

AN IPM SYNCHRONOUS GENERATOR-BASED GEARLESS VARIABLE SPEED WIND TURBINE WITH ADVANCED CONTROL SCHEME USING FUZZY LOGIC

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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.

Key words: Direct control, interior permanent magnet (IPM) synchronous generator, sensor-less speed estimator, variable speed wind turbine, Fuzzy logic.

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.

Moreover, the gearbox requires regular maintenance as it suffers from faults and malfunctions [4].

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 [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 [17]. 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 ω and ω axes 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 (θ_r) is eliminated.

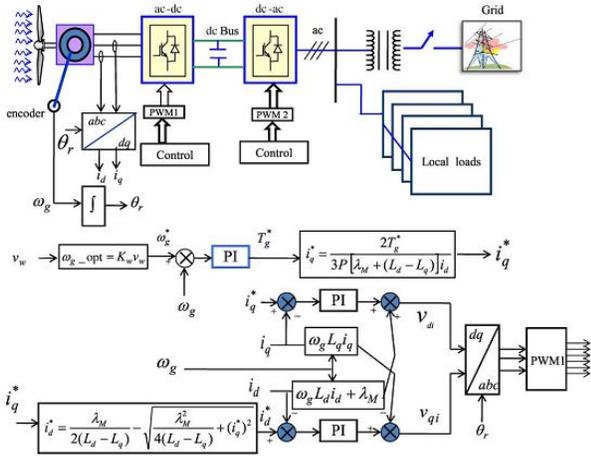


Fig. 1. Traditional vector control scheme for the IPM synchronous generator.

This method is inherently sensorless and have several advantages compared with the traditional indirect vector control scheme [19]–[22]. 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. MODELING OF PROPOSED THORY

WIND TURBINE MODEL AND MAXIMUM POWER EXTRACTION

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

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

where ρ is the air density (kg/m^3), v_w is the wind speed in m/s, A is the blade swept area (m^2), C_p is the power coefficient, which is a function of tip speed ratio (λ_r) and pitch angle (β), ω_m is the rotational speed of turbine rotor in mechanical (rad/s), and R is the radius of the turbine (m).

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

The wind turbine can produce maximum power when the turbine operates at maximum (i.e., at λ_{r_opt}). Therefore, it is necessary to keep the rotor speed at an optimum value of the tip speed ratio λ_r . If the wind speed varies, the rotor speed should be adjusted to follow the change [6]

The target optimum power from a wind turbine is given by

$$P_{m_opt} = 0.5\rho AC_{p_opt} \times (\omega_{m_opt} R/\lambda_{r_opt})^3 = K_{opt}(\omega_{m_opt})^3 \quad (3)$$

Where

$$K_{opt} = 0.5\rho AC_{p_opt} \times (R/\lambda_{r_opt})^3 \quad (4)$$

And

$$\omega_{m_opt} = \omega_{g_opt} = \left(\frac{\lambda_{r_opt}}{R}\right) v_w = K_w v_w \quad (5)$$

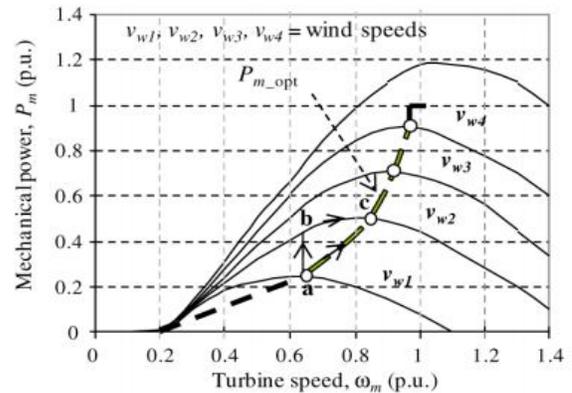


Fig.2. Mechanical power generated by the turbine as a function of the rotor speed for different wind speeds.

