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Output power smoothing of variable speed wind farms using rotor-inertia

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ABSTRACT

Due to variations of wind speed, the output power of small-scaled or mid-scaled wind farms is fluctuating and this may negatively impact the power system. This paper proposes a new fuzzy PID controller scheme for a variable speed wind farm. In this scheme, by using the rotor-inertia as an energy storage system, two purposes are satisfied. Firstly, the optimal power point of each turbine is tracked in such a way that the total output power of the wind farm is also smoothed. Secondly, the proposed scheme enables the wind farm to produce a predetermined output power. To show the performance of the proposed scheme, a doubly fed induction generator (DFIG) based wind farm is simulated and the results are compared with conventional scheme. Also, the tracking capability of the pre-scheduled output power is verified.

1. Introduction

The demand for the electrical energy is rapidly growing in the world wide. On the other hand, fossil fuels resources will be depleted and the environmental pollution will be inevitable. Therefore, special attention is being paid to renewable energy resources such as wind energy.

Unfortunately, due to stochastic nature of wind speed, the output power of the wind energy conversion system (WECS) will be fluctuated. Furthermore, the quality of the output power is highly dependent on the control strategy [1]. Tracking the optimal power of the turbine may cause additional fluctuations in the output power [2]. By increasing the number of WECSs in power systems and during islanding operation mode of a wind farm, the importance of the quality of the output power becomes salient [3,4]. The fluctuation of the output power of the wind farm may cause frequency deviations. When the wind farm is connected to the grid, the frequency deviation is very small; however, it is significant when the wind farm is working in islanded mode [5,6]. Moreover, other concerning issues such as instability problem, voltage fluctuation and excessive line losses may be caused due to power fluctuations [4,7,8].

To smooth the output power of the WECS, many solutions have been proposed [8]. It is an effective solution to employ the energy storage systems (ESSs) to smooth the output power [9–20]. But ESSs increase the cost of the entire WECS. The employment of the pitch angle control, to alleviate the power fluctuations, has been introduced in [4,21–23]. The activation of the pitch angle controller not only disturbs the peak power tracking strategy but also increases the stress on the blades. In [21], the blade stress has been mitigated. In other smoothing methods, the inertia of the WECS has been used to reduce the power fluctuations [24–26]. These methods have studied a single WECS. However, nowadays, the application of wind turbines in a wind farm is very important and should be studied. Therefore, in the present paper, an effective smoothing scheme for a wind farm is proposed, which also preserves the peak power capability of wind turbines. In addition, this scheme can be used to provide a pre-scheduled output power for entire wind farm.

This paper is organized as follows; in the next section, the modeling and control of the WECS will be introduced. The proposed fuzzy PID controller scheme will be discussed in Section 3. In Section 4, the simulation results of the new scheme are presented. Finally, the conclusion is drawn in the last section.

2. Modeling and control of WECS

2.1. System configuration of single WECS

The wind turbines can extract the wind power in a specified range of wind speed variations [27]. If the wind speed is below its cut-in speed ($V_{cut\text{-}in}$), the available mechanical power is very low and the WECS does not operate, however above this speed,

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the turbine starts to work. Until the rated wind speed (V_{rated}), it is useful to obtain the maximum aerodynamic efficiency (C_p^{max}). To achieve the optimal power, the pitch angle is fixed and the optimal rotational speed (ω_{opt}) is tracked [28]. When the wind speed exceeds the rated speed, the pitch angle of the turbine plays an important role in protecting the WECS from over-loading and the power will be constant till the cut-out speed ($V_{cut\text{-}out}$) appears. For speeds above $V_{cut\text{-}out}$, in order to protect the turbine from excessive mechanical stress, the turbine should be stopped.

Different types of generators are used in wind farms [6]. However, to capture the maximum power from turbines, it is useful to employ variable speed wind turbines. Among these types of turbines, WECSs based on DFIG are preferable and can improve the input power factor and operate in sub-synchronous and super-synchronous speeds. Considering the converter rated power, the slip of the generator generally varies in the range of ±(25–30)% [27]. As shown in Fig. 1, DFIG is a wound rotor induction generator. The stator is directly connected to the grid and the rotor is connected to the grid via a back-to-back converter. The converter connected to the generator is called the rotor side converter (RSC) and the other one is named as the grid side converter (GSC). Compared to other structures, due to the lower converter rating, the weight and costs of DFIG would be reduced [29].

2.2. Wind turbine system

The mechanical power of a turbine (P_m) in W depends on turbine characteristics, wind speed and environmental conditions, as follows [27]:

$$P_m = \frac{1}{2}\rho A C_p v^3 \tag{1}$$

where ρ is the air density in kg/m^3, A is the swept area in m^2, v is the wind speed in m/s and C_p is the turbine aerodynamic efficiency obtained from $C_p(\lambda,\beta)$ curve. This curve is unique for each particular design of wind turbine. λ and β are the tip speed ratio (TSR) and pitch angle, respectively. If the pitch angle increases, the C_p will be decreased and as a result, the turbine mechanical power will be reduced. Thus, to achieve the maximum power point (MPP) tracking, the pitch angle should be fixed.

