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An investment decision model for the optimal placement of phasor measurement units

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ABSTRACT

Safe operation and reliability of the electrical power systems necessitate full observability of the power grid. Phasor measurement units (PMUs) are the state-of-the-art intelligent devices that collect synchronized phasors of voltages and currents in real time. It is not economically justifiable to install PMUs at all buses of the power grid. Hence, designing the PMUs network and determining their optimal placement in the power grid is an investment decision. In this paper, we propose a new investment decision model to determine the optimal placement of PMUs that guarantees the full observability of the power grid. Network observability rules are applied to reduce the capital cost of installing PMUs. A problem-specific genetic algorithm is developed to determine the optimal investment decision. The $N-1$ reliability requirement of the power grid has been integrated in the model as well to obtain the resilient network design against all single contingencies such as failure of a PMU or a transmission line. Furthermore, a two-phase investment plan is proposed, which provides the power system investors with more flexibility and avoids unnecessary investment costs. In the first phase, PMUs are installed to achieve full observability of the power grid whereas additional PMUs will be installed in the second phase to guarantee the full observability in case of single contingencies. To test the efficacy of the proposed model, experiments are conducted on multiple IEEE test systems with and without considering zero-injection buses. The results are compared to the other methods such as integer linear programming and heuristic methods. The analysis shows that the proposed approach is promising and verifies its efficacy.

1. Introduction

Wide-area monitoring and full network observability of electrical power systems in real time was impractical until the emergence of phasor measurement units (PMUs). PMUs are the intelligent measurement devices that measure synchronized phasors of voltages and currents in real time (Singh, Sharma, Tiwari, Verma, & Singh, 2011). Synchronization is achieved by timing signals from the global positioning system (GPS) satellite with accuracy in the order of 1 microsecond. In the future, it is expected that at least 10,000 PMUs, each taking about 10–30 measurements per second, will be installed on the smart grid (Briman, Ganesh, & van Renesse, 2011).

To ensure the full observability of the power system, voltage phasors of all buses should be either directly measured or computed from other measurements (Monticelli, 1999). Two types of observability have been addressed in the literature, numerical and topological observability. A network is numerically observable if the measurement Jacobian matrix is of full rank (Antonio, Torreao, & Filho, 2001). Computations involving the measurement Jacobian matrix are extensive because of the iterative procedure of matrix manipulations (Sodhi, Srivastava, & Singh, 2010). Alternatively, topological observability considers interconnections among the buses and network observability rules to obtain the state vector of the power system. Unlike a conventional measurement device, a PMU can measure the current phasors of multiple lines and provide measurements to compute the voltage phasors of adjacent buses. Thus, there is no need, in terms of observability, to install a PMU at all buses.

The optimal PMU placement (OPP) problem considers the minimum number of PMUs and their installation locations that make the power system observable. Factors such as considering (or not considering) single contingencies, also known as $N-1$ observability, and zero-injection buses create four main classes of the OPP problem as follows.

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1. Optimal placement without considering zero-injection buses and single contingencies
2. Optimal placement including zero-injection buses and not considering single contingencies
3. Optimal placement considering single contingencies and not including zero-injection buses
4. Optimal placement considering single contingencies and zero-injection buses

Recently, these classes of the OPP problem have been studied by several researchers. Integer programming is used in Xu and Abur (2005), Azizi, Dobakhshari, Sarmadi, and Ranjbar (2012a) and Xia, Gooi, Chen, and Wang (2015) to find the optimal placement of PMUs for the mentioned classes. The authors in Azizi et al. (2012) applied integer linear programming (ILP) to solve the OPP problem considering conventional measurement units and single contingencies. Reviewing the results obtained by Azizi et al. (2012), given in Table 1, reveals that considering single contingencies increases the investment costs significantly, at least twice the initial costs in many cases. Therefore, a utility company may prefer to install PMUs in two phases to afford the substantial capital cost of installing PMUs. In the first phase, PMUs are installed to make the power grid fully observable by PMUs and postpone the $N-1$ observability placement to the second phase. However, installing PMUs in the first phase should be done wisely to avoid any unnecessary additional investment in the second phase. In this study, we propose a method that provides investors with flexibility on whether to install all PMUs in one or in two phases while avoiding any potential unnecessary investment costs.

