International Journal of Engineering and Technical Research (IJETR)
ISSN: 2321-0869, Volume-3, Issue-1, January 2015

A Novel Technique for Wind Energy-Grid Integration Based on Five-Phase PMSG

Dr/M.N. Abdel-Wahab

***Abstract*— The top notch technology in power electronics made the modern wind energy conversion system (WECS) integrated to utility grid has become reliable and efficient. This paper investigates the grid integration of a multi-phase permanent magnet synchronous generator (PMSG) connected to variable speed wind turbine (VSWT).**

The proposed system model consists of two back-to-back connected to converters with a common dc-link. The generator side converter is designed to achieve maximum power point tracking (MPPT). The grid side converter regulates the dc-link voltage, which is actively controlled to feed power generated, thus enabling the grid to supply only sinusoidal current at unity power factor (UPF).

A model of directly driven five-phase PMSG- based variable speed WECS is developed and simulated in MATLAB/SIMULINK environment. The quality performance of the proposed control technique is investigated and validated through extensive simulation results

***Index Terms*— Five-Phase PMSG, WECS, back-to-back converter, variable speed wind turbine (VSWT), MPPT**

I. INTRODUCTION

The rapid development of wind energy technology has significantly raised the penetration level of wind power in utility grids and consequently the wind turbines –grid integration.

The amount of energy extracted from wind depends not only on the incident wind speed, but also on the control strategy applied on the wind energy conversion system (WECS). Typically, maximum wind power extraction is accomplished by using fully controlled variable speed wind turbine generators. The rotational speed of wind turbine hub is adjusted according to the incident wind speed to track the maximum wind power trajectory [1]. As a power generating unit connected to the electrical grid, the wind turbine generator should have the capability to control both the active and reactive powers injected to it.

Variable speed wind turbine (VSWT) topologies include many different generator-converter configurations, based on cost, efficiency, annual energy capturing, and control strategy of the overall system [2]. Permanent magnet synchronous generator (PMSG) coupled to variable speed wind turbines are considered appropriate, fitting and feasible technology in wind generation industry since PMSGs are self excited, operable at high power factor and has high efficiency [3]-[5]. Furthermore, due to its low rotational speed the gearbox can be omitted.

Manuscript received January 12, 2015.

Dr/M.N. Abdel-Wahab, Dept. of Electrical Engineering Faculty of Engineering, Suez Canal University

In other WECSs, the gearbox is one of the most critical and panic wind turbine components, since its failure is highly expected, and it requires careful and regular maintenance [6].

There are two popular power electronic configurations employed for interfacing PMSG with utility grid, first PMSG system with passive diode rectifier followed by IGBT inverter, and the second configuration is PMSG system with two fully controlled full-size IGBT PWM converters [3], [5].

In this context of higher-power wind turbines and full power topologies, the use of multi-phase generators shows a promissing prospect for industrial applications because the power is inherently split and the additional phases allow some extra benefits and solutions [6]. For example, Spanish manufacturer Gamesa has developed a full-power 4.5 MW wind turbine with 6 parallel converters and 18 phases [7]. Some other topologies that use series connected generator-side converters have also been proposed to achieve medium voltage on the grid-side [8]-[9].

This paper studies the performance of grid connected direct driven five-phase PMSG based wind turbines. The PMSG is connected to the electrical grid at the point of common coupling (PCC) via an AC-DC-AC back-to-back converter set. Two control schemes are developed for machine- and grid-side converters. A shunt capacitor is employed as a DC-link between the two converters. Pulse width modulation (PWM) is used to produce the switching signals for converter switches. The dynamics of the system and control action is simulated with detailed model using MATLAB/SIMULINK.

II. WIND ENERGY CONVERSION SYSTEM

Wind energy conversion system (WECS) converts kinetic energy of wind to mechanical energy by means of wind turbine rotor blades; then the generator converts the mechanical power to electrical power.

