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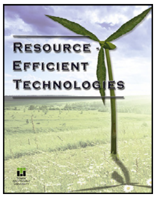

Research paper

A new fuzzy framework for the optimal placement of phasor measurement units under normal and abnormal conditions

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ABSTRACT

This paper presents a new procedure for finding the optimal placement of the phasor measurement units (PMUs) in modern power grids to achieve full network observability under normal operating conditions, and also abnormal operating conditions such as a single line or PMU outage, while considering the availability of PMU measuring channels. The proposed modeling framework is implemented using the fuzzy binary linear programming (FBLP) technique. Linear fuzzy models are proposed for the objective function and constraints alike. The proposed procedure is applied to five benchmark systems such as the IEEE 14-bus, 30-bus, 39-bus, 57-bus, and 118-bus. The numerical results demonstrate that the proposed framework is capable of finding a fine-tuned optimal solution with a simple model and acceptable solution characteristics compared with early works in the literature. Besides, four evaluation indices are introduced to assure the various criteria under study such as the observability depth, measurement redundancy, and robustness of the method under contingencies. The results show that full network observability can be met under normal conditions using 20% PMUs penetration; however, under contingencies, approximately 50% PMUs penetration is required. The novelty of the proposed procedure has proven the capability of the proposed linear fuzzy models to find better optimal number of PMUs with lower number of channels compared to other algorithms under various operating conditions. Hence, the proposed work represents a potential tool to monitor power systems, and it will help the operators in a smart grid environment.

Introduction

Smart grids (SGs) benefit from the continuous improvement in power systems control and the advances in the intelligent measurement technologies. However, controlling electric power systems is becoming more and more cumbersome because of the development of power grid structure and the advance in power markets complexity, especially in deregulated electricity markets. Accordingly, efficient utilization of energy resources is a crucial requirement for incorporating SGs that can present a highly reliable power system with the optimal use of all the available resources. The existing power grids all over the world require revolutionary changes to meet the dramatic growing demands and also to make the grid smarter and more reliable. Also, the instantaneous monitoring of the voltage, current and injected power at all buses in the network is another essential requirement for the SGs as the traditional monitoring systems cannot satisfy this requirement since they are designed based on nonlinear power flow equations [1,2].

Synchronized phasor measurement devices like PMUs, which were first launched in 1980, can measure values of phasor voltages at the buses where they are located. The phase angles of the bus voltages measured in the real-time domain have not been possible yet, as the synchronizing measurements from remote locations are technically challenging. PMUs can alleviate this problem by realizing a synchronization for voltage and current waveforms at remote locations using the global positioning system (GPS) clock, which has an accuracy less than 1 μs; this enables new avenues in power systems monitoring, security analysis, protection and stability control. One such new application of PMUs in power systems is the fault location detection [1].

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PMUs present a real-time snapshot of the entire power system with several critical benefits over the conventional measurement systems, as detailed in [3], such as the high sampling rate to enhance the power system dynamic behavior, typically above 30 measurements every second, while providing more simple linear state estimation compared to the conventional nonlinear state estimation.

PMU placement at all buses would permit direct measurement of the network state. But equipping the power system with PMUs at 100% of the buses is not practical or reasonable because of high costs of the devices, and also limitations of the substation communications network. However, complete observability is very desirable in power systems; therefore, the problem of placing PMUs in a power system to attain a full system observability can be formulated as a constrained optimization problem [4–8]. However, if the lowest number of PMUs is used, there can be situations when limited communication channels or PMU outages could lead to buses becoming unobservable. Therefore, these contingencies have to be taken into account during the design stage.

