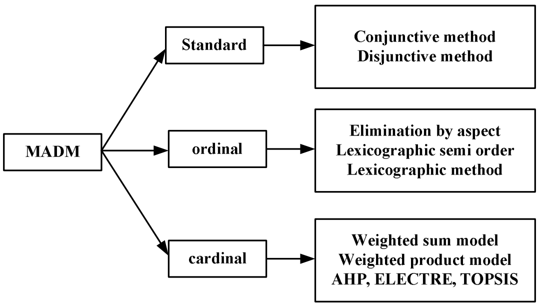

Fig. 1. The hierarchy of MADM

Just for illustration, consider the problem of selection of set of PMUs for the attributes such as Total Observability (TO) and System Observability Index (SOI). The TO represents the total observability that PMU set offers whereas SOI can be defined as the ratio of the sum of a number of buses observed for at least one time and the number of buses observed for more than one time to the total number buses in the system. For IEEE-14 bus system, the alternatives are given Table I.

TABLE I. ALTERNATIVES FOR IEEE-14 BUS SYSTEM

S. No.	Alternative PMU sets
1	2, 6, 7, 9
2	2, 7, 10, 13
3	2, 6, 8, 9
4	2, 7, 11, 13
5	2, 8, 10, 13

The Analytic Hierarchy Process (AHP) [33, 34] is the one among the best techniques for solving MADM problems. AHP enable us to define as many levels as possible to formulate a decision criterion. Its multiple functional characteristics made AHP more powerful tool in MADM. This includes handling subjective judgments, multiple decision makers etc... It handles both subjective and objective criteria effectively [35]. If we consider the AHP for solving the above problem of selection, it results in the Table II. The results say that the first alternative {2, 6, 7, 9} satisfies the two attributes at-most. Here, the utility or the user also has the choice to give the priority to any of the attributes.

TABLE II. SELECTION OF PMU SET

Alternative PMU sets	Ranking
2, 6, 7, 9	1
2, 7, 10, 13	3
2, 6, 8, 9	2
2, 7, 11, 13	3
2, 8, 10, 13	4

Similarly, there are methods such as Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), ELECTRE method, Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE), Compromise Ranking Method (VIKOR) to carry out the selection process.

VII. CONCLUSION

This paper, first, presents the modeling OPP problem and then it gives a list of the optimization methods applied to solve optimal PMU placement. These solution methodologies are broadly classified into three categories such as mathematical algorithms, topological algorithms and heuristic algorithms. Later, it presents various models considered for modeling the OPP problem. The Future scope will include the application of various meta-heuristic methods and hybridization of two or more optimization methods to OPP problem, constrained-based modeling of OPP problem formulation and multi-objective placement methodologies. Finally, after explaining the selection process using AHP technique, it recommends some of the MADM techniques to select the best set for the available set of solutions.

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