2014

A Flux Vector-Based Discrete-Time Direct Torque Control for Salient-Pole Permanent-Magnet Synchronous Generators

Zhe Zhang

University of Nebraska-Lincoln, zhang.zhe@huskers.unl.edu

Yue Zhao

University of Nebraska-Lincoln, yue.zhao@huskers.unl.edu

Jianwu Zeng

University of Nebraska-Lincoln, jzeng@huskers.unl.edu

Wei Qiao

University of Nebraska-Lincoln, wqiao@engr.unl.edu

Follow this and additional works at: <http://digitalcommons.unl.edu/electricalengineeringfacpub>

Part of the [Computer Engineering Commons](#), and the [Electrical and Computer Engineering Commons](#)

Zhang, Zhe; Zhao, Yue; Zeng, Jianwu; and Qiao, Wei, "A Flux Vector-Based Discrete-Time Direct Torque Control for Salient-Pole Permanent-Magnet Synchronous Generators" (2014). *Faculty Publications from the Department of Electrical and Computer Engineering*. 336.

<http://digitalcommons.unl.edu/electricalengineeringfacpub/336>

This Article is brought to you for free and open access by the Electrical & Computer Engineering, Department of at DigitalCommons@University of Nebraska - Lincoln. It has been accepted for inclusion in Faculty Publications from the Department of Electrical and Computer Engineering by an authorized administrator of DigitalCommons@University of Nebraska - Lincoln.

A Flux Vector-Based Discrete-Time Direct Torque Control for Salient-Pole Permanent-Magnet Synchronous Generators

Zhe Zhang, Yue Zhao, Jianwu Zeng, and Wei Qiao

Power and Energy Systems Laboratory

Department of Electrical Engineering

University of Nebraska-Lincoln

Lincoln, NE 68588-0511, USA

zhang.zhe@huskers.unl.edu; yue.zhao@huskers.unl.edu; jzeng@huskers.unl.edu; wqiao@engr.unl.edu

Abstract—This paper proposes a flux vector-based discrete-time direct torque control (DTC) scheme for salient-pole permanent-magnet synchronous generators (PMSGs) used in the variable-speed, direct-drive wind energy conversion systems (WECSs). The discrete-time control law is derived from the perspective of flux space vectors and load angle with the torque and stator flux information only. The saliency of the PMSG is eliminated by the active flux concept. Compared with the existing space vector modulation (SVM)-based DTCs, the proposed scheme removes the use of PI regulators and is less dependent on the machine parameters, e.g., stator inductances and permanent-magnet flux linkage, while maintaining the fast dynamic response of the system. By integrating the SVM into the control scheme, the torque and flux ripples are greatly reduced and the switching frequency becomes fixed. The effectiveness of the proposed DTC scheme is verified by real-time simulations implemented on an OPAL-RT real-time simulator and experimental results for a 180-W salient-pole PMSG used in a direct-drive WECS.

I. INTRODUCTION

Field-oriented control (FOC) and direct torque control (DTC) are the most popular control schemes used in high-performance industrial drive systems. Different from the FOC, the DTC directly controls the electromagnetic torque and stator flux linkage instead of the armature currents, hence possessing the merits of fast dynamic response, simple implementation, motion sensorless, and robustness to disturbances [1]. The DTC was primarily developed for induction motor drives [2] and then naturally introduced to permanent-magnet synchronous motor (PMSM) drives [3]. Recently, with the development of the wind power technologies, much effort has been made to investigate the DTC for wind energy conversion systems (WECSs). For WECS applications, the DTC may facilitate the realization of maximum power point tracking (MPPT) with the optimal torque control [5], since the optimal torque command can be applied directly in the DTC without knowing the wind speed information. In this way, the outer-loop speed or

power controller, which is necessary in the decoupled current control, can be eliminated [5].

