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Optimal power quality monitor placement in power systems using an adaptive quantum-inspired binary gravitational search algorithm

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ABSTRACT

This paper presents a novel adaptive quantum-inspired binary gravitational search algorithm (QBGSA) to solve the optimal power quality monitor (PQM) placement problem in power systems. In this algorithm, the standard binary gravitational search algorithm is modified by applying the concepts and principles of quantum behavior to improve the search capability with a fast convergence rate. QBGSA is integrated with an artificial immune system, which acts as an adaptive element to improve the flexibility of the algorithm toward economic capability while maintaining the quality of the solution and speed. The optimization involves multi-objective functions and handles the observability constraints determined by the concept of the topological monitor reach area. The objective functions are based on the number of required PQM, monitor overlapping index, and sag severity index. The proposed adaptive QBGSA is applied on several test systems, which include both transmission and distribution systems. To evaluate the effectiveness of the proposed adaptive QBGSA method, its performance is compared with that of the conventional binary gravitational search algorithm, binary particle swarm optimization, quantum-inspired binary particle swarm optimization, and genetic algorithm.

1. Introduction

In conventional power quality monitoring practice, power quality monitors (PQMs) are usually installed in locations where the utility or customer wishes to measure the power quality of the system by detecting and analyzing power quality events [1]. Voltage sag is the most frequent type of event captured among all power quality events [2]. Voltage sag is defined by the Institute of Electrical and Electronics Engineers (IEEE) standard 1159-1995 as a voltage reduction in the root mean square (RMS) voltage from 0.1 to 0.9 per unit for a duration of between half of a cycle and <1 min. Voltage sag has become a significant concern because it creates huge economic losses resulting from the failure or malfunction of sensitive equipment in industries. The installation of PQMs at selected buses in a power system is important to monitor and detect the occurrence of voltage sags.

In a distributed power quality monitoring scheme, selecting the number and location of PQMs is a critical problem because it is directly related to the efficiency of the monitoring system. Installing PQMs at all buses in a power distribution network to monitor voltage sags is uneconomical and inefficient. Thus, the number of PQMs must be decreased to reduce the total cost of the power quality monitoring system and the redundancy of the data being measured by monitors [3]. In the past, the procedure for selecting the minimum number and best locations for PQM installation is usually performed manually by power quality experts through their experience and knowledge on power quality and system topology. However, such a procedure is unreliable and inconsistent. Therefore, an automated approach to determine the optimal number and location of PQMs is necessary to establish how many PQMs are required to monitor the entire power network with the lowest possible redundancy. Each possible voltage sag that may occur in the power network can be observed by at least one of the installed monitors. The minimum number and optimal location of PQMs are often linked together because the number of monitors required is reduced by installing the monitors in strategic network buses with the highest observability capacities. The concept of monitor observability based on the monitor reach area (MRA) has been utilized to determine the optimal placement of PQMs in transmission networks [3–9]. In other applications similar to PQM placement, deciding where to place the optimal phasor measurement unit only applies to transmission networks [10–12]. Not enough evidence has been provided to prove that the concept is applicable to radial distribution networks. Therefore, a new optimal PQM placement method that is applicable for both transmission and distribution networks and caters to the system topology issue must be developed.

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A few optimization techniques have been utilized in the last few years to solve the optimal PQM placement problem. In [3], a PQM placement method based on covering and packing was developed with the GAMS software as an integer linear program. In [4–6], the branch and bound algorithm was applied by dividing the solution space into small spaces for easy solving. However, this algorithm may provide an incorrect solution when a branch is incorrectly selected in the earlier stages. In [7–9], the genetic algorithm (GA) was used to solve the optimal PQM placement problem. GA is commonly utilized to solve the optimization problem; however, the disadvantage of GA is its slow convergence rate. Thus, an alternative optimization technique with a faster convergence rate, such as particle swarm optimization (PSO), is recommended [13]. A relatively new heuristic optimization technique known as the gravitational search algorithm (GSA) is gaining popularity because it has been reported to provide a solution better than that of PSO in solving certain problems [14]. Therefore, GSA is examined in this study to evaluate its performance in solving the optimal PQM placement problem.

The main aim of this study is to develop a new method to solve the optimal PQM placement problem in both transmission and distribution networks through a new heuristic optimization technique that considers three concepts, namely, quantum behavior, binary gravitational search algorithm (BGSA), and artificial immune system (AIS). The observability concept based on the topological monitor reach area (TMRA) is introduced in the proposed optimal PQM placement method to allow for the application of observability to both transmission and distribution systems [15]. In addition, the monitor coverage control parameter is employed to provide flexibility to the search algorithms in complying with sensitivity and economic capability. Control parameter α is defined as a voltage threshold level in p.u. at a monitored bus to indicate whether a fault occurs inside or outside the monitor's coverage area. A PQM usually detects and captures voltage variations when the measured RMS voltage reaches 0.9 p.u. [16]. In this study, the maximum α value is set at 0.85 p.u. to allow some overlapping of the monitor coverage area at the boundary. This approach will help overcome the boundary issues and non-monitored fault on the line segment at the boundary.