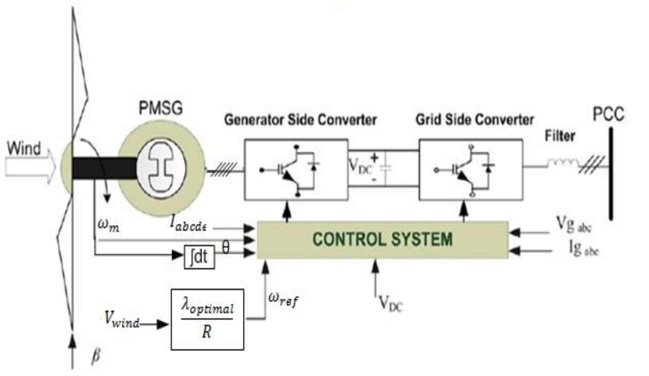


Fig. 1 Five-Phase PMSG based wind turbine

The output ele… l through power electronic converters. The WECS under scope of reseach consists of a gearless wind turbine coupled to PMSG generator with a generator side converter linked through a DC-link to electrical grid side converter as shown in Fig.1.

III. WIND TURBINE MODEL

The power of the wind captured by wind turbine depends mainly on its power coefficient (C_p) which is given by the relation:

$$C_p = \frac{P_{turbine}}{P_{wind}} \quad (1)$$

$$P_{turbine} = P_{wind}\, C_p = \frac{1}{2}\rho\pi R^2 V_w^3 C_p \quad (2)$$

Where ρ is the air density, V_w is the wind speed and R is the radius of circular area swept by rotor blades. But, for a given turbine C_p is not always constant. The most common parameters for C_p are function of the tip speed ratio λ and the pitch angle β. Where, the tip speed ratio is given as:

$$\lambda = \frac{Tip\ Speed\ Ratio}{Wind\ Speed} = \frac{\omega_r . R}{V_w} \quad (3)$$

Here the power coefficient $C_p = f(\lambda, \beta)$ is a function of both parameters. Consequently, different wind speeds will require the optimal values of tip speed and pitch angle to achieve a high C_p and therefore giving the highest power output at all available wind speeds [10]. The above-mentioned aspects make it very clear that to extract maximum power out of the varying wind we need to have a wind turbine that allows the change in rotor speed to reach optimal aerodynamic conditions. As every optimal $C_{p,optimal}$ has one optimal value of tip speed ratio $\lambda_{optimal}$, it is necessary to control the tip speed ratio according to the wind speed. This task of MPPT is achieved by using power co-efficient against tip speed ratio for different pitch angles of the turbine. The active pitch control is used during high wind velocity to shed off the aerodynamic power by turning the rotor blades through some angle from the direction of striking wind (also known as pitch angle control). The aerodynamic power captured by wind turbine is the cosine function of pitch angle. In this paper, the pitch angle is kept zero, which is a valid assumption for lower to medium wind velocities.

IV. PMSG MODEL

The voltage equations of five-phase permanent magnet synchronous generator expressed in the rotor reference frame using an extended park transformation (d_1,q_1 and d_2,q_2) axis.

$$V_{d1} = R_s i_{d1} + L\frac{di_{d1}}{dt} - L_q \omega_e i_{q1} \quad (4)$$

$$V_{q1} = R_s i_{q1} + L\frac{di_{q1}}{dt} + L_d \omega_e i_{d1} + \lambda\omega_e \quad (5)$$

$$V_{d2} = R_s i_{d2} + L\frac{di_{d2}}{dt} \quad (6)$$

$$V_{q2} = R_s i_{q2} + L\frac{di_{q2}}{dt} \quad (7)$$

Where V_{d1}, V_{d2} and V_{q1}, V_{q2} represent the stator voltages in the (d,q) axis, i_{d1}, i_{d2} and i_{q1}, i_{q2} represent the currents in the (d,q) axis, R_s represent stator resistance , L represent armature inductance , L_d, L_q represents the (d,q) axis inductance, $\omega_e = p\omega_m$ (p is number of pole pairs, ω_m represent the turbine rotor angular speed and λ is the permanent flux linkage).

The electrical torque of the generator can be expressed as:

$$T_e = \frac{5}{2} p\lambda i_{q1} \quad (8)$$

The mechanical equation of PMSG is given by:

$$T_m = T_e + B\omega_m + J\frac{d\omega_m}{dt} \quad (9)$$

Where B is the friction coefficient, J the total moment of inertia and T_m is the mechanical torque produced by wind turbine, T_e is electromagnetic torque of PMSG.

