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Regular paper

Optimum Torque Control of Direct Driven Wind Energy Conversion Systems Fed Sparse Matrix Converter

This paper proposes the sparse matrix converter as variable speed drives of a direct driven wind energy conversion system (WECs), because its features can provide excellent power quality at both sides of the converter and does not require dc-link energy storage. Variable speed control of the WECS is proposed to get maximum power of the generator on each wind speed variation based on the optimum torque control method. The electromagnetic torque of the generator is regulated using PI controller according to the optimum torque of the wind turbine located at the point of maximum power. The output of PI controller is the reference voltage for modulation of SMC switches based on Space Vector Modulation (SVM) method. The verification result of the proposed model through the simulation shows that the generator output power can reach the maximum point on each wind speed variation. The use of SMC has also been able to improve the power quality with low Total Harmonic Distortion (THD) of voltage and current at grid side.

Keywords: Sparse matrix converter; wind energy conversion system; optimum torque control; maximum power control.

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1. Introduction

Geographical and climatic conditions in Indonesia allow for the development of the wind energy conversion system (WECs) for electric power generation [1-3]. It has started to grow on a small scale in recent times. Small-scale WECs generally use a Permanent Magnet Synchronous Generator (PMSG), due many advantages such as smaller in size, easy to control and high eficiency with the absence of rotor losses [2-7].

WECS can be operated in stand alone mode or grid connected mode. Grid connected WECS is more efficient because it does not require energy storage system that can add loss of power [8]. Grid connected WECS with PMSG generally use full power converter to supply the power from generator to grid. In addition, the power converter can also function as a driver for the generator speed controller. The generator speed of WECs can be controlled for fixed speed or variable speed. However, variable speed is more advantageous than fixed speed, because it can maximize the output power of the generator, so that the efficiency of WECs can be improved [2].

The use of power converters on the WECs will cause serious power quality problems, ie high current and voltage harmonics due to the switching frequencies of the converters. Some converter models have been developed to minimize this problem, such as multilevel converter and matrix converter [6-10]. Matrix converters are a good choice for grid connected WECs, because it has advantages, such as high power densities, not require dc-link energy storage system and can produce sinusoidal input and output current using small LC filter [11-12]. Matrix converter provide transformation from ac-to-ac with adjustable voltage and frequency, so it is feasible for variable speed drive in WECs [8].

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Disadvantages matrix converter is using a lot of switches, making it more expensive and the modulation technique becomes more complicated. To solve this problem, it has developed sparse matrix converter in [10] with the number of switches that are less than the conventional matrix converter. This converter uses only 12 active switches, so the cost can be reduced. The structure of this converter is similar to back to back converter. This makes the modulation technique easier than conventional matrix converters.

Variable speed control of PMSG for maximum output power in WECs or also called Maximum Power Point Tracking (MPPT) can be done in several ways, namely Tip Speed Ratio (TSR) control, Optimum Torque Control (OTC), Perturbation and Observation (PO) control, Power Signal Feedback (PSF) control and inteligent control approach [13-19]. Each method has different features. In the OTC method, the maximum power point is achieved by controlling the mechanical torque of the wind turbine at the optimum point [16]. The advantages of this method is simple, efficient and does not require wind speed sensor [13].

The MPPT control strategy using OTC for PMSG driven wind turbine based on Field Oriented Control (FOC) method has been developed in [8],[17]. In this method, the electromagnetic torque of the generator is controlled at the optimum point by regulating the q-axis of stator current. This scheme requires a complex algorithm, because it uses two loop control to get the required reference voltage for modulation of converter switch. In this paper, the OTC method is proposed using a Direct Torque Control (DTC) scheme based on Space Vector Modulation (SVM). In this scheme, the electromagnetic torque is controlled at the optimum point using using PI controller based on the estimated electromagnetic torque values. This method is simpler than the FOC method and also provides a smooth torque response.

2. Notation

v_w	Wind speed (m/sec)
ω_m	Generator speed (rpm)
$T_e,\ T_m,\ T_{opt}$	Electromagnetic torque, mechanical torque, optimum torque
$R,\ R_s$	Blade radius, stator resistance
ψ_s, ψ_f	Stator flux and permanent magnet flux
$C_p, C_{p\max}$	Power coefficient and maskimum power coefficient
λ, λ_{opt}	TSR and optimum TSR
ρ	Air density
β	Pitch angle of wind turbine
B	Friction coefficient (N.m.s/rad)
n_p	number of pole pairs
L_d, L_q	Stator inductance (H)
i_d, i_q	dq-axis of current
$v_d, v_q, v_\alpha, v_\beta$	dq-axis and $\alpha\beta$-axis of voltages
$d_{\alpha i}, d_{\beta i}, d_{\alpha o}, d_{\beta o}$	Duty cycle of sparse matrix converter
θ_ψ	Rotor position

