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Two-stage voltage control of subtransmission networks with high penetration of wind power☆

Zhiyuan Tang[a,*], David J. Hill[a,b], Tao Liu[a]

[a] Department of Electrical and Electronic Engineering, The University of Hong Kong, Hong Kong
[b] School of Electrical and Information Engineering, The University of Sydney, NSW 2006, Australia

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ABSTRACT

Voltage issues are the main factors that limit the penetration level of wind power in subtransmission systems. In this paper, based on different control characteristics, we propose a two-stage coordinated control framework to deal with the negative voltage impacts caused by wind power fluctuations. In the first control stage, on-load tap changers (OLTCs) are used to deal with the voltage variations caused by large wind power fluctuations. In the second control stage, virtual power plants (VPPs) in the subtransmission network are used to handle the remaining slight voltage variations by controlling their reactive power. The second control stage only takes actions to support voltage regulations when control actions of the first control stage cannot meet the control requirements. Control actions of OLTCs and VPPs are obtained through multi-objective optimization based model predictive control and a fully distributed optimal dispatch scheme, respectively. The effectiveness of the proposed control method is tested through case studies based on the IEEE 14-bus test system and IEEE 30-bus test system with wind farms. In addition, through comparison with the traditional control method, our control scheme can reduce the control costs significantly and achieve the control targets at the same time.

1. Introduction

In view of economic considerations, there has been a trend in recent years that wind farms are increasingly connected to the main grid at subtransmission system levels. However, the characteristics of subtransmission networks, with higher resistance to reactance ratios and special network topologies, brings challenges for wind power integration. Among these challenges, voltage issues are the main problems that limit the penetration level of wind power. It has been reported in Baghsorkhi and Hiskens (2012) that varying power flows caused by wind power variations can lead to significant voltage variations and violations in the network. For example, there are two wind farms (each with a capacity of 50 MW) in a 40 kV subtransmission network that serves the south-eastern region of Michigan. When the wind power injections of these two wind farms simultaneously vary from zero to the rated power (i.e., 50 MW), the voltages of unregulated buses in the subtransmission network increase from 0.99 p.u. to 1.10 p.u., which exceeds the required voltage upper limit (Baghsorkhi and Hiskens, 2012).

Voltage control in subtransmission systems is traditionally exercised by automatically-controlled on-load tap changers (OLTCs) and manually-controlled fixed/switched capacitors. However, these devices are not inherently designed to handle the voltage fluctuations caused by wind power. On the one hand, their control actions are not fast enough compared with the variations caused by wind power. On the other hand, they may undergo excessive operations that will reduce their lifetimes significantly in the case of wind power (Baghsorkhi & Hiskens, 2012; Carvalho, Correia, & Ferreira, 2008; Turitsyn, Šulc, Backhaus, & Chertkov, 2010). To solve these issues, quick voltage support is needed (Valverde & van Cutsem, 2013; Baran & El-Markabi, 2007). An effective way to implement quick voltage support is to use distributed energy resources (DERs) such as distributed generators (DGs) and controllable demand in distribution networks. These devices can provide quick reactive power supply (absorption and injection) through properly controlling electronic devices that interface DERs with the grid (Hiskens, 2010; Joos, Ooi, McGillis, Galiana, & Marceau, 2000; Hui, Lee, & Wu, 2012).

Along this research direction, numerous papers have been published recently to regulate voltages by controlling these controllable resources. In Carvalho, Correia, and Ferreira (2008), the authors proposed a distributed automatic approach for voltage rise mitigation by controlling reactive power injections of DGs. In Mokhtari, Ghosh,

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* Corresponding author.
E-mail address: zytan@eee.hku.hk (Z. Tang).

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Nourbakhsh, and Ledwich (2013), based on localized and distributed control strategies, the authors dealt with the voltage rise issue by controlling both active and reactive power of photovoltaics and active power of storage units in distribution networks. In Tonkoski, Lopes, and El-Fouly (2011), the authors proposed a droop-based active power curtailment technique for over voltage prevention. Based on decentralised and distributed control methods the authors in Robbins, Hadjicostis, and Domínguez-García (2013) proposed a control architecture to regulate voltages in distribution networks within predefined ranges by controlling reactive power provided by DERs.

However, none of the abovementioned papers have focused on voltage control in subtransmission systems by controlling DERs in distribution networks. The integration of DERs in distribution systems into subtransmission system operations is not easy since there may be thousands and even millions of DERs connected to a subtransmission system. To solve this challenge, in this paper, we adopt the concept of virtual power plants (VPPs) proposed in Ruiz, Cobelo, and Oyarzabal (2009). These VPPs have the ability of aggregating the capability of many DGs and controllable demand in distribution networks, and hence, can be regarded as intermediaries between these controllable resources and the control center. Moreover, control strategies used in Carvalho et al. (2008), Mokhtari et al. (2013), Tonkoski et al. (2011), Robbins et al. (2013) aim at regulating voltages by using resources that can provide fast control actions such as DGs, but do not consider interactions with existing slow controllers such as OLTCs. It is pointed out in Carvalho, Correia, and Ferreira (2008) that an optimal control strategy of DGs may lead to a potential higher operation frequency of OLTCs. Therefore, coordination between different types of controllers should be considered to achieve an optimal operation.