In the conventional DTC, two hysteresis comparators were adopted to determine the voltage vector for the next control cycle. This led to irregular and unpredictable torque and flux ripples, particularly when the DTC was implemented in a digital system [6]. In literature, a variety of approaches have been investigated to solve the problems. One natural thought was to increase the number of available voltage vectors, e.g., using the multilevel converters [7] or equally dividing each sampling period into multiple intervals [1]. Another approach was to integrate the space-vector modulation (SVM) algorithm, which has been commonly used in the FOC, into the DTC [8]. In general, the SVM-based DTC methods fall into two categories based on how the voltage references were generated in the stationary reference frame. In the first category, the decoupled voltage references in the synchronously rotating reference frame were acquired first and then transformed to the stationary reference frame using the rotary coordinate transformation [9]. In the second category, the voltage references were obtained directly from the incremental stator flux vectors in the stationary reference frame without coordinate transformation [10]. Both methods could reduce torque and flux ripples, but need PI controllers to regulate the torque and stator flux errors. In this case, the PI gains were usually tuned by a trial and error procedure [9]. Poorly tuned PI gains would deteriorate the dynamic performance of the DTC. In addition, according to [1], a real DTC scheme should not contain PI regulators. More recently, the predictive current control [11] and the deadbeat direct torque and flux control (DTFC) [12] were investigated for surface-mounted and interior PMSMs. These control schemes ensured good dynamic performance of the systems. However, the accurate information of the machine parameters was indispensable in these control schemes. Moreover, the control algorithms were developed with detailed machine models or the graphical method, which

This work was supported in part by the U.S. National Science Foundation under grant ECCS-0901218 and CAREER Award ECCS-0954938.

increased the computational complexity.

This paper proposes a simple SVM-based DTC scheme for the direct-drive PMSG-based WECSs without using PI controllers. The discrete-time control law is derived from the prospective of flux space vectors and load angle. Several machine parameters, such as inductances and permanent magnet flux linkage, are not needed in the control law. This improves the robustness of the control system to parameter variations. By adopting the proposed DTC scheme, flux and torque ripples are reduced and fast dynamic response is retained when comparing with the conventional DTC scheme. The proposed scheme is validated by real-time simulations using an OPAL-RT real-time simulator and experimental results on a 180-W PMSG.

II. MODELING OF SALIENT-POLE PMSGs

The dynamic equations of a three-phase salient-pole PMSG can be written in the synchronously rotating dq reference frame as

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} R + pL_d & -\omega_e L_q \\ \omega_e L_d & R + pL_q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 \\ \omega_e \psi_m \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} \psi_d \\ \psi_q \end{bmatrix} = \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} \psi_m \\ 0 \end{bmatrix} \quad (2)$$

where p is the derivative operator; v_d and v_q are the d - and q -axis stator voltages, respectively; i_d and i_q are the d - and q -axis stator currents, respectively; ω_e is the rotor electrical speed; L_d and L_q are the d - and q -axis inductances, respectively; ψ_d and ψ_q are the d - and q -axis stator flux linkages, respectively; ψ_m is the flux linkage generated by the permanent magnets, and R is the stator resistance. The electromagnetic torque T_e can be calculated by

$$T_e = \frac{3}{2} \frac{n}{L_d} |\psi_s| \psi_m \sin \delta + \frac{3}{4} \frac{n}{L_d L_q} |\psi_s|^2 (L_d - L_q) \sin(2\delta) \quad (3)$$

where n is the pole pair number, $|\psi_s|$ is the magnitude of the stator flux linkage, and δ is the load angle. From (3) it can be seen that a salient-pole PMSG generates both magnetic and reluctance torques, which correspond to the first and second terms in (3), respectively. Compared to a nonsalient-pole PMSG ($L_d = L_q$), a salient-pole PMSG ($L_d \neq L_q$) can generate higher torque with the same levels of i_d and i_q owing to the reluctance torque. However, the nonlinear reluctance torque complicates the mathematical expression among T_e , $|\psi_s|$ and δ . In [9], an “active flux” concept is proposed to combine the reluctance torque and the magnetic torque as one term such that the salient-pole AC machines are turned into nonsalient-pole ones. The active flux $|\psi_d^a|$ in [9] is defined as

$$|\psi_d^a| = \psi_m + (L_d - L_q) i_d \quad (4)$$

The torque expression (3) can be simplified by expanding the term $\sin(2\delta)$ as

Fig. 1. Schematic of the proposed DTC for a direct-drive PMSG-based WECS.

$$T_e = \frac{3}{2} \frac{n}{L_d} |\psi_s| \left(\psi_m + \frac{|\psi_s|}{L_q} (L_d - L_q) \cos \delta \right) \sin \delta \quad (5)$$

Since $|\psi_s| \cos \delta = \psi_d = L_d i_d + \psi_m$, (5) is then derived as

$$T_e = \frac{3}{2} \frac{n}{L_d} |\psi_s| \left(\psi_m + \frac{(L_d - L_q)}{L_q} (L_d i_d + \psi_m) \right) \sin \delta \quad (6)$$