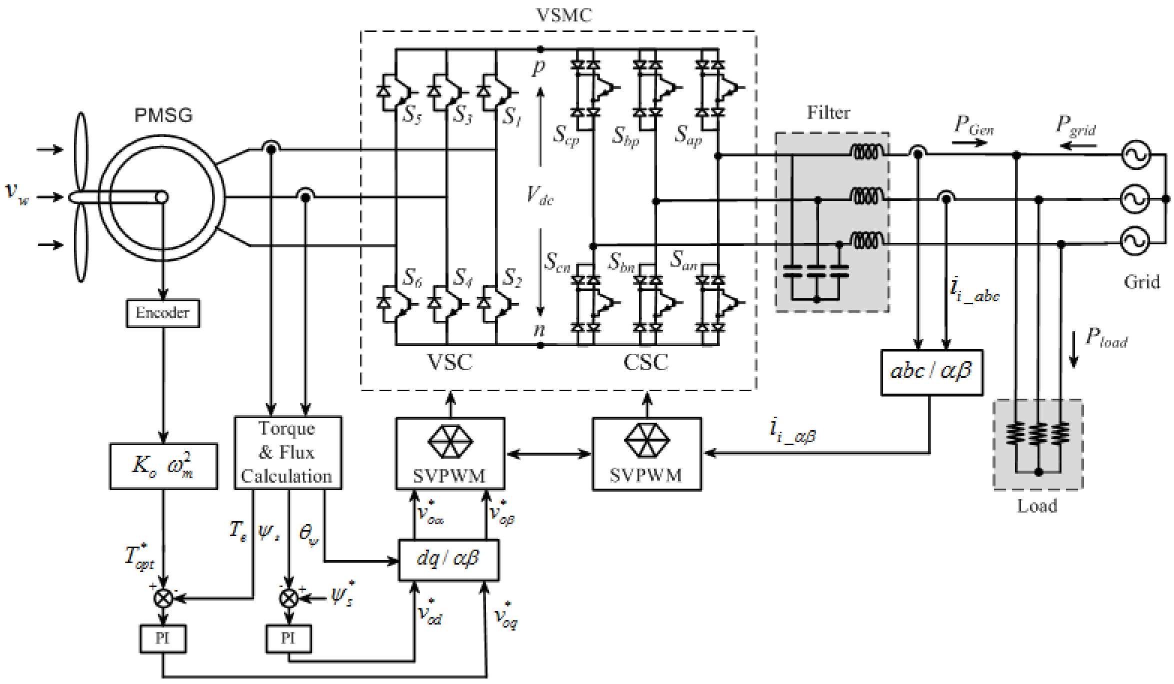


Fig. 1. The proposed WECs schemes

3. Wind Energy Conversion System Employing Sparse Matrix Converter

The proposed MPPT control of direct driven PMSG-wind turbine based on OTC by employing sparse matrix converter is shown in Fig. 1. The proposed system consists of horizontal wind turbine to drive PMSG, sparse matrix converter as a generator link to the grid side and MPPT controller based on OTC method. PMSG will supply power to the resistor load on the grid side. A small LC filter is added to the side of the grid to reduce harmonics due to the switching frequency of the converters.

The maximum output power of the generator is obtained by controlling the electromagnetic torque of the generator at the optimum point based on direct torque control strategy. In this method, the electromagnetic torque and the stator are regulated at reference values for maximum power. The reference stator flux ψ^*_s for maximum power is assumed to be equal to the permanent magnet flux ψ_f, while the reference torque for maximum power T^*_{opt} is obtained by validating the gain value K_o based on the wind turbine parameter, ie the maximum power coefficient value C_{pmax} and the optimum Tip Speed Ratio (TSR) value λ_{opt}, as shown in Fig. 1. Both ψ^*_s and T^*_{opt} are compared with the measured values, then and the error of these two parameters is regulated with PI controller to obtain the reference voltage for modulation of sparse matrix converter based on space vector modulation.

3.1. Permanent magnet synchronous generator model

MPPT strategy based on OTC for PMSG-wind turbine is applied with decoupled control of flux and torque in the rotating d-q reference frame. The dynamic model of PMSG in the rotating *d-q* reference frame can be written as :

$$v_d = R_s\ i_d - p\ \omega_m\ \psi_q + \frac{d\psi_d}{dt}$$
$$v_q = R_s\ i_q + p\ \omega_m\ \psi_d + \frac{d\psi_q}{dt} \tag{1}$$

with the *dq*-axis stator flux linkages ψ_d and ψ_q as follows :

$$\psi_d = L_d i_d + \psi_f \quad \text{and} \quad \psi_q = L_q i_q \tag{2}$$

The mechanical dynamics and the electromagnetic torque T_e of PMSG can be written as:

$$\frac{d\omega_m}{dt} = \frac{T_m - T_e - B\omega_m}{J} \tag{3}$$

$$T_e = 1.5\ p\left(\psi_d i_q - \psi_q i_d\right) \tag{4}$$

3.2. Horizontal wind turbine model

Based on the aerodynamic characteristics, The wind power captured by the turbine to drive the generator is determined by the blade radius R, the air density ρ and the power coefficient C_p, which is defined as the ratio of mechanical power P_m generated by the wind turbine to the wind power P_w captured by the wind turbine. The mechanical power P_m and the mechanical torque T_m generated by wind turbine to drive the PMSG can be written as :

$$P_m = P_w\ C_p = T_m\ \omega_m = 0.5\ C_p\ \rho\ \pi\ R^2\ v_w^3 \tag{5}$$

$$T_m = \frac{0.5\ C_p\left(\lambda\ \beta\right)\ \rho\ \pi\ R^2\ v_w^3}{\omega_m} \tag{6}$$

The power coefficient C_p is a function of the Tip Speed Ratio (TSR) λ and the pitch angle of blade β . TSR is defined as the ratio of the rotor turbine speed ω_m to the wind speed v_w [17], and can be written as :

$$\lambda = \frac{\omega_m\ R}{v_w} \tag{7}$$

In accordance with the characteristics of wind turbine, the mechanical power generated by the wind turbine varies at each wind speed and has a maximum point P_{max} . This maximum power point P_{max} is located at a different rotor speeds ω_m at each wind speed variation, as shown in Fig. 2(a). This maximum power point is the maximum power coefficient point C_{pmax} and the optimum TSR point λ_{opt} , as shown in Fig. 2(b).

Based on Equation (5) and the characteristics of the wind turbine in Fig. 2, the maximum mechanical power of wind turbine P_{max} can be expressed as :

$$P_{\max} = 0.5\ \pi\ \rho\ C_{p\max}(\lambda_{opt}, \beta)\ R^2\ v_w^3 \tag{8}$$

