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Coordinated online voltage management of distributed generation using network partitioning

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ABSTRACT

Due to the increasing penetration level of renewable energy resources in distribution systems, a new approach for voltage and reactive power control needs to be developed to deal with the fluctuations caused by intermittent changes of these resources. This paper, at first proposes a systematic approach which splits distribution networks into several separate control areas to control the voltage profile of each area in an admissible time calculation which is necessary for online operation. Then to solve the voltage regulation problem, a new method based on particle swarm optimization (PSO) algorithm is proposed to be applied to each center using only zonal data and also to calculate the optimum reactive power set points of the distributed generations (DG) units in the related area. Finally, the results of the proposed method on IEEE 123-bus unbalanced test system in comparison with another method based on interior point algorithm in both decentralized and centralized manner demonstrate the ability and efficiency of the proposed method for online control of smart grids voltage profile.

1. Introduction

Distributed generation has attracted the interest of many research [1]. Although DGs offer many benefits to the traditional distribution grids, increasing penetration level of renewable energy resources changes the nature of these networks from passive to active in which some problems such as voltage fluctuations may be emerged; therefore, it is essential to reconsider how to deal with their negative impacts with novel methods instead of conventional ones. Conventional controllers, manage voltage and reactive power of distribution grids by under load tap changers, step voltage regulators and static VAR compensators [2,3]. However, there are some problems due to the slow time constant and switching restrictions of some compensators to act fast and reliable and so, an efficient way of voltage and reactive power control is needed. Existing power inverters interfaced with DG units or energy storage systems are appropriate solutions for near real time management of voltage and reactive power [4]. There are two main methods in order to control these power electronic interfaces: (i) local control; (ii) coordinated control [5,6]. Although the methods based on local control have high response time, because of using local data, they are not optimum. Moreover, the lack of enough knowledge about other parts of the network may lead to decision mistakes [7,8]. To improve the performance of these methods, a secondary management level is employed which uses the bidirectional communication infrastructure between secondary control center (CC) and all reactive power controllers and coordinates the participation proportion of these sources in voltage management problem in an optimum way. Most of the previous coordination methods are based on centralized architecture in which one center is responsible for supervising network's operation [9,10]. According to the unbalanced nature of the distribution networks as well as increased number of generators and consequently control variables in a smart grid, the time required for the computational operations and the amount of information which need to be processed will greatly increase so that the majority of these methods cannot be implemented as online. Therefore, it is necessary to pursue other methods such as decentralized ones. The application of these solutions has been successfully tested in France and Italy transmission systems in which the whole transmission system is divided to some smaller

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control areas [11]. Moreover, other decentralized studies are trying to decompose original centralized optimization problem to some smaller sub-problems and solve them in a parallel manner; however, the disadvantage is that there is a need for a special center for coordinating other centers [12–14]. Furthermore, such solutions suffer from single point failure [15].

According to the demerits pointed out, this paper presents a new decentralized solution for coordinated voltage regulation problem for power distribution systems. The proposed method improves the computational burden and response time for online implementation by dividing the distribution network into some smaller partitions. One of the major challenges in the partitioning of a network is how to determine boundaries of each partition. Except the voltage regulation problem, network partitioning has been used in other problems, such as self-healing and network restoration [16], prevention of cascading events [17], rotor angle stability [18], and etc. These problems are analyzed with different partitioning methods such as graph-based solution [17], spectral-based solution [11,19], electrical distance based solution, and etc. The first contribution of this paper is to propose a pattern matrix for the partitioning stage with respect to the voltage regulation issue, and then provide a systematic spectral-based approach for partitioning this matrix. Unlike the transmission systems, voltage variations in distribution systems strongly depend on active power changes in addition to reactive power changes; thus, the proposed method is more efficient than the ones reported for transmission systems. It can be also used for systems with different dimensions, and there is not any dependency on the number and location of DG units in each area; therefore, the boundaries of each area are robust. The second contribution of this paper is to present a coordinated optimization approach based on particles swarm optimization algorithm for each area which calculates the optimum reactive power set points for distributed generators in an admissible time which is essential for online computation and transmission of data. In comparison to centralized approaches, the advantage of this approach is to reduce the computational burden and eliminate the need for all network's information. Moreover, semi-distributed control and independency from other areas are the merits of the proposed method in comparison with other decentralized one since there is no need for a coordinating center, and the failure of one center does not influence the performance of other centers.

