

## An Advanced Speed Control Scheme for IPM Based Synchronous Generator

R.Jaga n Babu <sup>1</sup> & S.Raj Shekar <sup>2</sup>

<sup>1</sup>M.Tech Scholar, Dept. of EEE, ASR College of Engineering and Technology, JNTUK, A.P

<sup>2</sup>Assistant Professor, Dept. of EEE, ASR College of Engineering and Technology, JNTUK, A.P

### Abstract:

*This paper proposes a direct control strategy for an interior permanent magnet synchronous generator-based variable speed wind turbine by using fuzzy logic. In this scheme, the requirement of the continuous rotor position is eliminated as all the calculations are done in the stator reference frame. This scheme possesses advantages such as lesser parameter dependence and reduced number of controllers compared with the traditional indirect vector control scheme. Fuzzy logic adds to bivalent logic an important capability—a capability to reason precisely with imperfect information. Imperfect information is information which in one or more respects is imprecise, uncertain, incomplete, unreliable, vague or partially true. In fuzzy logic, results of reasoning are expected to be provably valid, or *p*-valid for short. The direct control scheme is simpler and can eliminate some of the drawbacks of traditional indirect vector control scheme. The proposed control scheme is implemented in MATLAB/ Sim Power Systems and the results show that the controller can operate under constant and varying wind speeds. Finally, a sensor less speed estimator is implemented, which enables the wind turbine to operate without the mechanical speed sensor. The simulation and experimental results for the sensor-less speed estimator are presented.*

**Keywords:** Direct control; interior permanent magnet (IPM) synchronous generator; sensor-less speed estimator; variable speed wind turbine; Fuzzy logic Controller

### I. INTRODUCTION

The wind energy will play a major role to meet the renewable energy target worldwide, 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 [1]. This technology has an advantage of having power electronic converter with reduced power rating (30% of full rated power) 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.

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 airgap flux. Therefore, it can operate at higher power factor and efficiency [5], [6]. The previous works done on PMSG based wind turbines are mostly based on surface permanent magnet-type synchronous generator [7] [9]. Very few works have been done so far on interior PMSG based wind turbines, which can produce additional power by exploiting their rotor saliency [10]. 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 [10], [11]. This work is based on interior permanent magnet-type synchronous generator-based variable speed wind turbine.

There are many misconceptions about fuzzy logic. The principal misconception is that fuzzy

logic is fuzzy. The stated definition underscores that fuzzy logic is precise. In fuzzy logic precision is achieved through association of fuzzy sets with membership functions and, more generally, association of granules with generalized constraints [11]. What this implies is that fuzzy logic is what may be called precisiated logic.

Moreover, this scheme introduces high voltage surge on the generator winding which can reduce the life span of the generator [16]. Traditional vector control scheme, as shown in Fig. 1, is widely used in modern PMSG-based variable speed wind energy conversion system [6], [10], [11], [15]. In this scheme, the generator torque is controlled indirectly through current control. The output of the speed controller generates the  $d$ - and  $q$ -axis current references, which are in the rotor reference frame. The generator developed torque is controlled by regulating the currents and according to the generator torque equation. For high performance, the current control is normally executed at the rotor reference frame, which rotates with the rotor. 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 is eliminated.

