



A Direct Torque Control Method for CSC Based PMSG Wind Energy Conversion Systems

Nazanin Abdolghani*† Jafar Milimonfared* Gevorg B. Gharehpetian*

*Amirkabir University of Technology (Tehran Polytechnic),
Center of Excellence in Power Systems, No. 424, Hafez Ave., Tehran 15914, Iran.

† Corresponding author: ms_nazy@aut.ac.ir

Abstract— The Current Source Converter (CSC) technology is well suited for high power wind energy applications. Because it drives generally features like simple converter structure, smooth power injection at the grid side and excellent short circuit protection. The main drawback lays its dynamic torque response. An improved Direct Torque Control (DTC) method is proposed in this paper to overcome this drawback. Using DTC method for Permanent Magnet Synchronous Generators (PMSG) in a wind energy system has some advantages such as, simple control system and topology, ease of tracing Maximum available power from the wind and flux weakening control in high wind speeds. The simulation results demonstrate the effectiveness of the proposed control system, good dynamic response and acceptable MPPT capability.

Keywords—Direct Torque control Control (DTC), PMSG, current source converter (CSC), wind energy conversion system.

I. INTRODUCTION

Increasing power capacity of wind turbines is the trend of wind energy through reducing cost of generated electricity. Most recently wind turbine generators are in the power range of 1.5-5MW [1]. In high power wind energy applications, a direct driven PMSG has been proved to be a good choice because of its low maintenance cost; complete decoupling from the grid, wide operation rang [2].

Since a wind power generation system with PMSG use a full capacity converter as interface between the generator and the grid, variable-speed generation can be employed and maximum available power from the wind can be traced. Actually MPPT control adjusts the generator speed to best suit the wind speed for the reason of tracing maximum available power from the wind, this control in wind farms is one of the most important goals and gives a speed reference for the generator control system. For calculating the optimum

speed, many researchers have been used wind speed information [3], some estimation methods need to have the wind turbines parameters [3], on the other hand there are some methods which do not need to utilize wind speed information and wind turbine parameters like them have investigated in [4].

Typically for adjusting the optimum speed, a current control method in the rotating reference frame is developed [2],[5], in these cases a vector control method is employed for adjusting the generator speed when wind speed changes. In [6] a dc chopper is designed in dc link and MPPT control is investigated by adjusting duty cycle of the switches.

In wind energy systems, fast speed response for tracing maximum power is very important. In proposed control system, for adjusting the speed, DTC method will be used. DTC for PMSG have studied in several works [7],[8]. When DTC is compared with other control strategies it has some advantages such as: it is not necessary to know machine parameters except armature resistance, sensing rotor position is not necessary, there is a look up table for switching which makes control system simple.

When DTC method control is employed in a wind power generation system, there are some other advantages compare with other type of control systems such as: 1- Since there is a torque reference as input for control system, this control method is well suit to MPPT control and this is because MPPT control can be implemented by controlling the generator torque without measuring the wind speed [7].

2- Because of existing separate control on stator flux, in high wind speed the generating power can be limited easily.

3- Since there is no current control loop, the speed response is faster than vector control.

For a high power wind energy system with a direct driven PMSG, the CSC is proposed in [2], [9]. Using CSC for the defined system was proved to be a good choice because of its simple topology, super protection against short circuit faults, excellent grid integration

performance such as: smooth power at grid side and fully power factor control.

As shown in fig.1, proposed topology consists of a variable speed wind turbine, PMSG and a CSC as a bridge between the generator and the grid. The converter consists of a generator-side, a grid-side and filter capacitors at both sides to assist current commutation as well as filter out switching harmonics. The operation of CSC needs a constant current source at DC link which could be maintained by either the generator –side or the grid-side converter. Typically the grid-side converter controls the DC link current on the assumption of a stiff grid [10]. Since this paper mainly focuses on the generator side converter control, it is assumed there is a constant current source at DC link.

II. SYSTEM CONTROL SCHEME

In a variable speed wind energy system, the generator speed is adjustable for the reason of tracing maximum available power from the wind which is named MPPT control. MPPT control can be summarized as turbine-generator speed control and it is widely studied in previous works [3]. Mainly Two control functions are implemented on the generator side: one is MPPT control and the other one is optimization of generator operation.

