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Control Scheme for an IPM Synchronous Generator Based-Variable Speed Wind Turbine

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ABSTRACT

This paper proposes a control strategy for an IPM synchronous generator-based variable speed wind turbine this control technique is simple and has many advantages over indirect vector control technique as in this scheme, the requirement of the continuous rotor position is eliminated as all the calculations are done in the stator reference frame and can eliminate some of the drawbacks of traditional indirect vector control scheme. This scheme possesses advantages such as lesser parameter dependence and reduced number of controllers compared with the traditional indirect vector control scheme Furthermore, the system is unaffected to variation in parameters because stator resistance is the only required criteria. This control technique is implemented in MATLAB/Sim power systems and the simulation results shows that this suggested control technique works well and can operate under constant and varying wind speeds. Finally, a sensorless speed estimator is implemented, which enables the wind turbine to operate without the mechanical speed sensor.

KEYWORDS: *Direct control, interior permanent Magnet (IPM) synchronous generator, sensorless speed estimator, variable speed wind turbine*

I. Introduction

Wind energy is one of the best renewable sources for Power generation in Remote areas. over the past 25 years the electrical power generation through renewable energy resources especially with wind energy is increasing due to the limited conventional resources, increased environmental pollution and to reduce the dependency on fossil fuel, and to minimize the impact of climate change. Currently, variable speed wind turbine technologies dominate the world market share due to their advantages over fixed speed generation such as increased energy capture, operation at maximum power point, improved efficiency, and power quality.

Renewable energy resources exist over wide geographical areas, in contrast to other energy sources, which are concentrated in a limited number of countries. Rapid deployment of renewable energy and energy efficiency is resulting in significant energy security, climate change mitigation, and economic benefits. in international public opinion surveys there is strong support for promoting renewable sources such as solar power and wind power.

Most of these wind turbines use doubly fed induction generator (DFIG) based variable speed wind turbines with gearbox this technology has an advantage of having power electronic converter as the converter is connected to the rotor circuit. However, the use of gearbox in these turbines to couple the generator with the turbine causes problems. Moreover, the gearbox requires regular maintenance as it suffers from faults and malfunctions. Variable speed wind turbine using permanent magnet synchronous generator (PMSG) without gearbox can enhance the performance of the wind energy conversion system. The use of permanent magnet in the rotor of the PMSG makes it unnecessary to supply magnetizing current through the stator for constant air-gap flux. Therefore, it can operate at higher power factor and efficiency. The previous works done on PMSG based wind turbines are mostly based on surface permanent magnet-type synchronous generator. Very few works have been done so far on interior PMSG-based wind turbines, which can produce additional power by exploiting their rotor saliency. It can also be operated over a wide speed range (more than rated speed) by flux weakening, which will allow constant power-like operation at speeds higher than the rated speed. This work is based on interior permanent magnet-type synchronous generator-based variable speed wind turbine.

There are different control strategies reported in the literature for permanent synchronous generator based variable speed wind turbine such as switch mode boost rectifier (uncontrolled diode rectifier cascaded by a boost dc–dc chopper) , three-switch pulse width modulation (PWM) rectifier The control of PMSG-based variable speed wind turbine with switch-mode rectifier has the merit of simple structure and low cost because of only one controllable switch. However, it lacks the ability to control generator power factor and introduces high harmonic distortion, which affects the generator efficiency.

Moreover, this scheme introduces high voltage surge on the generator winding which can reduce the life span of the generator [5]. Traditional vector control scheme, as shown in Fig. 1, is widely used in modern PMSG-based variable speed wind energy conversion system [1], [2], [3], [4]. In this scheme, the generator torque is controlled indirectly through current control. The output of the speed controller generates the d-axes and q–axes current references, which are in the rotor reference frame. The generator developed torque is controlled by regulating the currents according to the generator torque equation.

In this paper, a direct control strategy is implemented where coordinate transformations are not required as all the calculations are done in stator reference frame Thus, the requirement of continuous rotor position (θr) is eliminated. This method is inherently sensorless and have several advantages compared with the traditional indirect vector control scheme. However, a speed sensor is required only for speed control loop. Therefore, a sensorless speed estimator is proposed and implemented in this paper to estimate the speed without a mechanical sensor.

II. TURBINE MODELING PROCEDURE FOR PAPER SUBMISSION

A. Wind Turbine Modeling and Maximum Power Extraction

The power captured by the wind turbine is given by [6]

$$P_m = 0.5AC_p(\lambda_r, \beta) \times (v_w)^3 = 0.5\rho AC_P \times (\omega_m R/\lambda_r)^3 \quad (1)$$

ρ = Density of air (kg/m3)

v_w =Velocity of wind (m/s)

A = Area enclosed by turbine blades (m2)

Cp = Power coefficient

ω_m = Speed at which turbine rotates

R = radius of wind turbine blades.