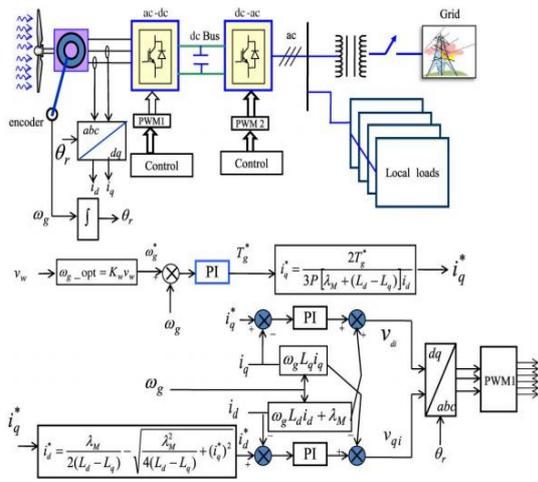


Fig. 1. Traditional vector control scheme for the IPM synchronous generator

## II. PROPOSED TOPOLOGY – IPM SYNCHRONOUS GENERATOR MODEL & PROPOSED CONTROLLING

The machine model in reference frame, which is synchronously rotating with the rotor, where  $d$ -axis is aligned with the magnet axis and  $q$ -axis is orthogonal to  $d$ -axis, is usually used for analyzing the interior permanent magnet (IPM) synchronous machine [13]. The  $d$ - and  $q$ -axes voltages of PMSG can be given by

$$v_d = -i_d R_s - \omega_r \lambda_q + p \lambda_d$$

$$v_q = -i_q R_s + \omega_r \lambda_d + p \lambda_q$$

The  $d$ - and  $q$ -axes flux linkages are given by

$$\lambda_d = -L_d i_d + \lambda_M$$

$$\lambda_q = -L_q i_q$$

The torque equation of the PMSG can be written as

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

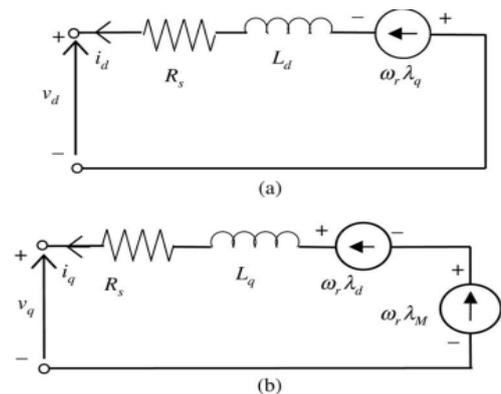


Fig. 2.  $dq$ -model of IPM synchronous generator: (a)  $d$ -axis equivalent circuit and (b)  $q$ -axis equivalent circuit.

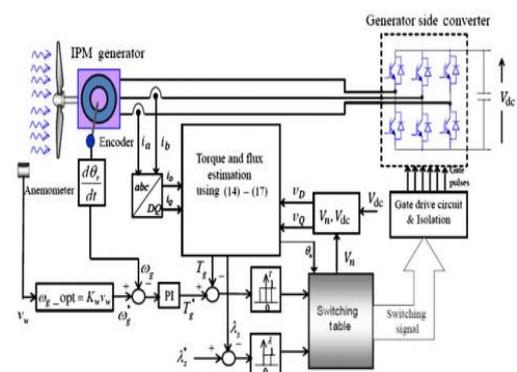


Fig. 3. Proposed direct control scheme for the IPM generator side converter.

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

### III. PROPOSED TOPOLOGY – DIRECT CONTROL SCHEME FOR IPM SYNCHRONOUS GENERATOR

The direct control scheme for IPM synchronous generator is shown in Fig. 3. In this scheme, current controllers are not used. Instead, the flux linkage and torque are controlled directly. The torque and flux are controlled using two hysteresis controllers and by selecting optimum converter switching modes, as shown in Fig. 3. The selection rule is made to restrict the torque and flux linkage errors within the respective torque and flux hysteresis bands to achieve the desired torque response and flux linkage [10]. The required switching-voltage vectors can be selected by using a switching voltage vector lookup table, as shown in Table I. 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. 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 bandwidth [11], [12]. 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 [10].

The optimal switching logic is based on the mathematical spatial relationships of stator flux, rotor flux, stator current, and stator voltage. These relationships are shown in Fig.4 as rotor reference, stator flux reference, and stationary reference frames. The angle between the stator and rotor flux linkages is the load angle if the stator resistance is neglected. In the steady state, is constant corresponding to a load torque and both stator and rotor fluxes rotate at the synchronous speed. In the transient operation, varies and the stator and rotor fluxes rotate at different speeds. The magnitude of the stator flux is normally kept as constant as possible, and the torque is controlled by varying the angle between the stator flux vector and the rotor flux vector [10].

