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Coordinated control of wind farm and VSC–HVDC system using capacitor energy and kinetic energy to improve inertia level of power systems

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ABSTRACT

For large-scale offshore wind power integration to main grids over a long distance, the VSC–HVDC transmission is a typical way. However, the asynchronous characteristic of HVDC link leads to the frequency decouple of the offshore grid and the main grid, i.e., the offshore grid has little or no inertia support for the main grid. The high level penetration of wind energy makes the main grid an "inertia-less" system and impairs the overall stability of the system. This paper proposes a new coordinated control strategy which uses the electrical energy stored in the DC capacitors and the kinetic energy stored in wind turbine rotors to emulate the inertia of synchronous generators. By this control strategy, the DC link capacitors release or absorb energy following the droop DC voltage control of the grid side VSC (GSVSC), and the wind farm VSC (WFVSC) changes its output frequency according to the DC voltage. Thus, an artificial coupling of the frequencies of the two-side AC systems is obtained without remote communication. According to the WFVSC's output frequency, the wind turbine power controller alters its power reference, and the wind turbine speed changes. Thus, the kinetic energy stored in wind turbine rotors is absorbed or released. As a result, the wind turbine is utilized to keep the main grid frequency stable. Based on the doubly fed induction generator (DFIG) wind turbine, this paper analyzes the influence of different additional power controllers and different control parameters of the proposed control strategy on the inertia time constant. Within the permissible range of the DC voltage variation, the proposed control strategy can provide a wide range of inertia time constant, which improves the overall stability of the main grid system. Simulation results of three operation conditions, i.e., sudden load changes, variation of the wind speed, and AC system faults, validated the effectiveness of the proposed coordinated control strategy.

1. Introduction

Wind energy has become one of the most important renewable resources for power generation worldwide. Among all types of wind turbines, the variable speed wind turbine with doubly fed induction generator (DFIG) has drawn great attention due to its intrinsic advantages. First, the DFIG can capture more wind power and obtain higher efficiency compared with the fixed speed induction generator (FSIG), because the rotor speed of the DFIG can vary within a wide range (usually around ±25% of the synchronous speed). Second, the active and reactive power can be regulated independently through the rotor side converter of the DFIG. Third, the rating of the converter is typically around 30% of the generator rating and is smaller than that of the full rated converter wind turbine using the permanent magnet synchronous machine (PMSM).

Due to the fast active power regulation by the rotor side converter of the DFIG, the inertia in the DFIG can be appropriately used for control. The variable speed operation characteristic enables the DFIG to make better use of the kinetic energy stored in the rotating turbine blades than the conventional FSIG that can only regulate its active power by the blade angle control [1]. An easy and direct way to use the inertia response in DFIGs is to artificially couple the DFIG rotor speed and the system speed [2,3]. One type of possible solutions, which is based on the modification of the DFIG's power reference through the derivative and deviation of the network frequency, is proposed in [4,5]. A supplementary control that combines the pitch adjusting and the maximum active power order is proposed in [6]. A scheme to provide frequency response by deloading the wind turbine is proposed in [7]. The DFIG would not

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operate at the maximum power point with this control scheme, which results in some reservation in power generation for the DFIG.

At present, large wind farms are integrated into the main grid by HVDC systems [8,9]. Wind farm integration by the conventional line commutated (LCC) HVDC system is studied in [10]. However, little voltage support for the offshore AC system can be provided by LCC. Due to the high flexibility in active and reactive power control, the VSC can operate like a reactive power source, and support the AC voltage of the connected AC grid such as an offshore wind farm, which is a benefit to the security of the AC grids. Ref. [11] demonstrates a coordinated control of a VSC–HVDC and a wind farm based on DFIGs under normal and fault conditions.

Till now, few literatures record the provision of inertia support for the offshore wind farms through VSC–HVDC integration. It was concluded that the above frequency regulation method is impossible unless remote communication is adopted [12], since the offshore wind farm and the onshore main grid are effectively decoupled by the VSC–HVDC. Ref. [13] proposes a VSC–HVDC control strategy to emulate the inertia constant of a conventional synchronous generator (SG) by using the energy stored in DC capacitors. However, this inertia constant is limited since large variation of the DC voltage is not permitted. Refs. [14,15] demonstrate a communication-less coordinated control scheme through the artificial frequency coupling of the offshore and the onshore AC grids. However, there is little information on the DFIG frequency response characteristic and the exact amount of the inertia that the system can provide.