The power coefficient is a function of tip speed ratio (λ_r) and pitch angle (β)

The tip speed ratio is given by

$$TSR=\lambda_r = \frac{\text{rotor tip speed}}{\text{wind speed}} = \omega_m R/v_\omega \quad (2)$$

The wind turbine can extract maximum power from wind only when Cp is at maximum value (Cp_opt) [1]. Cp value depends on β and λr. Therefore, it is required to make the TSR(λr) value always stays at an optimum value (λr_opt). If wind speed is varying, the turbine speed must be adjusted accordingly so as to see λr is at λr_opt.

we can see that maximum value of Cp is possible only when β = 0 and as pitch angle increases, the maximum possible value of Cp decreases. So it is desirable that β = 0 in order to get maximum power extraction from the wind with higher efficiency.

The target optimum power from a wind turbine is given by

$$P_{m\_opt} = 0.5\rho AC_{P\_opt}\left((\omega_{m\_opt} R)/\lambda_{r\_opt}\right)$$
$$=K_{opt}(\omega_{m\_opt}) \quad (3)$$

Where

$$K_{opt} = 0.5\rho AC_{p\_opt}(R/\lambda_{r\_opt})^3 \quad (4)$$

And

$$\omega_{m\_opt} = \omega_{g\_opt} = (\lambda_{r\_opt}/R)v_m = K_w v_w (5)$$

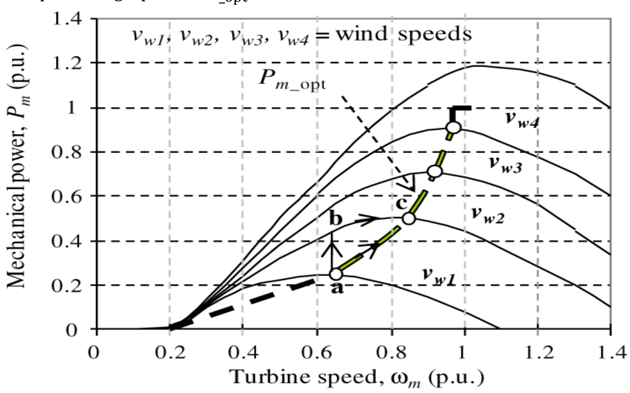

Fig.1. Mechanical power generated by the turbine as a function of the rotor speed for different wind speeds.

The optimum torque can be given by

$$T_{m\_opt}(t) = K_{opt}\,[W_{m\_opt}(t)]^2 \quad (6)$$

Optimum values are the values at which turbine can extract maximum energy from the varying wind speeds and thus producing maximum power from the generator. The purpose of the controller is to keep the turbine operating on this curve, as the wind speed changes [1]. There is always a matching rotor speed that produces optimum power for a particular wind speed. If the controller can properly follow the optimum curve, the wind turbine will produce maximum power at any speed within the allowable range. The optimum torque can be calculated from the optimum power given by (6).

III. Modeling of IPM Synchronous Generator

The PMSG is basically wound rotor synchronous generator where the rotor is replaced with permanent magnet. Because of permanent magnet, rotor does not require any exciting current for maintaining air gap flux. So the rotor excitation losses will be absent. So wind energy can be used efficiently for producing electric power. To analyze IPMSG, the machine is modeled in d-q reference frame, which is synchronously rotates with the rotor, where d-axis is along the magnetic axis and q-axis is orthogonal to it is used.

The d-axis and q-axis voltages of PMSG is given by

$$v_d = -i_d R_s - \omega_r \lambda_q + p\lambda_d \quad (7)$$

$$v_q = -i_q R_s + \omega_r \lambda_d + p\lambda_q \quad (8)$$

The d-axis and q-axis flux linkages are given by

$$\lambda_d = -L_d i_d + \lambda_M \quad (9)$$

$$\lambda_q = -L_q i_q \quad (10)$$

The torque euation of the PMSG can be written as

$$T_g = -\frac{3}{2}(\lambda_d i_q - \lambda_q i_d) = -\frac{3}{2}P[\lambda_M i_q + (L_d - L_q) i_d i_q] \quad (11)$$

Rs = Resistance of the stator.
ωr = Speed at which generator rotates
λ_M=Magnetic flux
P = Pole pairs.
p = d/dt operator

In equation (7)–(11) v_d, v_q, i_d, i_q, L_d and L_q are the d- and q-axes stator voltages, currents, and inductances, respectively.

