A Novel Technique for Direct Drive PMSG Based Wind Energy Conversion System Using Discrete-Time Direct Torque Control

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***Abstract*- This paper proposes a novel flux-space-vector-based direct torque control (DTC) scheme for permanent-magnet synchronous generators (PMSGs) used in variable-speed direct-drive wind energy conversion systems (WECSs). The discrete-time control law, which is derived from the perspective of flux space vectors and load angle, predicts the desired stator flux vector for the next time-step with the torque and stator flux information only. The space vector modulation (SVM) is then employed to generate the reference voltage vector, leading to a fixed switching frequency, as well as lower flux and torque ripples, when compared to the conventional DTC. Compared with other SVM-based DTC methods in the literature, the proposed DTC scheme eliminates the use of proportional-integral regulators and is less dependent on machine parameters, e.g., stator inductances and permanent-magnet flux linkage, while the main advantages of the DTC, e.g., fast dynamic response and no need of coordinate transform, are preserved. The proposed DTC scheme is applicable for both nonsalient-pole and salient-pole PMSGs. The overall control scheme is simple to implement and is robust to parameter uncertainties and variations of the PMSGs. The effectiveness of the proposed discrete-time DTC scheme is verified by simulation and experimental results on a 180-W salient-pole PMSG and a 2.4-kW nonsalient-pole PMSG used in variable-speed direct-drive WECSs.**

I. INTRODUCTION

OVER the last two decades, the increasing concerns on energy crisis and environmental pollutions have significantly promoted the utilization of renewable energy. Amongvarious renewable energy sources, wind energy has become one of the most cost-effective sources for electricity generation. The variable-speed wind energy conversion systems (WECSs), which can be operated in the maximum power point tracking (MPPT) mode, have attracted considerable interests, owing to their high energy production efficiency and lowtorque spikes [1]. Among different types of generators, the permanent-magnet synchronous generators (PMSGs) have been found superior, owing to their advantages such as high power density, high efficiency, and high reliability. Furthermore, a PMSG with a high number of poles can be connected directly to a wind turbine without the use of a gearbox, which significantly reduces the construction, operation, and maintenance costs of the WECSs [2], [3]. Typically, the control systems of PMSGs adopt a decoupled current control executed in a synchronized rotating reference frame. In the last few decades, an alternative electric machine control scheme called the direct torque control (DTC) has attracted extensive attention from both academia and industry. Different from the decoupled current control, the DTC directly controls electromagnetic torque and stator flux linkage instead of armature currents, hence possessing the merits of fast dynamic response, simple implementation, and high robustness to external disturbances. The DTC has been applied successfully in high-performance industrial servo drive systems [4]. For WECS applications, the DTC may facilitate the realization of MPPT with the optimal torque control [1], since the optimal torque command can be applied directly in the DTC without the need of wind speed measurements. 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, the voltage vector commands are determined primarily by the outputs of two hysteresis comparators. Once selected, the desired voltage vector will remain unchanged until the hysteresis states are updated. Although this voltage modulation scheme is simple to execute, it will lead to irregular and unpredictable torque and flux ripples, particularly when the DTC is applied on a digital platform [6]. To solve these problems, many approaches have been developed from different perspectives. One natural thought is to increase the number of available voltage vectors, e.g., using multilevel converters [7], [8] or equally dividing the sampling period into multiple intervals [9]. However, these methods will increase the hardware cost, need additional prediction for rotor speed, or have a limited ripple reduction improvement. Anothereffective technique is to integrate the space vector modulation (SVM) algorithm into the DTC [10]–[15]. The SVM is able to convert the input voltages into gate signals for the inverter using a fixed switching frequency. A variety of SVM-based DTC schemes have been investigated for permanent-magnet synchronous machines (PMSMs) in the last few decades. In general, they can be classified into two categories based on how the voltage references are generated in the stationary reference frame. In the first category, the decoupled voltage references in the synchronously rotating reference frame are acquired and then transformed to the stationary reference frame using the rotary coordinate transformation [12]–[14]. In the second category, the voltage references are obtained directly from the incremental stator flux vectors in the stationary reference frame without coordinate transformation [15]. Both methods can reduce torque and flux ripples, but need proportional–integral (PI) controllers to regulate the torque and stator flux errors. The PI gains are usually tuned by a trial-and-error procedure [12]. Poorly tuned PI gains will deteriorate the dynamic performance of the DTC. In addition, according to [9], a real DTC scheme should not contain PI regulators. More recently, a predictive current control [16], [17] and a deadbeat direct torque and flux control [18] were investigated for surface-mounted and interior PMSMs. These control schemes provide good dynamic performance, provided that the information of some machine parameters, e.g., stator inductances and permanent-magnet flux linkage, is accurate. Therefore, the performance of the control systems would be more or less influenced by the variations of the machine parameters. Moreover, these control schemes are based on the inverse machine model or a graphical method, which increase the computational complexity. This paper proposes a discrete-time SVM-based DTC without PI regulators for direct-drive PMSG-based WECSs. The discrete-time control law is derived from the prospective of flux space vectors and load angle. Several machine parameters, e.g., stator inductances and permanent-magnet flux linkage, are not presented in the control law. This improves the robustness of the control system to PMSG parameter variations. By adopting the proposed DTC scheme, the torque and flux ripples are reduced, and the fast dynamic response is retained when compared with the conventional DTC scheme. The proposed DTC scheme is validated by simulation and experimental results for a 2.4-kW nonsalient-pole PMSG and a 180-W salient-pole PMSG used in the direct-drive WECSs.

