



MPPT Control Technique for Direct-Drive Five-Phase PMSG Wind Turbines with Wind Speed Estimation

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Abstract: This paper has presented comprehensive modeling of direct driven five-phase PMSG based grid-connected wind turbines along with the control schemes of the interfacing converters. Wind speed estimation has been achieved based on measured rotor speed. Five-phase to three-phase interface power converter based back-to-back common dc-link converter has been used to achieve the system objectives. The machine side converter (MSC) is used to track the maximum power point at different wind speed. The grid side converter (GSC) uses a vector current controller to inject pure active power to the grid. The effectiveness of proposed control scheme is validated through extensive simulation results by using MATALB/SIMULINK.

Keywords: MPPT, Five-Phase PMSG, MSC, GSC

1. Introduction

Wind power is today's most rapidly growing renewable energy source. A wind turbine operates either at a fixed or variable speed [1]. Most of wind turbine manufacturers are developing new different scale wind turbines based on variable-speed operation with pitch control using either a permanent magnet synchronous generator (PMSG) or a doubly fed induction generator (DFIG) [2]. Due to the intensified grid codes, a PMSG wind turbine with full VSC-based converters is becoming more favored by the wind power industry [3]–[7]. The variable speed wind turbine with a multi-phase PMSG and full-scale/fully controllable voltage source converters (VSCs) is considered to be a promising, but not yet very popular, wind turbine concept [3]. The wind turbines based multi-phase PMSG configuration have many advantages such as gearless construction [4], elimination of a dc excitation system [5], full controllability of the system for maximum wind power extraction and grid interface, and ease in accomplishing fault-ride through and grid support [6]. Therefore, the efficiency and reliability of a VSC-based PMSG wind turbine is assessed to be higher than that based DFIG [7].

Recently, multiphase machines have gained much interest

due to their advantages over conventional three-phase machines. The use of multiphase permanent magnet synchronous generators PMSG to implement high power is an alternative to reduce the current rating of the converter power switches. Multiphase PMSG have many advantages such as reducing the amplitude and increasing the frequency of torque pulsations, higher reliability, and lowering the dc link current harmonics [8]–[11]. Therefore, multiphase PMSG are very suitable for the applications of high power, high reliability, and low dc bus voltage, such as renewable energy. These advantages have motivated the wind turbine manufacturers to use multiphase machines. For example, Spanish manufacturer Gamesa has developed a full-power 4.5 MW wind turbine with 6 parallel converters and 18-phase generator [13]. Some other topologies that use series connected generator-side converters have also been proposed to achieve medium voltage on the grid-side [14], [15].

Maximum power point tracking control in most of the conversion systems is implemented using wind speed data obtained from wind speed sensors [16]–[19]. However, accurate measurement of wind speed is not easy especially in case of large size wind turbines. Anemometer installed on the top of nacelle provides limited measurements of wind speed only at the hub height and cannot cover the whole span of

large blades [20]. Moreover, due to the interaction between the rotor and the wind, anemometer, usually placed on nacelles, leads to inaccurate wind speed measurements in both upwind and downwind turbines. Therefore, Speed control of wind turbine based sensorless algorithms has gained many interests due to its accuracy and simplicity in tracking the maximum power point during wind speed variations [21, 22].

In this paper, maximum power point tracking for wind turbine based five-phase PMSG has been achieved by wind speed estimation technique. Estimation of the wind speed has been achieved measure rotor speed and the estimated load torque. A full scale power converter based five-phase has been used. The dc-link, connecting the back-to-back converters, allow fully decoupled control of the five-phase PMSG from the grid side. The MPPT has been achieved by controlling the PMSG speed at the generator side, whereas the grid side converter has been controlled to achieve unity

power factor at the grid side. The effectiveness of the proposed control technique in addition to the efficient operation of the wind turbine system has been verified using Matlab/Simulink.

2. 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. The resulting electrical power is being fed to the electrical network through power electronic converters. In this paper, the WECS consists of a gearless wind turbine coupled to a five-phase PMSG, interfaced with the grid through back-to-back converters connected to each other through a common dc-link capacitor, as shown in Fig. 1.

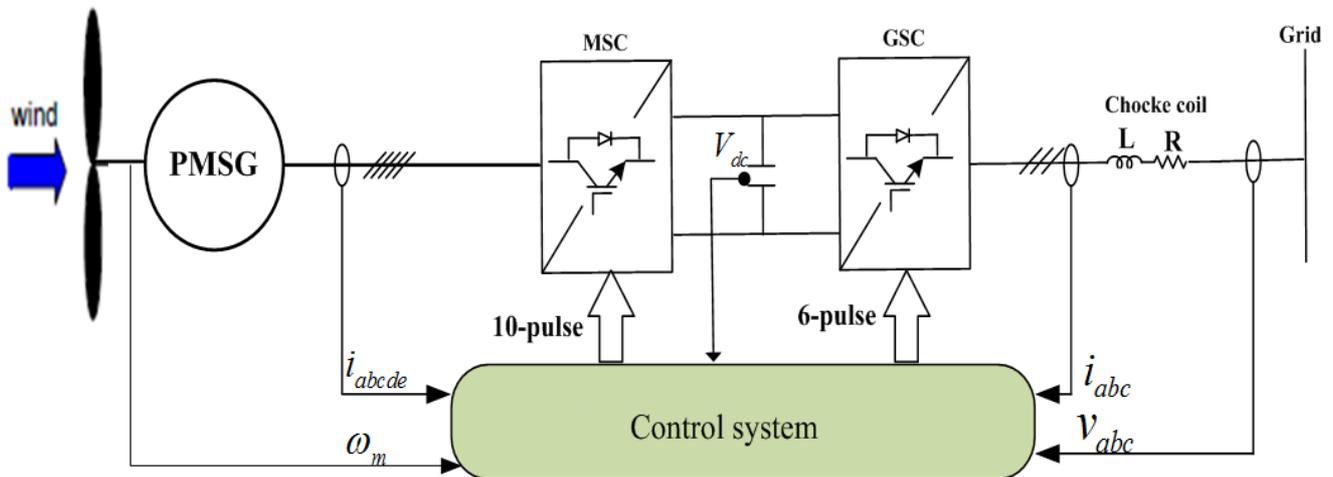


Fig. 1. Five phase PMSG based wind turbines.