The dq model of IPM synchronous generator is shown in Fig.2

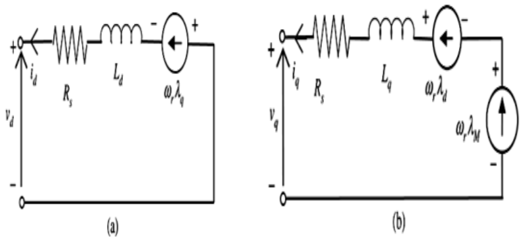

Fig.2. dq-model of IPM synchronous generator:(a) d-axis equivalent circuit and (b) q-axis equivalent circuit.

The first term in the torque equation (11) is the excitation torque that is produced by the interaction of permanent magnet flux i_q and is independent of i_d. The second term is the reluctance torque that is proportional to the product of i_d and i_q to the difference between L_d and L_q .For the surface PMSG, the reluctance torque is zero since $L_d = L_q$, while for the IPM synchronous generator, higher torque can be induced for the same i_d and i_q, if$(L_d - L_q)$ is larger. This is one of the advantages of IPM synchronous generator over surface PMSG.

The d- and q-axes current references can be expressed as

$$i_q^* = \frac{2T_g^*}{3P[\lambda_M + (L_d - L_q)]i_d} \quad (12)$$

$$i_d^* = \frac{\lambda_M}{2(L_d - L_q)} - \sqrt{\frac{\lambda_M^2}{4(L_d - L_q)} + (i_q^*)^2} \quad (13)$$

Various parameters of PMSG considered for simulation analysis is given in Table I

TABLE. I

Rated power	4Kw
Rated torque	24Nm
Rated speed	1600 rpm
Rated voltage	415 V rms
Rated current	9.6 A rms
Magnetic flux linkage	0.525723Wb
d-axis inductance (Ld) per phase	18.237mH
q-axis inductance (Lq) per phase	0.0049 kg-m2
Stator resistance	1.56 ohms
No.of poles	6
Static friction	0.637 Nm
Viscous damping	0.237 Nm/krpm

IV. Proposed Direct Control Scheme for IPM Synchronous Generator

In the proposed direct control scheme, current controllers are not used. Instead, the torque and stator flux can be regulated independently and directly by using two separate hysteresis controller bands for flux as well as torque. This control scheme for IPM synchronous generator is shown in Fig. 3.

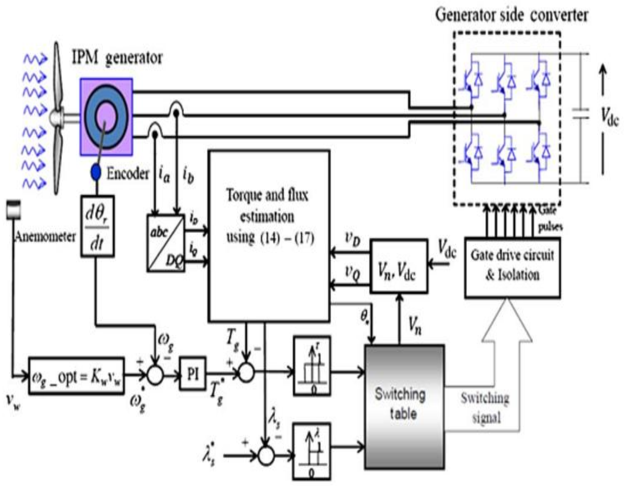

Fig. 3. Proposed direct control scheme

The selection rule is made in such a way that errors present in torque and flux will be within the hysteresis bands so as to get the required flux and torque response [6]. The required voltage vectors for switching the converter are selected according to the switching table as shown in Table. II

The selection of the voltage space vectors can be determined by the position of the stator flux linkage vector and the outputs of the two hysteresis comparators. The hysteresis control blocks compare the torque and flux references with estimated torque and flux, respectively. When the estimated torque/flux drops below its differential hysteresis limit, the torque/flux status output goes high.