Fig.2 illustrates block diagram of DTC method. The basic idea of direct torque control implemented in PMSG is to choose the appropriate stator current vector out of nine possible converter states, according to the difference between the reference and actual torque and flux linkage values. As a result the stator flux linkage vector rotates along the stator reference frame trajectory and products the desired torque. It should be noted that the symbols used in the following, α and β correspond to the stationary frame and d and q subscriptions denoted d -axis and q -axis of the selected synchronous frame respectively.

A. Flux and torque estimation

The α - and β -axis stator flux linkage is estimated by the following equations:

$$\psi_\alpha = \int (v_\alpha - R_a i_\alpha) dt + \Psi_{\alpha 0} \quad (1)$$

$$\psi_\beta = \int (v_\beta - R_a i_\beta) dt + \Psi_{\beta 0} \quad (2)$$

$$\Psi_s = \sqrt{(\psi_\alpha^2 + \psi_\beta^2)} \quad (3)$$

$$\theta_s = \tan^{-1} \left(\frac{\psi_\beta}{\psi_\alpha} \right) \quad (4)$$

v_α and v_β are the terminal voltages, i_α and i_β are armature currents, both in stationary frame, R_a is armature

resistance. Ψ_s is estimated stator flux linkage and θ_s is the estimated position of the stator flux linkage vector which is the angular difference between the stator flux-linkage vector and α -axis.

Since in the steady state operation, velocity of the generator corresponds to velocity of the stator flux, the estimated position of the stator flux can be used to determine the generator speed. Actually the estimated generator speed, ω_g , is calculated, using a subtraction over time of estimated position of the stator flux. In the proposed system, reference currents are used for flux estimation instead of armature currents.

The estimated electromagnetic torque T_g is calculated as below:

$$T_g = P_n (\varphi_\alpha i_\beta - \varphi_\beta i_\alpha) \quad (5)$$

Where P_n is the number of pole pairs.

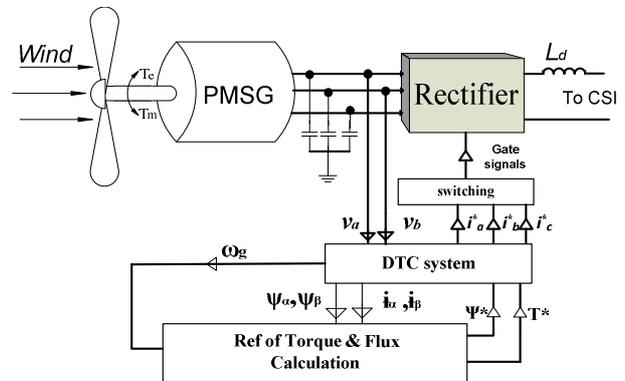


Fig.1. configuration of PMSG wind energy conversion system using CSC

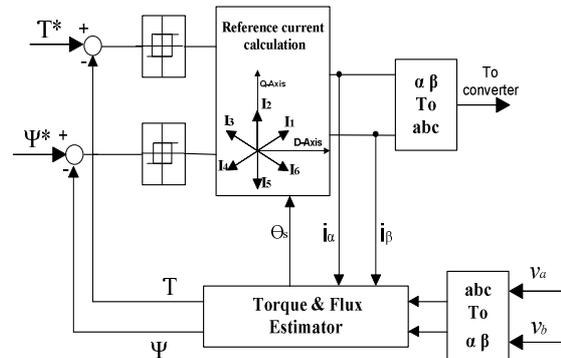


Fig.2. block diagram of the DTC system

III. CONTROL METHOD

Block diagram of calculating reference values are shown in fig.3. The torque reference is calculated so as maximize the generator output power, mainly related to the Armature current and the flux reference is calculated so as minimize losses and flux weakening control, mainly related to terminal voltages.

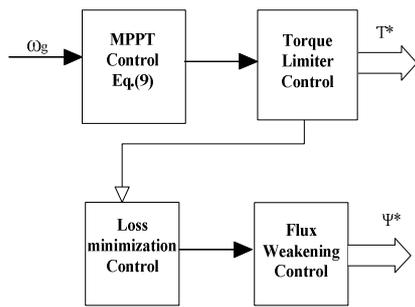


Fig.3. Block diagram of calculation of reference values

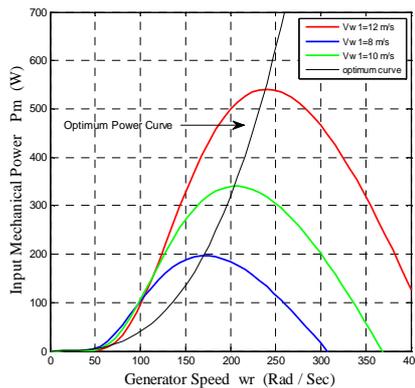


Fig.4. power of wind turbine versus generator speed at various wind speeds characteristic