A novel coordinated control strategy to provide inertia support is proposed in this paper. This control strategy is based on the use of the electric energy stored in DC capacitors and the kinetic energy stored in rotating rotors of the DFIGs, and it is realized by the droop control of the DC voltage at the grid side VSC (GSVSC), the variable frequency control of the wind farm VSC (WFVSC) and the active power alteration of the DFIGs in the wind farm. The proposed control strategy can provide a large inertia constant to support the main grid during and following disturbances. The influence by different power alteration strategies of the DFIGs on inertia support is studied. The DC voltage limitation of the VSC–HVDC system and the impact of control parameters on inertia support are also presented. The simulation results indicate that the proposed control strategy can improve the frequency response during the network disturbances.

The rest of the paper is organized as follows. Section 2 introduces the inertia response of a synchronous machine. Section 3 outlines the conventional control strategy of the VSC–HVDC wind power integration system. Section 4 describes the proposed coordinated control strategy for inertia support. Section 5 discusses the inertia support from the wind farm. Section 6 presents the influence of the control parameters on inertia support. The case studies have been conducted on three operation conditions in Section 7. Section 8 is the concluding section.

2. Inertia response of synchronous machine

Any imbalance between the load and generation in the power system will result in the alteration of the system frequency. A synchronous generator (SG) intrinsically utilizes the mechanical inertia to smooth the frequency deviation. This process is described in the following equation:

$$\frac{1}{2H}\frac{d\omega}{dt} = \Delta P. \tag{1}$$

Here, H is the inertia constant of the SG, ω is the rotation speed of the generator. ΔP is the deviation between the mechanical and the electrical power of the SG. It is noted that the amount of H determines the change rate of the system frequency. For a same time interval, the higher H is, the smaller frequency variation will reach, which can improve the stability of the entire power system.

3. System description and its conventional control strategy

An offshore wind farm integration scheme with VSC–HVDC system is studied in this paper, which is described in Fig. 1. The wind farm is composed of 150 DFIGs, and the rated power of each DFIG is 2MW. The DFIG model in this paper can be referred to [16–18].

The VSC–HVDC system for wind farm integration consists of two VSCs at both the wind farm side and the main grid side. The DC underwater cables are modeled by the R–L series circuits as a simplification. The wind farm VSC (WFVSC) collects the energy produced by the DFIGs, and controls the AC voltage amplitude and frequency of the wind farm where no external voltage support exists. The grid side VSC (GSVSC) is supposed to control the DC voltage and the reactive power at the main grid side, to ensure a unit power factor as shown in Fig. 1.

3.1. Grid side VSC (GSVSC)

As shown in Fig. 2, a typical controller is used for the GSVSC to transmit power from WFVSC to the grid. The entire control scheme is adopted in the grid voltage reference frame that the d-axis is chosen collinear to the grid voltage [19]. The phase-lock loop (PLL) is utilized to calculate the rotating angle θ_{PLL} for the dq transformation. The VSC controller is made up of two cascaded control loops. The outer power loop controls the DC voltage V_{DC} and the reactive power Q, which are associated with the d-axis current i_d and the q-axis current i_q, respectively. The reference voltage V_{DC}^{*} here is set as a constant. v_d and v_q, which are obtained from the inner current control loop, are used to generate the desired AC voltage. Limitation on i_d and i_q is needed considering the current rating of the converter.

3.2. Wind farm VSC (WFVSC)

First, since there is no commercial or domestic load directly connected to the wind farm grid, it is possible to make the wind farm grid operate at variable frequencies. Second, the DFIG rotor speed is effectively decoupled from the system frequency. Therefore, there is no similar power-angle characteristic as the conventional SG. Third, the electronic converters in the DFIG control the active and reactive power independently, which can be regulated very fast in about 10 ms. In other words, there will be slight active power changes of the wind farm when the system frequency alters. Consequently, the WFVSC can act like an ideal voltage source with the given frequency and the voltage amplitude. The controller diagram is shown in Fig. 3. The WFVSC reference frequency f_{WF}^{*} keeps a constant under the normal operation conditions. The wind farm AC voltage amplitude is controlled through an outer voltage control loop and an inner current control loop. It can guarantee the fast track of the reference current, and also limit the current under the wind farm network faults.

3.3. DFIG active power control

The active power of a DFIG is controlled by the Maximum Power Point Tracking (MPPT) and the pitch angle regulation as shown in Fig. 4 when below the rated power. The MPPT model is used to calculate the reference active power according to the rotor speed (ω_D). Optimal rotor speed will be automatically reached according to the rotor motion equation:

$$2H_D \cdot \omega_D \cdot \frac{d\omega_D}{dt} = P_{wind} - P_{ref}. \tag{2}$$