V. GENERATOR SIDE CONTROLLER

The generator side converter is mainly used to control the wind turbine speed in order to extract maximum power from wind turbineP_{max}. The turbine should operate at $C_{p\ max}$ in order to get P_{max}, so it is necessary to keep the generator rotor speed ω_m at an optimum value of tip speed ratio $\lambda_{optimal}$. The PMSG rotor speed should be adjusted to follow the change of speed and consequently adjust the turbine speed with wind variations [11],[12]. The PMSG speed control can be implemented through generator side converter. That allows the generator to rotate freely depending on wind variation.

To realize the control concept we should investigate the equation of motion [5]. So, The generator equation of motion is given from equation (9) as:

$$J\frac{\omega_m}{dt} = T_m - T_e - B\omega_e \quad (10)$$

The mechanical rotational speed of PMSG rotor is given by:

$$\omega_m = \frac{\omega_e}{p} = \omega_t G_r \quad (11)$$

Where, ω_e electrical rotational speed of PMSG rotor (rad/s) ω_t turbine rotational speed and G_r gear ratio (if existed). For gearless PMSG based wind turbine $G_r = 1$ and according to the characteristic of wind turbine at any value of wind speed the rotational speed of the turbine rotor ω_m is regulated to the value $\omega_{m\ optimal}$ through generator side control hence:

$$\omega_{ref} = \omega_{m\ optimal} = \frac{\lambda_{optimal} V_{wind}}{R} \quad (12)$$

So that C_p takes maximum value.

From eq. (10), the speed control of generator can be achieved by the control of electromagnetic torque T_e. From eq. (8) the electromagnetic torque may be controlled directly by q-axis current componentI_{q1}, therefore the speed can be controlled by changing $q_1$axis current.

It's clear that from equation (Iq_1) reference current component (torque controlling current component) can be derived using eq. (8)

$$i_{q1}^* = \frac{2}{5}\left(\frac{T_e^*}{p\lambda}\right) \quad (13)$$

(d_1, d_2 and q_2)-axis currents component I_{d1}, I_{d2} and I_{q2} is set to zero to minimize the current and resistive losses for a given torque. The generator side control diagram is shown in fig.(2)

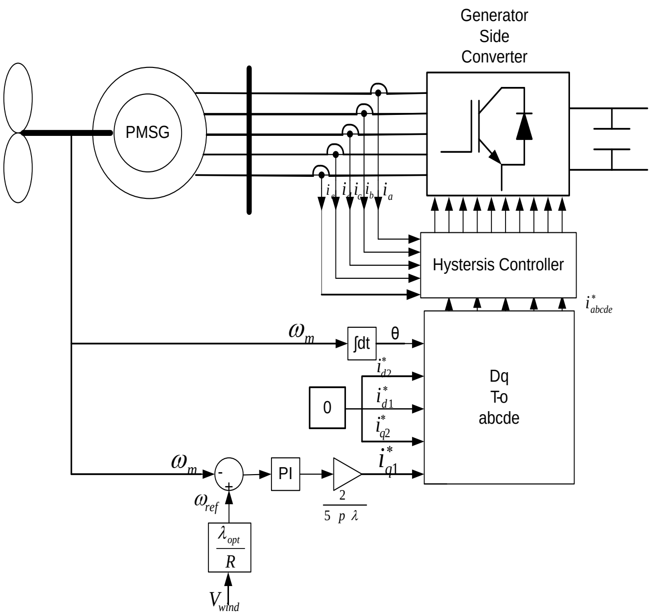


Fig.(2) Generator Side Converter

VI. GRID-SIDE CONVERTER CONTROL

The grid side converter control scheme contains two cascaded loops. The inner loop controls the grid currents and the outer loop controls the DC-link voltage and the reactive power. Harmonic compensation can be added to this controller to improve the power quality of the system. The outer loop regulates the power flow of the system by controlling the active and reactive power delivered to the electrical utility grid.