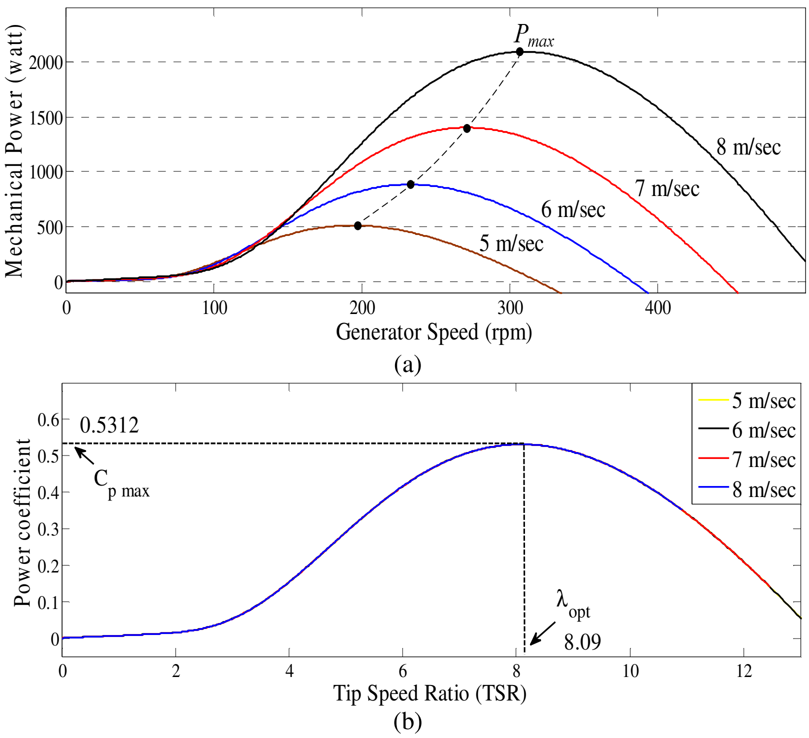


Fig. 2. Wind turbine characteristics

(a) Mechanical power versus rotor speed, (b) power coefficient versus TSR

To obtain maximum power at any wind speed variation, the generator speed must be adjusted to remain at the optimum TSR point λ_{opt}. The reference of rotor speed at maximum power point can be expressed as :

$$\omega_m{}^* = \frac{\lambda_{opt}}{R} v_w \tag{9}$$

3.3. Sparse matrix converter model

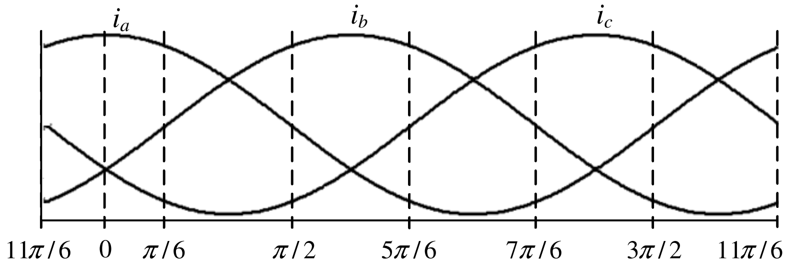
Sparse matrix converter is variant of indirect matrix converter with direct voltage and frequency conversion [2],[3] . This converter consists of the current source converters (CSC) with six bidirectional switches (S_{ap}, S_{bp}, S_{cp}, S_{an}, S_{bn}, S_{cn}) and the voltage source converters (VSC) with the same structure as the regular VSI (S_1, S_2, S_3, S_4, S_5, S_6), as shown in Fig. 1. The CSC stage and the VSC stage are separated by dc link without energy storage, so the modulation strategy becomes easier than direct matrix converter. This topology is functionally equivalent to a standard indirect matrix converter but has a reduced number of active switches [11]. The modulation of both the CSC and VSC switches are modulated using SVM with linear carrier method.

The switching strategy of the CSC switches are for generate the maximum dc-link voltage and keep unity input power factor [2]. At each switching state, only two switches are active, ie one positive switch S_{xp} and one negative switch S_{xn} with ($x = a, b, c$). The duty cycle of the CSC switches for each sector are calculated based on the input current vector as shown in Fig. 3. For example, the duty cycle for sector 1. The pair of switches conducting in sector 1 are (S_{ap} and S_{bn}) or (S_{ap} and S_{cn}). The duty cycle of the CSC switches for sector 1 in $\alpha\beta$ frame can be written as :

$$S_{bn} = d_{\alpha i} = -\frac{i_b}{i_a}, \quad S_{cn} = d_{\beta i} = -\frac{i_c}{i_a}, \quad \text{and} \quad S_{ap} = d_{\alpha i} + d_{\beta i} = 1 \tag{10}$$

According to Equation (10), the average voltage in the dc link is :

$$V_{dc} = d_{\alpha i} V_{\alpha i} + d_{\beta i} V_{\beta i} = 1.5\ V_{i\_\max} \tag{11}$$



Sector Switch	1	2	3	4	5	6
S_{ap}	$d_{\alpha i}+d_{\beta i}$	$d_{\alpha i}=-\frac{i_a}{i_c}$	0	0	0	$d_{\beta i}=-\frac{i_a}{i_b}$
S_{bp}	0	$d_{\beta i}=-\frac{i_b}{i_c}$	$d_{\alpha i}+d_{\beta i}$	$d_{\alpha i}=-\frac{i_b}{i_a}$	0	0
S_{cp}	0	0	0	$d_{\beta i}=-\frac{i_c}{i_a}$	$d_{\alpha i}+d_{\beta i}$	$d_{\alpha i}=-\frac{i_c}{i_b}$
S_{an}	0	0	$d_{\beta i}=-\frac{i_a}{i_b}$	$d_{\alpha i}+d_{\beta i}$	$d_{\alpha i}=-\frac{i_a}{i_c}$	0
S_{bn}	$d_{\alpha i}=-\frac{i_b}{i_a}$	0	0	0	$d_{\beta i}=-\frac{i_b}{i_c}$	$d_{\alpha i}+d_{\beta i}$
S_{cn}	$d_{\beta i}=-\frac{i_c}{i_a}$	$d_{\alpha i}+d_{\beta i}$	$d_{\alpha i}=-\frac{i_c}{i_b}$	0	0	0

Fig. 3. Switching strategy of the CSC switches

The switching status of the VSC switches are determined by the output voltage vector that are separated by 6 sectors, as shown in Fig. 4. Duty cycle of the VSC switches in $\alpha\beta$ frame can be written as :

$$d_{\alpha o} = M_o \sin\left(\frac{\pi}{3} - \theta_o\right), \quad d_{\beta o} = M_o \sin\left(\frac{\pi}{3}\right) \quad \text{and} \quad d_{0o} = 1 - d_{\alpha o} - d_{\beta o} \tag{12}$$

The output voltage angle θ_O and the modulation index M_o can be expressed as :

$$M_o = \frac{\sqrt{3}\ \sqrt{v_{o\alpha}^2 + v_{o\beta}^2}}{V_{dc}}, (0 \le M_o \le 1) \quad \text{and} \quad \theta_o = \tan^{-1}\frac{v_{o\beta}}{v_{o\alpha}} \tag{13}$$

The output voltages in $\alpha\beta$ frame ($v_{o\alpha}, v_{o\beta}$) are obtained from the output of torque controller.