TABLE. II

Vector	Sa	Sb	Sc	Vab	Vbc	Vca	
V_0 {000}	0	0	0	0	0	0	Zero vector
V_1 {100}	1	0	0	$+V_{dc}$	0	$-V_{dc}$	Active vector
V_2 {110}	1	1	0	0	$+V_{dc}$	$-V_{dc}$	Active vector
V_3 {010}	0	1	0	$-V_{dc}$	$+V_{dc}$	0	Active vector
V_4 {011}	0	1	1	$-V_{dc}$	0	$+V_{dc}$	Active vector
V_5 {001}	0	0	1	0	$-V_{dc}$	$+V_{dc}$	Active vector
V_6 {101}	1	0	1	$+V_{dc}$	$-V_{dc}$	0	Active vector
V_7 {111}	1	1	1	0	0	0	Zero vector

When the estimated torque/ flux rises above differential hysteresis limit, the torque/flux output goes low. The differential limits, switching points for both torque and flux, are determined by the hysteresis band width [7], [8]. The appropriate stator voltage vector can be selected by using the switching logic to satisfy both the torque and flux status outputs. There are six voltage vectors and two zero voltage vectors that a voltage source converter can produce. The combination of the hysteresis control block (torque and flux comparators) and the switching logic block eliminates the need for a traditional PW modulator [6]. The optimal switching logic is based on the mathematical spatial relationships of stator flux, rotor flux, stator current, and stator voltage. And the stator flux linkage is estimated as

$$\lambda_D = -\int (v_D - i_D R_s)\, dt \quad (14)$$

$$\lambda_Q = -\int (v_Q - i_Q R_s)\, dt \quad (15)$$

The stator flux linkage equation is given as

$$\lambda_s = \sqrt{\lambda_Q{}^2 + \lambda_D{}^2} \; and \; \theta_s = \tan^{-1}(\lambda_Q / \lambda_D) \quad (16)$$

The electromagnetic torque can be calculated by using

$$T_g = -\frac{3}{2} P(\lambda_D i_Q - \lambda_Q i_D) \quad (17)$$

The torque equation in term s of and generator parameters is given by [24]

$$T_g = -\frac{3P\lambda_s}{4L_d L_q}\left(2\lambda_M L_q \sin\delta - \lambda_s (L_q - L_d) \sin 2\delta\right) \quad (18)$$

V. Stator Flux Linkage Control Through Stator Voltage Vector

The stator voltages for a three phase machine in the form of voltage vector is given by

$$v_s = \frac{2}{3}(v_a + v_b e^{j2\pi/3} + v_c e^{j4\pi/3}) \quad (19)$$

According to the wind speed variations, it is needed to control the switches of generator side converter. Here, we are using the ideal bidirectional switches represents the power switches with their anti parallel diodes. The primary voltages are determined by the statue of these three switches shown in Fig.4

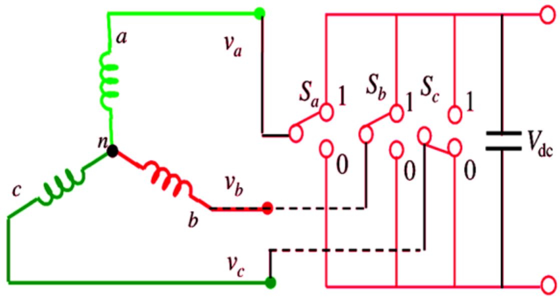

Fig. 4.Rectifier connected to IPM synchronous generator.

By making the use of a series of switches, from the 3 input legs, AC is converted into a controlled DC. Here total of eight switching vectors are possible for the rectifier, in that 6 are active switching vectors and 2 are zero vectors depending on the position of these 3 switches (Sa, Sb, Sc), the primary voltage vectors va, vb, vc are defined. The 6 non-zero voltage vectors are displaced 600 from one another. These eight voltage vectors can be written in single equation as

$$v_s(S_a, S_b, S_c) = V_D(S_a + S_b e^{j2\pi/3} + S_c e^{j4\pi/3}) \qquad (20)$$

Where $V_D = 2/3V_{dc}$ and $V_{dc} = \mathrm{dc-link\ voltage}$

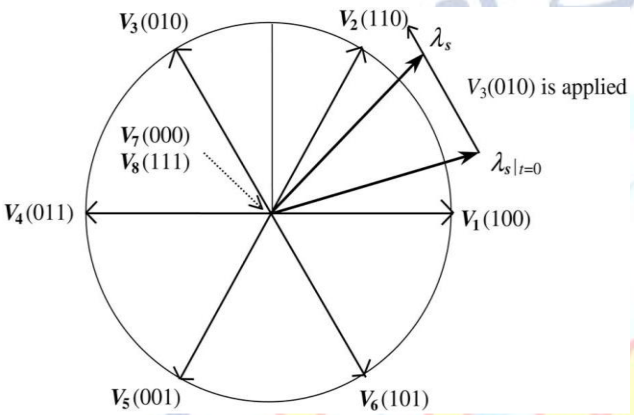

Fig.5.Vectorial representation of the stator voltage vectors.