II LITERATURER SURVEY

A review on position/speed sensorless control for permanent-magnet synchronous machine-based wind energy conversion systems Owing to the advantages of higher efficiency, greater reliability, and better grid compatibility, the direct-drive permanent-magnet synchronous generator (PMSG)-based variable-speed wind energy conversion systems (WECSs) have drawn the highest attention from both academia and industry in the last few years. Applying mechanical position/speed sensorless control to direct-drive PMSG-based WECSs will further reduce the cost and complexity, while enhancing the reliability and robustness of the WECSs. This paper reviews the state-of-the-art and highly applicable mechanical position/speed sensorless control schemes for PMSG-based variable-speed WECSs. These include wind speed sensorless control schemes, generator rotor position and speed sensorless vector control schemes, and direct torque and direct power control schemes for a variety of direct-drive PMSG-based WECSs Control of IPM synchronous generator for maximum wind power generation considering magnetic saturation Permanent-magnet synchronous generators (PMSGs) are commonly used for small variable-speed wind turbines to produce high-efficiency, high-reliability, and low-cost wind power generation. This paper proposes a novel control scheme for an interior PMSG (IPMSG) driven by a wind turbine, in which thed-axis and q-axis stator-current components are optimally controlled to achieve the maximum wind power generation and loss minimization of the IPMSG. The effect of magnetic saturation, which causes the highly nonlinear characteristics of the IPMSG, is considered in the control-scheme design. The optimal d-axis stator-current command is obtained as a function of the IPMSG rotor speed by solving a constrained nonlinear-optimization problem that minimizes the copper and core losses of the IPMSG. At any wind speed within the operating range, the IPMSG rotor speed is optimally controlled to extract maximum wind power. The optimal q-axis stator-current command is then obtained from the optimal IPMSG rotor speed and d-axis current. To eliminate the effects of nonlinearity caused by magnetic saturation, an input-output feedback linearization technique is applied to design the high-performance nonlinear current controllers. The proposed control scheme provides the wind generation system with the maximum efficiency and high dynamic performance. Wind speed and rotor position sensorless control for direct-drive PMG wind turbines This paper proposes a wind speed and rotor position sensorless control for wind turbines directly driving permanent magnetic generators (PMGs). A sliding-mode observer is designed to estimate the rotor position of the PMG by using the measured stator currents and the commanded stator voltages obtained from the control scheme of the machine-side converter of the PMG wind turbine. The rotor speed of the PMG (i.e., the turbine shaft speed) is estimated from its back electromotive force using a model adaptive reference system observer. Based on the measured output electrical power and estimated rotor speed of the PMG, the mechanical power of the turbine is estimated by taking into account the power losses of the wind turbine generator system. A back-propagation artificial neural network is then designed to estimate the wind speed in real time by using the estimated turbine shaft speed and mechanical power. The estimated wind speed is used to determine the optimal shaft speed reference for the PMG control system. Finally, a sensorless control is developed for the PMG wind turbines to continuously generate the maximum electrical power without using any wind speed or rotor position sensors. The validity of the proposed estimation and control algorithms are shown by simulation studies on a 3-kW PMG wind turbine and are further demonstrated by experimental results on a 300-W practical PMG wind turbine.