Finally, the expression of the electromagnetic torque has the form of

$$T_e = \frac{3}{2} \frac{n}{L_q} |\psi_s| (\psi_m + (L_d - L_q) i_d) \sin \delta \quad (7)$$

Substitute (4) into (7), the electromagnetic torque of the PMSG can be expressed as

$$T_e = \frac{3}{2} \frac{n}{L_q} |\psi_s| |\psi_d^a| \sin \delta \quad (8)$$

such that the torque only contains the magnetic term. Divide (8) by (5), the active flux in terms of $|\psi_s|$ and δ can be expressed as

$$|\psi_d^a| = \frac{L_q}{L_d} \left(\psi_m + \frac{|\psi_s|}{L_q} (L_d - L_q) \cos \delta \right) \quad (9)$$

The active flux, which is aligned with the d -axis, can be obtained by

$$|\psi_d^a| = |\psi_{sab} - L_q i_{sab}| \quad (10)$$

where ψ_{sab} and i_{sab} are the stator flux linkages and currents in the stationary reference frame, respectively.

III. PROPOSED DISCRETE-TIME DTC

The schematic of the proposed discrete-time DTC for a salient-pole PMSG is shown in Fig. 1. The idea of stator flux and electromagnetic torque estimations can be found in [13]. In the proposed method, a reference flux vector estimator (RFVE) is designed to calculate the desired stator flux vector ψ_{sab}^* using the estimated and reference values of the stator flux and electromagnetic torque without using PI regulators.

In (8), the electromagnetic torque T_e of a salient-pole PMSG is a function of three time-variant variables $|\psi_s|$, $|\psi_d^a|$ and δ . Taking the derivative of (8) with respect to time yields

$$\begin{aligned} \frac{dT_e}{dt} = & \frac{3}{2} \frac{n}{L_q} |\psi_d^a| \sin \delta \times \frac{d|\psi_s|}{dt} + \frac{3}{2} \frac{n}{L_q} |\psi_s| \sin \delta \times \frac{d|\psi_d^a|}{dt} \\ & + \frac{3}{2} \frac{n}{L_q} |\psi_s| |\psi_d^a| \cos \delta \times \frac{d\delta}{dt} \end{aligned} \quad (11)$$

The discrete-time form of (11) for a short period is written as:

$$\begin{aligned} \Delta T_e = & \frac{3}{2} \frac{n}{L_q} |\psi_{d0}^a| \sin \delta_0 \times \Delta |\psi_s| + \frac{3}{2} \frac{n}{L_q} |\psi_{s0}| \sin \delta_0 \times \Delta |\psi_d^a| \\ & + \frac{3}{2} \frac{n}{L_q} |\psi_{s0}| |\psi_{d0}^a| \cos \delta_0 \times \Delta \delta \end{aligned} \quad (12)$$

where $|\psi_{s0}|$, $|\psi_{d0}^a|$, and δ_0 are the stator flux magnitude, active flux amplitude, and load angle at the reference point, respectively. Equation (12) demonstrates that the flux linkages $|\psi_{s0}|$ and $|\psi_{d0}^a|$, and the load (related to δ_0 and $|\psi_{d0}^a|$) will affect the weights of the flux and load angle increments on the torque increment. At the k th step, $|\psi_{s0}| = |\psi_s[k]|$, $|\psi_{d0}^a| = |\psi_d^a[k]|$, and $\delta_0 = \delta[k]$. Then (12) in the discrete-time domain can be written as

$$\begin{aligned} \Delta T_e[k] = & \frac{3}{2} \frac{n}{L_q} |\psi_d^a[k]| \sin \delta[k] \times \Delta |\psi_s[k]| + \frac{3}{2} \frac{n}{L_q} |\psi_s[k]| \sin \delta[k] \times \Delta |\psi_d^a[k]| \\ & + \frac{3}{2} \frac{n}{L_q} |\psi_s[k]| |\psi_d^a[k]| \cos \delta[k] \times \Delta \delta[k] \end{aligned} \quad (13)$$

The torque $T_e[k]$ has the form of

$$T_e[k] = \frac{3}{2} \frac{n}{L_q} |\psi_s[k]| |\psi_d^a[k]| \sin \delta[k] \quad (14)$$

