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Control of a grid-connected direct-drive wind energy conversion system

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ABSTRACT

This paper investigates the current control for a grid-connected direct-drive wind energy conversion system (DDWECS) with a permanent magnet synchronous generator (PMSG), which utilizes a back-to-back pulse width modulation (PWM) converter. For the machine-side, the controller adopts a current vector control method based on the rotating reference frame (RRF) and the maximum power extraction (MPE) is realised through the tip speed ratio (TSR) method. For the grid-side, a novel controller is proposed for the first time to be successfully used for the DDWECS, which combining a proportional complex integral (PCI) current inner loop based on stationary reference frame (SRF) for regulating the grid-side current with a dc voltage outer loop for stabilizing the dc bus voltage and compare with the proportional resonant (PR) controller. A system simulation model is established by using the Matlab/Simulink to simulate the performance of the DDWECS and a prototype system has been build and tested to verify the validity of the developed control methods for both machine-side and grid-side and the excellent performance of the DDWECS.

1. Introduction

With the rapid development of the renewable energy source, especially in the field of wind power, the variable speed operation is widely employed in the wind energy conversion system (WECS). Moreover, the gearless direct-drive permanent magnet synchronous generator (PMSG) is considered to be promising due to its higher reliability, efficiency and lower acoustic noise [1–3]. Direct-drive WECS (DDWECS) generally employs a fully controllable voltage source converter (VSC) with a back-to-back topology to realise the maximum power extraction (MPE) of wind turbine and regulate the grid interface for satisfying the grid code [4–7]. The DDWECS with full VSC-based MOSFET or IGBT converter is becoming the dominant in low and high power applications, respectively [8].

From the control aspect, the VSC can be divided into a machine-side converter and a grid-side converter [9–12]. The machine-side converter mainly adopts a current vector control with a current inner loop and a speed outer loop to implement the variable speed operation for capturing the maximum wind power through the tip speed ratio (TSR) method [13]. The grid-side converter can either apply the voltage-oriented control based on the $d-q$ rotating reference frame (RRF) or use the proportional-resonant (PR) or recently proposed proportional complex integral (PCI) current inner control with a dc voltage outer loop control based on the $\alpha-\beta$ stationary reference frame (SRF) to satisfy the grid code [14–19]. The advantage of the control method based on SRF is that the phase lock loop (PLL) can be eliminated in comparison with that based on RRF. However, the bandwidth of the closed-loop system is larger than the grid frequency and the loop gain needs to be increased under other desired frequencies [20,21]. Fortunately, the grid frequency is generally constant so that the disadvantages of the control method based on the SRF can be neglected to some extent. Moreover, the PR control method based on the internal mode principle can offer the zero steady-state tracking error for sinusoidal signal and the PCI control method as a simplification and improvement of the PR control can improve the dynamic response in the start-up and has been successfully applied in the balanced system [17,18]. In DDWECS, the machine-side converter generally employs the flux-oriented current vector control method to regulate the speed of PMSG and realise the MPE according to the TSR method. In addition to considering the cost, PR or PCI control is available for gird-side converter without additional hardware or software PLL. Reference [17] points out that the PCI control is more

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suitable for the balanced grid-side converter due to its simplification in the control structure. However, successful applications of the PCI control in DDWECS have not yet been reported.

This paper studies the flux-oriented current vector control for the machine-side and the PCI control based on the SRF for the grid-side of DDWECS. For the machine-side, the reference speed is obtained by the TSR method and the speed is regulated to realise the MPE of the wind turbine. For the grid-side, the PCI inner loop combined with a dc voltage outer loop is firstly proposed to be used for the DDWECS to stabilise the dc voltage and to regulate the grid current. The two controllers are designed and analysed in details. Compared with the PR controller in grid-side, the PCI controller can improve the dynamic response effectively. A system simulation model is established based on the Matlab/Simulink to examine the performance of the used control methods and an experimental system is carried out to verify the feasibility and the excellent performance of the developed DDWECS.

2. Configuration of DDWECS

The DDWECS mainly consists of a wind turbine, a PMSG, a back-to-back converter, a filter induction and an isolated transformer, as shown in Fig. 1. The PMSG connects to the grid through a back-to-back converter, converting the mechanical energy produced by the wind turbine to the electrical energy [22,23]. The back-to-back converter contains a machine-side converter and a grid-side converter, which are connected by a dc bus.

The control system of the DDWECS is divided into a machine-side control sub-system and a grid-side control sub-system. The former can utilise the flux-oriented $d-q$ current vector control aiming to achieve the MPE from the wind turbine by a speed control loop, which offers the speed reference to the machine-side converter by the TSR method. The latter employs the PCI control based on the SRF to maintain the dc voltage constant and to adjust the power factor. It should be noted that for high power WECS the variable pitch wind turbine is adopted to prevent the turbine from operating over the rated power at relatively high wind speed [24,25].