Let the three-phase grid-side voltages as follows.

$$\left.\begin{aligned} e_a &= E\cos(\omega t) \\ e_b &= E\cos\left(\omega t - \frac{2\pi}{3}\right) \\ e_b &= E\cos\left(\omega t + \frac{2\pi}{3}\right) \end{aligned}\right\} \quad (14)$$

Where E is the maximum phase voltage and ω is the angular frequency of the grid-side supply.

The voltage equations in abc frame are:

$$\left.\begin{aligned} e_a &= L\frac{di_a}{dt} + v_a \\ e_b &= L\frac{di_b}{dt} + v_b \\ e_c &= L\frac{di_c}{dt} + v_c \end{aligned}\right\} \quad (15)$$

Where e_a, e_b, e_c are grid-side voltages , v_a, v_b, v_c are the inverter terminal voltages and L is the coupling inductance.

On converting the voltage (15) into synchronous d-q reference frame, we have

$$\left.\begin{aligned} e_d &= L\frac{di_d}{dt} - \omega L i_q + V_d \\ e_q &= L\frac{di_q}{dt} + \omega L i_d + V_q \end{aligned}\right\} \quad (16)$$

Now, the main goal of proposed controller is to generate the reference currents such that the grid always supplies only fundamental active power to the load at PCC. For UPF operation, the quadrature-axis reference current i_q^*. The active power exchange between WECS and grid is directly proportional to the direct-axis current i_d and can be derived as:

$$P = \frac{3}{2} e_d i_d \quad (17)$$

This direct-axis current id is also responsible for regulating the dc-link voltage. Therefore the d-axis reference current i_d^* is generated from the PI controller for the dc-link voltage regulator expressed as:

$$i_d^* = \left(K_{PV_{dc}} + \frac{K_{IV_{dc}}}{s}\right)(V_{dc}^* - V_{dc}) \quad (18)$$

Where $K_{pV_{dc}}$ is proportional gain and $K_{IV_{dc}}$ is the internal gain of the dc-voltage regulator.

Generally, the standard PI controllers perform satisfactorily in forcing the grid current to track the reference current exactly. However, the presence of coupling terms in (16) deteriorates the performance of the PI regulator. To avoid this problem, the system can be decoupled in the form of a first-order linear dynamic system having better controllability, as follows:

$$\left.\begin{aligned} 0 &= L\frac{di_d}{dt} - \Delta v_d \\ 0 &= L\frac{di_q}{dt} - \Delta v_q \end{aligned}\right\} \quad (19)$$

Where, the output signals, Δv_d and Δv_q are derived from inner current controllers loops as:

$$\left.\begin{aligned} \Delta v_d &= K_p(i_d^* - i_d) + K_i \int (i_d^* - i_d)dt \\ \Delta v_q &= K_p(i_q^* - i_q) + K_i \int (i_q^* - i_q)dt \end{aligned}\right\} \quad (20)$$

Inclusion of these decoupled terms in (16), results in the reference d-q voltages of the inverter as follows:

$$\left.\begin{aligned} v_d^* &= e_d + \omega L i_q - \Delta v_d \\ v_q^* &= e_q - \omega L i_d - \Delta v_q \end{aligned}\right\} \quad (21)$$

The reference d-q voltages obtained from (21) are transformed into a-b-c reference voltages with the help of grid voltage phase angle θ. The grid synchronizing phase angle can be extracted using the phase lock loop technique. The reference voltages are then applied to the PWM controller to generate control signals for the grid-side inverter. The complete control diagram of the grid-side inverter is shown in Fig. 3.

