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Optimal allocation of phasor measurement unit for full observability of the connected power network

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ABSTRACT

This paper presents binary particle swarm optimization (BPSO) technique for the optimal allocation of phasor measurement units (PMUs) for the entire observability of connected power network. Phasor measurement units are considered as one of the most important measuring devices in the prospect of connected power network. PMUs function may be incorporated to the wide-area connected power networks for monitoring and controlling purposes. The optimal PMU placement (OPP) problem provides reference to the assurance of the minimal number of PMUs and their analogous locations for observability of the entire connected power networks. Binary particle swarm optimization (BPSO) algorithm is developed for the solution of OPP problem. The efficacy and robustness of the proposed method has been tested on the IEEE 14-bus, IEEE 30-bus, New England 39-bus, IEEE 57-bus, IEEE 118-bus and Northern Regional Power Grid (NRPG) 246-bus test system. The results obtained by proposed approach are compared with other standard methods and it is observed that this BPSO based placement of phasor measurement units is found to be the best among all other techniques discussed.

Introduction

PMUs are becoming an essential instrument for the wide-area measurement system which is used in advanced connected power network monitoring, preservation and control operations. It gives synchronized measurements of real-time phasor of voltages and currents. Synchronization is achieved by the same time sampling of voltage and current waveforms using timing signals from the Global Positioning System (GPS). PMUs raise the standard of power network monitoring, control and preservation to an advanced level [1]. The existing and desirable future operations of PMUs are well documented in [2]. Supervisory Control and Data Acquisition (SCADA) system gives unsynchronized measurements leading to erroneous estimations of connected power network states. In addition, the slow data scan rate of about 2–4 samples per cycle makes them indecisive to capture very small disturbances of the order of sub-seconds on the power network. These complications can be overcome by using phasor measurement units (PMUs). A number of PMUs are already equipped in various utilities around the world for several operations such as post-mortem analysis, adaptive preservation, system preservation stratagem and state estimation. PMUs installation selection is one of the substantial issue that need to be addressed in the emerging technology. The implementation of PMUs at each bus would aid direct measurement of all the states of the connected power network. This is not only unprofitable proposition due to higher installation cost of PMUs but would be an impractical phenomenon because of limited accessible communication facilities. Hence, there is a necessity for crucial placement of PMUs across the connected power network. A connected power network can be observed completely when sufficient instruments are obtainable to estimate all the states of the system differently [3,4]. Numerous methods using classical techniques as well as soft computational approaches have been reported in referred journals.

A genetic algorithm-based approach for solving OPP issue is proposed in [5]. In [6], an efficient and capacious formulation for the OPP issue is reported to minimize the number of PMUs to ensure entire power network observability. Furthermore, the formulation is continued for encouraging entire power network observability under single PMUs loss or single line outage occurrence and the consequences of zero-injection buses (ZIBs) in the power network is also contemplate. Ref. [7], explains the instability related to the power network state variables obtained with the help of PMUs. An integer-quadratic programming based approach is used to decide the minimum number and the optimal locations of the PMUs for entire observability of the connected power network. In recent years, there has been a consequential research

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activity on the problem of finding the minimum number of PMUs and their optimal locations for power system state estimation [8]. In [9], a three stage OPP method is proposed using network connectivity particulars. In this approach authors have initially considered that the PMUs are present at all buses of the connected power network. Then the Stage I and Stage II of the developed algorithm repetitively decide (i) unsuitable bus locations from where PMUs are removed and (ii) suitable bus locations where PMUs are to be kept. Stage III of the approach minimizes the number of PMUs using pruning applications. The integer linear programming (ILP) is proposed to solve the OPP issue in the entire connected power network and the multi-criteria decision-making (MCDM) approach is developed to identify the suitable locations of PMUs for the network [10]. Reference [11], presented a novel integer linear programming framework for optimal multi-stage PMU placement (OMPP) towards improvement in the network observability during intermediate stages whereas the entire observability is assured at the end of the OPP operation. Recently, the authors reported a flocking approach based on the Fuzzy C-medoid algorithm (FCMdd) for discriminating and separating large power networks into comprehensible electric areas intensified around a representative so-called medoid-bus [12]. This bus was treated as a distinctive location for PMUs in the circumstances of wide-area measurement system (WAMS) composition for dynamic vulnerability assessment (DVA). In [13], a model for the optimal placement of contingency-constrained PMUs in power networks is suggested. The entire observability of power networks is first formulated and then different contingency conditions in networks containing measurement losses and line outages are combined to the main model. In [14], the authors carried out the consequence of channel capacity of PMUs on their optimal placement for entire power network observability. The authors in [15] contemplated the difficulty of OPP and typical power flow to fortify the observability conditions under faulted conditions in power networks. A binary differential evolution optimization algorithm for OPP and an intelligent approach for fault locations in power network is proposed in [16]. A binary imperialistic competition algorithm (BICA) for solving OPP problem is proposed in [17]. Introduction of a recursive Tabu search (RTS) approach to solve the OPP issue is presented in [18]. A novel method for OPP problem suffering from random component outages (RCOs) is presented in [19]. Two aspects of the OPP issue are discussed in [20]. Firstly, an integer linear programing (ILP) approach for the optimal multistage placement of PMUs is suggested. Secondly, a technique to identify buses to be observed for dynamic stability is given. A sequential quadratic programming approach is proposed in [21] to determine the minimal number of PMUs and their optimal locations. A new state estimator for minimizing the number of PMUs arrangement for allowing entire observability of the connected power network is documented in [22]. A non-linear programming-based model for the OPP is given in [23]. Multi-objective OPP (MOPP) to enhance the performance of network monitoring and control is discussed in [24].

