Electrical Power and Energy Systems 100 (2018) 117–128

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Decentralized and hierarchical voltage management of renewable energy resources in distribution smart grid

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ARTICLE INFO

Keywords:
Partitioning
Renewable resource
Primary control
Secondary control
Voltage regulation

ABSTRACT

Since renewable energy resources such as wind and solar energy have intermittent nature, they cause significant fluctuations in distribution system voltages. This paper proposes a hierarchical and decentralized voltage management method for renewable energy resources in smart distribution system of electrical energy with the participation of reactive power of these resources. In this regard, the partitioning strategy of renewable energy resources into different independent areas, the modeling of optimal coordinated control level and a novel local real-time control level for reactive power control of renewable resources have been considered. The solving solution is based on the network sensitivity matrices. Finally, the obtained results from simulating the 34-bus test system as well as PG&E 69-bus distribution system with different levels of generation and load show the efficacy of the proposed method.

1. Introduction

Today, distribution networks are being transferred to smart distribution grids. Unlike transmission networks, active power fluctuations affect the voltage magnitude of buses in distribution networks, sensibly [1]. Due to the existence of renewable DGs in smart distribution grids, frequent and intermittent fluctuations of active power lead to significant variations in voltage magnitudes of buses. So far, voltage management in distribution networks has been fulfilled by traditional devices such as on-load tap changer, step voltage regulators, fixed and switching capacitor banks [2]. But these devices are not designed by nature for managing the fast variations caused by renewable DGs. Also, following the variations of DGs' output active power leads the lifetime of these devices to be significantly reduced due to the depreciation of mechanical parts arising from frequent switching and tap changing operations. This problem can be properly solved by using the reactive power of DGs based on power electronic interfaces in addition to conventional devices [3].

In [4] two-stage architecture for voltage control problem has been proposed in which in the first stage local sources and in the second stage other neighbor sources supply the required reactive power in order to retrieve the voltage to its reference value. Moreover, Ref. [5] presents a method similar to the first stage of the method proposed in [4] in which the set points of sources are determined by referring to local database. As these methods are merely based on local information, they are not necessarily optimal. In some other researches [6,7], the reactive power and voltage control problem are based on a centralized management in which a central operator is needed to gather network's information and coordinate the whole system's operations. Although these researches remove the problem of the lack of optimality in previous works, by expanding the system's dimensions, the optimization problem would be long and time consuming. To solve such a problem, some studies have proposed a decentralized structure in which voltage control problem is fulfilled in several separate slave centers in a parallel manner while a central master center coordinates in order to eliminate every mismatches among the slave centers' information [8,9]. Even though these approaches have a high speed to respond, the operation of management system will fail if master center get lost.

Unlike power system frequency, the voltage of power systems has a local characteristic; Therefore, the voltage profile of an area of a power system can be mainly controlled using the regulation of the reactive power sources in that area. This characteristic proves that optimization and voltage control are much better to be zonally accomplished [10]. In [11] a method is proposed to divide distribution networks into different areas with the same number of DGs. But it is not a reasonable method as the number of areas increases by implementing more DGs in

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https://doi.org/10.1016/j.ijepes.2018.02.006
Received 28 August 2017; Received in revised form 2 January 2018; Accepted 2 February 2018

distribution networks. In addition, authors in [12] have presented another method based on ε-criterion for decomposition of Jacobian matrix in which determining the optimal value of ε is a real challenge. Except the voltage regulation problem, network partitioning has been used in other problems, such as self-healing and network restoration [13], prevention of cascading events [14], rotor angle stability [15], and etc. These problems are analyzed with different partitioning methods such as graph-based solution [14], spectral-based solution [16,17], electrical distance based solution, and etc.

In this paper, a novel method based on decentralized structure is proposed in which the output reactive power of DGs for voltage regulation goal is hierarchically set in two levels: (i) secondary level in which all DGs reactive power are optimized in control center coordinately, (ii) primary level in which the output reactive power of each DG is regulated locally in real-time. In this study, at first, using network sensitivity matrix, distribution network is divided into different areas with a unique management center for each; then, coordinated secondary level calculates and sets the optimal set point of each DG for the next one-minute period considering the average value of DGs' output active power over the previous one-minute time interval. On the other hand, each DG is equipped with a real-time primary level which corrects the received reactive power set point from the corresponding center in order to flatten the voltage of related area and compensate the voltage variations caused by instantaneous fluctuations of the renewable DGs' active power.