In the literature, several studies have dealt with it. However, most of them intended to minimize the number of installed PMUs using different sets of constraints to attaining a complete topological observable system. In the studies presented by [9–12], the optimal PMU placement under full observability constraint is given. The availability of communication channels was tackled in [13–15]. In [15], the Markov process was employed to find the optimal solution considering channel limitations. However, the channel availability at each PMU is not considered, nor the single-line or PMU contingencies. In [16], a cellular learning automata (CLA) method is proposed to find the optimal solution for a complete system observability. However, the number of PMU measuring channels was not considered. In [17], a heuristic method was developed for simultaneous optimal PMU placement and phasor data concentrators (PDCs) in a hierarchical structured wide area monitoring system (WAMS). In [18], the authors introduced three approaches to determine the optimal solution for complete observability, namely depth first search (DFS), simulated annealing (SA), and minimum spanning tree (MST). The authors presented a three-stage method that found the optimal solution using network connectivity information in [19]. In the first two stages, PMUs are placed initially at all buses, while in the second stage, the set of connected PMUs was pruned to obtain the optimal PMUs locations. A heuristic search method was proposed for complete topological observability in [20] for full numerical observability in [21]. In [22], the grenade explosion method (GEM) was proposed for finding the optimal solution to provide complete observability. Besides, different meta-heuristic techniques have been suggested for solving the optimal PMU placement problem such as the simplified chemical reaction optimization (SCRO) [23], cellular genetic algorithm (CGA) [24], hybrid discrete particle swarm optimization (HDPSO) [25], particle swarm optimization algorithm [26,27], non-dominated sorting differential evolution (NSDE) algorithm [28], and topology based formulated algorithms and branch and bound (B and B) optimization technique [29]. Also, a method to approach the optimal PMU placement problem with random component outages (RCOs) was suggested in [3]. In the RCO's model, the state estimation error covariance is minimized. In [30], large-scale power networks were considered when formulating the optimal placement of monitoring devices for fault location. Several methods were further presented in [31–36], which involve the ant colony and integer linear programming optimization techniques.

Fuzzy logic is one of the efficient tools that incorporated in the field of power systems. Several applications of fuzzy logic are examined in [37,38]. In [39], the prioritization of different PMU placement configurations is based on multi-criteria decision-making schemes such as the analytic hierarchy process (AHP), or the simple weighted average method. A revised AHP for PMU allocation is presented in [6].

The traditional PMU allocation problem can be formulated as a binary linear programming (BLP) problem. However, conventional BLP problems are hard to solve due to uncertainties present in parameters and the structure; and this may lead to uncertainties in the decision space. On the other hand, the fuzzy set theory can be successfully applied under these uncertainties. Added to that, allocation of PMU devices faces the problem of uncertainty; this implies that reducing the number of PMU devices does not mean it reaches a unique solution. Moreover, it would be nonsensical to expect that the selected optimal set of PMUs will be installed all at once. The problem with PMU placement aims at minimizing the number of PMU placement as much as possible. In fact, the expression "as much as possible" conveys to the fuzziness in this problem. Consequently, the PMU placement problem can be modeled in fuzzy environment. In [40], the optimal PMU placement was approached using fuzzy weighted average. An approach for optimal placement of PMU devices considering fuzzy logic based critical buses was presented in [41]. The basics of the FBLP solution methodology were given in [42]. Other efforts to solve the PMU placement problem were presented in studies [43–49]. In the studies presented by [43,48], two optimal PMU location approaches were presented for power system state estimation. The search optimization techniques were developed in [44–48]. In [50], a Lyapunov exponent-based approach for optimal placement of PMUs was presented to attain full network observability, and to develop real-time system stability monitoring and assessment. The proposed optimal PMU placement method is limited and tested on the IEEE 39-bus test system only. Finally, given the fact that less attention was paid to the application of fuzzy logic to the optimal placement problem as noticed in the literature; accordingly, this paper proposes a novel linear fuzzy modeling of the allocation of PMUs problem to achieving complete system observability. A comparative study is presented to evaluate the proposed procedure for normal and abnormal operating conditions.

Material and methods

Problem formulation

A PMU device installed at bus '*i*' measures the voltage phasor of that bus (magnitude/angle) and the phasor currents (magnitude and angle) of the outgoing lines from the bus directly [43]. The number of measured current phasors depends on the availability of PMU channels. The optimal PMU placement problem for full observability considering PMU measuring channels can be expressed as an optimization problem, as follows:

$$\text{Minimize } f(x) = \sum_{i=1}^{n_b} \omega_i x_i \tag{1}$$

Subject to:

$$g(x) = \sum_{i,j}^{n_b} A_{ij} x_j > b_i \tag{2}$$

where, *f*(*x*) is the objective function has to be minimized concerning the number and locations of PMUs with measuring channels. ω_i refers to the normalized weighting factor of the PMU located at bus '*i*', and this factor reflects the priority of each bus regarding the predetermined channel numbers at that bus. n_b is the size of the system, *i.e.* number of buses, and x_i is a vector represents the decision variables in a binary integer form.

$$x_i = \begin{cases} 1, & \text{if a PMU is installed at bus } i \\ 0, & \text{otherwise} \end{cases} \tag{3}$$

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