Dividing (13) by (14) yields

$$\frac{\Delta T_e[k]}{T_e[k]} = \frac{\Delta |\psi_s[k]|}{|\psi_s[k]|} + \frac{\Delta |\psi_d^a[k]|}{|\psi_d^a[k]|} + \frac{\Delta \delta[k]}{\tan \delta[k]} \quad (15)$$

where the torque and stator flux errors can be calculated as

$$\Delta T_e[k] = T_e^*[k] - T_e[k] \quad (16)$$

$$\Delta |\psi_s[k]| = |\psi_s[k]|^* - |\psi_s[k]| \quad (17)$$

Substitute (16) and (17) into (15), the increment of the load angle in the discrete form can be written as

$$\Delta \delta[k] = \tan \delta[k] \times \left(\frac{T_e^*[k]}{T_e[k]} - \frac{|\psi_s[k]|^*}{|\psi_s[k]|} - \frac{\Delta |\psi_d^a[k]|}{|\psi_d^a[k]|} \right) \quad (18)$$

where $\Delta |\psi_d^a[k]|$ is expected to be $|\psi_d^a[k]|^* - |\psi_d^a[k]|$ and $|\psi_d^a[k]|^*$ is the reference of the active flux in the k th step. Typically, the value of $|\psi_d^a[k]|^*$ can be determined from (4) provided that i_d^* is known. Since the torque of the PMSG can be expressed by

$$T_e = \frac{3}{2} n (\psi_m + (L_d - L_q) i_d) i_q \quad (19)$$

Fig. 2. Block diagram of the load angle increment calculator.

Fig. 3. The voltage vector neglecting the stator resistance in the space vector analysis.

Based on (2) and (19), the current commands i_d^* and i_q^* can be obtained from the torque and stator flux commands T_e^* and $|\psi_s|^*$, respectively. In practice, to reduce the computational burden of the control system, the relation between $|\psi_d^a|^*$ and $(T_e^*, |\psi_s|^*)$ can be found offline for different operating conditions based on (2), (4) and (19) and then stored in a lookup table for online use.

For a nonsalient-pole PMSG, the active flux $|\psi_d^a|$ is equal to ψ_m so that (18) can be simplified as

$$\Delta \delta[k] = \tan \delta[k] \times \left(\frac{T_e^*[k]}{T_e[k]} - \frac{|\psi_s[k]|^*}{|\psi_s[k]|} \right) \quad (20)$$

As can be seen from (14), it is straightforward and effective to realize fast torque changes via load angle adjustment. Therefore, to simplify the overall control algorithm, (20) is adopted as the control law for the salient-pole PMSGs. As $|\psi_d^a|$ is a function of $|\psi_s|$ and δ , the steady-state error of $\Delta |\psi_d^a|$ will be eliminated once $|\psi_s|$ and δ are settled down to their reference values.

Fig. 2 illustrates the block diagram of the algorithm for calculating the load angle increment. A small dead band should be set up for $T_e[k]$ and $|\psi_s[k]|$ to avoid zero denominators. The reference stator flux angle $\theta_s^*[k]$ can then be obtained by

$$\theta_s^*[k] = \Delta \delta[k] + \theta_s[k] + \omega_e[k] T_s \quad (21)$$

Fig. 4. The normalized active flux of the PMSG used in the simulation as a function of normalized stator flux magnitude and load angle.

The effect of the rotor speed is taken into consideration by adding the term $\omega_e[k]T_s$ to compensate the rotor position increment when the PMSG operates at a high speed. Combining (21) with the magnitude of the desired stator flux linkage $|\psi_s|^*$, the voltage space vector $u'_{sab}[k]$, neglecting the voltage drop on the stator resistance, can be acquired, as shown in Fig. 3. Considering the effect of stator resistance, the expression of the desired stator voltage vector in a discrete-time form can be written as

$$u_{sab}[k] = \frac{\psi_{sab}^*[k] - \psi_{sab}[k]}{T_s} + R_s i_{sab}[k] \quad (22)$$

Finally, $u_{sab}[k]$ are sent to the SVM module to generate proper switching signals to achieve a fast, accurate torque and flux linkage control.

IV. SIMULATION RESULTS

Real-time simulation studies are carried out to validate the proposed DTC scheme for a 180 W PMSG. The model of the PMSG is built in the RT-Lab and is executed on the OPAL-RT real-time simulator. The sampling frequency of the proposed DTC is 10 kHz. The step size of the real-time simulation is set as 5×10^{-6} s in order to emulate the ripple behaviors of the system. The machine parameters are given in Table I. The DC bus voltage is 41.75 V. The normalized active flux as a function of the normalized stator flux magnitude and load angle is illustrated in Fig. 4. The flux linkages are normalized in terms of ψ_m .

