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Distributed coordinated active and reactive power control of wind farms based on model predictive control

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ABSTRACT

This paper proposes a distributed coordinated active and reactive power control scheme for wind farms based on the model predictive control (MPC) along with the consensus-based distributed information synchronization and estimation, which can optimally dispatch the active power of wind turbines (WTs) and regulate the voltages within the wind farm. For the active power control, the pitch angle and generator torque of WTs are optimally controlled to alleviate fatigue loads of WTs while tracking the power reference of the wind farm required by system operators. For the reactive power/voltage control, the reactive power outputs of WTs are controlled to mitigate the voltage deviations and simultaneously optimize reactive power sharing. Considering the high R/X ratio of the wind farm collector systems, the impact of active power variations on voltages is taken into account to improve the voltage regulation. The proposed scheme is center-free and only requires a sparse communication network. Each WT only exchanges information with its immediate neighbors and the local optimal control problems are solved in parallel, implying good scalability and flexibility for large-scale wind farms. The predictive model of a WT is derived and then the MPC problem is formulated. A wind farm with ten WTs was used to verify the proposed control scheme.

1. Introduction

Wind energy has been developing rapidly due to the growing concerns over environmental issues around the world. As the wind power penetration level increases, its variability and uncertainty have brought a number of technical and economic challenges for power system operation [1]. Wind farms are required to meet the technical requirements specified in grid codes issued by system operators. With the fast development of modern wind turbine (WT) technologies, the controllability and fast-response capability of wind power are significantly improved. Modern wind farms are able to provide multiple ancillary services such as grid frequency and voltage support [2,3].

Generally, wind farm control applications may consist of several control objectives including active power dispatch and reactive power/voltage control [4]. Due to the decoupled control loops of active and reactive power of modern WTs, they are often separately designed.

For active power control, several control strategies such as proportional distribution [5,6] and proportional-integral (PI) control [7] are easy to be implemented. However, these dispatch methods mainly focus on power reference tracking of the wind farm without considering fatigue loads experienced by the WTs, which have significant impacts on the lifetime of WTs. In recent years, the optimization-based control strategies have been widely studied [8–10]. The optimal control problems are formulated as multi-objective optimization problems which can achieve power tracking as well as reduce the fatigue loads of WTs.

For reactive power control of wind farms, the main aim is to maintain the voltage at the point of connection (POC) within the feasible range, which is specified in many grid codes. Several reactive power dispatch strategies based on the proportional distribution and PI controller have been proposed in [4,10,11], which depend on the voltage at the POC and available reactive power capability of WTs while the terminal voltages of WTs are not considered. The optimization-based reactive power/voltage control strategies have also been proposed [12–14]. In [12], a hierarchical automatic voltage controller based on the sensitivity method was designed and implemented in a wind power base of northern China. In [13,14], the optimal power flow-based control strategies for high-voltage-direct-current (HVDC) connected offshore wind farms were proposed, in which the objectives are

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Nomenclature

Nomenclature

$(*)_0$	measurement at operating point
$\Delta(*)$	incremental value of variable
$(\hat{*})^{(i)}$	variables estimated by WT-i
$P_{\mathrm{ref}}^{\mathrm{WT}}$	active power reference of WT
P_{g}	active power output of WT
ω_{r}	rotor speed
ω_{g}, ω_{f}	generator and filtered speed
θ, θ_{ref}	pitch angle and its reference
T_{r}	aerodynamics torque
F_{t}	thrust force
T_{g}, T_{gref}	generator torque and its reference
T_{s}	shaft torque
v_{W}	effective wind speed
C_{p}	power efficient
C_{t}	thrust efficient
H_p	prediction horizon
N_p	prediction step
T_c	control period
λ	tip speed ratio
β	auxiliary variable in pitch control
Q_{W}	reactive power output of WT
$Q_{\mathrm{ref}}^{\mathrm{WT}}$	reactive power reference of WT
$Q_{\mathrm{meas}}^{\mathrm{WT}}$	measured reactive power
$Q_{\mathrm{int}}^{\mathrm{WT}}$	auxiliary variable in reactive power control
V_S	terminal voltage of the grid side converter
i_q, i_{qref}	q-axis current and its reference
$P_{\mathrm{ref}}^{\mathrm{WF}}$	wind farm power reference
$P_{\mathrm{avi}}^{\mathrm{WF}}$	available power of wind farm
$\bar{P}_{\mathrm{avi}}^{\mathrm{WT}}$	average available power of WTs
V_{ref}	voltage reference
V_{POC}	voltage at the POC
V_{W}	voltage at WT bus
N	number of WTs
H_c	control horizon
N_c	control step
$\bar{Q}_W$, $\underline{Q}_W$	reactive power limits of WT

to minimize the active power losses of the offshore system.