A. Torque reference calculation

Torque reference is calculated base of achieving MPPT control. Figure.4 shows a mechanical input power versus generator speed curve at various wind speeds. This figure indicates that the input mechanical power from turbine is functions of wind speed and the generator speed. The optimum operating point obtaining the maximum speed. In the optimum points, the generator speed is proportional to the wind speed as (6), moreover the maximum mechanical power and optimum torque power can be measured by wind speed as bellow: [4]

$$\omega_{opt} = K_w V_w \quad (6)$$

$$T_{opt} = K_t V_w^2 \quad (7)$$

$$P_{m-max} = K_p V_w^3 \quad (8)$$

Where K_w , K_t and K_p are constants determined by the wind turbine characteristics. When the generator speed is always controlled at the optimum speed, MPPT is investigated. The maximum power point in various wind speeds can also investigate by tracking optimum torque measured by: [4]

$$T_{opt} = \frac{K_t}{K_w^2} \omega_{opt}^2 = K_{opt} \omega_{opt}^2 \quad (9)$$

In proposed paper MPPT is achieved by controlling the generator torque on the optimum curve according to the generator speed as (9).

B. Flux reference calculation

The generator losses consist of mechanical, copper and iron losses. The mechanical loss is speed dependent and not controllable. Fig.5 shows the d- and q-axis equivalent circuits of PMSG in the d-q coordinate which rotate synchronously with an electrical angular velocity ω_g .

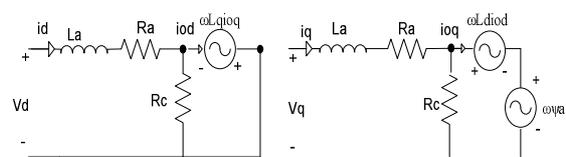


Fig.5. d-axis and q-axis equivalent circuits of PM generator

The equivalent circuit includes the effect of copper and iron losses; R_a represents the armature copper losses. The iron losses consists of hysteresis and eddy current which is represented by R_c . the copper and iron losses are expressed as:

$$W_{cu} = R_a (i_d^2 + i_q^2) = R_a \left\{ \left(i_{od} - \frac{\omega L_q i_{oq}}{R_c} \right)^2 + \left(i_{oq} + \frac{\omega (L_d i_{od} + \psi_f)}{R_c} \right)^2 \right\} \quad (10)$$

$$W_{fe} = R_c (i_{cd}^2 + i_{cq}^2) = \frac{\omega^2 (L_q i_{oq})^2}{R_c} + \frac{\omega^2 (\psi_f + L_d i_{od})^2}{R_c} \quad (11)$$

The electrical losses are given by:

$$W_E = W_{cu} + W_{fe} \quad (12)$$

W_E is a function of i_{od} , i_{oq} and ω_g .

The variable of i_{oq} in these equations can be canceled by:

$$T = P_n i_{oq} (\psi_f + (L_q - L_d) i_{od}) \quad (13)$$

As a result W_E can be expressed as a function of i_{od} , T and ω_g . In the steady state operation where the speed and torque are constants, the condition of minimizing electrical losses can be derived by differentiating W_E given as a function of i_{od} , T and ω with respect to i_{od} and equating the derivatives to zero. As a result, the loss minimization condition is given by [12]:

$$AB = T^2 C \quad (14)$$

Where

$$A = P_n^2 (R_a R_c^2 i_{od} + \omega^2 L_d (R_a + R_c) (L_d i_{od} + \psi_f))$$

$$B = \{ \psi_f + (L_d - L_q) i_{od} \}^3$$

$$C = R_a R_c^2 + (R_a + R_c) (\omega L_q)^2 (L_d - L_q)$$

In steady state operation when T and ω are constant, optimum value of i_{od} can be calculated by (14). The optimum value of flux in order to minimize the machine losses are derived by:

$$\psi_s = \sqrt{\left(L_q \frac{T}{P_n(\psi_f + (L_d - L_q)i_d)}\right)^2 + (L_d i_d + \psi_f)^2} \quad (15)$$

The optimal flux value is used as flux reference for the control system.

C. Limit values calculation

Terminal voltages and armature currents of the generator must be remain within limit values for the reason of generator and converter security. Limit values are defined by manufactures. In the proposed control system for achieving voltage and current security, torque and flux limits are calculated and they are applied to the control system.

