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Position-sensorless direct torque control of grid-connected DFIG with reduced current sensors

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Abstract. Direct torque control (DTC) of a grid-connected doubly fed induction generator (DFIG) necessitates at least 2 stator current sensors, 2 rotor current sensors and a rotor position sensor. This letter presents a position-sensorless DTC scheme of DFIG without rotor current sensors. The elimination of two rotor current sensors and position sensors improves hardware reliability by reducing the redundancy of physical components to be used. In the proposed scheme, the rotor flux vector magnitude and torque are estimated using measurable stator quantities. The effectiveness of proposed position-sensorless DTC scheme is validated using MATLAB/Simulink for a 2-MW DFIG-based wind energy conversion system (WECS).

Keywords. Direct torque control (DTC); position-sensorless control; doubly fed induction generator.

1. Introduction

The doubly fed induction generator (DFIG) is most popular in wind energy applications due to small power converters requirement. A sizable volume of literature has been published on different control systems to be used for the operation of DFIG [1]. Typically, the active and reactive power of grid-connected DFIG is controlled using field-oriented control (FOC), direct torque control (DTC) and direct power control (DPC) [1–4]. Both DTC and DPC offer simpler implementation than FOC [5]. DTC controls the electrical torque whereas DPC controls the stator power. Implementation of maximum power point tracking (MPPT) algorithm requires regulation of total power, making it complex for DPC as compared with DTC.

DTC scheme requires at least two stator currents and two rotor currents in addition to a rotor position (θ_r) sensor for the estimation of rotor flux vector magnitude, torque and sector [1, 3, 5]. The large number of current sensors increases complexity and decreases reliability. The generator and power electrical equipment in a wind energy conversion system (WECS) are separated by considerable distance, necessitating the need for position-sensorless control to increase the reliability. Therefore, a position-sensorless control scheme with reduced current sensors, either by signal processing or estimation, is desirable.

A notable research work on induction motor drive with reduced current sensor is discussed in [6]. Control of AC–DC grid side converter with single AC current sensor is presented in [7]. In [8], stand-alone DFIG-DC system with reduced current sensors is presented. FOC of DFIG with reduced current sensors is presented in [9, 10]. However, a research work on position-sensorless DTC of grid-connected DFIG based on reduced current sensors appears to be missing in existing literature. In [4], a DPC scheme without rotor flux estimation is presented for DFIG-based wind energy generation, which employs two current sensors and requires an encoder for the measurement of rotor position. In this letter, a novel position-sensorless DTC scheme is proposed, which can be implemented without rotor current sensors. The $\vec{i_r}$ components in $d^s - q^s$ frame and subsequently rotor flux vector magnitude and torque are estimated from measured stator voltages and stator currents, which are based on coordinate transformation. Different coordinate systems and vectors are presented in figure 1 [9].

The rest of the letter is organized as follows. Proposed DTC scheme and its validation are presented in sections 2 and 3, respectively. The letter ends with the conclusion in section 4.

2. Proposed DTC scheme

In the proposed DTC scheme, the rotor flux vector magnitude and torque are estimated using sensed stator voltage and current. The DTC control also requires rotor flux vector position (θ_{ψ_r}), which is estimated further using the switching states of rotor side converter (RSC). Figure 2 shows a block diagram of the overall DTC scheme and the required estimation is achieved in the following three steps.

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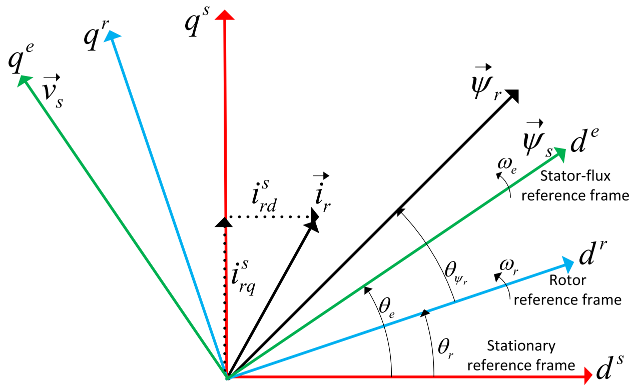

Figure 1. Phasor diagram of flux vectors in different coordinates.

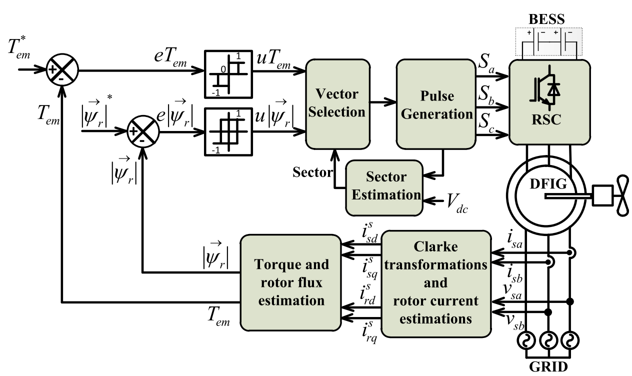

Figure 2. Block diagram of the proposed DTC of DFIG for WECS [3].