In equation (20), by substituting values of switching states, we can find the values of these 6 non-zero voltage vectors. These voltage vectors can be represented as in table III

SIX VOLTAGE VECTOR VALUES

	V_1	V_2	V_3	V_4	V_5	V_6
V_D	V_D	$0.5V_D$	$-0.5V_D$	$-V_D$	$-0.5V_D$	$0.5V_D$
V_Q	0	0.866 V_D	0.886 V_D	0	$-0.886V_D$	$-0.886V_D$

TABLE. III

A.Control of magnitude of stator flux linkages

The stator flux linkage in the stationary reference frame can be given as

$$\lambda_s = \int (v_s - i_s R_s)\, dt \qquad (21)$$

Above equation can be rewritten as

$$\lambda_s = v_s t - R_s \int i_s\, dt \qquad (22)$$

The above equation showing that the tip of the stator flux linkage vector λ_s will move in the direction of the applied voltage vector. How far the tip of the stator flux linkage will move is determined by the duration of time for which the stator vector is applied is shown in Fig. 6

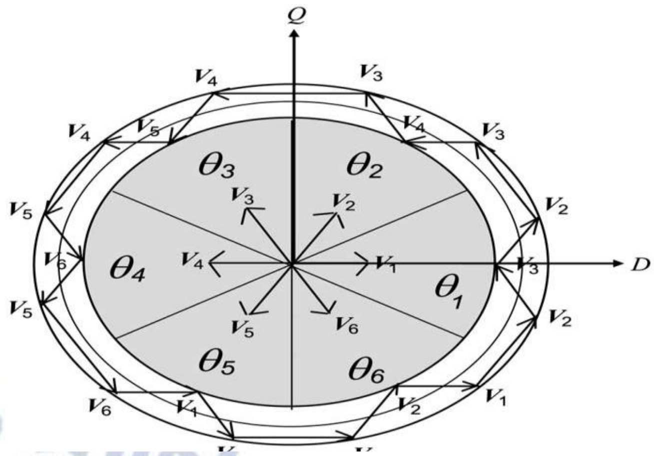

Fig. 6.Control of the magnitude and the direction of the stator flux.

Fig. 6 shows the regions to control magnitude and direction of the stator flux, the vector plane of the voltages is partitioned into six regions $\theta 1$–$\theta 6$ in order to select the required voltage vectors of the converter to control the amplitude and direction of the stator flux. In every region, two neighboring voltage vectors have to be chosen depending on hysteresis commands. When $\lambda_s$is in region $\theta 1$, V2 is selected to decrease the amplitude of λ_s andV3 is selected to increase the amplitude of λ_s . That means amplitude of λ_s is controlled by making error value to stay within hysteresis band limits. In this way, the controller works by choosing the switching vectors properly for the converter. [6], [8].

B. Rotation of stator flux linkage (λ_s)control

By controlling the direction of rotation of λ_s, the electromagnetic torque can be controlled, this is with respect to the equation (18). In anti-clockwise functioning, if the torque error is positive that means actual is less than reference, the appropriate switching vectors are chosen accordingly to make λ_s rotate in the same direction. This makes θ to decrease and so actual torque to increase. λ_s rotates in the same direction till the actual torque become more than the reference torque. When actual torque is more than the reference, error becomes negative and voltage vectors of opposite axes are selected to keep λ_s rotating in the reverse direction. This makes θ to decrease and so actual torque to decrease. By choosing the switching vectors in this pattern, λ_s is rotated in all directions and the rotation ofλ_s is controlled by the commands given by the torque hysteresis controller.

The effect of two nonzero voltage vectors V7 and V8 is more complicated. It is seen from (22) that λs will stay at its original position when zero voltage vectors are applied. This is true for induction machine since the stator flux linkage is uniquely determined by the stator voltage, where the rotor voltages are always zero. In the case of an IPM synchronous generator, λs will change even when the zero voltage vectors are applied, since magnet flux λs continues to be supplied by the rotor and it will rotate with the rotor. In other words, λs should always be in motion with respect to the rotor flux linkage.

The voltage vector switching table to control the amplitude as well as direction ofλs is given in Table IV. λ and τ denotes the hysteresis controller outputs of stator flux and torque, respectively.