Analysis of direct torque control in permanent magnet synchronous motor drives This paper describes an investigation of direct torque control (DTC) for permanent magnet synchronous motor (PMSM) drives. It is mathematically proven that the increase of electromagnetic torque in a permanent magnet motor is proportional to the increase of the angle between the stator and rotor flux linkages, and, therefore, the fast torque response can be obtained by adjusting the rotating speed of the stator flux linkage as fast as possible. It is also shown that the zero voltage vectors should not be used, and stator flux linkage should be kept moving with respect to the rotor flux linkage all the time. The implementation of DTC in the permanent magnet motor is discussed, and it is found that for DTC using available digital signal processors (DSPs), it is advantageous to have a motor with a high ratio of the rated stator flux linkage to stator voltage. The simulation results verify the proposed control and also show that the torque response under DTC is much faster than the one under current control. FOC and DTC: Two viable schemes for induction motors torque control Field-oriented control and direct torque control are becoming the industrial standards for induction motors torque control. This paper is aimed at giving a contribution for a detailed comparison between the two control techniques, emphasizing advantages and disadvantages. The performance of the two control schemes is evaluated in terms of torque and current ripple, and transient response to step variations of the torque command. The analysis has been carried out on the basis of the results obtained by numerical simulations, where secondary effects introduced by hardware implementation are not present.

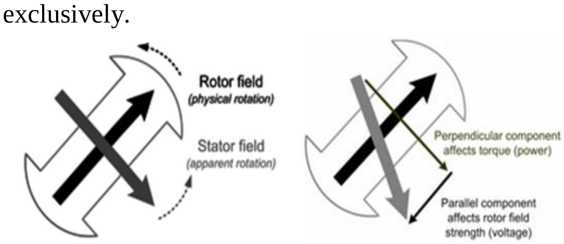
III. EXISTING AND PROPOSED SYSTEM

In the conventional DTC, the voltage vector commands are determined primarily by the outputs of two hysteresis comparators. Once selected, the desired voltage vector will remain unchanged until the hysteresis states are updated. Although this voltage modulation scheme is simple to execute, it will lead to irregular and unpredictable torque and flux ripples, particularly when the DTC is applied on a digital platform [6]. To solve these problems, many approaches have been developed from different perspectives. One natural thought is to increase the number of available voltage vectors, e.g., using multilevel converters [7], [8] or equally dividing the sampling period into multiple intervals [9]. However, these methods will increase the hardware cost, need additional prediction for rotor speed, or have a limited ripple reduction improvement. Another effective technique is to integrate the space vector modulation (SVM) algorithm into the DTC [10]–[15]. The SVM is able to convert the input voltages into gate signals for the inverter using a fixed switching frequency. A variety of SVM-based DTC schemes have been investigated for permanent-magnet synchronous machines (PMSMs) in the last few decades. In general, they can be classified into two categories based on how the voltage references are generated in the stationary reference frame. In the first category, the decoupled voltage references in the synchronously rotating reference frame are acquired and then transformed to the stationary reference frame using the rotary coordinate transformation [12]–[14]. In the second category, the voltage references are obtained directly from the incremental stator flux vectors in the stationary reference frame without coordinate transformation [15]. Both methods can reduce torque and flux ripples, but need proportional–integral (PI) controllers to regulate the torque and stator flux errors. The PI gains are usually tuned by a trial-and-error procedure [12].