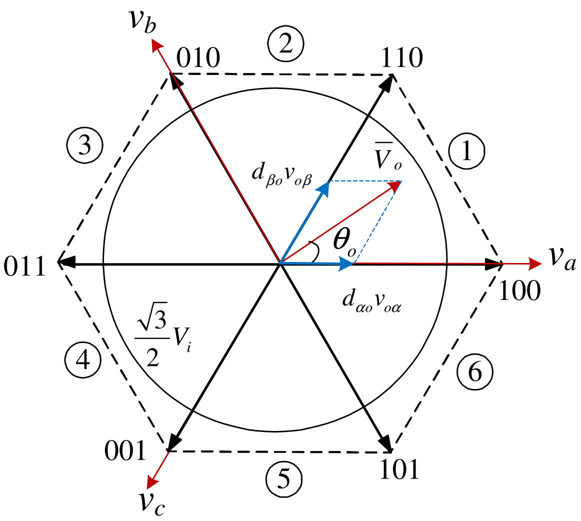


Fig. 4. Switching strategy of the VSC switches

One feature of smc is that the CSC stage is directly connected to the VSC stage. To avoid short circuit, the switching state of the CSC switches must be coordinated with the VSC switches. Note that the states change of the CSC switches always occurs during free-wheeling condition of the VSC switches. Fig. 5 shows the coordination between the CSC switches with the VSC switches for sector 1.

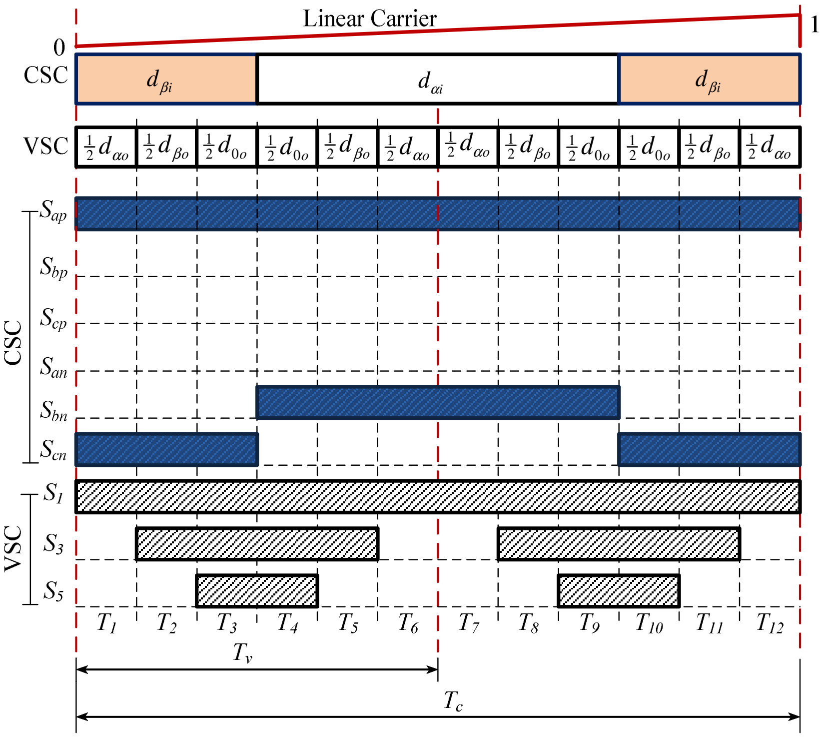


Fig. 5. The switching coordination between the CSC with the VSC for sector 1

Fig. 5 shows that each switching period of the CSC switches T_c, there are two switching period of the VSC switches T_v, and then one switching period of the CSC switches divided into 12 switching times with the following equation :

$$\begin{aligned} &T_1 = T_{12} = 0.5\, d_{\beta i}\; d_{\alpha o} && T_4 = T_9 = 0.5\, d_{\alpha i}\; d_{0o} \\ &T_2 = T_{11} = 0.5\, d_{\beta i}\; d_{\beta o} && T_5 = T_8 = 0.5\; d_{\alpha i}\; d_{\beta o} \\ &T_3 = T_{10} = 0.5\, d_{\beta i}\; d_{0o} && T_6 = T_7 = 0.5\; d_{\alpha i}\; d_{0o} \\ &T_c = T_1 + T_2 + \ldots + T_{12} = 1 && \end{aligned} \tag{14}$$

4. Optimum Torque Control Strategy

The optimum torque control (OTC) is one of the MPPT method based on a mechanical torque parameter as reference of the controller. The main idea of this method is to control the mechanical torque of the wind turbine at the optimum point, wich was located at the maximum power point. Fig. 6 shows the mechanical torque characteristics of the wind turbine. The values of the mechanical torque will vary according to changes in wind speed and rotor speed. The value of mechanical torque at maximum power is called the optimum point. When the mechanical torque is at optimum point, generator will rotate at the reference speed for maximum power. According to the Equation (6), the optimum mechanical torque can be written as :

$$T_{opt}^{*} = K_o\ \omega_m^2 \qquad \text{with} \quad K_o = 0.5\rho A C_{p\max}\left(\frac{R}{\lambda_{opt}}\right)^3 \quad \text{and} \quad A = \pi R^2 \tag{15}$$

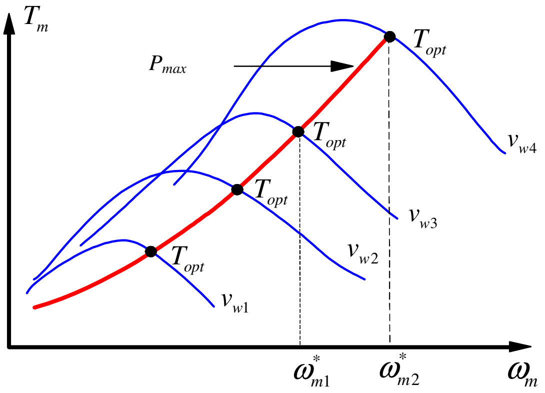


Fig. 6. The mechanical torque curve of the wind turbine

Maximum power control using OTC is done with DTC based SVM approach. In this method, the stator flux linkage and electromagnetic torque are regulated by using PI controller to obtain the reference voltages for modulation of the VSC switches, as shown in Fig. 1. The *dq*-axis reference voltages for modulation the VSC switches can be written as :

$$v_{od}^{*} = \left(K_p + \frac{K_i}{s}\right)\left(\psi_s^{*} - \psi_s\right) \tag{16}$$

$$v_{oq}^{*} = \left(K_p + \frac{K_i}{s}\right)\left(T_e^{*} - T_e\right) \tag{17}$$