Table. IV

SIX VECTOR SWITCHING TABLE FOR CONVERTER

	θ	θ_1	θ_2	θ_3	θ_4	θ_5	θ_6
λ	τ						
λ=1	τ=1	V_2(110)	V_3(110)	V_4(110)	V_5(110)	V_6(110)	V_1(110)
	τ=0	V_6(110)	V_1(110)	V_2(110)	V_3(110)	V_4(110)	V_5(110)
λ=0	τ=1	V_3(110)	V_4(110)	V_5(110)	V_6(110)	V_1(110)	V_2(110)
	τ=0	V_5(110)	V_6(110)	V_1(110)	V_2(110)	V_3(110)	V_4(110)

VI. Direct Control Technique for IPM Synchronous Generator-Based Wind Turbine

The direct control technique for IPM synchronous generator is shown in Fig. 3, where the switching scheme used is shown in Table IV. The three-phase variables are transformed into stationary DQ-axes variables. As shown in Table. II, torque error and flux error are the inputs to the flux hysteresis comparator and torque hysteresis comparator, respectively. The outputs of the hysteresis comparators (T, λ) are the inputs to the voltage-switching selection lookup table. As shown in Fig. 3, this scheme is not dependent on generator parameters except the stator resistance. Moreover, all calculations are in the stator DQ reference frame and without any co-ordinate transformation.

The DQ-axes flux linkage components $\lambda_{Q(k)}$ and $\lambda_{Q(k)}$ at the k th sampling instant is given by

$$\lambda_{Q(k)} = T_s\left[-v_{Q(k-1)} + R_s i_{Q(k)}\right] + \lambda_{Q(k-1)} \quad (23)$$

$$\lambda_{D(k)} = T_s\left[-v_{D(k-1)} + R_s i_{D(k)}\right] + \lambda_{D(k-1)} \quad (24)$$

Where Ts is the sampling time, the variables with subscript K are their values at the K the sampling instant, and the variables with K-1are the previous samples. The DQ -axes currents can be obtained from the measured three-phase currents and the DQ-axes voltages are calculated from the measured dc-link voltages. Table II shows Vd and Vq axes voltages for the applied voltage vectors.

The magnitude of the stator flux linkage is calculated by

$$\lambda_{s(k)}=\sqrt{\lambda_{D(k)}^2+\lambda_{Q(k)}^2} \text{ and } \theta_s = \tan^{-1}(\lambda_{Q(k)}/\lambda_{D(k)}) \quad (25)$$

The torque developed is given by

$$T_{g(k)} = -\frac{3}{2}P(\lambda_{D(k)}i_{Q(k)} - \lambda_{Q(k)}i_{D(k)}) \quad (26)$$

The generator developed torque, in terms of stator and rotor flux linkage amplitudes, is also given by

$$T_{g(k)} = -\frac{3P\lambda_{s(k)}}{4L_d L_q} \times [2\lambda_M L_q \sin\{\delta_{(k)}\} - \lambda_{s(k)}(L_q - L_d)\sin 2(\delta_{(k)})]$$

VII. Simulink Model

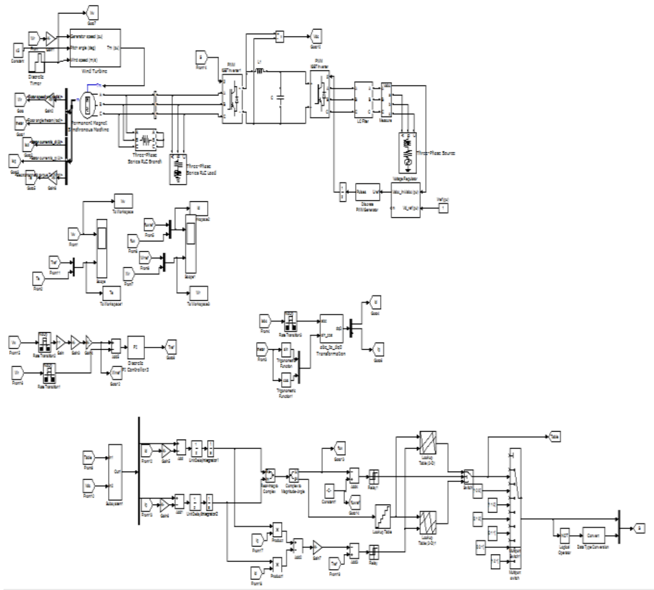

Fig. 7.Simulink model for direct control scheme

VIII. SIMULATION RESULTS AND ANALYSIS

By varying wind speed performance of this direct control technique is observed. It can be seen that for varying wind speeds, torque, flux, turbine speed are following the references shown in fig. 7 is implemented in MATLAB/Sim Power systems dynamic system simulation software.