Poorly tuned PI gains will deteriorate the dynamic performance of the DTC. In addition, according to [9], a real DTC scheme should not contain PI regulators. More recently, a predictive current control [16], [17] and a deadbeat direct torque and flux control [18] were investigated for surface-mounted and interior PMSMs. These control schemes provide good dynamic performance, provided that the information of some machine parameters, e.g., stator inductances and permanent-magnet flux linkage, is accurate. Therefore, the performance of the control systems would be more or less influenced by the variations of the machine parameters. Moreover, these control schemes are based on the inverse machine model or a graphical method, which increase the computational complexity. This paper proposes a discrete-time SVM-based DTC without PI regulators for direct-drive PMSG-based WECSs. The discrete-time control law is derived from the prospective of flux space vectors and load angle. Several machine parameters, e.g., stator inductances and permanent-magnet flux linkage, are not presented in the control law. This improves the robustness of the control system to PMSG parameter variations. By adopting the proposed DTC scheme, the torque and flux ripples are reduced, and the fast dynamic response is retained when compared with the conventional DTC scheme. The proposed DTC scheme is validated by simulation and experimental results for a 2.4-kW nonsalient-pole PMSG and a 180-W salient-pole PMSG used in the direct-drive WECSs.

IV. PERMANENT MAGNET SYNCHRONOUS GENERATOR

A permanent magnet synchronous generator is a generator where the excitation field is provided by a permanent magnet instead of a coil. The term synchronous refers here to the fact that the rotor and magnetic field rotate with the same speed, because the magnetic field is generated through a shaft mounted permanent magnet mechanism and current is induced into the stationary armature Synchronous generators are the majority source of commercial electrical energy. They are commonly used to convert the mechanical power output of steam turbines, gas turbines, reciprocating engines and hydro turbines into electrical power for the grid. Wind turbines of any significant scale use asynchronous generators exclusively.



In the majority of designs the rotating assembly in the center of the generator—the "rotor"—contains the magnet, and the "stator" is the stationary armature that is electrically connected to a load. As shown in the diagram above, the perpendicular component of the stator field affects the torque while the parallel component affects the voltage. The load supplied by the generator determines the voltage. If the load is inductive, then the angle between the rotar and stator fields will be greater than 90 degrees which corresponds to an increased generator voltage. This is known as an overexcited generator. The opposite is true for a generator supplying a capacitive load which is known as an underexcited generator. A set of three conductors make up the armature winding in standard utility equipment, constituting three phases of a power circuit—that correspond to the three wires we are accustomed to see on transmission lines. The phases are wound such that they are 120 degrees apart spatially on the stator, providing for a uniform force or torque on the generator rotor. The uniformity of the torque arises because the magnetic fields resulting from the induced currents in the three conductors of the armature winding combine spatially in such a way as to resemble the magnetic field of a single, rotating magnet. This stator magnetic field or "stator field" appears as a steady rotating field and spins at the same frequency as the rotor when the rotor contains a single dipole magnetic field. The two fields move in "synchronicity" and maintain a fixed position relative to each other as they spin.[1]

They are known as synchronous generators because f, the frequency of the induced voltage in the stator (armature conductors) conventionally measured in hertz, is directly proportional to RPM, the rotation rate of the rotor usually given in revolutions per minute (or angular speed). If the rotor windings are arranged in such a way as to produce the effect of more than two magnetic poles, then each physical revolution of the rotor results in more magnetic poles moving past the armature windings. Each passing of a north and south pole corresponds to a complete "cycle" of a magnet field oscillation. Therefore, the constant of proportionality is , where P is the number of magnetic rotor poles (almost always an even number), and the factor of 120 comes from 60 seconds per minute and two poles in a single magnet; The power in the prime mover is a function of RPM and torque. where is mechanical power in Watts, is the torque with units of , and RPM is the rotations per minute which is multiplied by a factor of to give units of By increasing the torque on the prime mover, a larger electrical power output can be generated.

V PROJECT DISCRIPTION AND CONTROL DESIGN

The configuration of a direct-drive PMSG-based WECS is shown in Fig. 1, where the wind turbine is connected to the PMSG directly without a gearbox. The electrical power generated by the PMSG is transmitted to a power grid or supplied to a load via a variable-frequency power converter. Typically, the power electronic conversion system consists of a machine-side converter (MSC) and a grid-side converter (GSC) connected back-to-back via a dc link. This paper considers the standard power converter topology in a PMSG-based WECS, where both the MSC and the GSC are two-level fully controlled voltagesource converters.

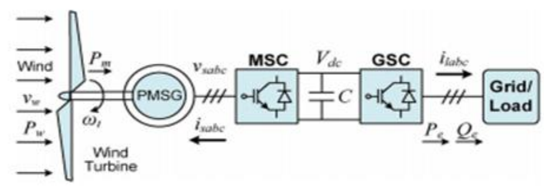


Fig. 1. Configuration of a direct-drive PMSG-based WECS connected to a power grid/load.