The estimated electromagnetic torque T_e is obtained from Equation (4), while the reference electromagnetic torque T_e^{*} can be calculated from Equation (3) and (15), which can be expressed as :

$$T_e^* = T_{opt}^* - J\frac{d\omega_m}{dt} - B\omega_m \tag{18}$$

The reference of stator flux linkage ψ_s^* is assumed equal to the flux linkage of permanent magnet ψ_f, while the estimated stator flux linkage ψ_s and the estimated rotor position θ_ψ can be calculated based on Equation (2), which can be expressed as :

$$\psi_s = \sqrt{\psi_d^2 + \psi_q^2} \quad \text{and} \quad \theta_\psi = \tan^{-1}\frac{\psi_q}{\psi_d} \tag{19}$$

Based on Equation (16)-(19), the reference voltages in *αβ* frame ($v_{o\alpha}, v_{o\beta}$) for modulation the VSC switches can be expressed as :

$$\begin{bmatrix} v_{o\alpha}^* \\ v_{o\beta}^* \end{bmatrix} = \begin{bmatrix} \cos(\theta_\psi) & -\sin(\theta_\psi) \\ \sin(\theta_\psi) & \cos(\theta_\psi) \end{bmatrix} \begin{bmatrix} v_{od}^* \\ v_{oq}^* \end{bmatrix} \tag{20}$$

Then, sparse matrix converter will adjust the stator voltage of PMSG through the VSC stage according to the reference voltage in (19), so that the PMSG will be operated at optimum point of the electromagnetic torque and make the generator output power to maximum.

5. Simulation Results

The proposed OTC for MPPT control of direct driven WECS in Fig. 1 is verified by simulation with parameters are listed in Table 1. The proposed WECS uses PMSG driven by a horizontal wind turbine. The PMSG is connected to the grid through sparse matrix converter. The proposed OTC is applied to regulate the electromagnetic torque of PMSG at optimum point using SVM-based DTC approach. The proposed system are simulated with variable wind speed, as shown in Fig. 7(a).

Table 1. Simulastion Parameters

Components	unit	Parameters
PMSG	Stator resistance (R_s)	0.5 Ω
	Stator inductance ($L_d = L_q$)	8.5 mH
	Pole pair numbers (n_p)	18
	Flux of permanent magnet (ψ_m)	0.23 Wb
	Momen of inertia (J)	0.075 kg m^2
	Friction coefficient (B)	0.005 N.m.s/rad
Wind turbine	Blade radius (R)	2 m
	Maximum power coefficient (C_{pmax})	0.5312
	Optimum TSR (λ_{opt})	8.09
Grid	Resistive load (R_L)	2 kW
	Voltage (V_i)	380 V
	Frequency	50 Hz

Fig. 7 shows the performances of the proposed OTC system using SMC. Fig. 7(a) shows that wind speeds vary from 4.2 m/sec to 7.8 m/sec. Fig. 7(b) shows that the electromagnetic torque T_e of PMSG can follow the reference value T_e^*, which is the optimum mechanical torque of the wind turbine to obtain maximum power. This shows that the OTC design with the SVM-based DTC approach has been able to regulate the electromagnetic torque at the optimum point, so that the generator operates at the point of maximum power. One of the advantages of OTC is to provide a smooth torque response, as shown in Fig. 7(b). The reliability of the proposed OTC system can also be seen from the rotor speed response, where the generator speed ω_m corresponding to the reference speed ω_m^* for maximum power, as shown in Fig. 7(c). The reference speed ω_m^* for maximum power is obtained from Equation (16). Due to the smooth torque response of the OTC, the rotor speed also has a smooth response. This makes the generator output power also has a smooth response, as shown in Fig. 8(a).