TABLE I  
SIX-VECTOR SWITCHING TABLE FOR CONVERTER

$\theta$		$\theta_1$	$\theta_2$	$\theta_3$	$\theta_4$	$\theta_5$	$\theta_6$
		$\lambda$	$\tau$				
$\lambda=1$	$\tau=1$	$V_{2(110)}$	$V_{3(010)}$	$V_{4(011)}$	$V_{5(001)}$	$V_{6(101)}$	$V_{1(100)}$
	$\tau=0$	$V_{6(101)}$	$V_{1(100)}$	$V_{2(110)}$	$V_{3(010)}$	$V_{4(011)}$	$V_{5(001)}$
$\lambda=0$	$\tau=1$	$V_{3(010)}$	$V_{4(011)}$	$V_{5(001)}$	$V_{6(101)}$	$V_{1(100)}$	$V_{2(110)}$
	$\tau=0$	$V_{5(001)}$	$V_{6(101)}$	$V_{1(100)}$	$V_{2(110)}$	$V_{3(010)}$	$V_{4(011)}$

Table.1 . SIX-VECTOR SWITCHING TABLE FOR CONVERTER

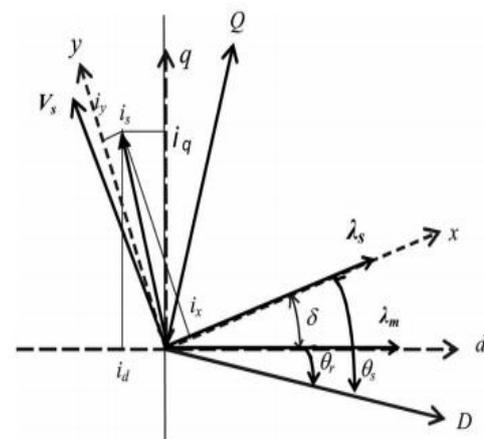


Fig.4. Stator and rotor flux linkages in different reference frames

**IV. PROPOSED TOPOLOGY – CONTROL OF STATOR FLUX LINKAGE BY SELECTING PROPER STATOR VOLTAGE VECTOR**

The stator voltage vector for a three-phase machine with balanced sinusoidally distributed stator windings is defined by the following equation:

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

where the phase axis is taken as the reference position and are the instantaneous values of line to neutral voltages. In Fig.5, the ideal bidirectional switches represent the power switches with their antiparallel diodes. The primary voltages and are determined by the status of these three switches . Therefore, there are six nonzero voltage vectors and and two zero voltage vectors and . The six nonzero voltage vectors are 60 apart from each other, as in Fig.6. These eight voltage vectors can be expressed as

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

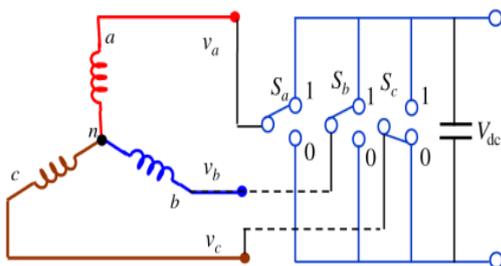


Fig. 5. Rectifier connected to IPM synchronous generator.

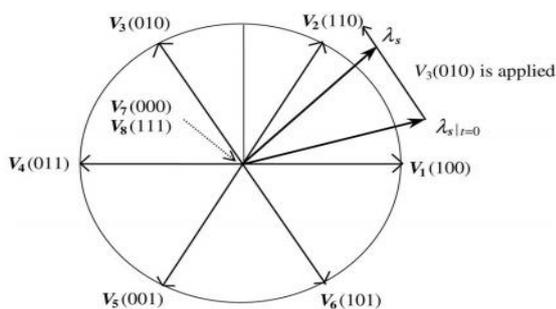


Fig. 6. Available stator voltage vectors

How far the tip of the statorflux linkage will move is determined by the duration of time for which the stator vector is applied. In Fig. 7, the voltage vector plane is divided into six regions – to select the voltage vectors for controlling the amplitude of the stator flux linkage. In each region, two adjacent voltage vectors are selected to keep the