2.1. Wind Turbine Model

The mechanical power captured from wind turbine can be formulated as follows:

$$P_m = \frac{1}{2} \rho A C_p(\lambda, \beta) v^3 \quad (1)$$

Where P_m the mechanical output power (Watt), ρ is the air density (kg/m^3), A is the swept area (m^2), C_p is the power coefficient of the wind turbine, v is the wind speed (m/sec), λ is the tip speed ratio, β is pitch angle.

Consequently, the output energy is determined by power coefficient C_p , swept area, air density, tip speed ratio (λ) and pitch angle (β). If β is equal zero, the turbine power coefficient C_p and the tip speed ration λ can be formulated as follows:

$$C_p(\lambda) = \frac{60.04 - 4.69\lambda}{\lambda} \exp\left(\frac{-21 + 0.735\lambda}{\lambda}\right) + \frac{0.0068\lambda}{1 - 0.035\lambda} \quad (2)$$

$$\lambda = \frac{\omega_m R}{v} \quad (3)$$

Where ω_m is the rotor rotational speed (rad/sec), R is the

radius of blade (m).

The relation between C_p and λ when β equal zero degree is shown in Fig. 2. It can be noticed that the optimum value of C_p is about 0.48 for λ equal 8.1. Maximum power extraction from wind turbine can be achieved when the turbine operates at the optimum C_p and λ during wind speed variation.

Based on the relations given in eq.(1) & (3), the optimum output power of the wind turbine can be formulated as follows:

$$P_{m_opt} = \frac{1}{2} \rho A C_{p_opt} \left(\frac{\omega_{m_opt} R}{\lambda_{opt}}\right)^3 \quad (4)$$

$$P_{m_opt} = K_{opt} (\omega_{m_opt})^3 \quad (5)$$

Fig. 3 shows the relation between the mechanical powers generated by the turbine and the turbine rotor speed at different wind speeds. It is cleared that the maximum power point changes with the variation of wind speed and there is a unique maximum power point at each wind speed. The

maximum power extraction can be achieved if the controller wind speed, as shown in Fig. 3. can properly follow the optimum curve with variation of

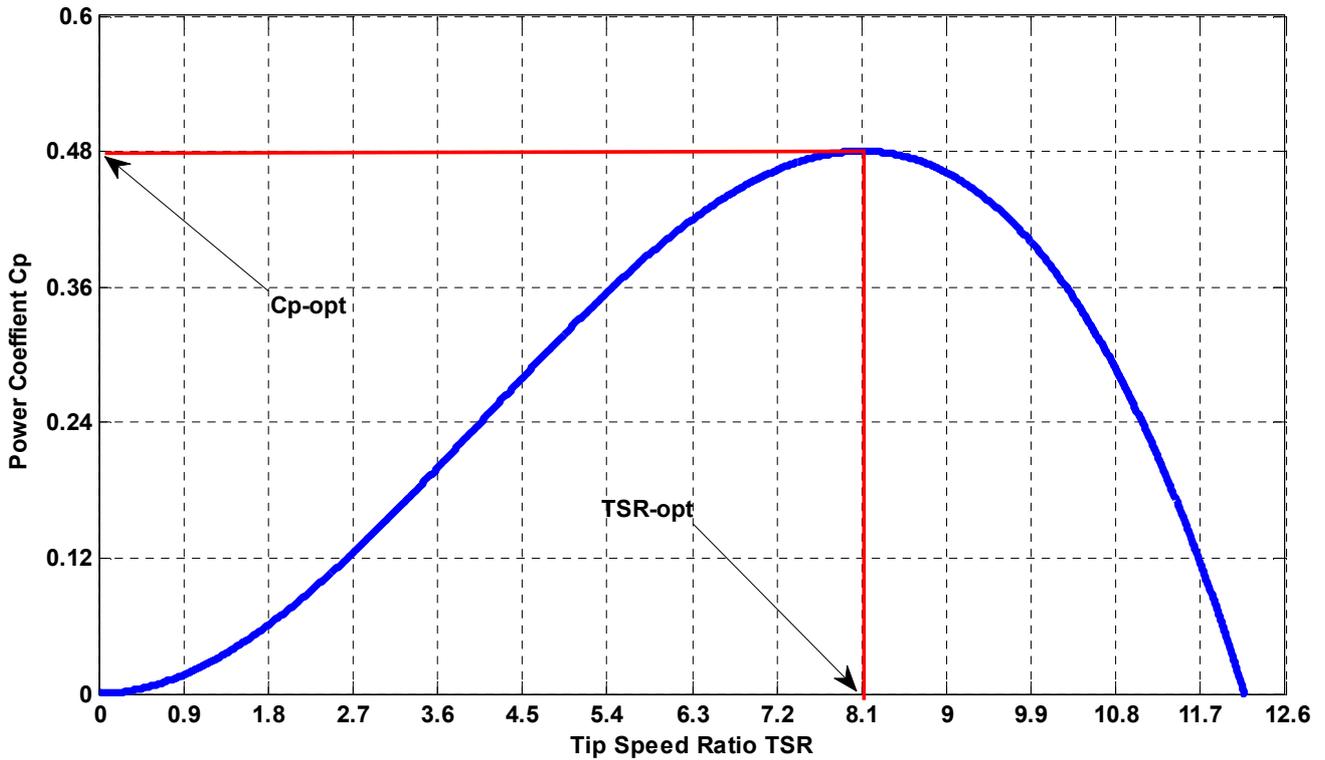


Fig. 2. The relation between power coefficient (C_p) and tip speed ratio (λ).