The bandwidths of torque and flux hysteresis controllers are 10% of their rated values. a smaller hysteresis Band width can reduce ripples in torque. The sampling time for the torque and speed control loops is 10 and 100μs, respectively. For comparisons, the traditional vector-controlled scheme shown in Fig.8 has also been implemented in MATLAB /SimPowerSystems using the same IPM synchronous generator. MATLAB/SimPower Systems wind turbine model is used in this work. The input to the wind turbine model is wind speed and the output is torque

A. Performance of the Indirect Vector Control Scheme

The performance of the indirect vector control of IPM synchronous generator-based variable speed wind turbine. The d-axes and q-axes currents and their references are shown in Fig. 8(b) and (c), respectively, and the wind speed in Fig. 8(a). It is seen that d-axes and q-axes currents follow their references quite well and regulate the generator current under different wind speeds. As shown in Fig. 8(d), the speed controller is able to regulate the speed for varying wind speeds.

B.Performance of Direct Torque and Flux Control Scheme

The performance of direct control scheme for IPM synchronous generator-based variable speed wind turbine. Fig. 9(a)–(d) shows the wind speed, torque response, flux linkage response, and speed response, respectively. As shown in Fig. 9(b) and (c), the torque and flux linkages are following these references quite well and regulate the torque and flux of the generator at different wind speeds. Fig. 9(d) shows the speed response, where the measured speed follows the reference speed well and the speed controller regulates the generator speed under varying wind conditions.

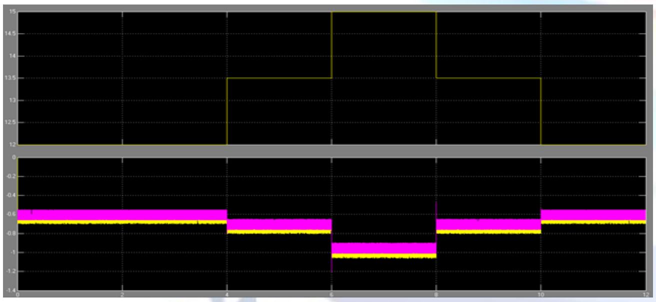

Fig. 8. Performance of the traditional indirect vector control scheme: (a) wind speed, (b) d-axis current and its reference

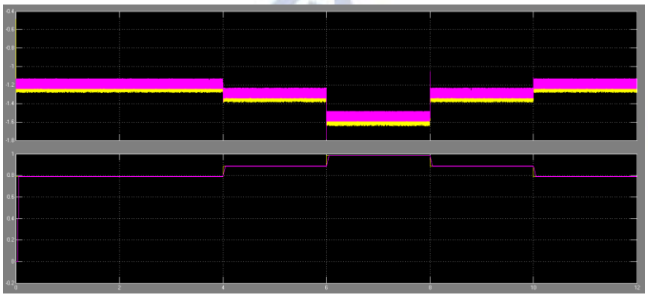

Fig. 8. Performance of the traditional indirect vector control scheme: q-axis current and its reference, and (d) speed reference and measured speed.

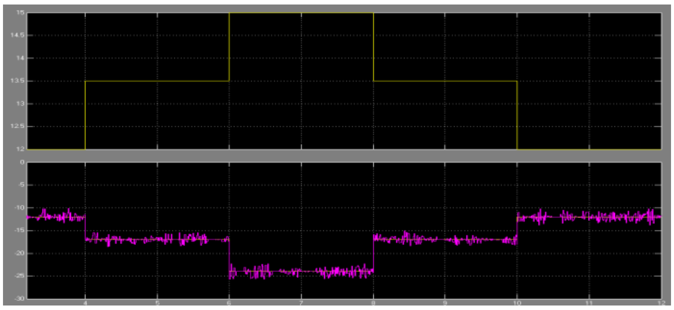

Fig. 9. Performance of the direct control scheme: (a) Wind speed, (b) torque and its reference

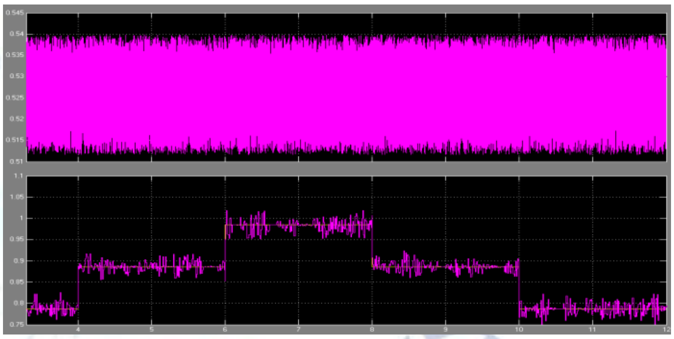

Fig. 9. Performance of the direct control scheme:(c) Flux linkage and its reference, and (d) speed reference and measured