2.1 *Rotor current estimation*

The rotor current components in $d^s - q^s$ frame is calculated as [11]

$$i^s_{rd} = \frac{v^s_{sq} - R_s i^s_{sq} - \omega_e L_s i^s_{sd}}{\omega_e L_m} \tag{1}$$

$$i^s_{rq} = \frac{R_s i^s_{sd} - v^s_{sd} - \omega_e L_s i^s_{sq}}{\omega_e L_m}. \tag{2}$$

The unknown term in (1) and (2) is ω_e, which can be computed as follows:

$$sin\theta_e = -\frac{v^s_{sd}}{\sqrt{(v^s_{sd})^2 + (v^s_{sq})^2}} \tag{3}$$

$$cos\theta_e = \frac{v^s_{sq}}{\sqrt{(v^s_{sd})^2 + (v^s_{sq})^2}} \tag{4}$$

$$\omega_e = \cos\theta_e \frac{d}{dt}\sin\theta_e - \sin\theta_e \frac{d}{dt}\cos\theta_e. \tag{5}$$

2.2 *Electromagnetic torque (T_{em}) and rotor flux vector ($\vec{\psi}_r$) magnitude estimation without rotor position sensor*

The magnitude of T_{em} and $\vec{\psi}_r$ are estimated from the $\vec{i}_s$ and $\vec{i}_r$ components in $d^s - q^s$ frame as follows:

$$T_{em} = \frac{3}{2} p L_m \left(i^s_{sq} i^s_{rd} - i^s_{sd} i^s_{rq} \right) \tag{6}$$

$$\psi^s_{rd} = L_m i^s_{sd} + L_r i^s_{rd} \tag{7}$$

$$\psi^s_{rq} = L_m i^s_{sq} + L_r i^s_{rq} \tag{8}$$

$$\left| \vec{\psi}_r \right| = \sqrt{(\psi^s_{rd})^2 + (\psi^s_{rq})^2}. \tag{9}$$

2.3 *Estimation of rotor flux space vector position (θ_{ψ_r})*

By neglecting the rotor resistance drop, the $\vec{\psi}_r$ components in the $d^r - q^r$ frame are given by

$$\psi^r_{rdq} = \int v^r_{rdq} dt + \psi^r_{rdq}(0). \tag{10}$$

Instead of the ideal integral in (10), a digital pass band filter is used to increase the performance of integral action [1]. The unknown term in (10) is v^r_{rdq}, which can be estimated from the switching states and dc voltage of the RSC as follows:

$$v^r_{rd} = V_{dc} \frac{(2S_a - S_b - S_c)}{3} \tag{11}$$

$$v^r_{rq} = V_{dc} \frac{(S_b - S_c)}{\sqrt{3}}. \tag{12}$$

Rotor flux space vector position (θ_{ψ_r}) with respect to $d^r - q^r$ frame can be estimated as

$$\theta_{\psi_r} = \tan^{-1} \frac{\psi^r_{rq}}{\psi^r_{rd}}. \tag{13}$$

Based on this formulation, the contribution of this letter in the field of DTC of DFIG-based WECS is as follows:

1. In the existing DTC scheme, both the torque and rotor flux vector magnitude computations require information of $\vec{i}_s$ and $\vec{i}_r$ components in $d^r - q^r$ frame. However, in the proposed DTC scheme, torque and rotor flux vector magnitude estimations require information of $\vec{i}_s$ and $\vec{i}_r$ components in $d^s - q^s$ frame.
2. There is a need of rotor current sensor and rotor position sensor in existing DTC scheme as $\vec{i}_s$ and $\vec{i}_r$ components are required in $d^r - q^r$ frame. The proposed DTC

scheme, in contrast, requires information of $\vec{i_s}$ and $\vec{i_r}$ components in $d^s - q^s$ frame; $\vec{i_r}$ components are directly estimated from the $\vec{v_s}$ and $\vec{i_s}$ components in $d^s - q^s$ frame, thereby, eliminating the need of rotor current sensors and rotor position sensor.

3. The existing DTC scheme estimates the θ_{ψ_r} from the components of $\vec{\psi_r}$ in $d^r - q^r$ frame. Due to this, there is an indirect need of rotor position sensor. In contrast, in the proposed DTC scheme the information of θ_{ψ_r} is directly derived from the switching states and dc voltage of the RSC, thereby eliminating the need of rotor position sensor.

The simulation validation of proposed algorithm for 2-MW DFIG-based WECS is presented in the next section.

Table 1. Parameters of 2-MW DFIG.