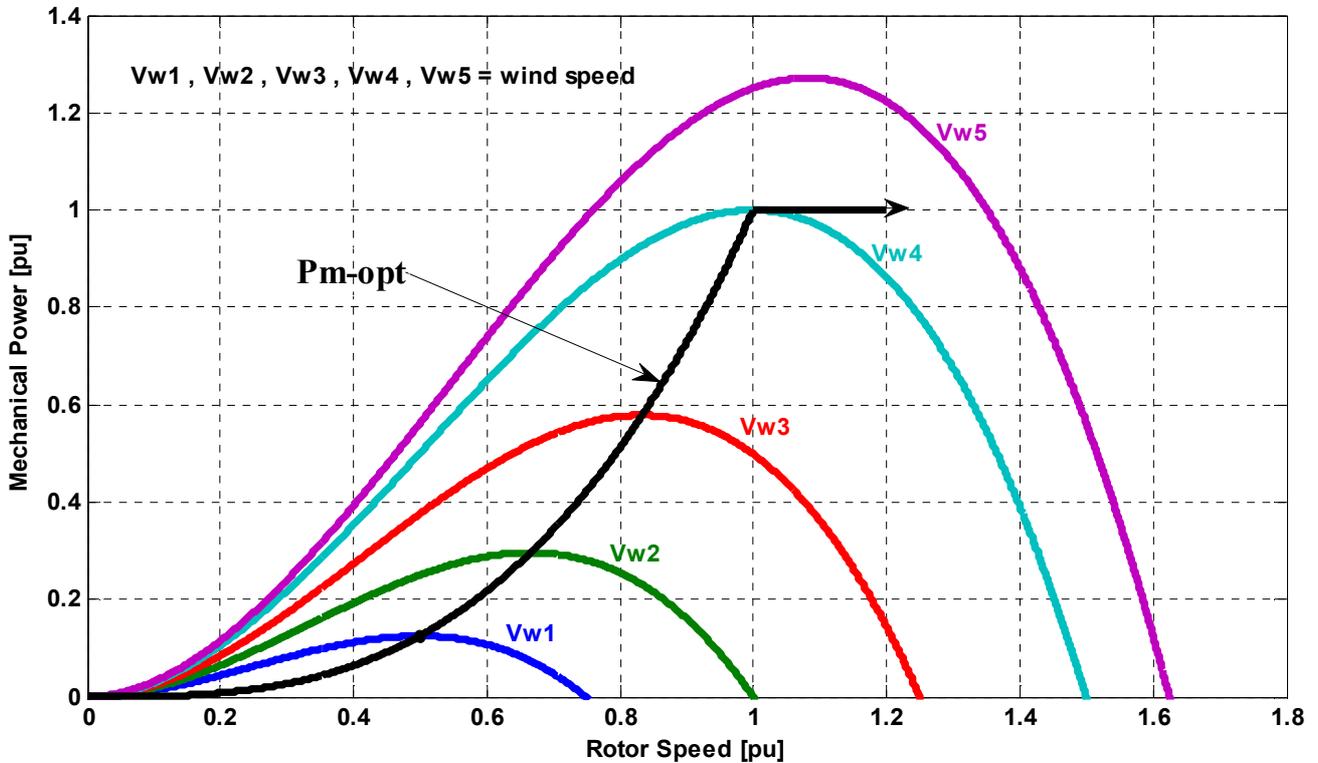


Fig. 3. The relation among generated mechanical powers and rotor speeds for different wind speeds.

2.2. Five-Phase 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 can be described as follows:

$$V_{d1} = R_s i_{d1} + L \frac{di_{d1}}{dt} - L_q \omega_e i_{q1} \quad (6)$$

$$V_{q1} = R_s i_{q1} + L \frac{di_{q1}}{dt} + L_d \omega_e i_{d1} + \psi \omega_e \quad (7)$$

$$V_{d2} = R_s i_{d2} + L \frac{di_{d2}}{dt} \quad (8)$$

$$V_{q2} = R_s i_{q2} + L \frac{di_{q2}}{dt} \quad (9)$$

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 ψ is the permanent flux linkage).

The electrical torque of the five-phase PMSG can be formulated as:

$$T_e = \frac{5}{2} p \psi i_{q1} \quad (10)$$

The mechanical equation of PMSG is given as follows:

$$T_m = T_e + f\omega_m + J \frac{d\omega_m}{dt} \quad (11)$$

Where f 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.

3. Wind Speed Estimation Technique

Prior to explaining the wind speed estimation method, the nonlinear blade power coefficient curve needs to be approximated as third order polynomial [21] as follows;

$$C_p = a_0 + a_1 \lambda + a_2 \lambda^2 + a_3 \lambda^3 \quad (12)$$

Substituting (3) and (12) into (1) results in mechanical power as follows.

$$P_m = \frac{1}{2} \rho A \left(a_0 + a_1 \frac{\omega_m R}{v} + a_2 \frac{\omega_m^2 R^2}{v^2} + a_3 \frac{\omega_m^3 R^3}{v^3} \right) v^3 \quad (13)$$

Based on (13) wind speed can be formulated as follows

$$v^3 + \frac{a_1}{a_0} R \omega_m v^2 + \frac{a_2}{a_0} R^2 \omega_m^2 v + \frac{a_3}{a_0} R^3 \omega_m^3 - \frac{P_m}{0.5 \rho A} = 0 \quad (14)$$

Where

$$P_m = T_m \omega_m, a_0 = 0.00715814, a_1 = -0.04454063, a_2 = 0.02899277, a_3 = -0.00202519$$

The numerical solution for (14) generates three values for the wind speed. The second answer value is the more accurate empirical solution [23]. The mechanical power in (15) can be

estimated using the detected rotor speed and the calculated torque as follows:

$$P_m = \omega_m \left(J \frac{d\omega_m}{dt} + f\omega_m + \frac{5}{2} p \psi i_{q1} \right) \quad (15)$$

4. Control of Machine Side Converter (MSC)

Since the PMSG is a five-phase machine, the machine side converter has been built using five-leg of bidirectional IGBT switches, as shown in Fig. (4). The generator side converter is mainly used to control the wind turbine speed in order to extract maximum power P_{max} . In this case, the turbine should operate at maximum power coefficient C_{pmax} . Therefore, 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 reference speed based on the change of wind speed and consequently adjust the turbine speed at wind variations. The MSC allows the generator to rotate at specified reference speed depending on wind speed variation. Fig. (4) shows the schematic diagram of the generator side converter control scheme.