switching frequency minimum. Two voltages may be selected to increase or decrease the amplitude of. For instance, voltage vectors and are selected to increase or decrease the amplitude of, respectively, when is in region and the statorflux vector is rotating in counter clockwise direction. In this way, the amplitude of can be controlled at the required value by selecting the proper voltage vectors. How the voltage vectors are selected for keeping within a hysteresis band is shown in Fig. 8 for a counter clockwise direction of. The hysteresis band here is the difference in radii of the two circles in Fig. 7. To reverse the rotational direction of, voltage vectors in the opposite direction should be selected.

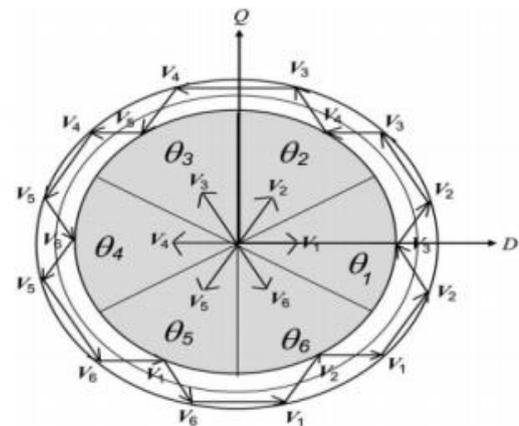


Fig. 7. Control of the amplitude of stator flux linkage

For example, when is in region and is rotating in the clockwise direction the voltage vectors pair and are selected to reverse the rotation of [10], [14]. B. Control of Rotation of The effect of two nonzero voltage vectors and is more complicated. It is seen that will stay at its original position when zero voltage vectors are applied. This is true for induction machine since the statorflux linkage is uniquely determined by the stator voltage, where the rotor voltages are always zero. In the case of an IPM synchronous generator, will change even when the zero voltage vectors are applied, since magnetflux continues to be supplied by the rotor and it will rotate with the rotor. In other words, should always be in motion with respect to the rotor flux linkage. Therefore, zero voltage vectors are not used for controlling in IPM synchronous machine [10], [11]. The electromagnetic torque is controlled by controlling the direction of rotation of, according to the torque equation .For counter clockwise operation, if the actual torque is smaller than the reference value, the voltage vectors that keep rotating in the same direction are selected. The angle increases as fast as it can and the actual torque increases as well. Once the actual torque is greater than the reference value, the voltage vectors that keep rotating in the reverse direction are selected instead of the zero voltage vectors.

The angle decreases and torque decreases too. By selecting the voltage vectors in this way, is rotated all the time and its rotational direction is determined by the output of the hysteresis controller for the torque [6], [8]. The six-vector switching table for controlling both the amplitude and rotating direction of is shown in Table I and is used for both the directions of operations. In Table I, and are the outputs of the hysteresis controllers for flux linkage and torque, respectively. If , then the actual flux linkage is smaller than the reference value. The same is true for the torque. – are the region numbers for the stator flux linkage positions.

**V. MATLAB BASED SIMULATION & RESULTS DISCUSSION**

The direct control scheme for IPM synchronous generator based variable speed wind turbine shown in Fig. 3 is implemented in MATLAB/ Sim Power Systems dynamic system simulation software. The IPM synchronous generator data are given in Table III. Table I is used for switching the converter. The bandwidths of torque and flux hysteresis controllers are 10% of their rated values.

