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Intelligent-search technique based strategic placement of synchronized measurements for power system observability

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ABSTRACT

Synchronized phasor measurements placement problem is commonly solved by formulating it as a mathematical optimization problem, which is limited by huge computational burden especially for larger systems. This paper proposes a novel intelligent search based approach for placement of phasor measurement units (PMUs) in the power system while maintaining complete observability. The proposed approach works in two stages. Stage I utilizes best first search to identify the possible locations of PMUs in order to obtain system observability and these locations are used as inputs to stage II. Stage II determines the optimal locations of PMUs by applying pruning to the inputs received from stage I, such that the system observability is achieved with the minimum number of PMUs. The proposed approach has been further extended to incorporate the presence of conventional flow measurements. An important feature of the proposed placement method is its capability to handle both single as well as multiple flow measurements connected to a bus. The proposed method has been tested on IEEE 14-bus, IEEE 30-bus and a practical 246-bus Indian networks for system intact condition as well as during single transmission line and single PMU loss. The effectiveness of the proposed method has been demonstrated by comparing the numerical results obtained using the proposed method with the existing methods.

1. Introduction

State estimation precisely calculates the voltage phasors at all system buses based on power flow measurements, injection measurements and voltage magnitude measurements. However, these measurements are not time-synchronized, which leads to error in the state estimation results. The advent of phasor measurement units (PMUs) has revolutionized the field of state estimation because of its ability to provide synchronized measurements. The state estimation results can be significantly improved in terms of speed and accuracy by using PMUs in the networks. With more PMUs deployed in electric power grids, the conventional supervisory control and data acquisition (SCADA) systems can be made more effective. Furthermore, the dynamic performance of the power system can be analyzed due to its high sampling rate. A PMU when placed at a bus can directly measure the voltage phasor of that bus and the current phasors of all the incident branches. Thus, the deployment of PMUs at each bus would directly measure all the voltage phasors eliminating the need of state estimator. However, due to the high cost associated with the PMU device and its communication facilities, it is neither economical nor feasible to install PMUs at all the system buses. Therefore, it is imperative to determine the optimal placement of PMUs.

In the past two decades, valuable research has been done to solve the optimal PMU placement problem through graph theory based approaches, mathematical and evolutionary programming techniques. Graph theory based approaches such as depth first search (DFS) and spanning tree (ST) were the first used to solve this PMU placement problem (Baldwin, Mili, Boisen Jr, & Adapa, 1993). The DFS method is based on placing the PMUs in the order of the largest connectivity hence, it ensures complete observability but with a more number of PMU locations. These additional PMUs causes the observable islands to overlap each other resulting in unwanted redundancy at a few system buses. In Anderson and Chakrabortty (2014), the authors have used two graph theoretic based approaches to find the sub-optimal PMU locations. Then a statistical analysis is performed by considering a large set of bipartite graphs generated by the two approaches. This iterative method is capable of offering close to optimal solution, but it is computationally intensive for larger networks.

Over the past years, various integer programming (IP) based methods have been proposed to solve the PMU placement problem incorporating different kinds of constraints. In Aminifar, Khodaei, Fotuhi-Firuzabad, and Shahidehpour (2010), integer linear

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Nomenclature

C_{ij}	ijth element of original connectivity matrix with $C_{ij} = 1$ if buses i and j are connected or if $i = j$, otherwise $C_{ij} = 0$
C'_{ij}	ijth element of connectivity matrix after topology transformation due to the presence of conventional flow measurements (CFM)
C'_{mn}	mnth element of connectivity matrix after topology transformation due to the presence of zero injection buses (ZIB)
F_{ij}	ijth element of flow matrix with $F_{ij} = 1$ if measured flow is available on a line k–j where, 'k' is connected to both 'i' and 'j', else $F_{ij} = 0$
f_i	evaluation function at bus 'i'
f_l^b	evaluation function of the unobserved node 'l' at the bth iteration
f_r^{b-1}	evaluation function retained at the non-PMU nodes during the end of $(b-1)$th iteration
I_{kj}	current phasor on the line connecting buses 'k' and 'j'
L	location vector
M	vector containing buses which are observed only once
N	number of PMUs obtained at the end of stage I
nb	total number of system buses
OV_i^b	ith element of the observability vector obtained at the bth iteration
p	PMU count
P^{bp}	product of redundancy obtained at all the system buses
P_{kj}	real power flow on the line connecting buses 'k' and 'j'
P_N	product vector with product elements, P^{bp}
Q_{kj}	reactive power flow on the line connecting buses 'k' and 'j'
R_j	redundancy value at bus 'j'
T_{mn}	mnth element of transformation matrix with $T_{mn} = 0$ if both the buses 'm' and 'n' are radial buses (RB) or ZIB else, $T_{mn} = 1$
TO_i^b	ith element of the total observability vector obtained at the bth iteration
V_k	voltage phasor at bus 'k'
X	cost of PMU installation
Y_i	coverage value of a PMU at bus 'i'
λ	biasing coefficient