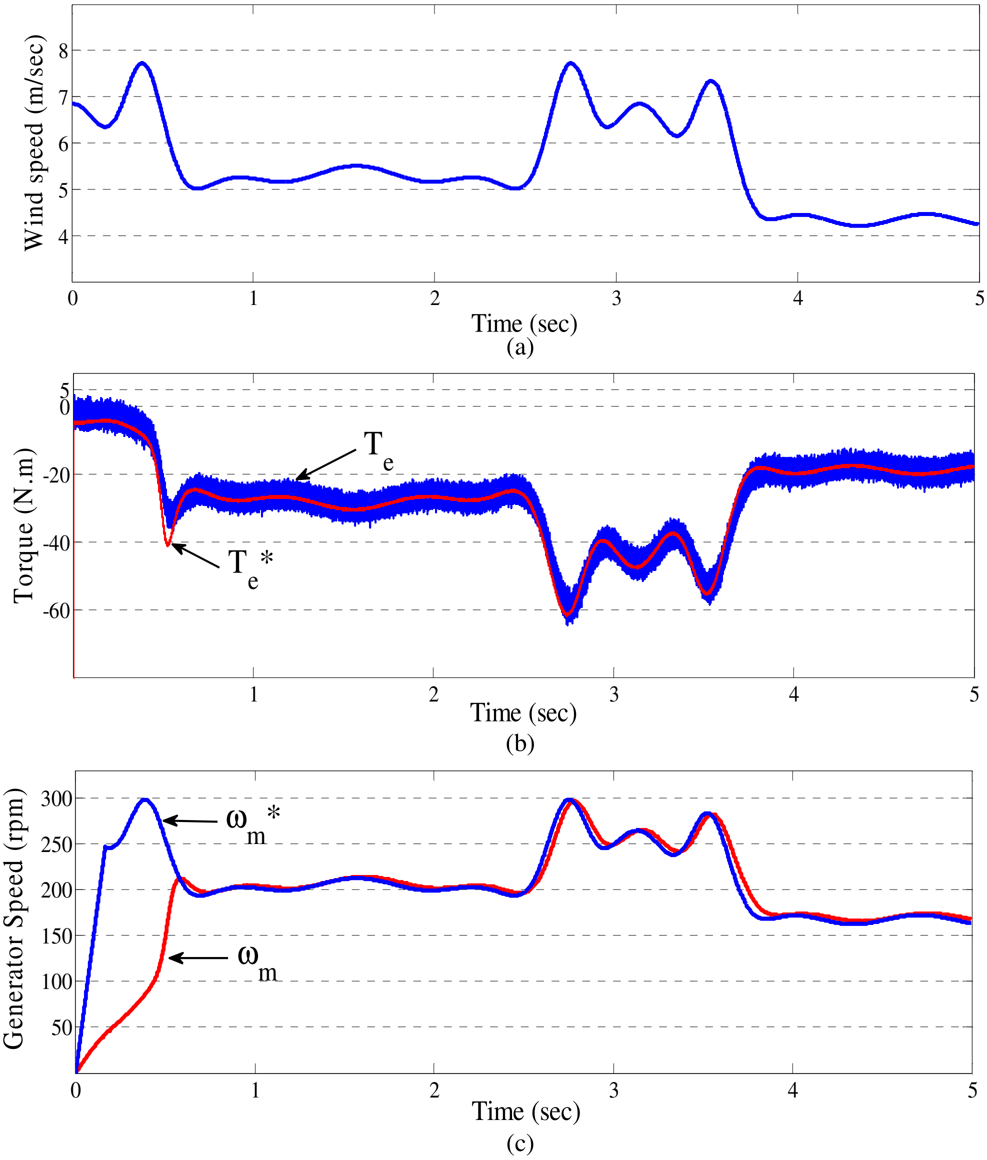


Fig. 7. The performances of the OTC
(a) Wind speed, (b) electromagnetic torque, (c) generator speed

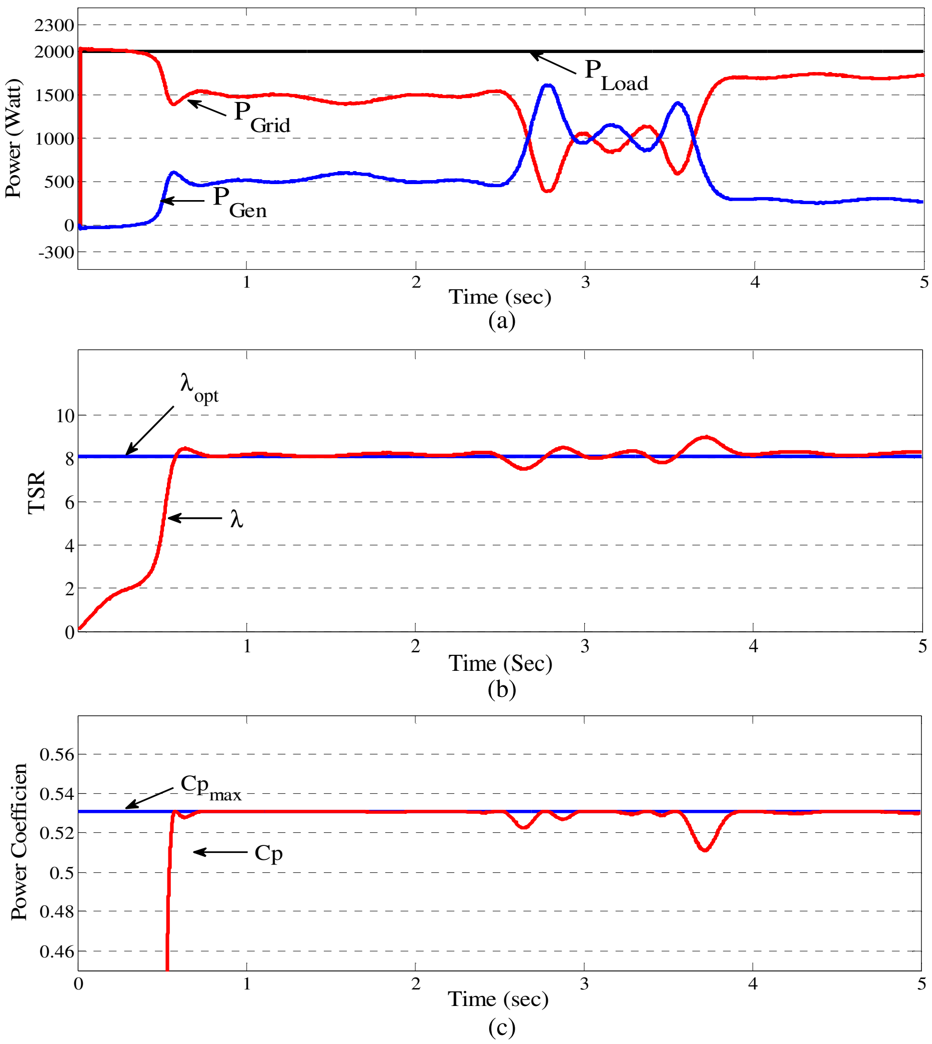
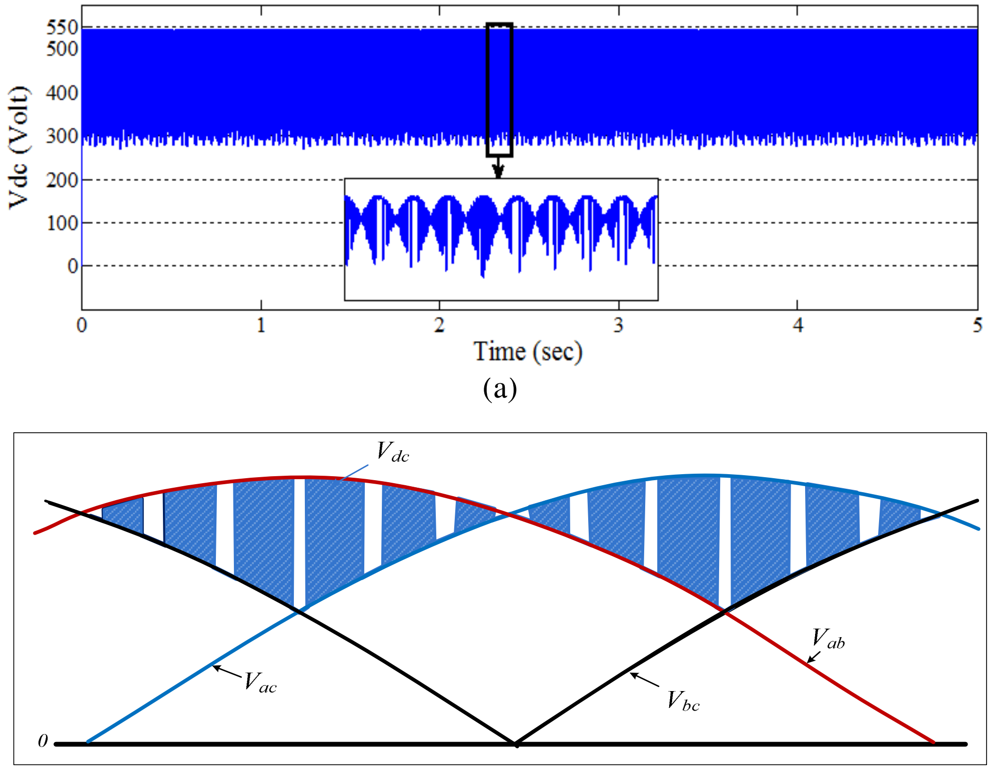