In order to understand the speed control concept, the PMSG dynamic model should be studied [24]. The PMSG motion equation is given based on (11) as follows:

$$J \frac{d\omega_m}{dt} = T_m - T_e - f\omega_e \quad (16)$$

The mechanical rotational speed of PMSG rotor is given by:

$$\omega_m = \frac{\omega_e}{p} = \omega_t G_r \quad (17)$$

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 $G_r = 1$. 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 $\omega_{moptimal}$ through generator side control hence:

$$\omega_{ref} = \omega_{mopt} = \frac{\lambda_{opt} v}{R} \quad (18)$$

Therefore, the turbine power coefficient C_p is kept at its maximum value.

From (16), the speed control of generator can be achieved by the control of electromagnetic torque T_e . From (10) the electromagnetic torque can be controlled directly by q-axis current component i_{q1} , therefore the speed can be controlled by controlling the q_1 axis current, as shown in Fig. (4). The reference q_1 axis current component can be formulated, based on (10), as follows.

$$i_{q1}^* = \frac{2}{5} \left(\frac{T_e^*}{p\psi} \right) \quad (19)$$

(d_1, d_2 and q_2)-axis current components i_{d1}, i_{d2} and i_{q2} are set to zero to minimize the current and resistive copper losses for a given torque.

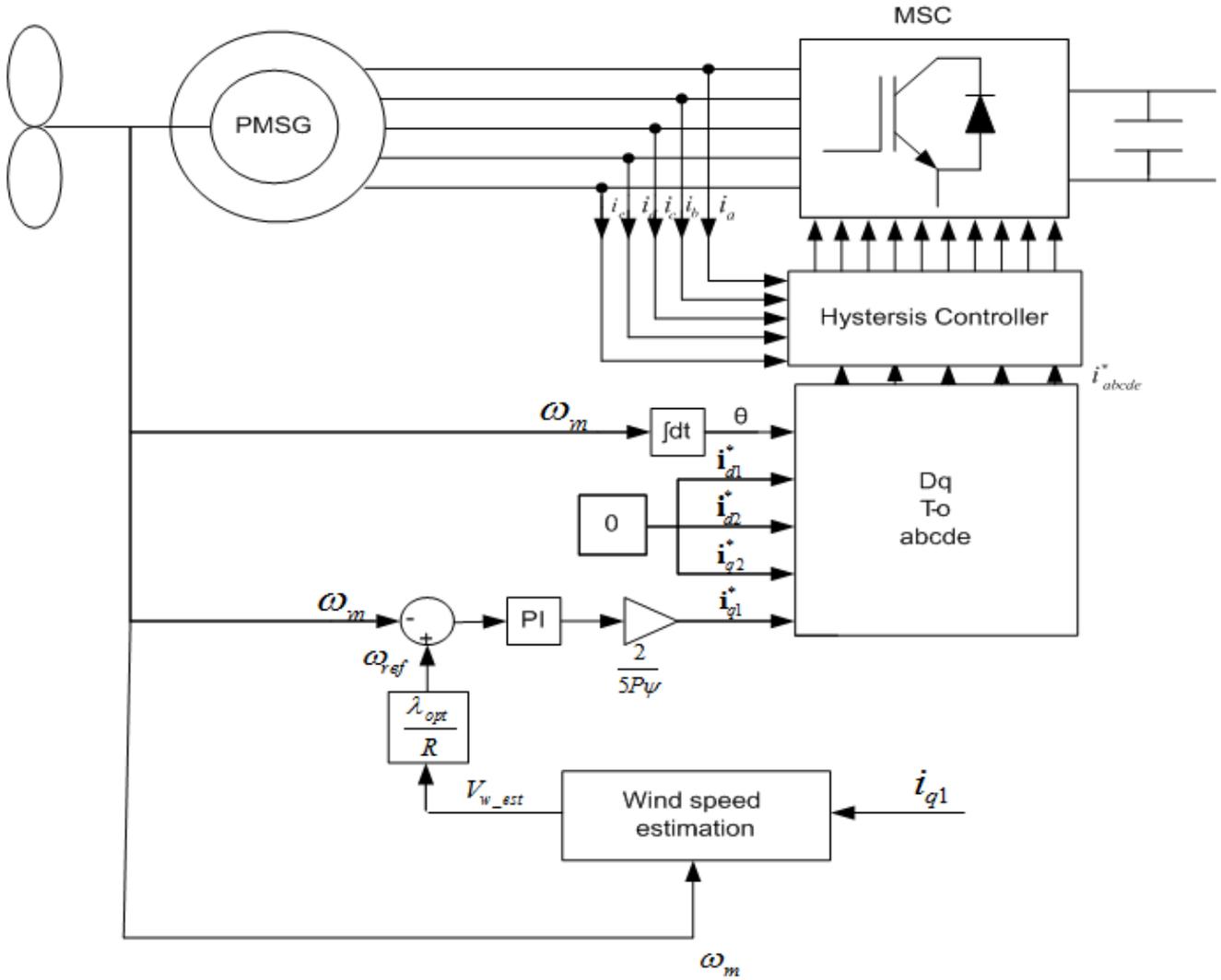


Fig. 4. Generator Side Controller GSC.

