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Active participation of variable speed wind turbine in inertial and primary frequency regulations

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ABSTRACT

Power systems have increasingly exhibited a need for a potential frequency governor with virtual inertial control (VIC) and primary frequency regulation (PFR) functions in recent years, due to the increased penetration of wind turbines that almost have no frequency response. In this paper, a novel integrated frequency governor applied to a wind turbine is proposed to provide fast active power support and scheduled power allocation for both temporary inertial response and continued PFR. Below rated wind speed, an initial pitch angle is calculated firstly to preset a proper de-loading level for PFR in response to frequency drops, according to the presented relations of C_P-λ-β. Under the de-loading operation conditions, the de-loading power tracking curve is replaced by the defined VIC curves, and the inertial response is then obtained by rapidly shifting the VIC curves. Based on analysis of the mechanical characteristics of wind turbines with frequency droop, a primary frequency control strategy facilitated by the regulation of pitch angles is additionally proposed. A preset β/f droop curve is added to the de-loading pitch controller to regulate the mechanical power for scheduled power allocation, and thus satisfying the P/f droop demand of system PFR. Finally, the experiments and simulation results demonstrate that by using the proposed frequency governor a doubly fed induction generator (DFIG) based wind turbine can provide both temporary virtual inertia and continued load sharing to improve the dynamic frequency stability of the power grid with high wind power penetration.

1. Introduction

In recent years, the reduced frequency stability as a result of increased wind power penetration in power grid has attracted wider attentions from wind turbine manufacturers and system operators [1–3]. At present, in order to increase the wind energy capture, the popular wind turbines always regulate their rotor speed to track the maximum power point [4,5]. The variable rotor speed depends directly on the wind velocity rather than the system frequency. Consequently, the wind turbines lose the ability to respond to system frequency, and then conventional generators have to shoulder greater responsibility of regulating the frequency. As wind power penetration increases, this issue may become a serious threat to grid security due to a lack of frequency regulators.

Considering this scenario, variable speed wind turbines have been exploited to provide frequency support for power systems. At present, two types of control can be adopted to provide contributions for system frequency regulation, including VIC and PFR. However, under the traditional MPPT control scheme, although there are large amounts of kinetic energy stored in the rotating mass, variable speed wind turbines do not naturally contribute to system inertia due to the decoupling between rotor speed and system frequency, thus preventing the generators from responding to system frequency variations [6–8]. In order to address this issue, the supplementary $\mathrm{d}f/\mathrm{d}t$ control loop is adopted widely to add a derivative signal to the nominal active power reference of the MPPT controller, as described in Refs. [9–11]. However, the wind turbine can only maintain this additional support for a few seconds due to the rapid decrease of the system frequency derivative's absolute value. In addition, if the $\mathrm{d}f/\mathrm{d}t$ controller reverses the direction of the power signal after the frequency reaches its limit value, the wind turbine will require extra help to recover to MPPT operating condition. In this case, the P/f droop loop is used to produce a change in the wind power to be proportional to the system frequency deviation. Thus, in Refs. [12–14] a proportional derivative (PD) controller, which is a combination of the $\mathrm{d}f/\mathrm{d}t$ and P/f droop controls, is proposed to maintain the active power support over an extended response time. Actually, however, the wind turbine with VIC can only provide a temporary inertial response during the initial frequency change period [15]. This is due to the fact that the wind

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turbine has not operated in de-loading conditions, and thus there is no reserve capacity for its output power increase to participate in PFR in response to large frequency drops.

As a precondition, the de-loading control schemes are proposed to reserve necessary capacity required by PFR. In Refs. [16,17], the de-loading level of wind turbines is defined as a percentage of the maximum available power, so as to measure the available wind primary power reserve. By shifting the MPPT curve to the right sub-optimal curve, the de-loading function is achieved under overspeed operation conditions [18,19]. Moreover, the spare power can also be obtained by pitch control at the same time control of the speed of the wind turbine is at its optimum [20]. In Refs. [21,22], another de-loading control schemes are proposed through pitch angle changes. However, the wind turbine with the presented droop on pitch angle cannot obtain the *P*/*f* droop characteristic similar to that of a synchronous generator's frequency governor below the rated output power. Moreover, in Refs. [23–25], a primary frequency control has been developed along with de-loading schemes, so that the spare capacity is further utilized for PFR by pitch angle control with frequency droop. It is worth noting that the wind turbine's primary frequency governor has to regulate mechanical power with characteristics similar to that of conventional units, so as to achieve load allocation and satisfy operating demands for PFR. Therefore, the PFR scheme adapted for wind turbines still needs to be discussed. Moreover, the control limits of the virtual inertial response are set to confirm the operational constraints of the wind turbines under normal operating condition. Thus, although the de-loading schemes discussed in previous researches can obtain required power reduction, the wind turbines must re-estimate the capability of providing inertia support. Until now, the VIC and PFR of wind turbines cannot coordinate well with each other in providing more integrated power support.

