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A two-phase investment model for optimal allocation of phasor measurement units considering transmission switching

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ABSTRACT

Ensuring the reliability of an electrical power system requires a wide-area monitoring and full observability of the state variables. Phasor measurement units (PMUs) collect in real time synchronized phasors of voltages and currents which are used for the observability of the power grid. Due to the considerable cost of installing PMUs, it is not possible to equip all buses with PMUs. In this paper, we propose an integer linear programming model to determine the optimal PMU placement plan in two investment phases. In the first phase, PMUs are installed to achieve full observability of the power grid whereas additional PMUs are installed in the second phase to guarantee the $N-1$ observability of the power grid. The proposed model also accounts for transmission switching and single contingencies such as failure of a PMU or a transmission line. Results are provided on several IEEE test systems which show that our proposed approach is a promising enhancement to the methods available for the optimal placement of PMUs.

1. Introduction

Wide-area monitoring and full network observability of the electrical power systems in real time was impractical until the emergence of phasor measurement units (PMUs). PMUs are power system devices that measure synchronized phasors of voltages and currents in real time [1]. Synchronization is achieved by timing signals from the global positioning system (GPS) satellite with the accuracy in the order of 1 microsecond. In the future, it is expected that the smart grid will consist of at least 10,000 PMUs each taking about 30–120 measurements per second [2].

To ensure the observability of the power system, voltage phasors of all buses should be either directly measured or computed from other measurements [3]. Two types of observability have been addressed, numerical and topological observability. A network is numerically observable if the measurement Jacobian is of full rank [4,5]. These methods are computationally extensive due to the iterative procedure of matrix manipulations [6]. Alternatively, topological observability considers interconnections of the buses and network observability rules to obtain the states vector of the power system. Unlike conventional measurement devices, 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.

Recently, the problem concerning optimal placement of PMUs (OPP) has been studied by researchers. The OPP problem considers the minimum number of PMUs and their locations that make the power system observable. Many researchers have developed heuristic and meta-heuristic methods to solve the OPP problem. Chakrabarti and Kyriakides in [7] applied an exhaustive binary search methodology to tackle the OPP problem and find the associated locations of PMUs. An iterative three-stage heuristic method has been introduced in [8] where in the first two stages less important and strategically important buses are determined. The last stage returns the optimal solution using a pruning operation. In [9,10], simulated annealing is used to solve the OPP problem. Other meta-heuristic methods such as Tabu search [11] and binary particle swarm optimization [12] have been applied to find the minimum number of PMUs required for full observability of the power system. Integer programming is used in [13,14] to find the optimal placement of PMUs. The authors in [15] applied integer linear programming (ILP) to solve the OPP problem considering conventional measurement devices. Although the OPP problem has been studied by many researchers, there are still certain practical aspects of the problem that need to be considered. In this paper, we propose

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Nomenclature

Ω	set of buses
Φ	set of power grid topologies stem from transmission switching
i, j	indices of buses
ϕ	index of topologies

Constants

α_i	observability number of bus i
α_i^ϕ	observability number of bus i after the first phase of PMU placement under topology ϕ
β_i^ϕ	observability number of bus i after the second phase of PMU placement under topology ϕ
C_j	cost of installing a PMU at bus j
γ	the annual percentage of the change in PMU prices
$H_{i,j}$	binary parameter that equals to 1 if $i=j$ or there is a transmission line between bus i and bus j, and 0 otherwise.
$H_{i,j}^\phi$	binary parameter that equals to 1 if $i=j$ or there is a transmission line between bus i and bus j under topology ϕ, and 0 otherwise.
I	inflation-free interest rate
K	number of years between two phases of investment

Decision variables

x_j	binary decision variable which is equal to 1 if bus j is equipped with a PMU in the first phase, and 0 otherwise.
y_j	binary decision variable which is equal to 1 if bus j is equipped with a PMU in the second phase, and 0 otherwise.

new investment decisions on the placement of PMUs and deliver the following outcomes as our contributions.

First, failure of any PMU or transmission line may affect full observability of the power grid. Therefore, considering the $N-1$ reliability requirement, which assures the full observability of the power grid even in the case of single contingencies, is essential in optimal allocation of PMUs [15]. However, considering single contingencies increases the investment costs substantially, more than twice the initial costs in many cases. Table 1 shows the solutions to the optimal PMU placement problem, obtained by other researchers [8,16], for different test systems with and without considering single contingencies. The solutions provided in Table 1 are the best solutions available in the literature.

Considering the results provided in Table 1, it can be inferred that achieving the $N-1$ observability placement costs almost twice the minimum observability placement. Regarding the substantial capital cost of installing PMUs, a utility company may prefer to install PMUs in two phases. 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. Hence, we formulate an integer linear programming problem that minimizes the total investment costs and determines the optimal placement of PMUs in two investment phases. In the first investment phase, PMUs are installed to achieve full observability of the grid. In the second phase of investment, additional PMUs are placed in service to meet the $N-1$ reliability requirement.

Table 1
Optimal number of PMUs for full observability.

Power system	Minimum observability	$N-1$ observability
IEEE 14-bus	4	9
IEEE 24-bus	7	14
IEEE 30-bus	10	21
IEEE 39-bus	13	28
IEEE 57-bus	17	33
IEEE 118-bus	32	68

Furthermore, electric transmission planning is one of the major concerns in the field of power system engineering. Transmission switching has been studied in the literature as a method to increase economic efficiency [17,18], improve system security [19], reduce cost or loss [20], control over- or under-voltage situations [21] or avoid line overloads [21] through temporarily changing the power grid topology. Therefore, transmission switching should be considered in the optimal placement of PMUs since it changes the power grid structure. PMU placement without considering transmission switching may put the observability of the power grid at risk. In this paper, we incorporated transmission switching concept in our ILP model for the optimal allocation of PMUs. It is worth mentioning that considering transmission switching requires more PMU to maintain the $N-1$ observability of the power grid, which puts more emphasis on necessity of a two-phase optimal PMU placement model.

The rest of this paper is organized as follows: Section 2 discusses our proposed two-phase optimal PMU placement model considering transmission switching. Section 3 uses a case study to illuminate the necessity of the two-phase model and considering transmission switching in the optimal allocation of PMUs. Section 4 provides some experimental results and Section 5 reports our conclusions.

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 cost is minimized. Network observability rules can be used to avoid installing PMUs at all buses and reduce associated costs significantly.

2.1. Network observability rules

The network observability rules for topological observability of the power system given in [12] are described here.

1. If a PMU is installed at bus i, voltage phasor of bus i and current phasors of all incident transmission lines to bus i are known (Fig. 1).
2. If voltage phasor of one end of a transmission line and the current phasor of the transmission line are known, the voltage phasor of the other end of the transmission line can be calculated (Fig. 2).
3. If voltage phasors of both ends of a transmission line are known, the current phasor of the transmission line can be calculated (Fig. 3).

Measurements obtained by Rule 1 are direct measurements. Rules 2 and 3 provide pseudo measurements. Zero-injection buses, which do not inject currents into the system, have the potential to reduce the number of required PMUs for observability of the power

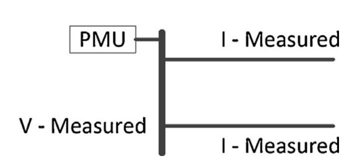

Fig. 1. Network Observability Rule 1