On the other hand, model predictive control (MPC) has been widely studied as an effective control method to regulate voltages in power systems for its receding horizon, closed-loop nature and combination with optimization techniques (Larsson, Hill, & Olsson, 2002; Larsson & Karlsson, 2003; Wen, Wu, Turner, Cheng, & Fitch, 2004). For example, in Larsson and Karlsson (2003) the authors aimed to prevent voltage collapse by coordinating dissimilar controllers such as generator, tap changer, and load shedding controls based on MPC. However, the aforementioned works do not consider voltage impacts introduced by renewable energy sources such as wind farms.

In view of these issues, in this paper, a two-stage control architecture is proposed to regulate voltages in a subtransmission system with high penetration of wind power. OLTCs and VPPs in the network are the two types of controllers used in our approach. The main idea is that OLTCs are primarily used to deal with the significant voltage variations introduced by wind power fluctuations, which forms the first control stage. Then, VPPs are used to handle the remaining smaller and faster voltage variations by providing necessary reactive power support, which forms the second control stage. The key contributions of this work are as follows:

- Based on different characteristics of the two different types of controllers, the proposed control framework can coordinate these controllers in a complementary way to regulate voltages within predefined ranges in the subtransmission network. Compared with the traditional control method, the proposed control strategy can significantly reduce control costs and achieve the control targets at the same time.
- For OLTCs, control flexibility is realised by selecting the best control actions from the Pareto front obtained by a multi-objective optimization based MPC. Whereas, for VPPs, a fully distributed optimal dispatch scheme is designed. All information needed for the dispatch scheme is realised only by local measurements and communications between neighboring buses.

There are three main differences between this work and our previous conference paper (Tang, Hill, & Liu, 2015). Firstly, the fast-responsive voltage controllers used in the current paper are many distributed VPPs, whereas controllers used in Tang et al. (2015) are few static compensators (STATCOMs) with wind farms. Secondly, in this paper, based on three-step communications a fully distributed optimal dispatch scheme is designed for VPPs to minimize the total reactive power required, whereas in Tang et al. (2015) we used an average consensus algorithm to share reactive power required equally. Thirdly, in the current work, two case studies including the IEEE 14-bus test system and IEEE 30-bus test system are presented to show the effectiveness of our proposed control scheme, whereas in Tang et al. (2015) only the IEEE 14-bus test system was used.

The rest of this paper is organized as follows. Section 2 introduces the power system model to be studied and the communication network for information exchange between neighboring buses. The proposed two-stage control architecture is explicitly presented in Section 3. Section 4 presents two case studies involving the modified IEEE 14-bus test system and IEEE 30-bus test system with high penetration of wind power. Conclusions and future works are given in Section 5.

2. System model and communication network

Consider a power system operating at a normal operation point. The whole power grid is assumed to be connected, and its topology can be described by an undirected graph $\mathcal{G} = \{\mathcal{V}, \mathcal{E}\}$, where $\mathcal{V}$ is the set of nodes (buses) and $\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V}$ represents the set of edges (branches). We partition the set $\mathcal{V}$ of $n + m$ buses as $\mathcal{V} = \mathcal{L} \cup \mathcal{G}$ where sets $\mathcal{L}$ and $\mathcal{G}$ are load bus (PQ bus) set and generator bus (PV bus) set with cardinality $n \geq 1$ and $m \geq 1$, respectively. The grid consists of two regions: a subtransmission network and a transmission network which are connected to each other through d step-down transformers (referred to as OLTCs in this paper). Then the graph $\mathcal{G}$ can be divided into 2 subgraphs $\mathcal{G} = \mathcal{G}_{sub} \cup \mathcal{G}_{trans}$, where $\mathcal{G}_{sub} = \{\mathcal{V}_{sub}, \mathcal{E}_{sub}\}$ represents the topology of the subtransmission network and $\mathcal{G}_{trans} = \{\mathcal{V}_{trans}, \mathcal{E}_{trans}\}$ represents the topology of the transmission network (see Figs. 4 and 12 for examples).

The subtransmission network to be studied has a high resistance ratio. We suppose there are h buses and all are load buses in the subtransmission network. Wind farms are connected to different load buses in the subtransmission network. We assume that each load bus in the subtransmission network has a VPP which has the ability to aggregate the capacity of many DGs and controllable loads in the distribution systems connected to the corresponding load bus. In this paper, we consider each VPP as an aggregate controllable reactive power resource from a subtransmission system level. The detailed control management for each VPP is beyond the scope of the paper and will be studied in the future.

Communication networks are needed in the second control stage for information exchange between buses. The communication network topology is assumed to be the same as the physical grid topology (the benefits of such a design will be explained in Section 3.3.1 in details). Thus the communication network topology can still be described by the graph $\mathcal{G} = \{\mathcal{V}, \mathcal{E}\}$. The difference is that each edge $\{i, j\} \in \mathcal{E}$ in the communication network is weighted by a particular coefficient during the information exchange process. We assume that each bus in the power system has the capability of local measurement, communication with neighbors and basic calculation. We also assume that time delays in the communication network are negligible.

3. Two-stage voltage control architecture

3.1. Overview

In this paper, we build a two-stage control framework to regulate voltages in the subtransmission system with high penetration of wind power. The control targets are threefold. Firstly, it is to maintain all the bus voltages in the subtransmission network within the acceptable