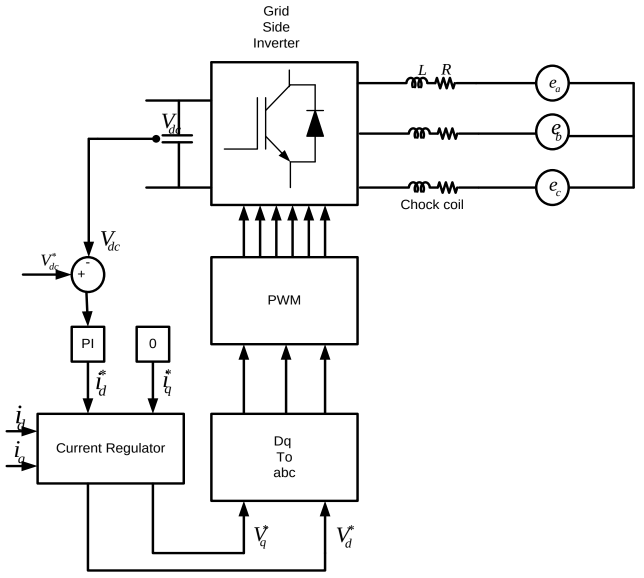


Fig.(3) Grid-side Converter Control

VII. SIMULATION RESULTS AND DISCUSSION

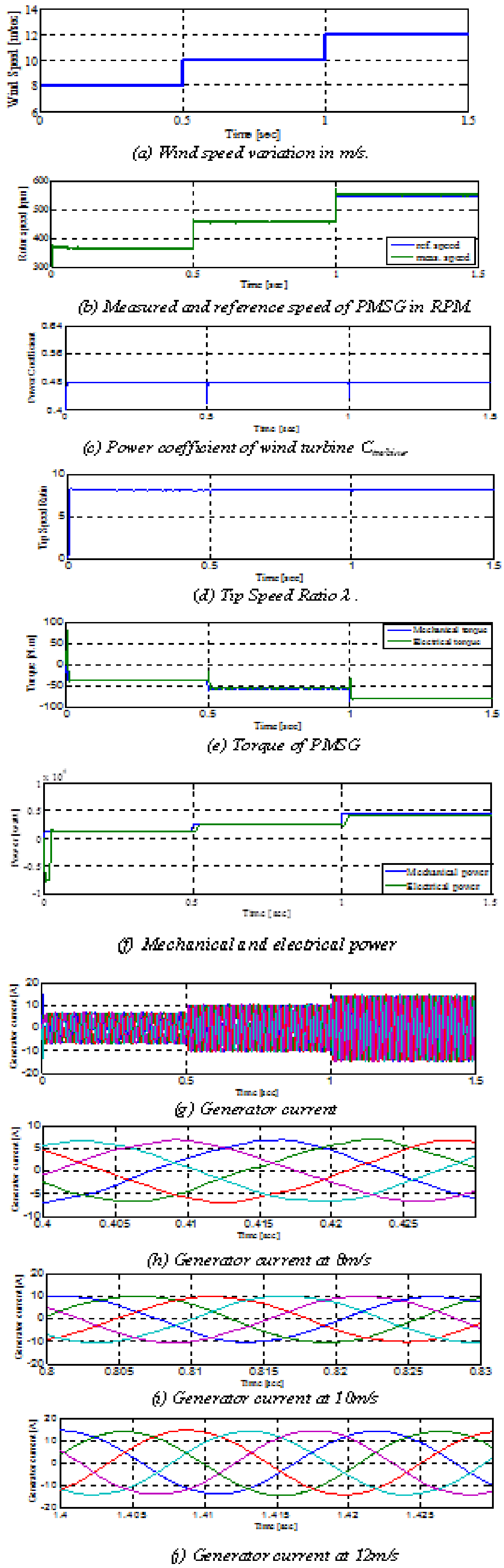
The parameters of the system under study are given in Table 1. MATLAB/SIMULINK software is used to perform the simulation using power system block sets with a simulation time of 1.5 seconds.

Table (1) System Parameters

PMSG parameters		
$R_s = 0.425\Omega$	$L_s = 0.00835H$	$\lambda = 0.433wb$
$J = 0.01197$	$\beta = 0.001189$	
Wind turbine parameters		
$V_{wind} = 12m/s$ Rated wind speed	R=1.8m	$\beta = 0$
$\lambda_{optimal} = 8.1$	$\rho = 1.225kg/m^3$	
Grid parameters		
$V = 380v$	$R = 0.015\Omega$	$L = 2mh$
DC link voltage = 620v		

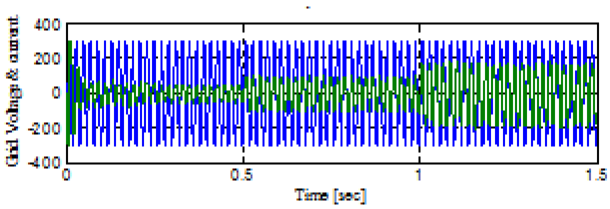
The proposed control strategy for PMSG-based variable speed WECS is simulated using MATLAB/Simulink under different operating conditions. When the wind speed profile is considered varying smoothly with different values, as seen in Fig. 4(a) and according to wind turbine characteristic; when wind speed varies the controller adjust PMSG rotor speed to follow the same value of $\omega_{m-optimal}$ as shown in Fig. 4(b).