Symbol	Parameters	Value
p_N	Rated power	2 MW
U_N	Stator voltage	690 V
f_N	Stator frequency	50 Hz
T_L	Rated load torque	12732 N m
u	Stator to rotor turns ratio	0.34
R_s	Stator resistance	2.6 mΩ
R_r	Rotor resistance referred to stator	2.9 mΩ
L_m	Mutual inductance	2.5 mH
L_{ls}	Stator leakage inductance	0.087 mH
L_{lr}	Rotor leakage inductance referred to stator	0.087 mH
p	Number of pole pairs	2
J	Rotor inertia	75 kg m^2

3. Simulation validation

Simulations for wind speed variations between 8.66 and 11.33 m/s are carried out in MATLAB/Simulink to validate the proposed control scheme for 2-MW DFIG-based WECS and results presented in figure 3. Parameters of a 2-MW DFIG are shown in table 1 [3]. To extract the maximum power, generator speed is varied between 0.866 and 1.133 p.u. corresponding to wind speed shown in figure 3a. The torque reference is derived from wind speed using the look-up-table-based MPPT algorithm [9]. The rotor flux reference is set for achieving unity power factor operation at stator side. Alternatively, rotor flux reference can be derived from torque and reactive power references [3]. The control parameters set in the simulation are (a) torque hysteresis: 5% of the rated torque, (b) flux hysteresis: 1% of the rated flux and (c) maximum switching frequency: 5 kHz.

The estimated θ_{ψ_r} tracks the actual θ_{ψ_r} with negligible error as shown in figure 3b. The information of sector is derived from the θ_{ψ_r} and as the sector is changed after 60°, impact of errors in estimation of θ_{ψ_r} is negligible on sector estimation. The rotor current phase changes with speed transition from sub-synchronous speed to hyper-synchronous speed and vice-versa as shown in figure 3c. The rotor flux changes its direction with respect to rotor reference frame during the transition from sub-synchronous speed to hyper-synchronous speed and that can be observed in figure 3d with sector number. Figure 3e and f illustrates, respectively, the torque and flux behaviours under rotor

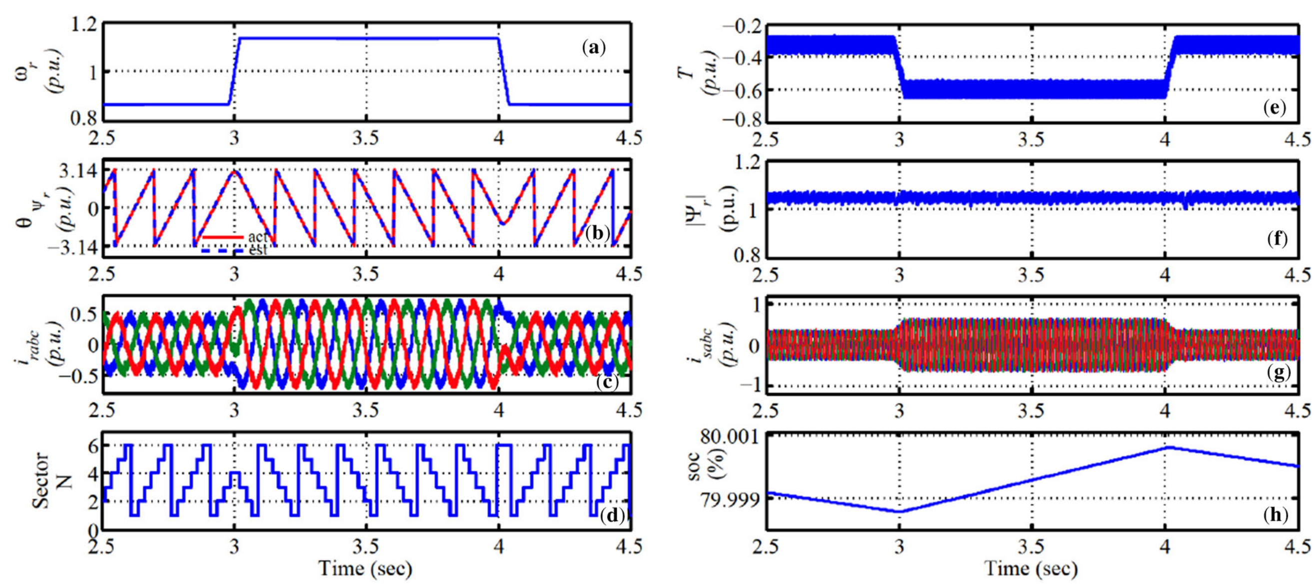

Figure 3. Performance of WECS under rotor speed variation between 1300 rpm (0.866 p.u.) and 1700 rpm (1.133 p.u.): (a) rotor speed, (b) rotor flux space vector position (actual and estimated), (c) three-phase rotor current, (d) sector, (e) torque, (f) rotor flux magnitude, (g) three-phase stator current and (h) battery SOC.

speed variation. Increase of stator current with speed is observed in figure 3g. The variation in battery State-of-Charge (SOC) is observed in figure 3h. Simulation results are very encouraging and endorse the proposed scheme with satisfactory performance of WECS.

4. Conclusions

A minimum of four current sensors are required in existing position-sensorless DTC scheme used for DFIG-based grid-connected WECS. The proposed scheme makes it feasible using only two current sensors, making it still reliable and also reducing the system complexity and cost. The proposed DTC scheme has the potential to open new avenues in the field of position-sensorless DTC scheme based on reduced current sensor for DFIG. The proposed control scheme is tested under steady-state and dynamic wind speed conditions and results are found to be promising. In a nutshell, this letter proposes a simple and innovative DTC scheme with high potential and can be employed for both DFIG-based WECS and high-power-drive applications.

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