1) Torque limit:

For wind speeds higher than rated speed, MPPT control can no longer be used due to current limiting of generator and converter. Equation (16) shows the situation when armature currents reach the limiting value.

$$\sqrt{i_q^2 + i_d^2} = I_{am} \quad (16)$$

Stator flux can be calculated as bellow:

$$\psi_s = \sqrt{(L_q i_q)^2 + (L_d i_d + \phi_f)^2} = \sqrt{L_q^2 (I_{am}^2 - i_d^2) + (L_d i_d + \phi_f)^2} \quad (17)$$

By substituting i_q from (16) and i_d from (17) into (13) the limit value of torque can be measured .The

torque limit is a function of stator flux and current maximum allowable value.

2) Flux limit

For wind speeds which make the voltages of generator exceed limiting value, flux-weakening control is applied. This control allows the generation system to operate even at high speeds. Equation (18) shows the situation when the terminal voltage reaches the limiting:

$$\sqrt{v_q^2 + v_d^2} = V_{am} \quad (18)$$

Where V_{am} is the limiting value of the terminal voltage, v_q and v_d are the terminal voltages in synchronous frame. In the steady state operation, on the assumption of $R \approx 0$ the stator voltages in synchronous frame are measured as:

$$v_q = \omega(L_d i_d + \phi_f) \quad (19)$$

$$v_d = -\omega(L_q i_q) \quad (20)$$

Substituting (19) and (20) into (18), yields the limiting value of stator flux-linkage for the case of $V_a = V_{am}$ as:

$$\psi_{s-max} = \frac{V_{am}}{\omega_r} \quad (21)$$

D. Control modes

Table I shows definition of control modes in addition to the association between wind speeds. Cut-in wind speed is 3m/s and there is no power generating bellows it. For wind speeds within 3 and 7 m/s, MPPT and loss minimization control methods is applied, for wind speeds within 7 and 10 m/s flux weakening method is used for control system because of voltage security. For wind speeds above 10 m/s, MPPT control is no longer applied because of current security. In this condition limit value of torque is used as torque reference.

TABLE I.
DEFINITION OF CONTROL MODES

Mode Definition				
	Mode 0	Mode I	Mode II	Mode III
Control Method	-	MPPT & loss Minimization	MPPT & Flux Weakening	Torque limiting & Flux weakening
Generator Condition	$V_a=0$ $I_a=0$	$V_a < V_{am}$ $I_a < I_{am}$	$V_a = V_{am}$ $I_a < I_{am}$	$V_a = V_{am}$ $I_a = I_{am}$
	0	1	2	3
	4	5	6	7
	8	9	10	11
	12			

IV. SIMULATION RESULTS

Simulations are carried out using MATLAB/simulink to investigate the model

performance. Proposed system is derived by a wind turbine model provided by equation [17]. The turbine receives wind speed and makes a mechanical power as

shown in fig.4 which drives the generator. Table II lists parameters of the wind turbine which is used in this study. The AC output of PMSG is converted to DC by IGBT rectifier which is completely consumed by load. Table III lists the parameters for the proposed generator and limit values. The limiting voltage corresponds to maximum terminal voltage. The limiting current is determined from the maximum available current in DC link. In order to evaluate transient performance of the proposed control system, wind speed is varied in the range of 1 to 11 m/s as shown in fig.6. Fig.7 demonstrates changing of the generator speed, it can be seen that the generator speed tracks wind speed accurately. For wind speeds above nominal value (Mode III) the generator speed stays at nominal value.

TABLE II.
PARAMETERS OF WIND TURBINE

Type	Variable speed type
Air Density ,	2.065
Turbine Radius, m	0.74
Rated Power, MW	2
Cut-in wind speed, m/s	3
Nominal wind speed, m/s	10
Optimum coefficient (Kopt), Nm/(rad/s) ²	1.6×10^{-5}

TABLE III.
PARAMETERS OF THE GENERATOR

Type	Variable speed
Rated voltage , V	280
Rated current ,A	30
Rated Power, KW	9
Rated Generator speed ,(rad/s)	130
D-axis inductance ,(mH)	0.79
Q-axis inductance ,(mH)	0.79
Number of pole pairs	6
Armature Resistance , Ω	0.05
Iron losses Resistance , Ω	240

The machine torque curve is shown in fig.8. As discussed before, for tracing Maximum available power from the wind, the machine torque should follow the optimal torque curve based on (9). This figure shows that the control system makes this happen appropriately. Optimum torque curve is tracked until maximum allowable current happens at turning point. After this

specific point, as wind speed increases the torque decreases and so the stator currents remain constant at maximum allowable value.

