Electrical Power and Energy Systems 104 (2019) 593–602

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

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

Distributed cooperative voltage control of wind farms based on consensus protocol

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ARTICLE INFO

Keyword:
Consensus protocol
Reactive power
Voltage control
Wind farm

ABSTRACT

The increasing penetration level of wind power brings a number of challenges to power system operations. Voltage/reactive power control is an important task of a wind farm to fulfill the grid requirements and avoid the cascading trip faults of wind turbines (WTs). To address this issue, a distributed cooperative voltage control strategy is proposed for wind farms based on the consensus protocol in this paper. In the proposed voltage control scheme, a droop-based local controller is adopted for the primary voltage control based on the local measurements. A consensus-based distributed secondary voltage controller is proposed, aiming to regulate the voltages within the feasible range while optimizing reactive power sharing among the reactive power sources using the local and neighboring information. The controller parameters are determined by the closed-loop system stability analysis using a linearized model. A wind farm with 20 WTs was used for the case study to validate the proposed control scheme under both steady-state and fault-ride-through (FRT) conditions. Moreover, the robustness against a communication link failure and plug-and-play capability of the proposed voltage controller were tested.

1. Introduction

Wind energy has become one of the most important and promising renewable energy in last few years due to the growing public concerns with energy shortage and environment. According to the global wind statistics provided by the Global Wind Energy Council (GWEC), the new installed wind capacity in 2017 is 53 GW and the global cumulative installed capacity has reached up to 540 GW by the end of 2017 [1]. The rolling five year forecast sees the cumulative installed capacity will be over 800 GW by the end of 2021 [2].

The fast increasing penetration of wind power has brought a number of technical and economic challenges to power system planning and operation due to its uncertainty and variability [3,4]. A number of new technical requirements and grid codes for wind power integration have been introduced by system operators and regulators [5,6]. The modern wind farms are required to be equipped with voltage and reactive power control system and consequently can regulate the voltage at the point of connection (POC) within a specific range to mitigate the negative effects induced by intermittent wind power. Besides, terminal voltages of wind turbines (WTs) should be also maintained within the feasible range to avoid cascading trip-off failures of WTs.

Centralized voltage control schemes have been widely investigated. In [7,8], the total required reactive power of wind farms is calculated according to the voltage at the POC based on the proportional-integral (PI) control loop and then dispatched to each WT based on the proportional distribution according to their the available reactive power capacity. In recent years, the optimization-based coordinated voltage control strategies are widely studied, in which voltage control problems are formulated as an optimization problem and solved by the central controllers every few seconds [9–15]. In [9], a hierarchical automatic voltage control (AVC) for wind farms was designed and implemented in a large-scale wind pool area of Northern China. Three different control modes were designed for different operating requirements ranked by the priority: 1) corrective mode, which aims to regulate the terminal voltage of WTs; 2) coordinated mode, which aims to track the reference sent from the control center while mitigating voltage fluctuations considering operation constraints; 3) preventive mode, in which the dynamic reactive power reserve is optimized while the voltage profile is controlled within the feasible range. In [10], a model predictive control (MPC) based coordinated voltage control scheme was proposed to coordinate various voltage regulation devices with different response time including WTs, Static Var Compensators (SVCs) and on-load tap changing (OLTC) transformers. As an extension of [10], a combined active and reactive power control strategy was proposed to take into account the effects of active power control on voltage profile considering the high R/X ratio of the wind farm collector system [11]. In [12], an

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https://doi.org/10.1016/j.ijepes.2018.07.030
Received 29 March 2018; Received in revised form 20 June 2018; Accepted 16 July 2018

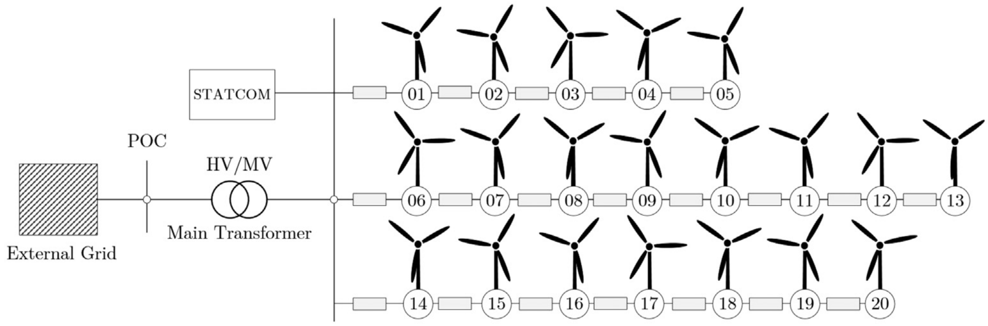

Fig. 1. The typical structure of a wind farm.