A performance comparison between the proposed DTC and the conventional switching table-based DTC [3] is shown in Figs. 5 and 6, where the PMSG is operated at 1500 RPM. In the conventional DTC, the bandwidths of the torque and stator flux hysteresis controllers are 0.02 N·m and 0.0001 V·s, respectively. The torque and stator flux commands are -0.2 N·m and 0.0135 V·s, respectively, at the beginning. Then they are changed to -0.5 N·m and 0.0131 V·s at 0.1s, and to -0.75 N·m and 0.0134 V·s at 0.35s,

Fig. 5. The dynamic responses of torque and stator flux using the proposed DTC.

Fig. 6. The dynamic responses of torque and stator flux using the conventional DTC.

respectively. The variations of all the commands are step changes. It can be seen that the maximum peak-to-peak torque ripples of the proposed DTC and the conventional DTC are 0.08 N·m and 2 N·m, respectively, as shown in Figs. 5 and 6. The maximum peak-to-peak stator flux ripples of the proposed DTC and the conventional DTC are 0.0009 V·s and 0.008 V·s, respectively. As a result, compared with the conventional DTC, the proposed DTC shows superiority in reducing the steady-state torque and stator flux ripples under different loading conditions.

The proposed DTC is tested for the PMSG under various parameter variations, where the PMSG is operating at 2000 RPM, the stator flux reference is 0.01345 V·s, and the torque command changes from -0.1 N·m to -0.6 N·m at 2×10^{-4} s. Fig. 7 shows the torque responses when: 1) all of

Table I. The parameters of the PMSG.

Number of pole pairs	p	4
Magnet flux linkage	ψ_m	0.01344 V·s
Stator resistance	R_s	0.235 Ω
d -axis inductance	L_d	0.275 mH
q -axis inductance	L_q	0.364 mH

Fig. 7. The torque responses of the PMSG controlled by the proposed DTC under machine parameter variations.

Fig. 8. The torque tracking capability of the proposed DTC under variable rotating speeds.

the machine parameters are at their nominal values; 2) the d - and q - axis inductances are increased by 20%; and 3) the rotor magnet flux linkage is increased by 10%. As shown in Fig. 7, the three torque curves are almost on top of each other, and the torque command is tracked within two switching cycles in all cases. Therefore, the proposed DTC can achieve a fast dynamic response and its robustness to machine parameter variations is proven.

Finally, the torque tracking capability of the proposed DTC under a variable shaft speed condition, which is the real case in the WECS operation and control, is evaluated. As shown in Fig. 8, the shaft speed is set to 1000 RPM from the beginning and then linearly increased to 2500 RPM from 0.1 s to 0.2 s; after 0.15 s, the speed decreases linearly to 1500 RPM between 0.35 s and 0.5 s. Meanwhile, the torque command starts from -0.2 N·m, then increases to -0.5 N·m from 0.13 s to 0.2 s; and further increased to -0.75 N·m from 0.35 s to 0.45 s. From Fig. 8 it can be seen that the estimated torque can keep track of its command closely and quickly. They are always on top of each other. The maximum peak-to-peak torque ripple is 0.08 N·m.

Fig. 9. The experimental system setup. (a) The schematic and (b) the real setup.

Therefore, by applying the proposed DTC, the goals of fast torque dynamics and ripple reduction are achieved, which demonstrates the effectiveness of the proposed DTC for salient-pole PMSGs.

V. EXPERIMENTAL RESULTS

Experimental studies are carried out to further validate the performance of the proposed DTC scheme for the PMSG used in the simulation. Fig. 9(a) illustrates the schematic of the experimental system setup for the PMSG. A DC motor is operated as the prime mover, which is powered by a DC source through a full-bridge DC-DC converter. The power generated by the PMSG is fed back to the DC bus via a three-phase converter. The PMSG and the DC motor are connected through a mechanical coupling. The control algorithms are implemented on a dSPACE 1104 controller board. Fig. 9(b) shows the real experimental system setup. The control algorithms are executed with a sampling period of 100 μ s. All of the experimental results are recorded using the ControlDesk interfaced with dSPACE 1104 and a laboratory computer (PC).