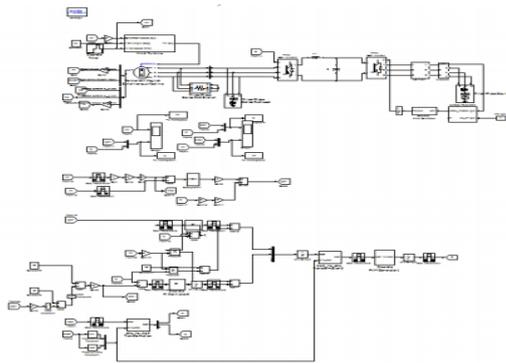


Fig.8. MATLAB based simulation diagram of proposed system with masked blocks

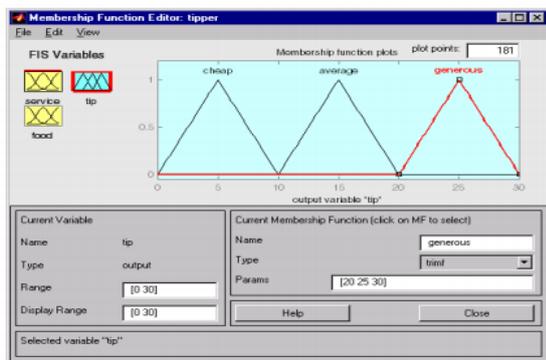


Fig.9. MATLAB based simulation diagram of traditional system FFL block

Fig.10. Shows the MATLAB based simulation of the traditional control scheme responses- wind speed

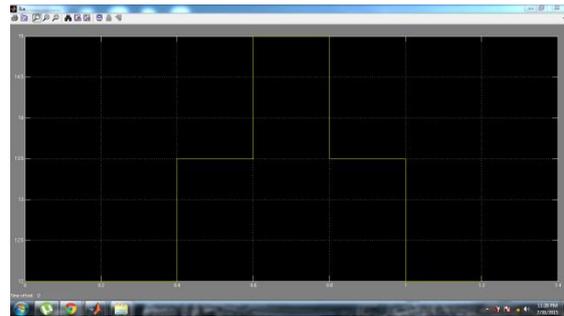


Fig.10. MATLAB based simulation of the proposed control scheme responses-wind speed

Fig.11. Shows the MATLAB based simulation of the traditional control waveform q-axis current and its reference

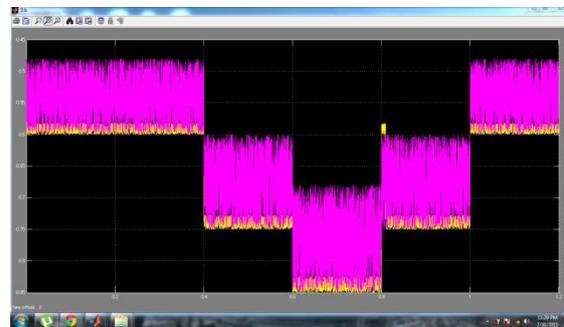


Fig.11. MATLAB based simulation of the traditional control waveform- waveform q-axis current and its reference

Fig.12. Shows the MATLAB based simulation of the traditional control scheme- d-axis current and its reference

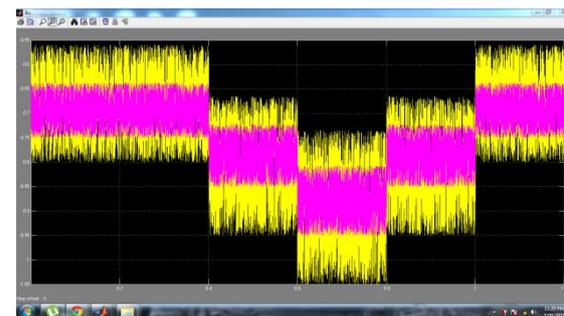


Fig.12. MATLAB based simulation of the traditional control scheme-- d-axis current and its reference

Fig.13. Shows the MATLAB based simulation of the traditional control scheme - speed reference and measured speed.

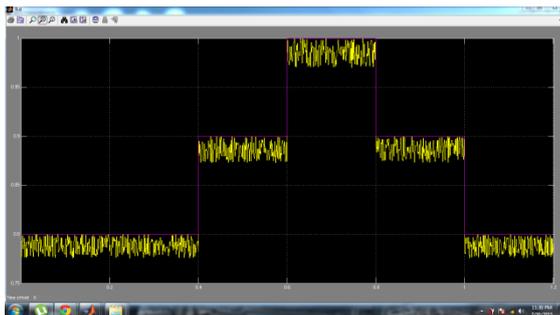


Fig.13. MATLAB based simulation of the traditional control scheme - speed reference and measured speed.

