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An adaptive zone-division approach for voltage control of power grid with distributed wind farms: A case study of a regional power grid in central south China

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ABSTRACT

With the increasing penetration level of wind power generation, it is essential to coordinate the dispersed wind farms with the automatic voltage control (AVC) system to take part in the voltage regulation of the power grid. In this paper, an adaptive zone-division approach is proposed to identify the optimal controllable zone for each wind farm. The reactive power generation capability of wind farms with inverters is adequately exploited. A multidimensional *V-Q* sensitivity analysis is implemented to evaluate the ability of reactive power regulations, based on which an online zone-division method is adopted to determine the control clusters for wind farms. The proposed approach can be applied in the AVC system of power grid to alleviate the regulation burden for voltage stability. Moreover, the reactive power generations from wind farms can be effectively utilized to improve the penetration of wind power. A case study on a regional power grid from central south China is carried out, which indicates that, with the proposed approach the capability to maintain the voltage stability for power system operations can be enhanced with more wind power penetration.

1. Introduction

Recent years have witnessed the penetration of distributed generation (DG) power plants in power network is roaring increasing around the world. Various incentive government policies and programs have encouraged the investment on renewable energy source-based DGs. The adoption of DGs to achieve the ambitious governments targets related to the promotion of a more sustainable development in the energy sector and decarbonisation. For the mature technology and cost-effective advantage of wind power, the investment on wind energy is encouraged worldwide to reduce greenhouse gas emissions and diversify energy supplies in recent years [1–3]. Consequently, with the increase of the installation capacity for wind power generations, it brings new challenges on different issues. One of the main concerns is how to improve the penetration ratio to the power grid and meanwhile maintain the voltage stability in desired profiles. With the fast development of wind power generation technology, nowadays high power electronic converters are widely applied, these electronic converters decouples the power and generate reactive power. This make the wind farms become more advantage in voltage stability, especially large-scale wind farms. These wind power generations can operate like continuous reactive power adjustment device such as SVC, SVG, and STATACOM, which can provide fast and flexible reactive power support in the system. And high penetration and large-scale wind farms means a wide spread of this kind of reactive power sources with considerable regulation capacity, which can participate into voltage regulation.

In fact, the penetration level of wind farms affects the performance of AVC on voltage regulation, which makes the regulation procedure much more complicate. On the other hand, the reactive power from wind power generations provides more measures for voltage regulation by using the reactive power characteristics favourable inverters, e.g. fully rated converted wind turbine. Thus, in order to deal with the aforementioned dilemma it lies on the appropriate use of wind power generations to participate in the voltage control of power grid.

Some contributions can be found in literatures to analyse the inverter capability of voltage control ancillary in distributed generations to solve voltage regulation problems [4–9]. Especially, many studies have been carried out for DGs with wind power and photovoltaic power generations. Turitsyn et al. proposed some schemes focusing on the inverter power control which can balance the requirements on power

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quality and minimize power losses [10,11]. The optimal inverter sizing for various renewable power generations are studied to enable DGs as voltage control sources in [12,13]. Moreover, some studies have been done which aimed to deal with the problem on how to coordinate DGs in dispersed locations [14].

Generally, there are several kinds of methods to realize coordination operation of the voltage regulation dispersed in the system, i.e. centralized strategies, decentralized control strategies, centralized/decentralized strategies and local control strategies. In fact, decentralized control strategies like multi-agent system are usually applied for the low voltage (LV) or the middle voltage (MV) distribution networks with the advantage of less capital investment [15–18]. Centralized control strategies relay on reliable communication networks, which are needed to achieve a global coordination [18–21]. While local control strategies only considers the voltage level of one terminal node. Nowadays, in china the highest percentage of DG is the concentrated large-scale DGs, the reactive power generation of which can reach wider area than local control. And the dispersive location of these DGs makes the coordination control more difficult. With the widely applied AVC systems in many countries, centralized control strategies of DGs can be achieved by taking advantage of the structure of the existing AVC system with its optimal control [22]. In [23], an inverter control strategy was proposed, which allows DGs to provide voltage support during voltage sags. Nevertheless, by using DGs as reactive power sources it is necessary to consider the determination of the voltage control area in order to prevent repeated dispatch. In [24], a method with sensitivity analysis was used to determine the voltage control boundaries for DG dispatching to support short- and long-term voltage regulation. In [25], a concept of a decentralized non-hierarchal voltage regulation architecture is proposed. A coordinated voltage control for DGs and on-load tap-changer (OLTC) is illustrated in [26] and [27] to improve the voltage level of the networks.