The steady-state and dynamic performances of the proposed DTC and the conventional DTC for the salient-pole PMSG are compared in Figs. 10 and 11. The PMSG is operated at 1500 RPM. The boundaries of the hysteresis controllers for the conventional DTC are the same as those

Fig. 10. The dynamic responses of torque and stator flux controlled by the proposed DTC.

Fig. 11. The dynamic responses of torque and stator flux controlled by the conventional DTC.

in the real-time simulation. The commands of torque and stator flux linkage start from $-0.2 \text{ N}\cdot\text{m}$ and $0.0135 \text{ V}\cdot\text{s}$, and then change to $-0.5 \text{ N}\cdot\text{m}$ and $0.013 \text{ V}\cdot\text{s}$ at 1.5 s , respectively. Both reference variations are step changes. With the proposed DTC, the maximum peak-to-peak torque and stator flux ripples are $0.15 \text{ N}\cdot\text{m}$ and $0.0005 \text{ V}\cdot\text{s}$, respectively, as shown in Fig. 10. However, when the conventional DTC is used, the maximum peak-to-peak torque and stator flux ripples increase to $1.8 \text{ N}\cdot\text{m}$ and $0.009 \text{ V}\cdot\text{s}$, respectively, as shown in Fig. 11.

Fig. 12 shows the torque tracking performance of the PMSG under a complete torque reversal from $-0.4 \text{ N}\cdot\text{m}$ to $0.4 \text{ N}\cdot\text{m}$ (80% rated torque), where the shaft speed is 2000 RPM, the stator flux reference is $0.0135 \text{ V}\cdot\text{s}$, and the torque command is changed within one step at 0.25 s . The estimated torque and its command are on top of each other during the steady-state operation. The complete torque reversal is fulfilled within 4 switching cycles. Consequently, although neglecting the transient of the active flux, the proposed DTC can still attain fast dynamic response when the controlled PMSG has saliency.

Fig. 12. The transient performances of the PMSG controlled by the proposed DTC under a complete torque reversal.

Fig. 13. The dynamic performance of the PMSG-based direct-drive WECS controlled by the proposed DTC: (a) wind speed, (b) shaft speed, and (c) actual and optimal power coefficients.

Fig. 14. The electromagnetic torque and stator flux responses of the PMSG-based direct-drive WECS controlled by the proposed DTC.

Finally, the proposed DTC is applied to emulate the operation of a direct-drive WECS, where the DC motor is controlled to emulate the dynamics of a real wind turbine. As shown in Fig. 13(a), the wind speed profile used in this test consists of two segments. In the first 10 seconds, the wind speed changes alternatively between 6 m/s and 8 m/s. The frequency of the periodic wind speed variations is 0.25 Hz. The slew rate of the wind speed changes is 20 m·s⁻¹/s. In the second segment, a randomly generated 10-second wind speed profile is used, as shown in Fig. 13(a). The random wind speed varies in the range of ±1.25 m/s around the mean value of 7 m/s. The optimal torque command to realize the MPPT is given as [14], [15]

$$T_e^* = K_{opt} \omega_t^2 \quad (23)$$

where K_{opt} is a constant determined by the wind turbine characteristics, which is equal to 5.6553×10^{-6} according to the parameters of the emulated wind turbine. The command of the stator flux magnitude is obtained from the principle of maximum torque per ampere (MTPA). The dynamic responses of the shaft speed and the actual and optimal power coefficients are shown in Fig. 13(b) and (c), respectively. The actual power coefficient of the WECS approaches the optimal value closely. Due to the moment of inertia of the system, the shaft speed cannot be varied abruptly when sudden wind speed changes occurred. However, the actual power coefficient can keep tracking the optimal value within 0.2 seconds. Fig. 14 shows the tracking performance of the electromagnetic torque and the stator flux magnitude. With the proposed DTC, the estimated torque and stator flux and their commands are always on top of each other. The peak-to-peak torque and stator flux ripples are less than 0.1 N·m (8% of the maximum torque) and 0.0004 V·s (3% of the base flux value), respectively. Moreover, the torque and stator flux tracking performance of the PMSG controlled by the proposed DTC is not deteriorated under load and speed variations.