Fig. 8. The performances of the WECS
(a) Power, (b) TSR, (c) power coefficient

WECS is designed to connect with the grid and supply a constant resistor load 2 kw, as shown in Fig. 1. Resistor loads will be supplied from WECS and the grid. Fig. 8(a) shows the generator power P_{Gen}, grid power P_{Grid} and load power P_{Load}. Generator power varies according to wind speed change. When the wind speed is high, the generator power becomes large and the power delivered from the generator to the resistor load is higher than the power delivered from the grid. This can be seen when the wind speed 7.8 m/sec at the simulation time of 2.7 seconds. Likewise, when the wind speed is low, the resistor load is more supplied from the grid. This shows that SMC has been able to control the power distribution from the generator to the grid in accordance with its function.

The generator power P_{Gen} in Fig. 8(a) is the maximum power from PMSG at any wind speed variation. This can be proved from the graph of power coefficients and TSR, as shown in Fig. 8(b) and 8(c). TSR of the wind turbine remains at the optimum point of 8.09 and the wind turbine coefficient remains around the maximum point of 0.5312 although wind speed varies. This indicates that WECS operates at the maximum power point. Maximum error of TSR and power coefficients occurs only when the wind speed changes in the extreme at the time of 2.5 seconds to 3.8 seconds. These results indicate that the MPPT strategy using the OTC method has been able to regulate the generator power around the maximum point, although the wind speed changes.



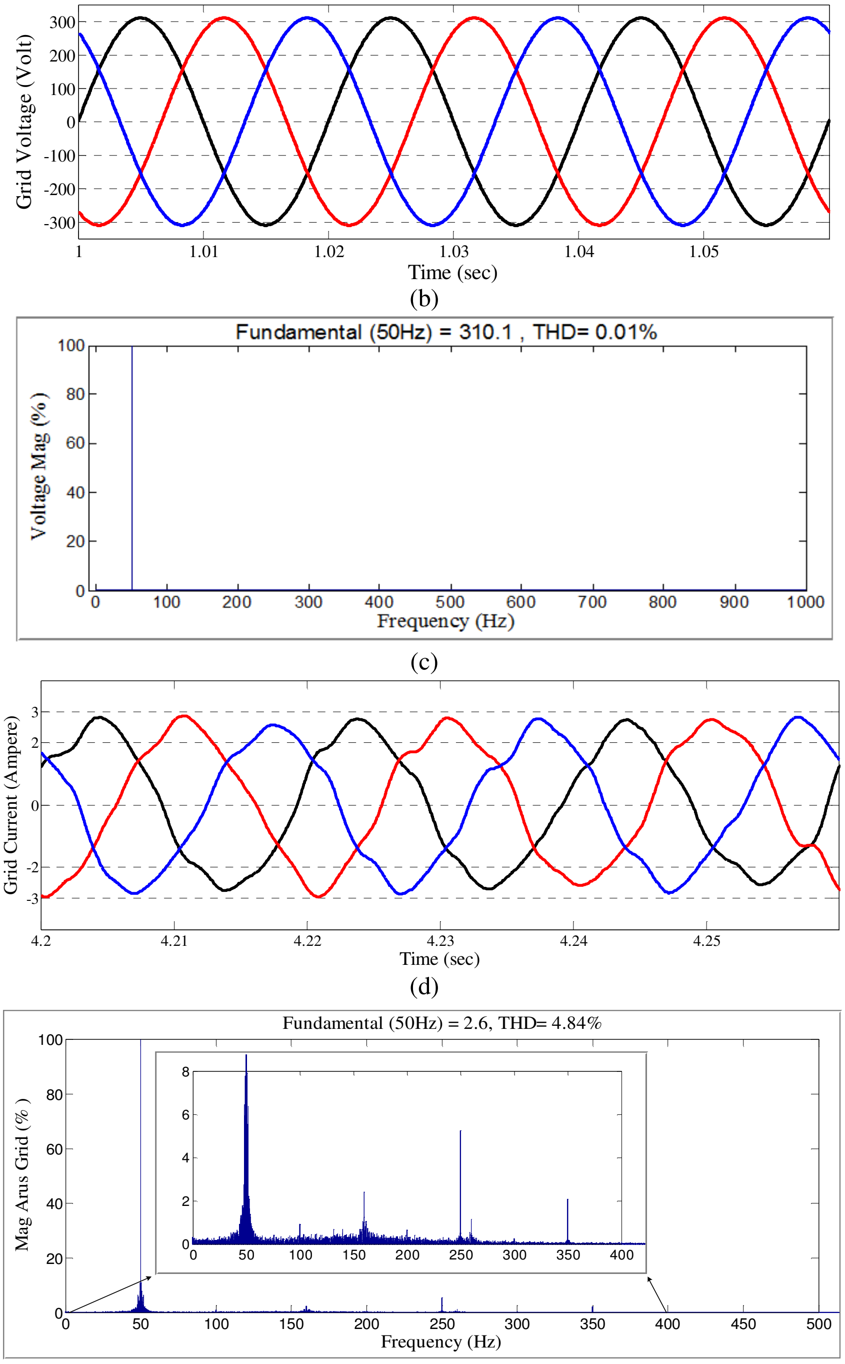
(a)

(b)

Fig. 9. DC link voltage of sparse matrix converter.
(a) DC link voltage, (b) Pattern of DC link voltage

The use of sparse matrix converter has also provided a good performance for the WECS. The modulation strategy using linear carrier SVM has produced maximum DC-link voltage, as shown in Fig. 9 (a). The CSC stage of SMC's modulation index is set 1, so the maximum value of dc link voltage which is the output of the CSC stage is the maximum value of the line to line voltage of the input. Fig. 9(b) shows the dc link voltage pattern, where the maximum value of dc link voltage is at the maximum value of line to line voltage of input (V_{ab}, V_{bc}, V_{ac}). Due to the zero-voltage vector cancellation in CSC modulation, the DC-link voltage does not consist of the zero voltage level, as shown in Fig. 9(a).