In order to verify output maximization performance of the proposed control system, power characteristic of wind turbine at various wind speeds, mechanical input power to the generator and optimum power curve, all versus shaft speed are shown in fig.9.

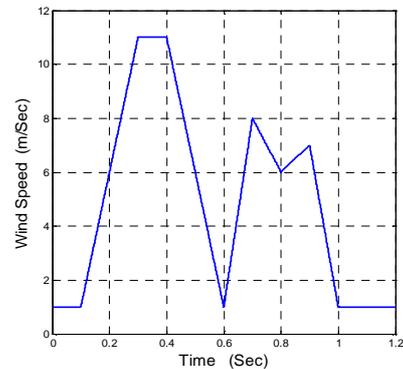


Fig.6. wind speed pattern used for evaluation

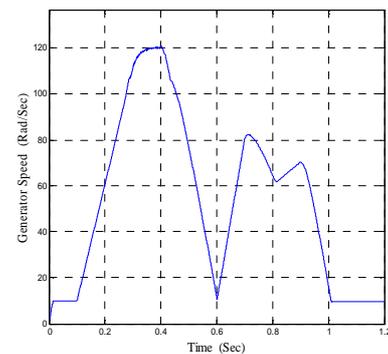


Fig.7. generator speed

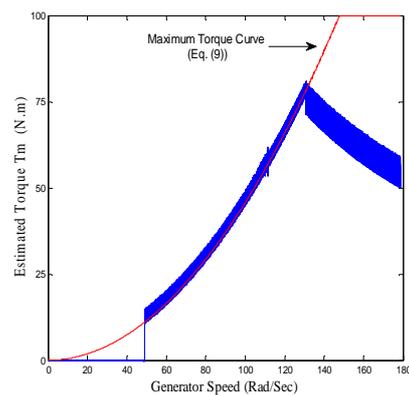


Fig.8. torque trajectory

As it can be seen, below the nominal wind speed, power follows the optimal power curve and maximum available power from the wind is captured, for wind speeds higher than nominal wind speed value, a constant power is obtained. This constant value for power relates to the limit values of current and voltage.

Fig.10 shows steady state characteristics of the generator torque vs. wind speed. MPPT method control is applied until nominal wind speed (10 m/s), in normal operation because of tracing Maximum available power from the wind, the generator torque increases as well as wind speed based on (7). At the moment wind speed get higher than nominal wind speed value because of current generator security, the limit value of torque is applied as torque reference. So as wind speed increases in steady state operation the electromagnetic torque decreases and armature currents remain constant.

Fig.11 shows steady state characteristics of stator flux linkage vs. wind speed. For wind speeds bellow 7 m/s loss minimization strategy is applied, as a result as wind speed increases, the stator flux and terminal voltages increases either. For wind speeds higher than 7 m/s (entering mode II) because of generator voltage security the limit value of flux by (21) is used as flux reference value. In this situation as wind speed increases the stator flux decreases and the terminal voltage remains constant as shown in fig.9.