As a special optimization-based method, model predictive control (MPC) has been widely used in wind power systems both in WT level [15,16] and wind farm level [17–22]. In [17], a MPC scheme was proposed to balance the wind farm power reference tracking as well as fatigue loads reduction. In [18–20], the distributed MPC (D-MPC) schemes were proposed for optimal active power dispatch for wind farms, in which the optimal control problems are solved by the distributed optimization algorithms, however, in which a central unit is also required for WT coordination to track the power reference required by system operators. In [21,22], the centralized MPC-based coordinated wind farm voltage control schemes were designed. In [21], the reactive power sources inside a wind farm including WTs, static Var compensators and on-load tap changing transformer are optimally coordinated. In [22], WTs and wind farm side HVDC converter are optimally coordinated.

In the centralized optimization-based voltage control schemes [12–14,17–22], the wind farm is modeled as a constrained multiple input and multiple output system whose order drastically grows as the number of WTs increases. As the number of WTs increases, the computation burden of the central controller will be heavy. Moreover, the cost of the communication infrastructures may be quite high for large-scale wind farms. Distributed control is appealing for the wind farm control since a wind farm consists of a number of WTs, which has a high degree autonomy. Besides, the typical R/X ratio of the wind farm collector system is high and consequently voltages are sensitive to variations in active power injections. The conventional active and reactive power control schemes of wind farms were designed in a separated manner, which neglects the impact of active power variations of WTs on system voltages and consequently voltage control performance might not be optimal.

In this context, the main contribution of this paper is a distributed coordinated active and reactive power control design which aims to optimally regulate active and reactive power outputs of WTs in a wind farm. For the active power control, the controllers reduce the fatigue loads of WTs while tracking the wind farm power reference. For the reactive power control, the voltages are regulated and reactive power sharing is optimized. The impact of active power variations on voltages is taken into account to improve the voltage control. The global reference information including the power reference of the wind farm and voltage at the POC is synchronized by a distributed finite-time observer. The total available active power of the wind farm is estimated using a distributed estimator based on the average-consensus protocol.

Compared with the traditional centralized control, the proposed distributed control scheme has several advantages as follows: 1) Eliminate the requirement of a central controller; 2) Reduce the cost of communication infrastructures (All WTs only exchange information with their immediate neighbors, and when the wind farm is expanded, the newly connected WTs are only required to build the communication link with the neighboring WTs instead of the far central controller); 3)

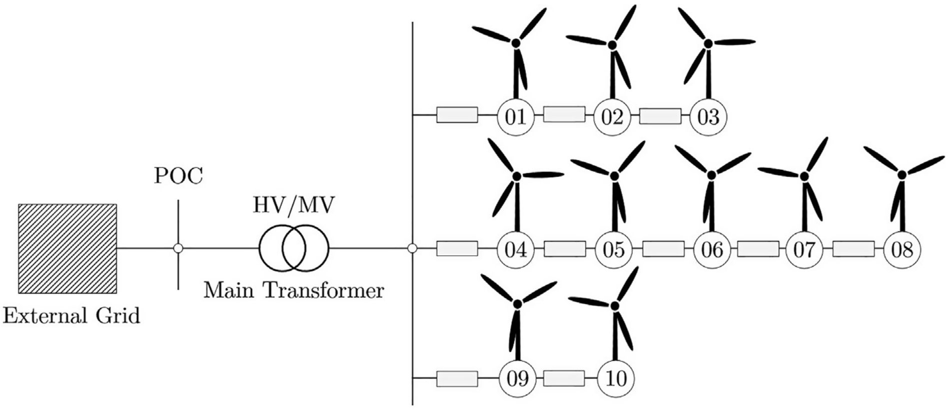

Fig. 1. Structure of a wind farm.