The reminder of the paper is organized as follows: Section 2 presents the formulation of the partitioning approach and the results for the areas of the test system. Section 3 describes proposed coordinated voltage regulation algorithm for each area. Section 4 demonstrates the simulation results on an unbalanced 123-bus test network. Finally, the conclusions are drawn in Section 5.

2. Network partitioning

This section will seek the boundaries of smaller areas of the original network in a way that each area is composed of buses which are closely connected to each other from voltage regulation point of view. The spectral method which is a powerful network partitioning method can fulfill this task by suitable definition of a graph for the network.

2.1. Graph theory

Considering N as a set of nodes of a graph and E as a set of weighted edges; G = (N, E) represents the graph which will be partitioned. In distribution networks where a unique number is allocated for each bus, by proper definition of G, N represents the same number of network buses, and the weight of edge as $e = (v_i, v_j)$, represents the cost of putting the two buses in two separate areas.

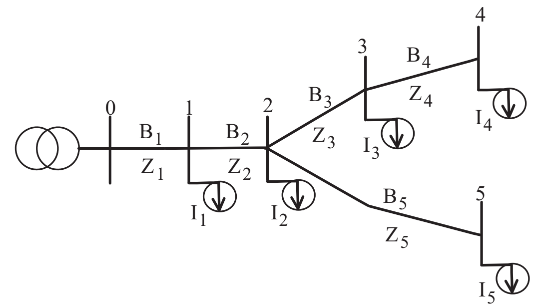

Fig. 1. Single-line diagram of typical distribution system.

2.2. Pattern matrix derivation

Using the input data, graph partitioning methods provide the possibility of clustering objects in several separate groups. Indeed, input data reflect the similarity or the difference between objects that are mainly expressed as a matrix named pattern matrix [20]. Therefore, a key step in the partitioning problem is to find pattern matrix. According to the goal of voltage regulation problem, buses voltage variations specify this similarity or difference which is in correspondence with changes in their power consumption to each other; it is called the sensitivity matrix. Therefore, in order to partition a distribution network, at first this matrix must be calculated as follows:

Considering single-line diagram of athree-phase balanced network in Fig. 1, the vector of buses voltage variations versus active and reactive power consumption will be as Eq. (1):

$$[\Delta V] = -[S^{vp}][\Delta p] - [S^{vq}][\Delta q] \tag{1}$$

Given that bus 0 is a slack bus,$[\Delta V]$, $[\Delta p]$ and $[\Delta q]$ are vectors which depict voltage variations, active and reactive power consumption of buses respectively. Furthermore, $[S^{vp}]$ and $[S^{vq}]$ are sensitivity matrices of voltage variations into consumed active and reactive power variations, respectively. In order to get an idea to calculate these two matrices for a radial distribution system, the direct load flow approach presented in Ref. [21] can be used. This approach is based on the development of two matrices representing the relationship between the Bus Injection to Branch Current (BIBC) and Branch Current to Bus Voltage (BCBV). These matrices for an above illustrated typical distribution system is as follows:

$$[B] = \begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \\ I_5 \end{bmatrix} = [\mathrm{BIBC}][I] \tag{2}$$

$$\begin{bmatrix} V_0 \\ V_0 \\ V_0 \\ V_0 \\ V_0 \end{bmatrix} - \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \\ V_5 \end{bmatrix} = \begin{bmatrix} Z_1 & 0 & 0 & 0 & 0 \\ Z_1 & Z_2 & 0 & 0 & 0 \\ Z_1 & Z_2 & Z_3 & 0 & 0 \\ Z_1 & Z_2 & Z_3 & Z_4 & 0 \\ Z_1 & Z_2 & 0 & 0 & Z_5 \end{bmatrix} \begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \end{bmatrix} = [\mathrm{BCBV}][B] \tag{3}$$