5. Grid-Side Converter Control

The objective of grid side converter control is to adjust the DC link capacitor voltage at its reference value, and adjust the active power and reactive power delivered to grid while wind changing. In grid side converter, a PI controller is used to stabilize the DC voltage reference value. The dynamic model of the grid connection, in reference frame rotating synchronously with the grid voltage, is given as follows [25]

$$V_{gd} = V_{id} - RI_{gd} - L \frac{d}{dt} I_{gd} + L\omega_g I_{gq} \quad (20)$$

$$V_{gq} = V_{iq} - RI_{gq} - L \frac{d}{dt} I_{gq} - L\omega_g \quad (21)$$

Where L and R are the grid inductance and resistance, respectively. V_{id} and V_{iq} are the d-q axis inverter voltage components. If the reference frame is oriented along the supply voltage, the grid vector voltage is:

$$V = V_{gd} + j0 \quad (22)$$

Active and reactive power can be expressed as follows [25].

$$P_g = \frac{3}{2} V_{gd} I_{gd} \quad (23)$$

$$Q_g = \frac{3}{2} V_{gd} I_{gq} \quad (24)$$

It could be seen from above equations that we can control the active and reactive powers by respectively changing the d and q-current components. Also in order to transfer all the active power generated by the wind turbine the dc-link voltage must remain constant [26].

$$C \frac{dV_{dc}}{dt} = \frac{P_t}{V_{dc}} - \frac{P_g}{V_{dc}} \quad (25)$$

Where subscript ‘g’ refers to the grid and ‘t’ refers to the wind turbine.

Based on (25), if the two powers (the wind turbine power and the grid power) are equal there will be no change in the dc-link voltage. The grid side converter control scheme contains two cascaded loops. The inner loop controls the

network currents and the outer loop controls the DC-link voltage. The inner loop regulates the power flow of the system by controlling the active and reactive power delivered to the

electrical grid. Further, unity power factor flow (zero reactive power exchange) could be easily obtained, unless the grid operators require different reactive power settings.

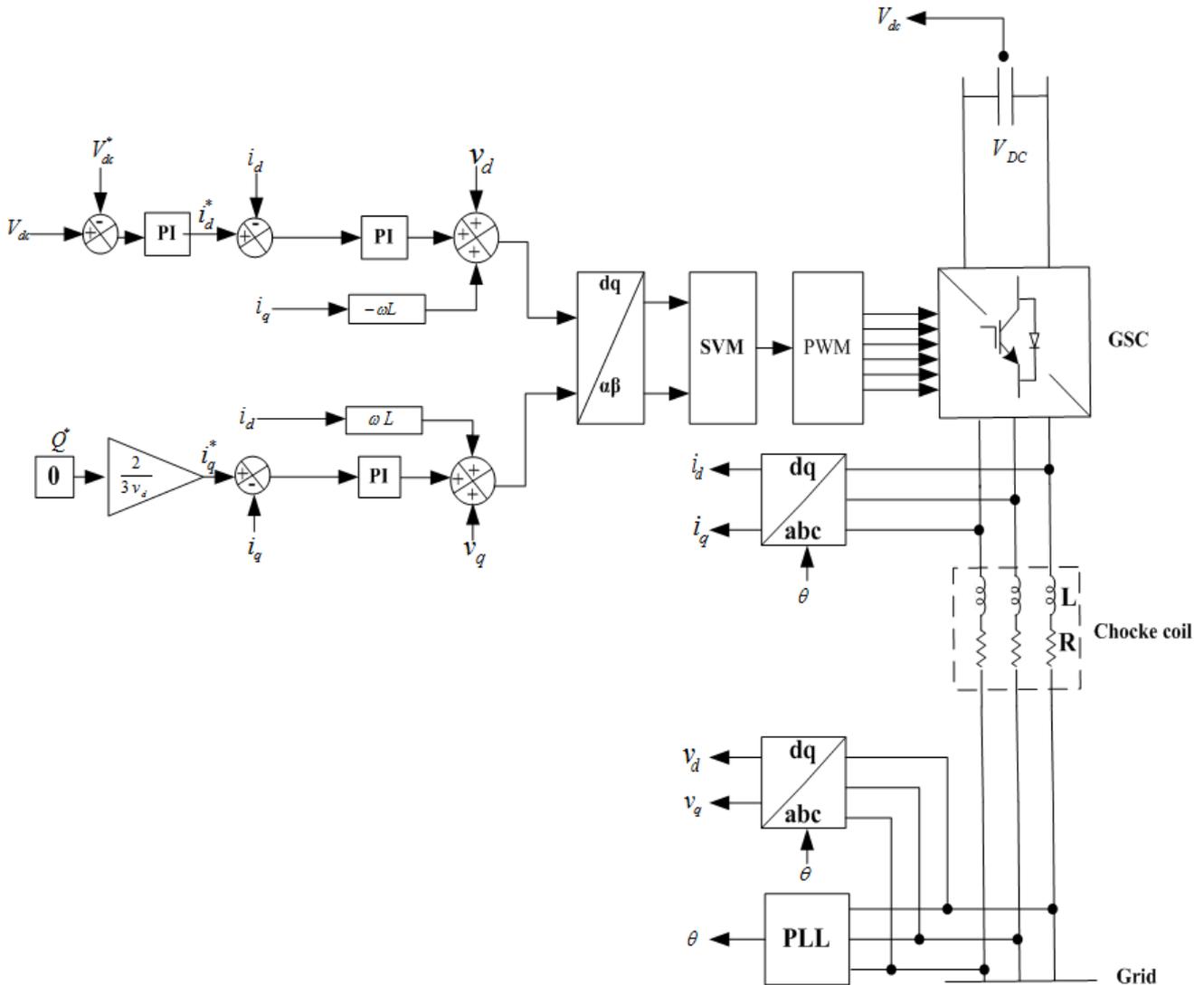


Fig. 5. Grid side converter control.

6. Simulation Results and Discussion

The model of wind turbine based five-phase PMSG in addition to the back-to-back- interface converters for grid connection have been carried out using Matlab/Simulink. The parameters of the system under study are given in appendix A. The proposed control scheme of the five-phase PMSG based variable speed WECS has been carried out using MATLAB/Simulink at different values of wind speed in order to investigate the wind speed estimation technique and the MPPT at the generator side in addition to the unity power factor control at the grid side and common dc-link capacitor voltage control of the interface converters.