The use of a power converter on the WECS will cause serious power quality problems due to the switching frequency of the converter. The purpose of using sparse matrix converter to improve the power quality of the WECS, according to the characteristics of the matrix converter which has better power quality compared to conventional back to back converter. The matrix converter can provide sinusoidal waves on both sides of the converter This objective has been achieved by obtaining sinusoidal currents and voltages at the grid side, as shown in Fig. 10(a) and 10(c). By adding a small LC filter, the Total Harmonic Distortion (THD) of the grid voltage only 0.01%, while the grid current THD only 4.84%, as shown in Fig. 10(b) and 10(d). This shows that the use of sparse matrix converter has been able to improve the power quality of the WECS. All the simulation results of the proposed system are in line with the objectives. OTC based MPPT control system has been able to regulate generator output power around the maximum point and SMC usage has also resulted in excellent power quality for WECS.



(b)

(c)

(d)

(e)

Fig. 10. The performances of a sparse matrix converter, (a) Grid voltage, (b) THD of grid voltage, (c) grid current, (d) THD of grid current

6. Conclusion

The proposed OTC to obtain maximum power of the WECS has been discussed. In this method, the maximum power is achieved by regulating the electromagnetic torque of generator at optimum point using SVM-based DTC approach. The optimum torque point is sought using wind turbine parameters. The simulation results show that the proposed system has been able to control the generator output power at its maximum point, although the wind speed changes. The use of SMC has also given an excelent result in improving the power quality of WECS with low THD of grid currents and grid voltages.

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References

[1] M. Yuhendri, M. Ashari, and M.H. Purnomo, Maximum output power tracking of wind turbine using inteligent control approach, *Telkomnika*, 9(2), 217-226, 2011.

[2] M. Yuhendri, M. Ashari, and M.H. Purnomo, A novel sensorless MPPT for wind turbine generators using very sparse matrix converter based on hybrid inteligent control, *International Review of Electrical Engineering*, 10(2), 233-243, 2015.

[3] M. Yuhendri, M. Ashari, and M.H. Purnomo, Adaptive type-2 fuzzy sliding mode control for grid-connected wind turbine generator using very sparse matrix converter, *International Journal of Renewable Energy Research*, 5(3), 668-676, 2015.

[4] A. Lebsir, A. Bentounsi, M. E. H. Benbouzid and H. Mangel, Electric generators fitted to wind turbine systems: an up-to-date comparative study, *Journal of Electrical Systems*, 11(3), 281-285, 2015.

[5] Z. Zhang, Y. Zhao, W. Qiao and L. Qu, A Space-Vector Modulated Sensorless Direct-Torque Control for Direct-Drive PMSG Wind Turbines, *IEEE Transactions on Industry Applications*, 50(4), 2331 – 2341, 2014.

[6] M. Wang, Y. Hu, W. Zhao, Y. Wang and G. Chen, Application of modular multilevel converter in medium voltage high power permanent magnet synchronous generator wind energy conversion systems, *IET Renewable Power Generation*, 10(6), 824 – 833, 2016.

[7] M. Yuhendri, Ahyanuardi, and Aswardi, Direct Torque Control Strategy of PMSM Employing Ultra Sparse Matrix Converter, *International Journal of Power Electronic and Drive System*, 9(1), 133-143, 2018.

[8] M. Aner and E. Nowicki, Two-level backward operation of a VSMC for PMSG grid-connected variable speed wind turbine systems, *Proceeding of IEEE International Electric Machine & Drives Conference,* 1100–1106, 2011.

[9] V. Yaramasu, A. Dekka, M.J. Durán, S. Kouro, B. Wu, PMSG-based wind energy conversion systems: survey on power converters and controls, *IET Electric Power Applications*, 11(6), 956–968, 2017.

[10] R. Melício, VMF. Mendes and J.P.S. Catalao, Comparative study of power converter topologies and control strategies for the harmonic performance of variable speed wind turbine generator system, *Energy*, Vol. 36, hal. 520-529, 2011.

[11] JW. Kolar, T. Friedli, J. Rodriguez and PW. Wheeler, Review of three-phase PWM ac–ac converter topologies*"*, *IEEE Transaction on Industrial Electronic*, 58(11), 4988-5006, 2011.

[12] M. Yuhendri, M. Ashari, and M.H. Purnomo, "Linear quadratic regulator design for modular matrix converter using genetic algorithm," *Proceeding of 3rd International Conference on Communication Software and Networks*, 175-179, 2011.

[13] M.A. Abdullah., A.H.M. Yatim, C.W. Tan and R. Saidur, A review of maximum power point tracking algorithms for wind energy systems, *Renewable and Sustainable Energy Reviews*, 16, 3220-3227, 2012.

[14] B. Jain, S. Jain and RK. Nema, Control strategies of grid interfaced wind energy conversion system: an overview, *Renewable and Sustainable Energy Reviews*, 47, 983–996, 2015.

[15] M. Nasiri, J. Milimonfared and S.H. Fathi, Modeling, analysis and comparison of TSR and OTC methods for MPPT and power smoothing in permanent magnet synchronous generator based wind turbines, *Energy Conversion and Management*, 86, 892–900, 2014.

[16] S. Ganjefar, A. A. Ghassemi and M. M. Ahmadi, Improving efficiency of two-type maximum power point tracking methods of tip-speed ratio and optimum torque in wind turbine system using a quantum neural network, *Energy*, 67, 444–453, 2014.

[17] Y. Zhu, M. Cheng, W. Hua and W. Wang, A novel maximum power point tracking control for permanent magnet direct drive wind energy conversion systems, *Energies*, *5*, 1398-1412, 2012.

[18] S. Lalouni, D. Rekioua, K. Idjdarene and A.M. Tounzi, An improved MPPT algorithm for wind energy conversion system, *Journal of Electrical Systems*, 10(4), 484-494, 2014.

[19] C. Wei, Z. Zhang, W. Qiao and L. Qu, An adaptive network-based reinforcement learning method for MPPT control of PMSG wind energy conversion systems, *IEEE Transactions on Power Electronics*, 31(11), 7837 – 7848, 2016.