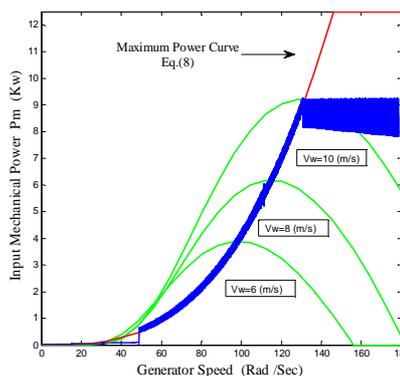


Fig.9. mechanical input power trajectory

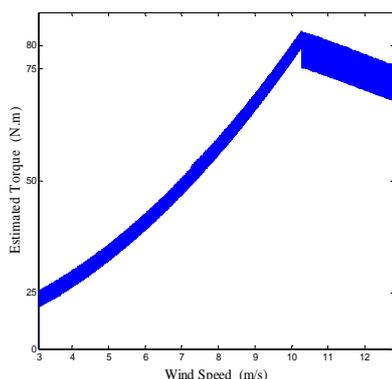


Fig.10. steady state characteristic of torque

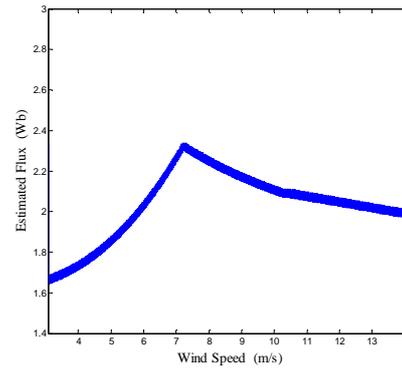


Fig.11. steady state characteristic of flux

V. CONCLUSIONS

In this paper a direct torque control method for CSC based direct driven PMSG based wind energy conversion system was proposed. The control strategy was developed for independent torque and flux control while tracing the maximum power from wind. In particular, electric power losses are minimized in steady state. Torque and flux limits are employed to ensure generator security at high wind speeds. The proposed control scheme is verified in simulation on a wind energy conversion system, it was confirmed that stable power generation from the cut-in wind speed and fast speed response were achieved.

REFERENCES

- [1] F. Blaabjerg, Z. Chen, R. Teodorescu, and F. Iov, "Power electronics in wind turbine systems," in *Proc. CES/IEEE 5th Int. Power Electron. Motion Control Conf. 2006, IPEMC 2006*, pp. 1–11.
- [2] Jingya Dai, Dewei (David) Xu, Bin Wu, "A novel control scheme for current-source-converter-based PMSG wind energy conversion systems," *IEEE Trans. Power Electron*, vol. 24, no. 4, APRIL 2009.
- [3] T. Senjyu, S. Tamaki, N. Urasaki, K. Uezato, H. Higa, *et al.*, "Wind velocity and rotor position sensorless maximum power point tracking control for wind generation system," *2004 35th Annual IEEE Power Electronics Specialists Conference Record*, pp. 2023-2028, Jun. 2004.
- [4] Shigeo Morimoto, Hideaki Nakayama, Masayuki Sanada, "Sensor less output maximization control for variable-speed wind generation system using IPMSG," *IEEE Trans. Industry Applications*, vol. 41, no. 1, January/February 2005.
- [5] Mónica Chinchilla, Santiago Arnaltes, and Juan Carlos Burgos, "Control of permanent-magnet generators applied to variable-speed wind-energy systems connected to the grid," *IEEE Trans. Energy Conversion*, vol. 21, no. 1, march 2006.
- [6] Hongyuan Liu 1, Ping Wang 2, and Zhen Wang 3," Control Principles of Current Source Inverter DC Terminal Voltage in Direct-Drive Wind Power Generation System." *Power electronic and motion control conference 2009.IPEMC '09.IEEE 6th international*.
- [7] Yukinori Inoue, Shigeo Morimoto, and Masayuki Sanada"Control Method for Direct Torque Controlled PMSG in Wind Power Generation System," *Electric Machines and drives for direct torque controlled PMSG in wind power generation*.
- [8] Behrooz Majidi, Jafar Milimonfared and Kaveh Malekian. "Performance Improvement of Direct Torque Controlled Interior Permanent Magnet Synchronous Motor Drive by Considering Magnetic Saturation." *Power Electronics and motion control conference,2008.EPE-PEMC 2008.13*
- [9] Aleksandar Nikolic, Borislav Jeftenic." Current Source Converter Topologies for PMSG Wind Turbine Applications" *14th International Power Electronics and Motion Control Conference, EPE-PEMC 2010*

- [10] Jingya Dai, Dewei Xu, Bin Wu, Navid R. Zargari, Yongqiang Lang." Dynamic Performance Analysis and Improvements of a Current Source Converter Based PMSM Wind Energy System." *Power electronics specialists conference,2008.pesc 2008.IEEE*
- [11] C. Yiguang, W. Zhiqiang, Sh. Yonghuan, and K. Lingbing, "A control strategy of direct driven permanent magnet synchronous generator for maximum power point tracking in wind turbine application," *International Conference on Electrical Machines and Systems (ICEMS2008)*, pp. 3921-3926, 17-20 Oct. 2008.
- [12] Shigeo Morimoto, Yi Tong, Yoji Takeda and Taka0 Hirasaka,"Loss Minimization Control of Permanent Magnet Synchronous Motor Drives". IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, VOL. 41, NO. 5, OCTOBER 1994 511
- [13] Ming Yin, Gengyin Li, Ming Zhou." Modeling of the Wind Turbine with a Permanent Magnet Synchronous Generator for Integration." *Power Engineering society general meeting,2007.IEEE*.