VI. RESULTS

Simulation studies are carried out in MATLAB/Simulink to validate the proposed discrete-time DTC scheme for two PMSGs. The parameters of the two PMSGs are listed in Table I. The power rating of the salient-pole PMSG #1 is 180 W, and its dc-bus voltage is 41.75 V. The nonsalient-pole PMSG #2 is used in a practical direct-drive WECS (Skystream 3.7) with a 2.4-kW rated power and a dc-bus voltage of 300 V. In the simulation, the value of k in (14) and (15) is set as 1/ √2. The sampling period is 100 μs for both PMSG control systems, which is typically equal to one pulsewidth modulation (PWM) control cycle in practical applications. The deadtime of the insulatedgate bipolar transistors (IGBTs) in the MSC is set as 1 μs and is compensated by the algorithm introduced in [22]. B. Validation of the Proposed DTC on PMSG #1 The performance comparison of the proposed DTC, the conventional DTC, and a stator flux-oriented SVM-DTC (named PI-DTC) in [12] is first investigated on PMSG #1. The conventional

TABLE I
PARAMETERS OF THE PMSGs

Parameter	PMSG #1	PMSG #2
Number of pole pairs p	4	21
Magnet flux linkage ψ_m	0.01344 V·s	0.2532 V·s
Stator resistance R_s	0.235 Ω	1.5 Ω
d-axis inductance L_d	0.275 mH	0.87 mH
q-axis inductance L_q	0.364 mH	0.91 mH

DTC in this paper is implemented by adopting the switching table in [10], where the torque error is regulated by a three-level torque hysteresis controller. The stator flux is estimated by using the PMSG current model in the stationary reference frame, which is given by

$$\begin{bmatrix}\psi_{s\alpha}\\ \psi_{s\beta}\end{bmatrix}=\begin{bmatrix}L+\Delta L\cos(2\theta_{re}) & \Delta L\sin(2\theta_{re})\\ \Delta L\sin(2\theta_{re}) & L-\Delta L\cos(2\theta_{re})\end{bmatrix}\begin{bmatrix}i_{s\alpha}\\ i_{s\beta}\end{bmatrix}+\psi_m\begin{bmatrix}\cos\theta_{re}\\ \sin\theta_{re}\end{bmatrix} \quad (30)$$

where L = (Ld + Lq)/2 and ΔL = (Ld − Lq)/2. The current-model-based stator flux estimator could achieve good performance in both steady and transient states, but needs more machine parameters compared to the voltage-model-based stator flux estimator used in the proposed DTC.

In this test, the speed of PMSG #1 is kept at 1500 r/min; the torque reference is −0.1 N • m, from the beginning, and then is decreased to −0.5 N • m at 0.025 s; the command of the stator flux magnitude is 0.0135 V • s, at the beginning, and then is decreased to 0.013 V • s at 0.025 s; and both reference variations are step changes. In the conventional DTC, the torque and stator flux hysteresis bandwidths are set as 0.2 N • m and 0.0003 V • s, respectively. The PI gains of the PI-DTC are tuned carefully to achieve good control performance for PMSG #1. Fig. 7 compares the torque, stator flux magnitude, and instantaneous phase-A stator current of PMSG #1 controlled by the conventional DTC, the PI-DTC, and the proposed DTC with a 10-kHz sampling frequency, as well as by the conventional DTC with a 67-kHz sampling frequency (named DTC-1). The switching behavior of the conventional DTC determines that its switching frequency is lower than the SVM-DTCs when using the same sampling frequency [14]. Thus, in the DTC-1 case, the sampling frequency of the conventional DTC is increased to 67 kHz, to obtain an equivalent switching frequency of 10 kHz, which is obtained by calculating the average turningon/off frequency of an inverter leg within 0.05 s [23]. As shown in Fig. 7, the maximum peak-to-peak torque ripples of the conventional DTC, the PI-DTC, the proposed DTC, and the DTC-1 are 1.2, 0.1, 0.1, and 0.33 N • m, respectively; and the maximum peak-to-peak ripples of the stator flux magnitudes in the four cases are 0.008, 0.0004, 0.0004, and 0.0012 V • s, respectively. The stator currents controlled by the PI-DTC and the proposed DTC are much smoother with less harmonic contents than those controlled by the conventional DTC and DTC-1. Thus, compared with the conventional DTC, the SVMDTCs (including the proposed DTC and the PI-DTC) showed