This paper is organized as follows. The core subject, which refers to the monitor coverage concept in the PQM placement method, is explained in Section 2. The existing MRA concept is briefly reviewed, and then the proposed TMRA concept is described. The problem formulation for optimal PQM placement is discussed in Section 3. The overview and procedures of BGSA, quantum-inspired binary gravitational search algorithm (QBGSA), and AIS are presented in Section 4. The test results on the power systems under study and the optimal solutions are provided and discussed in Section 5.

2. Monitor coverage concept

Monitor coverage is the most important entity in the determination of PQM placement. This concept is employed to evaluate the placement and guarantee the observability of the entire power network. The monitoring coverage concept is called MRA [4]. Residual voltages at each bus for all fault cases are required in the formation of MRA. Therefore, residual voltages should be saved in the form of the fault voltage (FV) matrix where the matrix columns (j) represent the bus numbers of residual voltage readings and the matrix rows (k) relate to the specific type of fault position [7]. The MRA matrix can be obtained by comparing all the FV matrix elements for each phase with the threshold value, α. Each element of the MRA matrix is given the value of 1 when the voltage is less than or equal to α p.u. in any phase and given the value of 0 otherwise as provided by the following equation.

$$\mathrm{MRA}(j,k) = \begin{cases} 1, & \text{if } \mathrm{FV}(j,k) \leqslant \alpha \text{ p.u. at any phase} \\ 0, & \text{if } \mathrm{FV}(j,k) > \alpha \text{ p.u. at all phases} \end{cases} \quad \forall j,k \tag{1}$$

TMRA is introduced in this study and applied to both distribution and transmission systems. The TMRA matrix is a combination of the MRA matrix and the topology (T) matrix by using the operator "AND" as expressed in Eq. (2). Similar to MRA and FV matrices, the T matrix columns represent the bus number and its rows are correlated to fault location and type of fault. The T matrix is constructed based on the concept of paths as in graph theory. During the occurrence of a fault, the faulted bus voltage level drops to nearly ground level and becomes a cut vertex. At this moment, the faulted bus can be separated into several independent vertices that correspond to the number of branches connected to the bus. Thus, a path is considered when at least one route from start vertex to end vertex, which does not go through the cut vertex, is available. In this case, each generating station can be a start vertex, and a bus under consideration for PQM placement can be an end vertex. Based on the condition, the T matrix is given the value of 1 when a path from any generating bus to a particular bus under consideration exists and given the value of 0 otherwise. As a result, all downstream PQMs from the faulted location require another upstream PQM for effective event recording.

$$\mathrm{TMRA}(j,k) = \mathrm{MRA}(j,k) \cdot \mathrm{T}(j,k) \tag{2}$$

Fig. 1 shows examples of a particular row in a T matrix for a radial system with a single power source, a radial system with two power sources, and a ring system with a single power source. When a fault occurs at bus 3, the system can be represented in a graph with bus 3 separated into several numbers depending on the number of branches connected to the bus. The T matrix column is then given the value of 1 or 0 by checking the connectivity between the generator bus and the other bus based on the criteria mentioned previously. The system in Fig. 1(a) has only one generator located at bus 1. Obviously, a path from the generator bus (bus 1) to buses 1, 2, and 3 exists in this system, but not for the rest. Therefore, the T matrix column is given the value of 1 up to column 3 and 0 for the rest. A different situation is observed when another generator is added to the system at bus 5 as shown in Fig. 1(b). In this case, buses 4 and 5 have a link to the second generator. Thus, the T matrix is given the value of 1 up to column 5. The ring system shown in Fig. 1(c) provides a value of 1 to all columns of the T matrix because a path connects the generator bus (bus 1) to the other buses. As a result, this T matrix provides information on system topology. These examples are considered only for a fault at bus 3 and must be implemented at all buses in the system to obtain a complete T matrix.

3. Optimal PQM placement problem formulation

The three common elements required in the binary optimization technique are decision vectors, objective functions, and optimization constraints. Each element is formulated and explained to obtain the optimal solution of PQM placement. The optimization technique explores the optimal solution as defined in the objective function through the manipulation of the bits of the decision vector subject to the constraints in each generation. The process is iterated for a fixed number of times or until a convergence criterion is achieved.