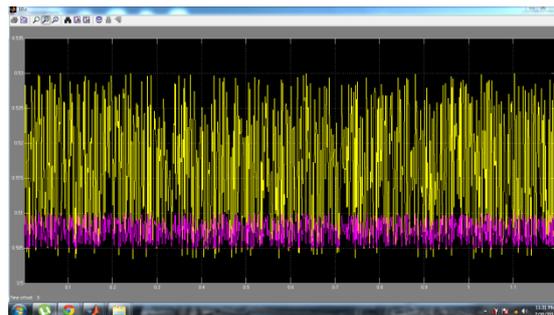


Fig.16. MATLAB based simulation of the proposed control scheme – flux linkage and its reference

Fig.14. Shows the MATLAB based simulation of the proposed control scheme – wind speed

Fig.16. Shows the MATLAB based simulation of the proposed control scheme – speed reference and measured.

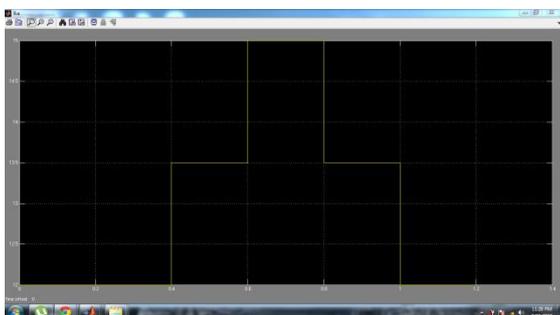


Fig.14. MATLAB based simulation of the proposed control scheme – wind speed

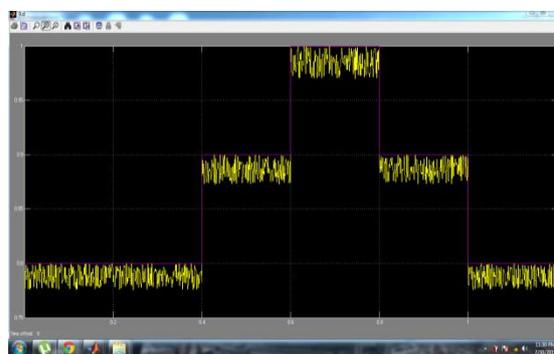


Fig.16. MATLAB based simulation of the proposed control scheme – speed reference and measured.

Fig.15. Shows the MATLAB based simulation of the proposed control scheme - torque and its reference

TABLE.II.SIMULATION SPECIFICATIONS

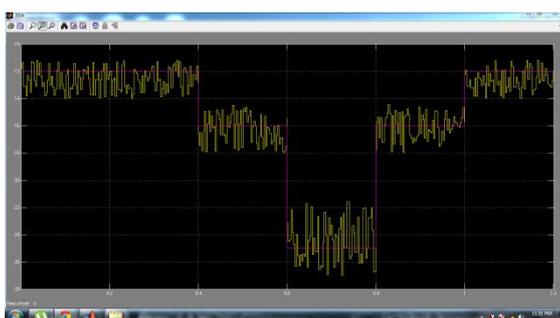


Fig.15. MATLAB based simulation of the proposed control scheme - torque and its reference

PARAMETER OF IPM SYNCHRONOUS GENERATOR	
Rated power	4.7 kW
Rated torque	34.8 Nm
Rated speed	1280/ 1600 rpm
Rated voltage	400/480 V rms
Rated current	8.1 A rms
Magnet flux linkage	0.525723 Wb
<i>d</i> -axis inductance ( $L_d$ ) per phase	18.237 mH
<i>q</i> -axis inductance ( $L_q$ ) per phase	49.239 mH
Stator resistance	1.56 $\Omega$
No. of poles	6
Rotor inertia	0.0049 kg.m <sup>2</sup>
Static friction	0.637 N.m
Viscous damping	0.237 N.m/krpm