3. Control of machine-side converter

3.1. Mathematic model of PMSG

The stator voltage mathematic model of the PMSG in the $d-q$ RRF is expressed as [26,27],

$$\begin{pmatrix} v_{sd} \\ v_{sq} \end{pmatrix} = -R_s \begin{pmatrix} i_{sd} \\ i_{sq} \end{pmatrix} - \frac{d}{dt} \begin{pmatrix} \psi_{sd} \\ \psi_{sq} \end{pmatrix} + \omega_e \begin{pmatrix} -\psi_{sq} \\ \psi_{sd} \end{pmatrix} \tag{1}$$

where R_s is the stator resistance; v_{sd}, v_{sq}, i_{sd}, i_{sq}, ψ_{sd} and ψ_{sq} are the d and q components of stator voltage, current and flux linkage respectively; ω_e is the electrical angular speed

$$\omega_e = p\omega \tag{2}$$

where p is the pole pair number and ω is the mechanical speed of PMSG.

When the d-axis is aligned along the rotor flux position, the $d-q$ stator flux linkage equation is

$$\begin{pmatrix} \psi_{sd} \\ \psi_{sq} \end{pmatrix} = \begin{pmatrix} L_{sd} & \\ & L_{sq} \end{pmatrix} \begin{pmatrix} i_{sd} \\ i_{sq} \end{pmatrix} + \begin{pmatrix} \psi_f \\ 0 \end{pmatrix} \tag{3}$$

where L_{sd} and L_{sq} are the d and q components of the stator inductance respectively; ψ_f is the flux linkage produced by PM. The electromagnetic torque is

$$T_e = 1.5p\left[\psi_f i_{sq} + (L_{sd} - L_{sq}) i_{sd} i_{sq}\right] \tag{4}$$

If L_{sd} is equal to L_{sq}, represented by L_s, as in the surface mounted PMSG, the electromagnetic torque of the PMSG is simplified as

$$T_e = 1.5p\psi_f i_{sq} \tag{5}$$

Besides, the mechanical equation of the PMSG is

$$J\frac{d\omega}{dt} = T_i - T_e \tag{6}$$

where, J is the inertia of the PMSG; T_i is the input torque.

3.2. Current vector control

The current vector control of the machine-side converter contains a faster current inner loop and a slower speed outer loop. The d-axial current is only affected by v_{sq}. Meanwhile, the q-axial current is affected by v_{sd} [1]. Therefore, the current inner loop is decoupled, as shown in Fig. 2. The current inner loops of d and q axis jointly adjust the wind turbine speed and regulate the d-axial current to zero to enhance the efficiency of the PMSG.

The decoupled control strategy of d and q current loops is obtained by rewriting Eq. (1) and Eq. (3) as

$$v_{sd} = -\left(R_s i_{sd} + L_s \frac{di_{sd}}{dt}\right) - \omega_e L_{sq} i_{sq} \tag{7}$$

$$v_{sq} = -\left(R_s i_{sq} + L_s \frac{di_{sq}}{dt}\right) + \omega_e L_s i_{sd} + \omega_e \psi_f \tag{8}$$

where the items in the bracket of Eq. (7) and Eq. (8) are the state equations between the voltage and current in the d and q loops respectively, while the others are the compensation terms.

3.3. MPE by TSR method

The output power of the wind turbine can be calculated as [28]

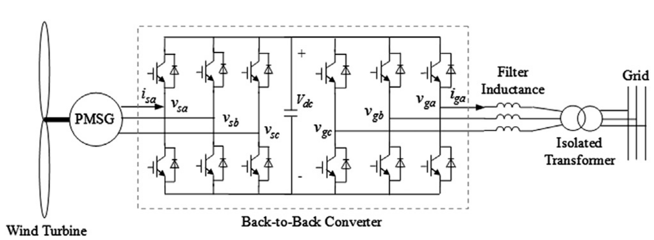

Fig. 1. Configuration of DDWCES.

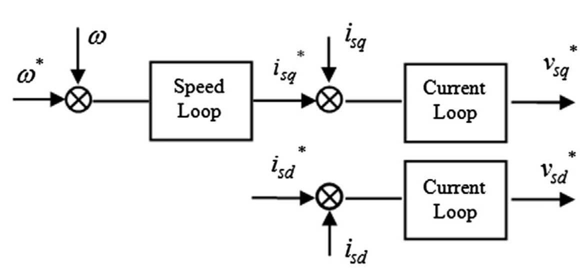

Fig. 2. Vector control structure for machine-side converter.