Furthermore, since ILP solvers suffer from the curse of dimensionality, ILP methods are prohibitive for large power systems. Hence, other researchers have studied heuristic and meta-heuristic methods to solve different classes of the OPP problem. In Baldwin et al. (1993) and Nuqui and Phadke (2005), simulated annealing is used to solve the second class of the OPP problem. Similarly, an immunity algorithm is developed by Aminifar, Lucas, Khodaei, and Fotuhi-Firuzabad (2009) to solve the second class of the OPP problem. However, the solutions obtained by the mentioned methods on larger power systems are not the optimal placements comparing to the solutions provided by ILP. Therefore, developing a heuristic or meta-heuristic method is necessary that performs as well as an ILP method specially on larger systems. Authors in Liao, Hsieh, Guo, Liu, and Chu (2015) developed a hybrid search algorithm to solve the second class of the OPP problem. Although their model has a better performance, it does not consider single contingencies. Likewise, other meta-heuristic methods such as tabu search in Peng, Sun, and Wang (2006) and binary particle swarm optimization in Ahmadi, Alinejad-Beromi, and Moradi (2011) have been applied to solve the OPP problem, but single contingencies have not been integrated in the proposed methods. The authors in Mahari and Seyedi (2013) studied the second and forth classes of the OPP problem and have considered single line outage and single PMU failure separately. A more comprehensive approach is developed by Roy, Sinha, and Pradhan (2012) to tackle all classes of the OPP problem. In this approach, an iterative three-stage heuristic method has been introduced where in the first two stages less important and strategically important buses are determined, and the last stage returns the optimal solution using a pruning operation. However, the solution obtained by Roy et al. (2012) lacks accuracy when considering single contingencies and zero-injection buses. Hence, we propose a new comprehensive method that can be used to solve all classes of the OPP problem, is resilient against all types of single contingencies, obtains comparable solutions to those obtained by ILP methods, and provides power system investors with the benefits of the two-phase investment plan. We develop our method based on the genetic algorithm (GA). GA is well-known to have superior performance on solving discrete-binary optimization problems. The main reason is that genetic algorithms use a parallel search from a population of points to avoid being trapped in local optimal solution. Besides, GA has been used successfully in related power system optimization problems. It has been used to find optimal power flows (Bakirtzis, Biskas, Zoumas, & Petridis, 2002), select contingencies in the static security analysis of power systems (Santos, Costa, & Nogueira, 2015), solve the unit commitment problem (Dudek, 2013; Kazarlis, Bakirtzis, & Petridis, 1996), and find the optimal location of multi-type FACTS devices (Gerbex, Cherkaoui, & Germond, 2001). Moreover, it is expected to find multiple optimal solutions for the OPP problem since it is a discrete-binary optimization problem. Another advantage of the genetic algorithms, as a population-based heuristic, is that it can be designed to provide multiple alternative optimal solutions as well. Alternative optimal solutions, obtained from the last population of the algorithm, are necessary in determining the optimal two-phase PMU placement plan. Our GA results are compared to the results available in the literature that have used integer linear programming and other meta-heuristic methods to solve the OPP problem. Furthermore, a two-phase optimal PMU placement approach using the developed GA is described. In the first phase, PMUs are installed to achieve full observability of the power grid whereas additional PMUs will be installed in the second phase to guarantee the full observability considering single contingencies. The two-phase optimal PMU placement approach gives investors more flexibility on whether to install all PMUs in one or in two phases while avoiding any potential unnecessary investment costs.

The rest of this paper is organized as follows: Section 2 describes the optimal PMU placement model. Section 3 discusses developed genetic algorithm for obtaining the optimal allocation of PMUs. Section 4 provides some experimental results and describes the two-phase investment plan and Section 5 reports the conclusions.

Table 1
Optimal number of PMUs for full observability with ZIBs (Azizi et al., 2012).

Power system	Minimum observability	Single contingencies
IEEE 30-bus	7	14
IEEE 39-bus	8	17
IEEE 57-bus	11	22

2. Optimal PMU placement model

The optimal PMU placement problem is defined as finding the installation location of PMUs required for the observability of the power system such that the total investment cost is minimized. Network observability rules can be used to avoid installing PMUs at all buses and reduce associated costs.

2.1. Network observability rules

The network observability rules for topological observability of the power system are given in Ahmadi et al. (2011) and are described here.

Rule 1: If a PMU is installed at bus i, then the voltage phasor of bus i and current phasors of all incident transmission lines to bus i are measured by this PMU (Fig. 1).
Rule 2: If the voltage phasor on one end of a transmission line and the current phasor of the transmission line are measured, the voltage phasor on the other end of the transmission line can be calculated (Fig. 2).