optimal power flow (OPF)-based reactive power dispatch method was proposed to reduce the electrical losses inside offshore wind farms including not only the losses in cables and transformers but also in WTs and HVDC converters. In [13], a two-layer voltage control scheme for offshore wind farms was designed which combines the optimization-based method and a PI controller. In the upper layer, the offline OPF calculation is executed every several minutes to determine the voltage reference of the pilot bus and then a PI controller is used to track the voltage reference in the lower layer. In [14,15], the MPC-based voltage control strategies for offshore HVDC connected wind farms were proposed to regulate the voltage across the offshore networks by optimally coordinating the HVDC converter and WTs. In [16], an optimization-based approach to couple AVC system to the market price was proposed in order to accurately evaluate the operation cost, where the control objective is to minimize the operation cost including the grid loss, the shunt switching cost, the tap change cost and the cost of voltage control service provided by the power plant owners.

The centralized voltage control strategies can guarantee the optimal control performance based on the global information. However, they might not be suitable for the future large-scale wind farms with several hundred or even thousands of WTs due to the limitations as follows: i) The computation burden of central controllers dramatically grows with the increasing number of WTs [18]. ii) In terms of cost, the centralized control schemes require complicated communication networks to acquire the remote information (voltage, power, etc.) at each bus, indicating that there will be a huge investment of communication infrastructures for a large-scale wind farm [19–21]. iii) The control performance highly depends on the properties and reliability of the communication systems and central controller without adequate robustness and flexibility [18,21,22]. iv) The optimization-based methods are designed with the control period of several seconds or even minutes [9–15] with slow response time. Hence, they might fail to handle the ultra short-term voltage issue with the time-scale of milliseconds such as the fault-ride-through (FRT) control.

The distributed control technique has been rapidly developed in recent years, which is widely used in voltage and frequency control of smart microgrids and distribution networks [17–24]. The distributed active power dispatch strategies of wind farms have been investigated, which aim to minimize the fatigue loads of WTs while tracking the active power reference set by system operators [28–30]. [25,26], decentralized (local) voltage control schemes were designed based on the local information without coordination. In [27], the stability boundaries of decentralized voltage control were investigated. For the local voltage control, once the estimation of the system parameters is poor, it can lead to reactive power oscillations and voltage flicker caused by unwanted interaction between individual control loops [27]. Moreover, the local control only addressed on voltage performance without considering the fair reactive power sharing.

In this paper, a distributed cooperative voltage control strategy (DCVCS) is proposed for wind farms based on the consensus protocol. A droop-based local voltage controller is designed as the primary control of WTs and Static Synchronous Compensators (STATCOMs) to achieve fast response. A consensus-based distributed secondary voltage controller is designed to mitigate the steady-state voltage deviations generated by droop controllers while maintaining fair reactive power sharing among the reactive power sources using the local and neighboring information. The small-signal stability analysis of the closed-loop system is performed based on a linearized model. Compared with the centralized control strategies, the proposed DCVCS has several advantages as follows: i) It is center-free, eliminating the requirement of a central (supervisor) controller. ii) It consists of two layers: primary control and secondary control. The primary control is carried out based on the local voltage measurements to provide fast response especially under emergency conditions and the secondary control is performed to improve the voltage performance and achieve fair reactive power sharing, which only requires information exchange with its immediate neighbors, largely reducing the cost of the communication infrastructures. iv) It eliminates the requirements of the network parameters and implying better robustness against network changes. Compared with the pure local control, the proposed scheme can avoid the closed-loop instability by properly selecting control parameters and address the fair reactive power sharing issue.

The rest of this paper is organized as follows. Section 2 gives an overview of the proposed DCVCS. In Section 3, the droop-based primary voltage controller is presented. In Section 4, the consensus-based distributed cooperative secondary voltage controller is proposed. Section 5 presents the stability analysis of the close-loop system based on a linearized model. In Section 6, the simulation results and discussions are presented, followed conclusions.

2. Overview of the distributed cooperative voltage control scheme of a wind farm

2.1. Problem description

The typical structure of a wind farm with 20 WTs is illustrated in Fig. 1. The wind farm as shown in Fig. 1 with 20×5 MW full-converter (FC)-WTs and $1 \times \pm 20$ MVar STATCOM is considered. The WTs are connected by three 33 kV feeders and placed with a distance of 1.5 km between two adjacent WTs. The STATCOM is placed at the MV side of the main transformer to provide reactive power support for the wind farm. For simplification, the set of reactive power source including WTs and the STATCOM are denoted together by the set $\mathscr{I}$. All WTs and the STATCOM should be cooperatively controlled to achieve the following objectives:1) The voltage profile across the wind farm network including the voltage at POC and WT buses should be controlled around the voltage reference V^*,

$$V \to V^*. \tag{1}$$

Generally, for the WT terminal voltage, they should be controlled within the deviations of 0.07–0.08 p.u. to avoid be tripped by the protection configuration (generally 0.9–1.1 p.u.) [9]. For the POC, the