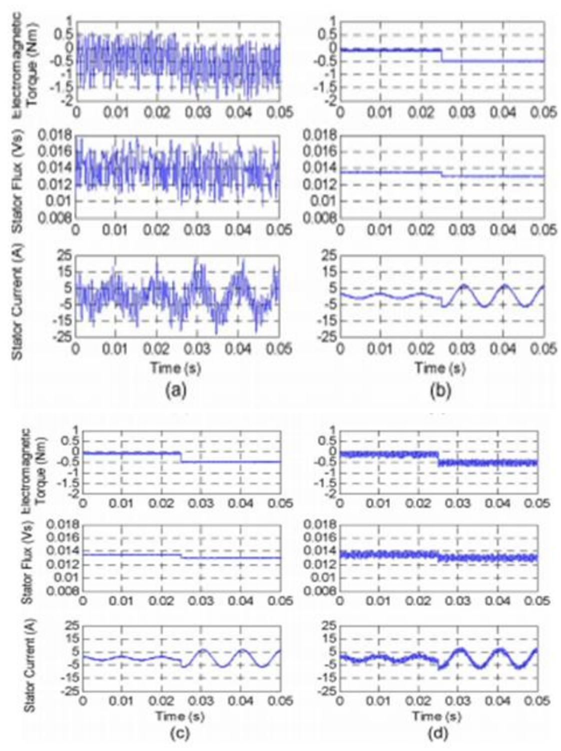


Fig. 7. Dynamic responses of torque, stator flux magnitude, and instantaneous phase-A stator current of PMSG #1 using (a) the conventional DTC, (b) the PI-DTC, and (c) the proposed DTC with a 10-kHz sampling frequency as well as (d) the conventional DTC with a 67-kHz sampling frequency (DTC-1).

distinct superiority in reducing the steady-state torque and stator flux magnitude ripples and stator current harmonics for different loading conditions. This is true even when the conventional DTC is implemented with a much higher sampling frequency (leading to a higher computational cost) so as to have an equivalent switching frequency same as the switching frequency of the proposed DTC and the PI-DTC.

The tracking performance of the proposed DTC is shown in Fig. 8. In this test, PMSG #1 is operated at 2000 r/min, and the torque command is step changed from −0.2 to −0.5 N • m at 3 × 10−4 s. The references of the stator flux and active flux magnitudes are calculated based on the maximum torque per ampere (MTPA) curve. The dynamics of the torque angle increment (top) and the torque (bottom) with/without active flux compensation are compared in Fig. 8. The active flux term does not affect the dynamic performance of the proposed DTC, which proves the feasibility of the assumption (26). The torque is capable of tracking its command within two switching cycles.

The proposed DTC is also tested with various parameter variations, where the operating condition of the PMSG is the same as that in Fig. 8. Fig. 9 shows the percentage torque errors with respect to the values in Fig. 8, when the rotor magnet flux linkage or the d- and q-axis inductances change while all other parameters of the machine are kept at the nominal values.

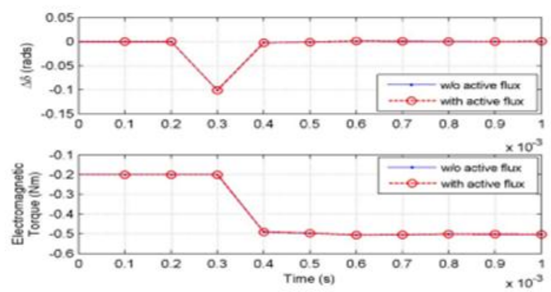


Fig. 8. Dynamic responses of the torque angle increment (top) and the electromagnetic torque (bottom) under a step torque change for PMSG #1.