programming has been proposed for finding the optimal locations of PMUs considering single PMU loss or single line loss. The effect of single line outage is added directly to the model by using auxiliary variables. The model proposed in Gómez and Ríos (2013) have considered an optimal multistage PMU placement alongwith measurement redundancy. It also incorporates user defined time constraints for PMU allocation, which allows the user to define the time at, or after, which a bus must be observed. The authors have a proposed a new formulation in Tai, Marelli, Rohr, and Fu (2013) to excite all the possible PMU placement solutions. Then, the optimal solution is chosen to minimize the state estimation error covariance. Due to potential difficulty in computation, the authors have proposed sequential algorithm to estimate error covariance. However, the selection of optimal solution from the multiple placement sets is time consuming for larger networks. Optimal PMU placement problem considering channel limitations has been initially introduced in Korkali and Abur (2009). The authors in Abiri, Rashidi, Niknam, and Salehi (2014) have offered an efficient formulation based on integer linear programming for optimal PMU placement problem with channel limits. The formulation is also extended in the cases of single line and single PMU outages. Although the method provides the global optimal solution, it is based on the assumption that all the PMUs have unlimited channel capacities to record as many phase voltages and currents as needed. The same authors in Rashidi, Abiri, Niknam, and Salehi (2015) have reformulated the problem such that varying number of channels for each PMU can be considered. In Kavasseri and Srinivasan (2011), optimal locations of PMUs are determined considering the existence of conventional flow measurements. With this approach, a smooth transition from the current SCADA-based system monitoring to the future PMU-dominated WAMS can be facilitated. However, the solution time increases because the number of variables and constraints rapidly scale with the system size. The integer programming methods have been found to be effective in finding the optimal solution is a lesser simulation time. However, the optimal solution obtained using the IP methods is dependent upon the initial guess chosen.

Recently, many evolutionary algorithms have been applied to solve the PMU placement problem due to their capability to achieve a near global optimal solution as well as to handle multi-objective problems efficiently. In Milosevic and Begovic (2003), the authors have used non dominated sorting genetic algorithm (NSGA) for the multi objective PMU placement. Although genetic algorithms find the better optimal trade off among the multiple conflicting objectives, drawbacks such as, poor convergence, slow operation speed and too many setting parameters have limited its application. The authors in Nuqui and Phadke (2005) have used simulated annealing (SA) in their graph procedure to find the optimal PMU locations. However, these methods are computationally extensive. In Peng, Sun, and Wang (2006), tabu search method based on augmented incidence matrix has been developed to optimize PMU placement. But the method needs complicated matrix construction and computation. The authors in Chakrabarti, Venayagamoorthy, and Kyriakides (2008) have suggested a binary particle swarm optimization (BPSO) to achieve the dual objectives of minimizing the number of PMUs and maximizing the measurement redundancy. In Ramachandran and Thomas Bellarmine (2014), the authors have used fruit fly optimization (FFO) for the PMU placement problem. The major drawback of these evolutionary algorithms is the higher simulation time for larger power system network.

Further, new algorithms are adopted by researchers to solve the various optimization problems. An inventory planning model based on single item lot sizing problem with fuzzy parameters is suggested in Ketsarapong, Punyangarm, Phusavat, and Lin (2012), to make decisions during uncertainties. In Bastos-Filho, Chaves, Pereira, and Martins-Filho (2011), the authors have specifically developed a training algorithm based on evolutionary computation for handling conflicting optimization objectives for wavelength assignment. The authors in Precup, David, Petriu, Preitl, and Paul (2011) have suggested gravitational search algorithm (GSA) to solve the optimization problem with non-convex objective functions used in fuzzy controllers. Due to the slow convergence rate and local searching behavior of the original PSO, the authors in El-Hefnawy (2014) have proposed a modified PSO for solving fuzzy single and bi-objective problems. This is achieved by introducing adaptive inertia weight according to the variance of the fitness function, so that a proper coordination between the local searching ability of the PSO with the global searching behavior is maintained. Since these methods are used to solve complex optimization problems, they have a lot of potential for solving the optimal PMU placement problem also.