The first novelty of the proposed method in this paper compared with the centralized one is distribution network partitioning into various independent areas with separate local management centers. In the proposed method, local management centers are similar to the centralized control center, but the supervised geographical areas are a part of the whole system; consequently, by interrupting a local management center or communication links in an area, the voltage profile control of other areas does not fail. The advantages of the proposed method are as follows: (i) it is cost-effective in comparison to the centralized methods due to the reducing communication links length; (ii) it has less computational burden in comparison to the centralized methods due to the reducing problem dimensions; (iii) it does not need to the whole system information to control DGs but regional information. Furthermore, another contribution of this paper considering proposed hierarchical structure is presenting a new control scheme for real-time primary level in which the negative impact of renewable DGs' fast active power variations on the voltage profile is compensated.

Other decentralized studies are trying to decompose original centralized optimization problem to some smaller sub-problems and solve them in a parallel manner [9,18]; However, the disadvantage of these methods is that there is a need for a special center for coordinating other centers [19]. But the proposed method in this paper improves the computational burden and response time for online implementation by partitioning the distribution network into some smaller partitions. In this regard, the failure of one center doesn't influence the performance of other centers.

The rest of the paper has been structured as follows. In Section 2, the procedure of distribution network partitioning is described. Section 3 explains the proposed management idea which includes optimal coordinated secondary and real-time primary levels. Two case studies are considered to assess the efficiency of the proposed method in Sections 4 and 5 and the relevant discussions are presented. Finally, the conclusion is drawn in Section 6.

2. Decentralized voltage management modeling from spatial-scale insight

In the proposed decentralized method, voltage control problem is locally divided into several independent areas. Depending on the aim of distribution network partitioning, there may be different scenarios in this regard. As voltage should be maintained in a permissible range in the voltage management problem, the sensitivity of buses' voltage to active/reactive power fluctuations is of considerable importance. Therefore, in order to divide a distribution network, sensitivity matrix information should be used. In a typical radial distribution network, the vector of buses' voltage variations versus consumed active/reactive power fluctuations is expressed as (1):

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

Assuming that the bus 0 is a slack bus, the vectors $[\Delta V]$, $[\Delta p]$ and $[\Delta q]$ are generally defined with the dimension of $N \times 1$ which respectively represents the variations of voltage magnitude, the consumed active and reactive power variations of buses. In addition, the matrices $[S^{vp}]$ and $[S^{vq}]$ which are sensitivity matrices of voltage variations to consumed active/reactive power variations have the dimension of $N \times N$. In order to calculate these two matrices for a radial distribution network, an idea can be taken from the direct load flow viewpoint presented in [20]. This viewpoint is based on the developing of two matrices $[BIBC]$ and $[BCBV]$ which reflect the relation between the Bus Injection to Branch Current (BIBC) and Branch Current to Bus Voltage (BCBV). The representation of these matrices for a typical distribution network shown in Fig. 1 is as follows.

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

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

Using the expressions (2) and (3), the relation between voltage and current for buses can be expressed by DLF matrix as defined in (4):

$$[V_0] - [V] = [BCBV][BIBC][I] = [DLF][I] \tag{4}$$

The $[DLF]$ matrix is used for direct load flow and calculated only once, and it will not change if the topology of the network is fixed. Indeed, this matrix reflects the sensitivity of voltage variations to current variations for the network's buses. So matrices $[S^{vp}]$ and $[S^{vq}]$ are different from discussed DLF matrix because these ones should be expressed in terms of active and reactive power injections. In distribution networks, the voltage drop between two adjacent buses can be written as:

$$V_i - V_j = \frac{(R_j \cdot P_j + X_j \cdot Q_j)}{V_j} \tag{5}$$

where P_j and Q_j are flowed active and reactive power respectively, as well as R_j and X_j are resistance and reactance of the line between them respectively. When all variables are declared as per-unit, this voltage drop can be approximated as follows [21]:

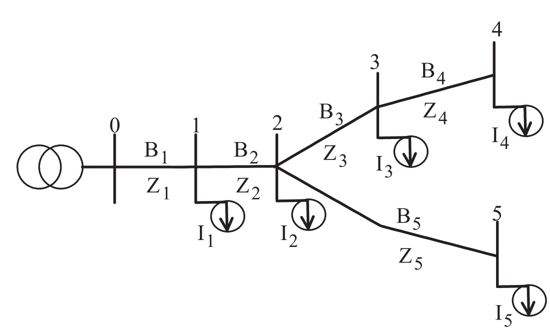

Fig. 1. A typical radial distribution network.