**CONCLUSION**

This paper proposed a fuzzy logic control strategy for an IPM synchronous generator-based variable speed wind turbine. In this control scheme, no rotor position is required as all the calculations are done in stator reference frame. It may help to see fuzzy logic as the way reasoning really works and binary or Boolean logic is simply a special case of it. 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) sensor less operation without mechanical sensor. The results show that the direct controller can operate under varying wind speeds. However, direct control scheme has the problem of higher torque ripple that can introduce speed ripples and dynamic vibration in the power train. The methods to minimize the torque/ speed ripples need to be addressed. 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] S. Müller, M. Deicke, and R. W. D. De Doncker, "Doubly fed induction generator system for wind turbines," *IEEE Ind. Appl. Mag.*, vol. 8, no. 3, pp. 26–33, May 2002.
- [2] J. Hu, H. Nian, H. Xu, and Y. He, "Dynamic modeling and improved control of DFIG under distorted grid voltage conditions," *IEEE Trans. Energy Convers.*, vol. 26, no. 1, pp. 163–175, Mar. 2011.
- [3] M. Mohseni, M. S. M. Islam, and M. A. Masoum, "Enhanced hysteresis based current regulators in vector control of DFIG wind turbine," *IEEE Trans. Power Electron.*, vol. 26, no. 1, pp. 223–234, Jan. 2011.
- [4] T. F. Chan and L. L. Lai, "Permanent-magnet machines for distributed generation: A review," *IEEE Power Engg. Annual Meeting, Tampa, FL, USA*, Jun. 24–28, 2007, pp. 1–6.
- [5] M. E. Haque, M. Negnevitsky, and K. M. Muttaqi, "A novel control strategy for 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.
- [6] R. Esmali and L. Xu, "Sensorless control of permanent magnet generator in wind turbine application," *IEEE Industry Applications Society Annual Meeting, Tampa, FL, USA*, Oct. 8–12, 2006, pp. 2070–2075.
- [7] Z. Q. Zhu and J. H. Leong, "Analysis and mitigation of torsional vibration of PM brushless ac/dc drives with direct torque controller," *IEEE Trans. Ind. Appl.*, vol. 48, no. 4, pp. 1296–1305, Jul./Aug. 2012.
- [8] H. Zhu, X. Xiao, and Y. Li, "Torque ripple reduction of the torque predictive control scheme for permanent-magnet synchronous motors," *IEEE Trans. Ind. Electron.*, vol. 59, no. 2, pp. 871–877, Feb. 2012.
- [9] P. C. Krause, O. Wasynczuk, and S. D. Sudhoff, *Analysis of Electrical Machinery and Drive System*. Piscataway, NJ, USA: IEEE Press, 2002.
- [10] M. E. Haque, M. Negnevitsky, and K. M. Muttaqi, "A novel control strategy for 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.
- [11] S. Zhang, K. J. Tseng, D. M. Vilathgamuwa, T. D. Nguyen, and X. Y. Wang, "Design of a robust grid interface system for PMSG-based wind turbine generators," *IEEE Trans. Ind. Electron.*, vol. 58, no. 1, pp. 316–328, Jan. 2011.
- [12] K. Nishida, T. Ahmed, and M. Nakaoka, "A cost-effective high-efficiency power conditioner with simple MPPT control algorithm for wind-power grid integration," *IEEE Trans. Ind. Appl.*, vol. 47, no. 2, pp. 893–900, Mar. 2011.
- [13] C. N. Bhende, S. Mishra, and S. G. Malla, "Permanent magnet synchronous generator based standalone wind energy supply system," *IEEE Trans. Sustain. Energy*, vol. 2, no. 4, pp. 361–373, Oct. 2011.
- [14] S. M. R. Kazmi, H. Goto, H. J. Guo, and O. Ichinokura, "A novel algorithm for fast and efficient speed-sensorless maximum power point tracking in wind energy conversion systems," *IEEE Trans. Ind. Electron.*, vol. 58, no. 1, pp. 29–36, Jan. 2011.