6.1. Ramp Change Wind Speed

Fig.6 shows the actual and estimated wind speed, error in

wind speed, the reference and actual rotor speed, power coefficient, tip speed ratio, mechanical power, the mechanical and electromagnetic torque of the PMSG and the five-phase current of PMSG. According to wind turbine characteristic, the estimated and actual wind speed values coincide well and when wind speed varies the controller adjust PMSG rotor speed to follow the same value of ω_{m-opt} . It is clear that the actual and reference rotor speed agree well and the error between them is very small. Moreover, the power coefficient and tip speed ratio are almost constant following their optimal values for the whole simulation period. This in-turn prove that the MPPT has been achieved. The actual and estimated mechanical power agree well with the maximum power. The mechanical and electromagnetic torques of five-phase PMSG are varying according to the change in wind speed. Fig.7 shows the dc-link capacitor voltage, grid voltage and current, dq-axis grid current, power factor, and injected active and reactive power. It is the clear that sinusoidal grid voltage and

current are in-phase for the whole simulation period to achieve unity power factor. The reference and actual dc-link voltage coincide well. The actual and reference q-axis current at grid side is always controlled to be zero to achieve unity power factor. Therefore, the injected reactive power is zero during the whole simulation time, whereas the injected active power has a changes according to the change in the wind speed.

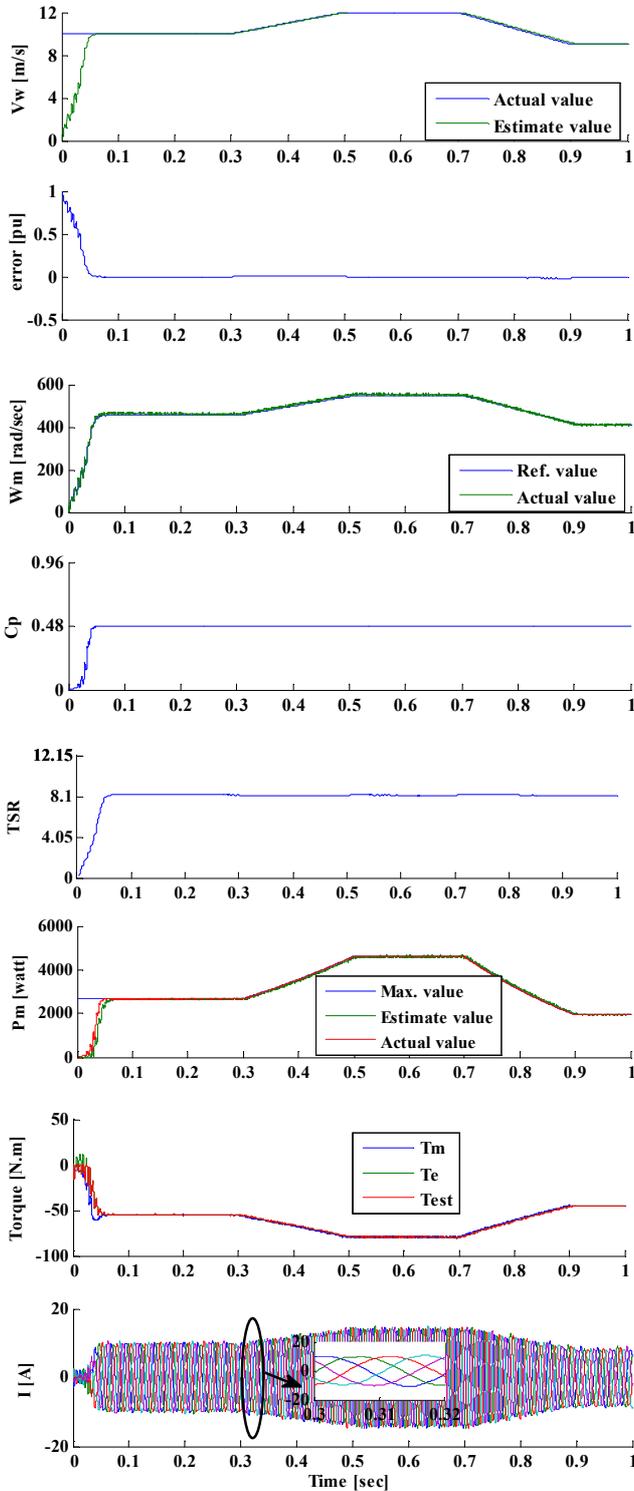


Fig. 6. Simulation results under machine side converter.