VI. CONCLUSION

This paper has proposed a novel discrete-time DTC based on flux space vectors for salient-pole PMSGs. The algorithm is easy to implement and is suitable for digital control systems using relatively low sampling frequencies. The torque and flux ripples have been significantly reduced with the integration of the SVM. In addition, the overall DTC scheme has eliminated the use of PI controllers, showed strong robustness to machine parameter variations, and achieved fast dynamic responses. The effectiveness of the proposed DTC scheme has been validated by real-time simulation and experimental results for a 180 W salient-pole

PMSG.

REFERENCES

- [1] D. Casadei, F. Profumo, and G. Serra, "FOC and DTC: Two viable schemes for induction motors torque control," *IEEE Trans. Power Electron.*, vol. 17, no. 5, pp. 779-787, Sept. 2002.
- [2] M. Depenbrock, "Direct self-control of inverter-fed induction machines," *IEEE Trans. Power. Electron.*, vol. PE-3, no. 4, pp. 420-429, Oct. 1988.
- [3] L. Zhong, M. F. Rahman, W. Y. Hu, and K. W. Lim, "Analysis of direct torque control in permanent magnet synchronous motor drives," *IEEE Trans. Power Electron.*, vol. 12, no. 3, pp. 528-536, May 1997.
- [4] Y. Zhao, C. Wei, Z. Zhang, and W. Qiao, "A review on position/speed sensorless control for permanent-magnet synchronous machine-based wind energy conversion systems," *IEEE J. Emerging and Selected Topics in Power Electron.*, vol. 1, no. 4, pp. 203-216, Dec. 2013.
- [5] Y. Inoue, S. Morimoto, and M. Sanada, "Control method for direct torque controlled PMSG in wind power generation system," in *Proc. IEEE Electric Machines and Drives Conf.*, May 2009, pp. 1231-1238.
- [6] Z. Zhang, W. Qiao, and L. Qu, "Saturation controller-based ripple reduction for direct torque controlled permanent-magnet synchronous machines," in *Proc. IEEE Applied Power Electronics Conference and Exposition*, Mar. 2014, pp. 799-805.
- [7] C. A. Martins, X. Roboam, T. A. Meynard, and A. S. Carvalho, "Switching frequency imposition and ripple reduction in DTC drives by using a multilevel converter," *IEEE Trans. Power Electron.*, vol. 17, no. 2, pp. 286-297, Mar. 2002.
- [8] G. S. Buja and M. P. Kazmierkowski, "Direct torque control of PWM inverter-fed AC motors—A survey," *IEEE Trans. Ind. Electron.*, vol. 51, no. 4, pp. 744-757, Aug. 2004.
- [9] I. Boldea, M. C. Paicu, G. D. Andreescu, and F. Blaabjerg, "Active flux' DTFC-SVM sensorless control of IPMSM," *IEEE Trans. Energy Conversion*, vol. 24, no. 2, pp. 314-322, Jun. 2009.
- [10] L. Tang, L. Zhong, M. F. Rahman, and Y. Hu, "A novel direct torque controlled interior permanent magnet synchronous machine drive with low ripple in flux and torque and fixed switching frequency," *IEEE Trans. Power Electron.*, vol. 19, no. 2, pp. 346-354, Mar. 2004.
- [11] H. Moon, H. Kim, and M. Youn, "A discrete-time predictive current control for PMSM," *IEEE Trans. Power Electron.*, vol. 18, no. 1, pp. 464-472, Jan. 2003.
- [12] J. Lee, C. Choi, J. Seok, and R.D. Lorenz, "Deadbeat-direct torque and flux control of interior permanent magnet synchronous machines with discrete time stator current and stator flux linkage observer," *IEEE Trans. Ind. Appl.*, vol. 47, no. 4, pp. 1749-1758, July-Aug. 2011.
- [13] Z. Zhang, Y. Zhao, W. Qiao, and L. Qu, "A discrete-time direct-torque and flux control for direct-drive PMSG wind turbines," in *Proc. IEEE Industry Applications Society Annual Meeting*, Oct. 2013, pp. 1-8.
- [14] S. Morimoto, H. Nakayama, M. Sanada, and Y. Takeda, "Sensorless output maximization control for variable-speed wind generation system using IPMSG," *IEEE Trans. Ind. Appl.*, vol. 41, no. 1, pp. 60-67, Jan/Feb. 2005.
- [15] Z. Zhang, Y. Zhao, W. Qiao, and L. Qu, "A space-vector modulated sensorless direct-torque control for direct-drive PMSG wind turbines," *IEEE Trans. Ind. Appl.*, vol. 50, no. 4, Jul./Aug. 2014, to appear.