In this paper, an adaptive zone-division approach is proposed for power grid voltage control of distributed wind farms. It aims to make full use of wind farms reactive power generation ability to participate in regional voltage regulation effectively, and alleviate the shortage of voltage regulation equipment in the system, as well as the problem of low efficiency of DG utilization. Firstly, the framework of AVC system is took use of to solve the problem of DGs having no communication with each other to coordinate in this article. Secondly, an adaptive zone-division approach based on reactive power and voltage sensitivity of DG is proposed to identify the strongest voltage control area for the DGs. In order to adapt to the distributed characteristics of DG, this paper modifies the traditional cluster results determination method, and try to focus on the cluster merging process including DG to realize the identification of the strong control area of DG.

The remainder of the paper is organized as follows. In Section 2, the general scheme of the AVC system embedded with DGs is explained. Section 3 describes the proposed adaptive zone-division approach, which is implemented to build control spaces with reactive power sources and determine the cluster ranges. In Section 4, a case study with a real power grid from central south China is demonstrated to validate the proposed approach. The article is concluded in Section 5.

2. Automatic voltage control with DGs

The structure of DG embedded regional AVC system can be briefly described as in Fig. 1. Generally, the AVC system can be organized in a three-level hierarchy: the primary, the secondary and the tertiary control levels. These three levels systematically realize the AVC from global optimization level to equipment response level. The highest level of the whole system is tertiary voltage control, which is used to perform a system-wide optimization control and aim to minimize power losses or maximize the reactive reserve of generators with security constraints. The secondary voltage control is a kind of zonal control to regulate voltage profile by keeping the crucial node in the zone which is close to the reference voltage. Accordingly, the desired voltage profile can be obtained by identifying the appropriate partitions and changing the set-point values of associated generators within a given zone. Both tertiary and secondary voltage controls are implemented via software at the same dispatch control center. While the primary control level is based on local voltage regulation and serves to give a rapid response to random voltage variations according to the defined value range. With the primary control scheme the generator terminal voltage is expected to be maintained at set-point levels. With DGs participating in the AVC system, the allocable reactive power quantity will be increased to support the voltage stability in the power grid. It should be noted that wind farm DGs are mainly considered in this study. Without loss of generality, DG stands for wind farm in the following sections when not specifically indicted.

The improvement of wind power penetration can alleviate reactive power shortage of voltage regulation for the whole system. However, it also makes the AVC system more complicate to coordinate with the added voltage regulation devices. It is essential to consider the problems like the priorities of regulation as well as repeated regulations. Thus, an adaptive zone-division approach is proposed for the dispersed wind farms in the power grid. The adaptive method is applied for fitting flexible changing network topology in high DG penetration networks. In addition, the zone-division approach is implemented to coordinate dispersed wind farms from the whole system to improve the regulation efficiency.

The proposed approach is incorporated into the AVC system to coordinate wind farms with the other voltage regulation devices such as switched shunt capacitors/reactors, on load tap changer (OLTC), and Static Var Compensator (SVC). As shown in Fig. 1, the wind farms as the DGs participate the voltage regulation in the primary voltage control level to support the AVC. The proposed adaptive zone-division approach for wind farms is embedded into the secondary voltage control (as shown in Fig. 1 secondary voltage control). According to the Jacobian matrix from load flow results, the *V-Q* sensitivity is calculated for voltage space structure, and the DG cluster algorithm is applied in voltage control coordination module to implement the coordination strategy. The cluster result is changeable due to the dynamic and intermittent nature of continuous variation of power generation from DGs. Considering the minute timescale calculation of the secondary voltage control and the uncertainty of the DG operations, the time interval for the adaptive cluster calculation is set to 15 min in this study. Consequently, the information of dispatch control is sent to wind farms and other controllable devices for system-level voltage regulations.

3. Adaptive zone-division method

3.1. DG voltage control space structure

In order to divide the wind farms into different zones considering the voltage control area, it is necessary to analyse the effect of control ability for each DG on node voltages. At first, some nodes are excluded before we structure a DG voltage control space, because these nodes are locally controlled, reactive power sensitivities of them related to other nodes are zero. Excluding locally controlled nodes, we assume there are n nodes in the power grid in which d nodes are connected with DG. In the power system, DG connected nodes can be considered as two types: those nodes which have reactive power to support the voltage regulation are treated as *PV* nodes, otherwise, *PQ* nodes. In this sensitivity calculation, the j^{th} DG connected node, which is selected to evaluate its impact on other nodes, is set as *PQ* node. As for the other DGs, if they still have reactive power to support the voltage regulation, they are treated as *PV* nodes, otherwise, *PQ* nodes.

The *V-Q* sensitivities of the voltages respect to j^{th} DG reactive power injection of all n nodes are calculated. The results are formed into a vector S_j as written in (1), which implicate the voltage control abilities of the j^{th} DG on each nodes.