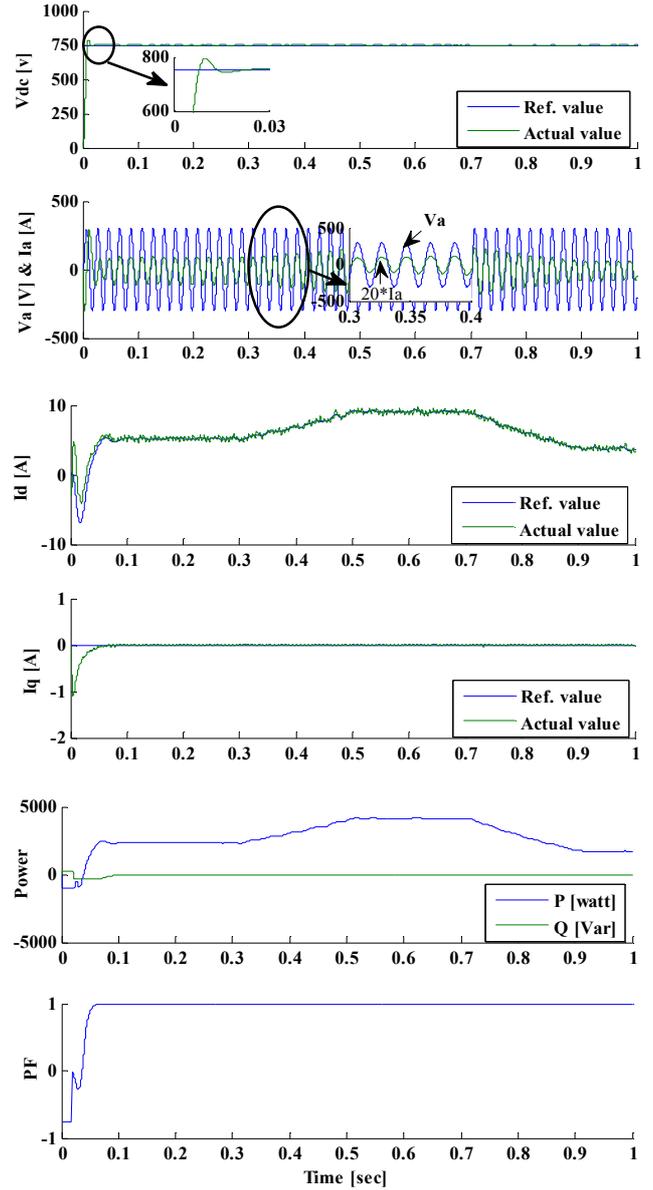


Fig. 7. Simulation results under grid side converter.

6.2. Random Wind Speed

The effectiveness of the proposed control techniques has been investigated with Random wind speed variation. Fig.8 shows the actual and estimated wind speed, the reference and actual rotor speed, power coefficient, tip speed ratio, mechanical power, the mechanical and electromagnetic torque of the PMSG and the five-phase current of PMSG. It is clear that the difference between estimated and actual wind speed is very small, the turbine shaft speed is controlled to track its reference value. Achievement of MPPT is known, from the power coefficient, which is almost constant value at (0.48) and the change of the tip speed ratio that varies in a relatively small range around the optimal value of (8.1). The actual and estimated mechanical power agrees well with the maximum. The mechanical and electromagnetic torques of PMSG coincides well. Fig. 9 shows the dc-link capacitor voltage,

grid voltage and current, dq-axis grid current, power factor and injected active and reactive power. It is clear that sinusoidal grid voltage and current are in-phase for the whole simulating period to achieve unity power factor. The reference and actual dc-link voltage coincide well. The actual and reference q-axis current at grid side is always controlled to be zero to achieve unity power factor. The injected reactive power is zero during the whole simulation time, whereas the injected active power has a step change according to the change in the wind speed.

Simulation results prove that the wind speed estimation algorithm has the ability to estimate the wind speed, the MSC has the ability to control the PMSG to extract the maximum power based on MPPT control technique, and the GSC has the ability to achieve unity power factor at the grid side.

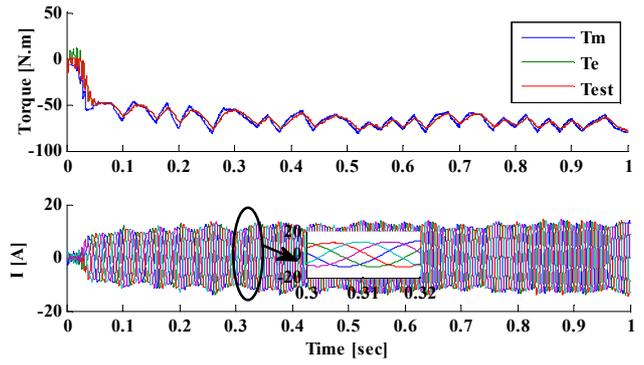
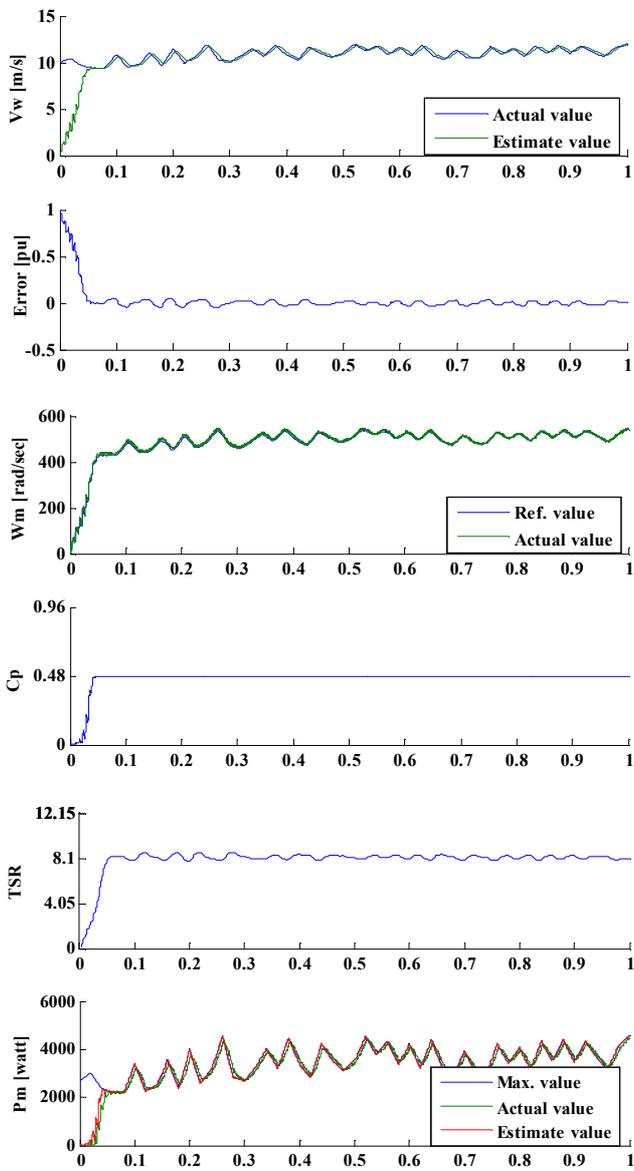


Fig. 8. Simulation results under machine side converter.