IX. SENSORLESS OPERATION

In direct control strategy of PMSG-based variable speed wind turbine, position sensor is not required for torque or flux control loop. However, for speed control, the sensor/optical encoder is required the generator speed is measured by measuring the position using position sensor (encoder). However, the existence of the position sensor adds several disadvantages. An emphasis is placed on eliminating the position sensor from the IPM synchronous generator-based variable speed wind turbine to enhance the robustness and reliability of the drive system. The generator speed is estimated from the measured variables, that is generator voltages and currents. Knowing the torque $T_{g(k)}$from (26), the torque angle $\delta_{(k)}$ can be found from (27). The rotor position is then given by $\lambda_{s(k)} \pm \delta_{(k)}$which after differentiation gives the speed signal. The proposed speed estimator is thus based on the following steps and inputs [7].

1) Estimate the stator flux linkage using (25).
2) Calculate the actual developed torque from(26). The torque angle δ can be calculated from the torque equation (27), or It may be obtained from a lookup table representing (27).
3) The rotor position can be obtained from the stator flux position and the torque angle.

4) Change of the rotor position in certain time interval gives the rotor speed. This must be filtered to get a smooth speed signal.

VIII. Conclusion

The Direct control scheme to control IPMSG based variable speed wind turbine is developed and It is seen that this controller is capable to maximize the power output from variable speed wind turbine system under varying wind velocities. Simulation results show that the controller works well by achieving controlled torque and speed under fluctuating wind. In this control scheme, no rotor position is required as all the calculations are done in stator reference frame. The proposed direct control scheme possesses several advantages compared with indirect vector control scheme, such as: 1) lesser parameter dependence; 2) torque and flux control without rotor position and PI controller which reduce the associated delay in the controllers; and 3) sensorless operation without mechanical sensor. However, direct control scheme has the problem of higher torque ripple that can introduce speed ripples and dynamic vibration in the power train. The simulation and experimental results for the sensorless speed estimator are presented, and the results show that the estimator can estimate the generator speed quite well with a very small error.

References

[1] M. E. Haque, M. Negnevitsky, and K. M. Muttaqi, “Anovel control strategyfor a variable-speed wind turbine with a permanent-magnet synchronous generator,” IEEE Trans. Ind. Appl., vol. 46, no. 1, pp. 331–339,Jan./Feb. 2010.

[2] S. Morimoto, H. Nakayama,M. Sanada, and Y. Takeda, “Sensorless outputmaximization control for variable-speed wind generation system usingIPMSG,” IEEE Trans. Ind. Appl., vol. 41, no. 1, pp. 60–67, Jan./Feb. 2005.

[3] W. Qiao, L. Qu, and R. G. Harley, “Control of IPM synchronous generatorfor maximum wind power generation considering magnetic saturation,”IEEE Trans. Ind. Appl., vol. 45, no. 3, pp. 1095–1105, May/Jun. 2009.

[4] A. Uehara, A. Pratap, T. Goya, T. Senjyu, A. Yona, N. Urasaki, andT. Funabashi, “A coordinated control method to smooth wind powerfluctuation of a PMSG-based WECS,” IEEE Trans. Energy Convers., vol. 26, no. 2, pp. 550–558, Jun. 2011.

[5] K. Nishida, T. Ahmed, and M. Nakaoka, “A cost-effective high-efficiencypower conditioner with simple MPPT control algorithm for wind-powergrid integration,” IEEE Trans. Ind. Appl., vol. 47, no. 2, pp. 893–900,Mar. 2011.

[6] L. Zhong, M. F. Rahman, and K. W. Lim, “Analysis of direct torque controlin permanent magnet synchronous motor drives,” IEEE Trans. PowerElectron., vol. 12, no. 3, pp. 528–536, May 1997.

[7] M. F. Rahman, L. Zhong, M. E. Haque, and M. A. Rahman, “Adirect torquecontrolled interior permanent magnet synchronous motor drive without a speed sensor,” IEEE Trans. Energy Convers., vol. 18, no. 1, pp. 17–22,sMar. 2003.

[8] M. E. Haque and M. F. Rahman, Permanent Magnet Synchronous Motor Drives: Analysis, Modeling and Control. Germany: VDM Verlag, 2009.

[9] H. Zhu, X. Xiao, and Y. Li, “Torque ripple reduction of the torque predictivecontrol scheme for permanent-magnet synchronous motors,” IEEE Trans.Ind. Electron., vol. 59, no. 2, pp. 871–877, Feb. 2012