In this paper, a novel approach based on BPSO technique is proposed to decide the minimal number and optimal locations of PMUs for the observability of the entire power network under normal operating conditions. The suggested method is applied on standard IEEE 14-bus, IEEE 30-bus, IEEE 57-bus and IEEE 118-bus, on the New England 39-bus test system and on the Northern Regional Power Grid (NRPG) 246-bus power network. The obtained results are compared with the existing approaches to find the effectiveness of the suggested approach on the OPP issue.

The rest of the paper is structured as follows. Section 'Connected power network observability analysis based on PMU' explains the concept of power network observability and the decree which is used to evaluate entire power network observability. Problem formulation for OPP is presented in section 'Problem formulation for PMU placement'. The proposed approach for the determination of optimal location of PMU is explained in section ''Proposed BPSO method'. Case study results are reported in section 'Case studies' where the superiority of the proposed technique over the other existing methods is also validated. Finally, section 'Conclusion' concludes the paper.

Connected power network observability analysis based on PMU

PMUs have been extensively placed in connected power networks in recent years. They provide positive sequence voltage and current mensuration synchronized within a microsecond. A PMU placed at a bus precisely calculate the voltage phasor at that bus and current phasors of each branch attached to that bus rely upon the number of channels in connected power network. As a result, a given power network is said to be completely observable provided all buses are observable through direct or indirect measurement. There are two approaches to determine system observability namely, numerical observability and topological observability. A system is said to be numerically observable if design matrix H is well defined and is of full rank [25]. Topological observability is built upon graph theory where system is depicted by non-oriented graphs. A power network can be considered as topologically observable if not less than one spanning mensuration tree is of full rank [26]. A topological observability approach is used in the paper. It has been suggested that PMU set-up at particular buses can calculate current phasors of all the branches attached to it and also the voltage phasors of that bus [27]. The voltage phasors at the buses next to the PMU set-up bus can be determined by calculating branch current phasors, bus voltage phasor and accepted line parameters [28]. In this manner, the placement of PMUs at a bus not only monitor that bus but also all the neighboring buses attached to it. As displayed in Fig. 1(a) assume PMU is placed at bus 3 and this bus will observe all the adjacent buses (bus 1, 2 and 4) those are connected to it. In addition, a connected power network also involve those buses in which both load nor generator is connected and such buses are mentioned as zero injection bus (ZIB). If an observable ZIB is encircled by all the observable buses except one, the unobservable bus can be observed by applying the Kirchhoff's Current Law (KCL) at zero injection bus. Assume that in Fig. 1(b), bus 3 is a zero injection bus which is encircled by bus 1, 2, 4 and bus 2, 3 and 4 are observed by PMU except bus 1. Hence, for the observability of bus 1, KCL is applied. Nevertheless, if an unobservable ZIB is encircled by all the observable buses, then the unobserved ZIB can be made observable by applying KCL at ZIB. Similarly as in Fig. 1(c), consider an unobservable bus 3 is a zero injection bus is encircled by all the observable buses (bus 1, 2 and 4), then the unobserved zero injection bus made observable by using KCL. PMUs will not be implanted at ZIB. By applying KCL, ZIB measures voltage phasors at that bus. Moreover, the placement of PMUs at radial buses is dodged on account of considering the cost and that makes only one bus observable. So, zero injection bus (ZIB) connected to radial bus is not selected for PMUs placement as it is unwise. From Fig. 1(d), if PMU is placed at bus 3, a radial bus (RB), then it observe only bus 2 and itself. For example in IEEE 14 bus system, if PMU is placed at bus 8 (RB) then it observes only bus 7 (ZIB) and itself. But if PMU is placed at bus 7 (ZIB), then it observes bus 4, 8, 9 and itself. Therefore, it is not feasible to place PMU at zero injection bus connected to radial bus. If ZIB is connected to more than two radial buses, then the PMUs must be placed at ZIB for the observation of radial buses attached to it. As in Fig. 1(e), assume PMU is placed at bus 3 which is a zero injection bus (ZIB) encircled by all the radial buses (bus 1, 2 and 4), then PMU at bus 3 not only observe that bus but all the buses connected to it.