The purpose of this paper is to propose a novel frequency control approach applied to wind turbines that not only provides temporary inertial support, but also achieves scheduled power allocation with synchronous generators for system PFR. Below rated wind speed, the reserve capacity of de-loading wind turbines is prepared by the calculated pitch angles according to the relations of C_P-λ-β. In order to achieve the desired *P*/*f* droop characteristic similar to that of a synchronous generator's primary frequency governor, the pitch angle is then regulated in accordance with the defined β/*f* droop curve. Moreover, the de-loading power tracking curve is replaced by the defined VIC curves, and the rapid inertial support is provided by shifting VIC curves. In this way, the operational constraints of the VIC under de-loading operation conditions also apply to the wind turbine. Thus, the proposed VIC and PFR of the wind turbine coordinate well with each other to share frequency support with conventional generators.

This paper is organized as follows. Section 2 briefly introduces the traditional power control scheme of variable speed wind turbines. Section 3 focuses on analyzing the specific *P*/*f* characteristics of the wind turbine and proposes three schemes: the de-loading operation, the VIC, and the PFR, to compose an integrated frequency governor. Experimental studies based on a laboratory power network containing two conventional generators and a DFIG-based wind turbine with a wind penetration of approximately 25% are presented in Section 4, and moreover, a grid scale simulation system is also carried out to demonstrate the effectiveness of the proposed schemes. Finally, Section 5 draws the conclusions.

2. Conventional wind turbine controller for variable speed wind generation systems

The proposed control methods are developed considering the power regulation of variable speed wind turbines. Therefore, the wind turbine controller of a doubly fed induction generator (DFIG)-based wind turbine is illustrated firstly in Fig. 1. The active power output of the wind turbine mainly depends on the two controllers: variable speed operation controller below rated wind speed, and pitch angle controller for rotor speed limitation under over-speed condition to prevent the captured mechanical power from exceeding its rated value. This paper mainly focuses on improving the wind turbine controller, so as to regulate the electric power and the mechanical power for integrated support with virtual inertia and primary frequency responses.

According to different wind velocities, the operating stages of wind turbine are generally divided into four operation stages [26,27], as illustrated in Fig. 1(c). In the first operation stage (A → B), the output power of the wind turbine follows a linear trend. However, it is unsuitable for the wind turbine to provide frequency support to the grid at low wind speeds. With increasing wind speed, the wind turbine enters the MPPT stage (B → C), and tracks the maximum power points of the mechanical power curves. In the next constant speed stage (C → D), to avoid an abrupt power change at around the maximum speed ω_{max}, a linear relation of *P*-ω is used, and the rotor speed of the wind turbine is approximately a constant. When the wind speed exceeds the rated value, the wind turbine will operate in the constant power mode, and the traditional pitch controller will be activated to maintain the rated output power.

Under normal operating conditions of $\omega_0 < \omega_r < \omega_{max}$, the active power reference from the variable speed operation controller is determined by the predefined *P*-ω characteristic curve, and the reference power P^*_{opt} can be expressed as

$$P^*_{opt} = \begin{cases} k_{opt}{\omega_r}^3 & (\omega_0 < \omega_r < \omega_1) \\ \dfrac{(P_{max} - k_{opt}{\omega_1}^3)}{(\omega_{max} - \omega_1)}(\omega_r - \omega_{max}) + P_{max} & (\omega_1 < \omega_r < \omega_{max}) \\ P_{max} & (\omega_r > \omega_{max}) \end{cases} \quad (1)$$

where k_{opt} is defined as the MPPT curve coefficient, ω_0 is the cut-in angular speed. ω_1 is the initial angular speed in this stage. P_{max} is the maximum active power output of the wind turbine.

From (1), it can be seen that, the generated power of the wind turbine is under variable speed turbine control according to its rotor speed, and is independent of the grid frequency due to the fast converter control. In addition, the slow mechanical power regulated by the pitch controller cannot share system power change as well. Therefore, the wind turbines do not naturally contribute to system inertia or response to frequency change. In order to emulate frequency response similar to that of synchronous generators using wind turbines, advanced control schemes by introducing the grid frequency deviation need be added to both the variable speed operation controller and the pitch controller. In such schemes, the rotor speed of the wind turbine is regulated to release/store the kinetic energy to make the "hidden inertia" available to the grid, and its mechanical power control can also be utilized to participate in PFR.

3. Integrated wind turbine controller with virtual inertia and PFR

3.1. De-loading control

The wind turbines which participate in PFR on request have to preset some reserve capacity for providing continued power support even after the recovery of system frequency. Obviously, this part of wind turbines should find new ways to track power point under de-loading operation condition. Moreover, for an expected frequency support, the de-loading scheme should also be suitable to coordinate with the proposed VIC, so as to further corporate with the PFR.