2.3. Pitch angle control system

In this paper, the pitch angle control is activated only to limit the turbine over-speeding or over-loading. Fig. 2 depicts the pitch angle control system [4,27]. The actuator of the pitch controller is modeled by a first-order system [27]. Since the speed of the actuator response is subjected to physical limitations, a rate limiter should be used to model these constraints, especially when the actuator is a hydraulic type. For speeds lower than the rated wind speed (V_{rated}), the optimal rotational speed is tracked. Certainly in this condition, the rotational speed of the turbine is lower than its maximum allowable limit (ω_r^{max}), and consequently (as depicted in Fig. 2) the pitch control system is not activated. When the rotational speed exceeds the ω_r^{max}, the pitch angle controller will be activated and the generator is protected from over-speeding and over-loading.

2.4. DFIG modeling

In the DFIG based WECS, if the RSC is properly controlled, the speed and reactive power of the generator can be independently adjusted. GSC also controls the dc-link voltage and the reactive power exchanged with the grid. However, in this paper, the control of the RSC under normal operations will be discussed. The control of the GSC has been studied in [30].

By neglecting losses, the active powers can be presented, as follows [31]:

$$P_r = sP_s \tag{2}$$

$$P_{grid} = P_s - P_r = (1-s)P_s \tag{3}$$

where s is the slip, P_s and P_r are stator and rotor active powers, respectively, and P_{grid} is the total power, which is injected to the grid.

In the stator flux oriented reference frame, the d-axis is being aligned to the stator flux vector position. Therefore, the relationship among electrical torque, stator powers, d–q axis voltage and current can be written, as follows [30,32]:

$$T_e = -\frac{L_m}{L_s}\psi_{ds} i_{qr} \tag{4}$$

$$P_s = \omega_s \frac{L_m^2}{L_s} i_{ms} i_{qr} \tag{5}$$

$$Q_s = -\frac{L_m^2}{L_s} i_{ms}(i_{ms} - i_{dr}) \tag{6}$$

$$v_{dr} = v_{dr}^* - s\omega_s(\sigma L_r i_{qr}) \tag{7}$$

$$v_{qr} = v_{qr}^* - s\omega_s(\sigma L_r i_{dr} + L_m i_{ms}) \tag{8}$$

$$v_{dr}^* = R_r i_{dr} + \sigma L_r \frac{di_{dr}}{dt} \tag{9}$$

$$v_{qr}^* = R_r i_{qr} + \sigma L_r \frac{di_{qr}}{dt} \tag{10}$$

$$i_{ms} = \frac{v_{qs} - R_s i_{qs}}{\omega_s L_m} \tag{11}$$

$$\sigma = 1 - \frac{L_m^2}{L_s L_r} \tag{12}$$

where i, v and ψ are current, voltage and flux, respectively. The subscripts d, q, r and s represent the d-axis component, q-axis component, rotor and stator quantities, respectively. L_s and L_r are the stator and rotor self inductances, respectively, L_m is the mutual inductance, R_s and R_r are the stator and rotor resistances, respectively. ω_s is the synchronous reference speed.

2.5. Conventional vector control of RSC

Since the stator resistance is generally negligible, Eqs. (4) and (6) confirm that by properly adjusting i_{qr} and i_{dr}, the electrical torque and the reactive power can be independently controlled. As shown in Fig. 3a, RSC controller involves two cascaded control loops. In the outer-loop, the errors of the speed and the reactive power are traced by PI controllers to give i_{qr}^{ref} and i_{dr}^{ref}, respectively. The inner control loops are based on Eqs. (7)–(10). According to these equations, if cross-coupling terms, i.e., $s\omega_s\cdot(\sigma L_r i_{qr})$ and $s\omega_s\cdot(\sigma L_r i_{dr} + L_m\cdot i_{ms})$, are fully compensated, the v_{dr} and v_{qr} can independently control the i_{dr} and i_{qr}, respectively. Thus, the current errors are processed by PI controller to give v_{dr}^* and v_{qr}^*, then, by adding compensation terms, v_{dr} and v_{qr} are obtained [30].

In this paper, the outer-loop conventional PI controller is named "speed controller", shown by dotted frame in Fig. 3a.

3. Proposed scheme

3.1. Maximum power point tracking

When the wind velocity is below the rated speed, if the rotational speed of the turbine (ω_t) is set to the optimal value (ω_{opt}), the maximum available power of the turbine can be extracted. The