Fig. 4(b) shows that the PMSG speed varies according to the reference speed with a slight error. The tip speed ratio and power coefficient of wind turbine variations are given in Fig.4(c) and 4(d) respectively. It is obvious from these Fig. 4(c) and 4(d) that λ and $C_{turbine}$ are almost constant for the simulating period except for the jump start at 0 s. The mechanical and electromagnetic torque of PMSG is varying with different values -40,-60 and -80 N.m for the same change in wind speed with values 8,10 and 12m/sec respectively as seen in Fig.4(e). Mechanical and electrical power change, during change in wind speed as shown in Fig.4 (f). On the other hand, generator terminal current change simultaneously with change in wind speed as shown in Fig.4 (g,h,i and j).

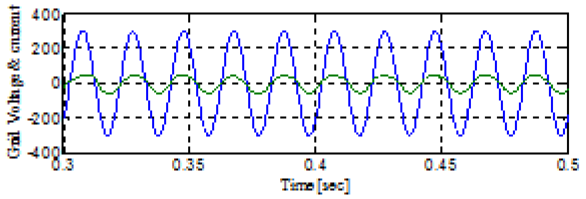


Fig(4) Simulation results of WECS under generator side converter.

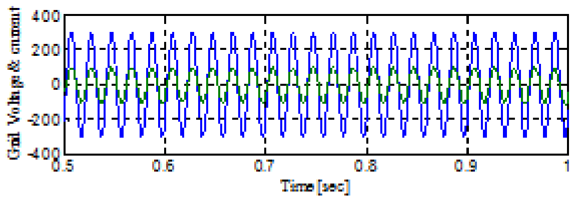
The grid side converter is actively controlled to inject the generated power and regulate DC-link voltage. Simulation results in Fig.5 show grid voltage and current in-phase, DC-link voltage compared with reference value, direct-axis current, quadrature-axis current, active and reactive power injected into grid.



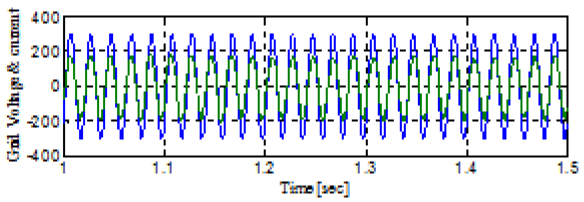
(a) Grid Voltage and current



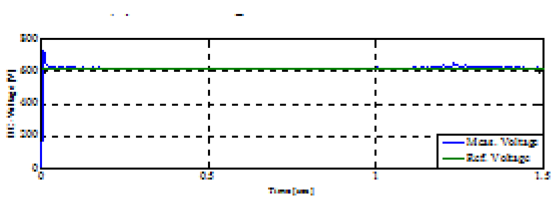
(b) Grid Voltage and current at 8m/s



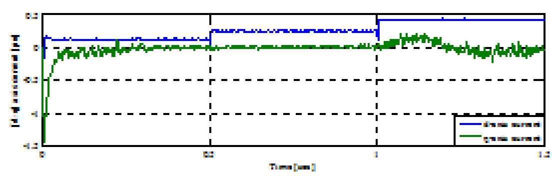
(c) Grid voltage and current at 10m/s



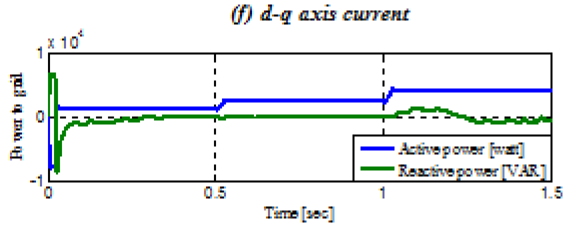
(d) Grid voltage and current at 12m/s



(e) DC-link voltage



(f) d-q axis current



(g) Active and reactive power injected into grid

Fig.5 Simulation results of WECS at grid side converter.