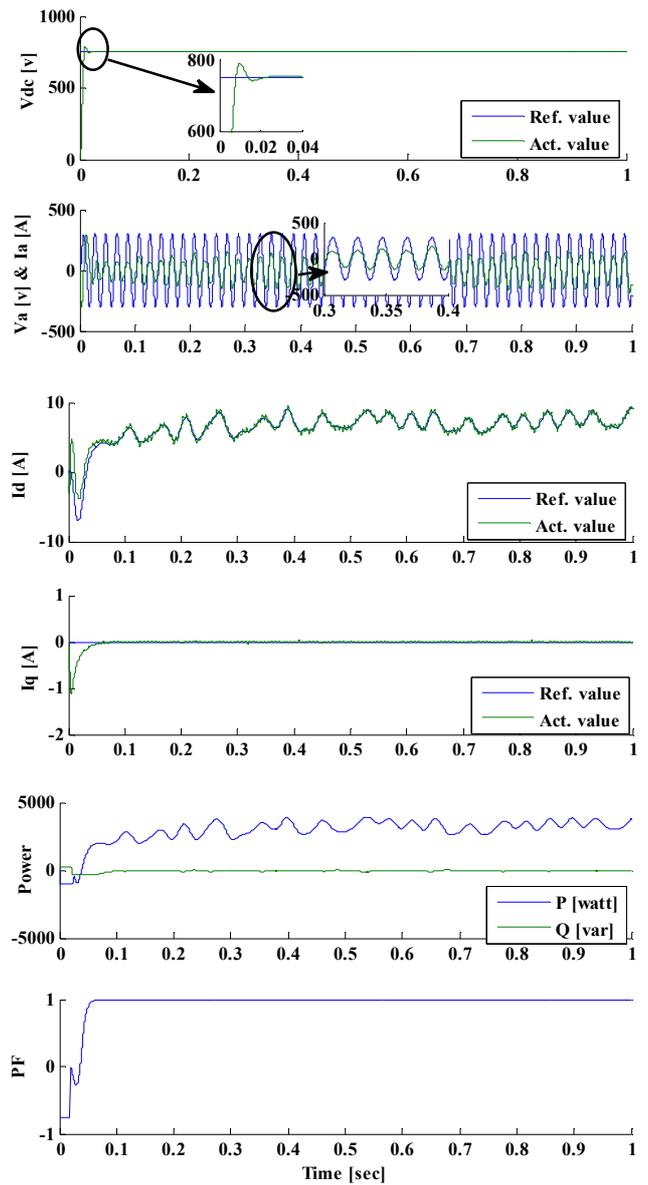


Fig. 9. Simulation results under grid side converter.

7. Conclusion

This paper has presented comprehensive modeling of direct driven five-phase PMSG based grid-connected wind turbines

along with the control schemes of the interfacing converters. Wind speed estimation has been achieved based on measured rotor speed. Five-phase to three-phase interface power converter based back-to-back common dc-link converter has been used to achieve the system objectives. The generator side converter has been used to achieve maximum power operation point at each wind speed. The grid side converter has been used to inject sinusoidal current in-phase with the grid voltage

in addition to controlling the common dc-link capacitor voltage. Vector current controller has been employed on the grid side VSI to obtain unity power factor. Simulation results prove that the proposed control scheme has a great capability to obtain unity power factor at the grid side and to achieve sensorless maximum power point tracking of wind turbine based five-phase PMSG during wind speed variation.

Appendix

Appendix 1. Specification of Wind Turbine

blade radius	$R = 1.8m$
Air density	$\rho = 1.225 kg/m^3$
Optimal tip speed ratio	$\lambda_{opti} = 8.1$
Maximum power Coefficient	$C_{p-max} = 0.48$

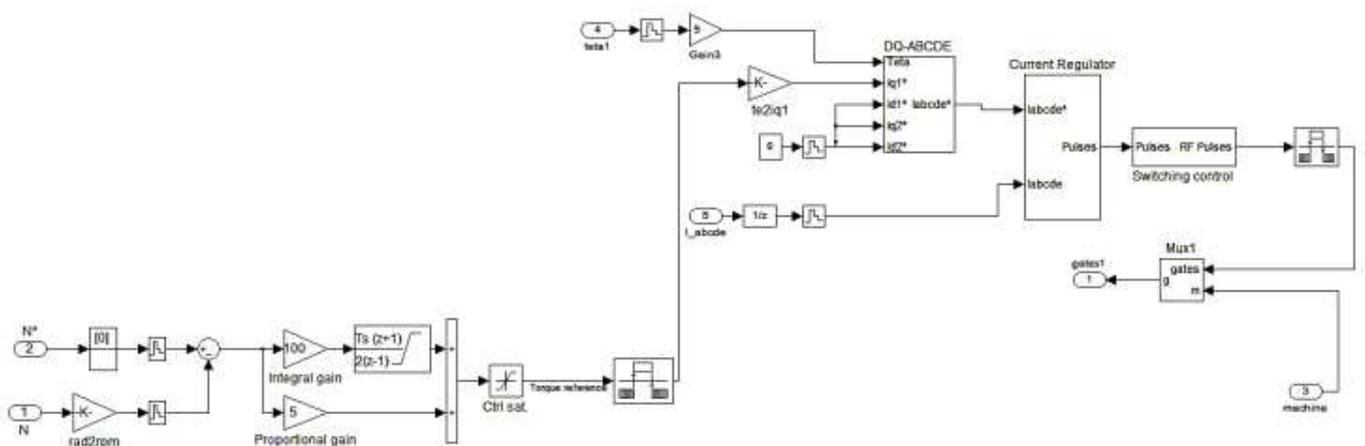
Appendix 2. Five-Phase PMSG Parameters

Pole pairs number	$n_p = 5$
Stator resistance	$R_s = 0.425\Omega$
Direct-axis inductance	$L_d = 0.00835H$
quadrature-axis inductance	$L_q = 0.00835H$
Moment of inertia	$J = 0.01197kg.m^2$
Flux linkage	$\psi = 0.433wb$

Appendix 3. DC Bus and Grid Parameters

dc-link voltage	$V_{dc} = 750V$
Capacitor of the dc-link	$C = 2000\mu F$
Grid frequency	$F = 50hz$
Grid resistance	$R_g = 0.015\Omega$
Grid inductance	$L_g = 0.002H$

Appendix 4. Machine Side Control



Hysteresis-current control of five-phase PMSG

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