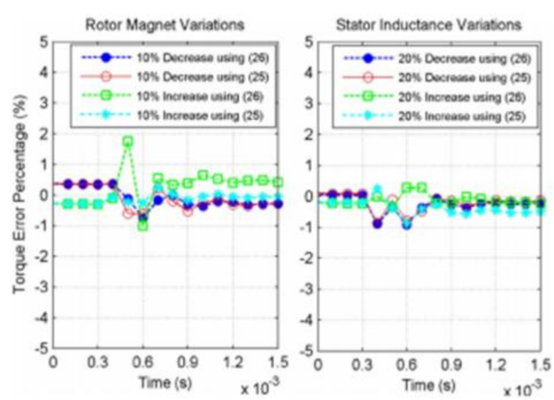


Fig. 9. Torque errors in percentage with respect to the results in Fig. 8, when the rotor magnet flux linkage (left) or the stator inductances (right) vary.

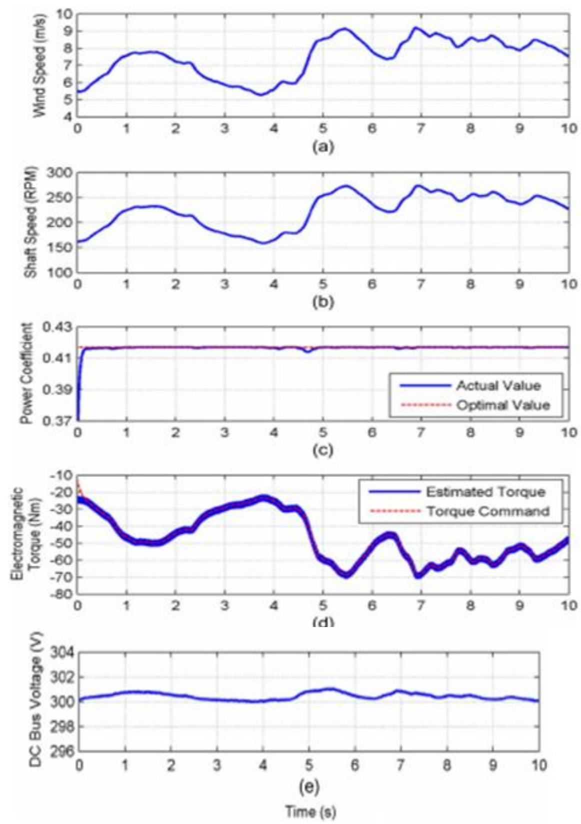


Fig. 11. Dynamic performance of the PMSG #2-based direct-drive WECS controlled by the proposed DTC under variable wind speed conditions: (a) wind speed; (b) shaft speed; (c) actual and optimal power coefficients; (d) electromagnetic torque and its command; and (e) dc-bus voltage.

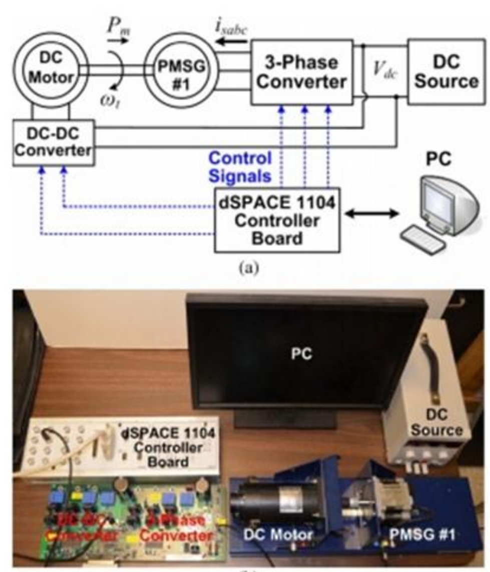


Fig. 12. Experimental setup for PMSG #1: (a) the schematic and (b) the real experimental system setup.

CONCLUSION

This paper has proposed a novel discrete-time DTC based on flux space vectors for PMSGs used in direct-drive WECSs. 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 eliminated the use of PI controllers, showed strong robustness to machine parameter variations, and achieved fast dynamic responses. The proposed DTC scheme can be applied to both nonsalient-pole and salient-pole PMSGs. Simulation and experimental results have been carried out to validate the effectiveness of the proposed DTC scheme on a 180-W salientpole PMSG and a nonsalient-pole PMSG used in a 2.4-kW Skystream 3.7 direct-drive WECS.

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