Grid voltage and current in-phase at different values of wind speed as shown in Fig.5 (a,b,c,d). Fig.5 (e) show DC-link voltage as the same value of reference value, the direct-axis current change with change in wind speed but quadrature-axis current is zero as seen in Fig.5(f). Fig.5 (g) show the active power change with wind speed and reactive power is zero.

VIII. CONCLUSION

Direct driven PMSG wind turbine modeling and simulation have been investigated. Two control schemes at both generator side and grid side converters are presented. Results show that turbine tip speed ratio and power coefficient can be controlled to a constant value for different wind speed profiles.

Generator side converter can be implemented to achieve such control. Active and reactive powers produced to the utility grid can also be controlled to meet the utility grid code through grid side converter. DC-link voltage is controlled to ensure the transmission of power from generator to the electrical grid within the designated value. These control schemes can also be used to achieve a unity power factor (i.e. Q = 0) delivered to electrical grid and consequently not alter the overall power factor of the system.

REFERENCES

[1] I.Munteanu, I.U.Bratcu, N.A. Cutulis, and E. Ceanga,"Optimal Control Of wind Energy Systems" Springer 2008.
[2] J.A.Baroudi, V.Dinavahi, and A.M.Knight,"A Review of Power Converter Topologies for Wind Generators" Renewable Energy, Vol.32, No.19, Jan.2007, pp.2369-238.
[3] M.Chinchilia, S.Arnaltes, and J.Burgos, "Control of Permanent – Magnet Generator Applied to Variable- Speed Wind –Energy Systems Connected to the Grid," IEEE Trans. Energy conversion, Vol.21, No.1 March.2006.
[4] S.Li, T.A.Haskew, and L.Xu, "Conventional and Novel Control Designs for Direct Driven PMSG Wind Turbines" Electric Power System Research, Vol.80, Oct.2009, pp.328-338.
[5] W.Qiao, L.Qu,and R.G.Harely, "Control of IPM Synchronous Generator for Maximum Wind Power Generation Considering Magnetic Saturation," IEEE Trans. Industry application, Vol.45, No.3, May/Jun 2009.
[6] Z. Xiang-Jun, Y. Yongbing, Z. Hongtao, L. Ying, F. Luguang, and Y. Xu, "Modelling and control of a multi-phase permanent magnet synchronous generator and efficient hybrid 3L-converters for large direct-drive wind turbines," IET Electric Power Applications, vol. 6,no.6, pp. 322–331, 2012.
[7] B. Andresen and J. Birk, "A high power density converter system for the Gamesa G10x 4,5 MW wind turbine," in Proc. European Conf. on Power Electronics and Applications EPE, CD-ROM, 2007.
[8] M. J. Duran, S. Kouro, B. Wu, E. Levi, F. Barrero, and S. Alepuz, "Six-phase PMSG wind energy conversion system based on medium voltage multilevel converter," in Proc. European Conference on Power Electronics and Applications EPE, CD-ROM, 2011.
[9] H.S. Che, W.P. Hew, N.A. Rahim, E. Levi, M. Jones, M.J. Duran, "A six-phase wind energy induction generator system with series connected DC-links," in Proc. IEEE Power Electronics for Distributed Generation Systems PEDG, pp. 26-33, 2012.
[10] MULJADI E., BUTTERFIELD C.P.: 'Pitch-controlled variable speed wind turbine generation', IEEE Trans. Ind. Appl., 2001, 37, (1), pp.240–246.
[11] F .Iov, A. D. Hansen, P. Sorensen, F.Blaabjerg, "Wind Turbine Blackest in Matlab/Simulink," esearch Project, Institute of Energy Technology, Alborg University, March.2004.
[12] T. Ackermann "Wind Power in Power Systems", book, John Wiley & Sons Ltd, Royal Institute of Technology, Stockholm, Sweden,