The optimum torque can be given by

$$T_{m_opt}(t) = K_{opt}(\omega_{m_opt}(t))^2 \quad (6)$$

The mechanical rotor power versus rotor speed for varying wind speeds is shown in Fig. 2. The optimum power curve (P_{m_opt}) is also shown in Fig. 2, which shows how maximum energy can be captured at different wind speeds. The purpose of the controller is to keep the turbine operating on this curve, as the wind speed changes [6]. 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).

IPM SYNCHRONOUS GENERATOR MODEL

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 [23]. The d - and q -axes voltages of PMSG can be given by

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

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

The d - and q -axes 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 equation of the PMSG can be written as

$$\begin{aligned} T_g &= -\frac{3}{2} P (\lambda_d i_q - \lambda_q i_d) \\ &= -\frac{3}{2} P (\lambda_M i_q \\ &\quad - (L_d - L_q) i_d i_q) \quad (11) \end{aligned}$$

In (7)–(11), v_d , v_q , i_d , i_q , R_s , L_d , L_q , λ_M , λ_d , λ_q , and ω_r are the d - and q -axes stator voltages, currents, and inductances, respectively, R_s is the stator resistance, ω_r is the rotor speed in rad/s, λ_M is the magnet flux, P is the number of pole pairs, and p is the operator. Fig. 3 shows the model of IPM synchronous generator.

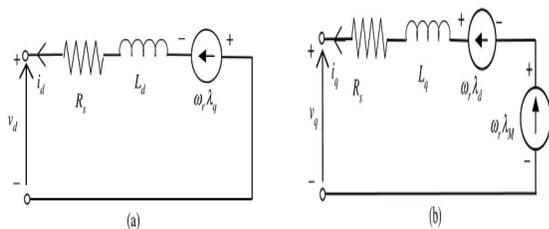


Fig. 3. dq-model of IPM synchronous generator: (a) d -axis equivalent circuit and (b) q -axis equivalent circuit.

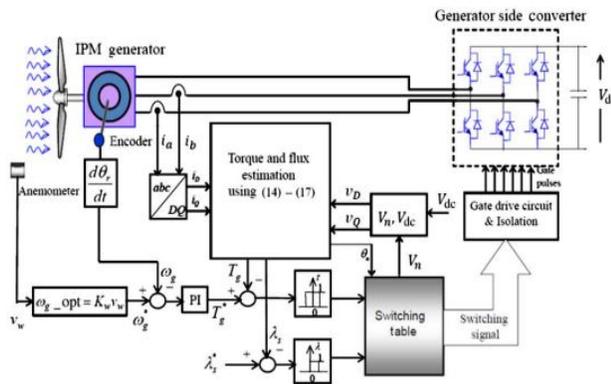


Fig. 4. Proposed direct control scheme for the IPM generator side converter.

The first term in the torque equation (11) is the excitation torque that is produced by the interaction of permanent magnet flux and 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 and 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

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

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

III. PROPOSED DIRECT CONTROL SCHEME FOR IPM SYNCHRONOUS GENERATOR

The direct control scheme for IPM synchronous generator is shown in Fig. 4. In this scheme, current controllers are not used. Instead, the flux linkage and torque are controlled directly.

TABLE I
SIX-VECTOR SWITCHING TABLE FOR CONVERTER

θ		θ_1	θ_2	θ_3	θ_4	θ_5	θ_6
λ	τ						
$\lambda=1$	$\tau=1$	$V_2(110)$	$V_3(010)$	$V_4(011)$	$V_5(001)$	$V_6(101)$	$V_1(100)$
	$\tau=0$	$V_6(101)$	$V_1(100)$	$V_2(110)$	$V_3(010)$	$V_4(011)$	$V_5(001)$
$\lambda=0$	$\tau=1$	$V_3(010)$	$V_4(011)$	$V_5(001)$	$V_6(101)$	$V_1(100)$	$V_2(110)$
	$\tau=0$	$V_5(001)$	$V_6(101)$	$V_1(100)$	$V_2(110)$	$V_3(010)$	$V_4(011)$

The torque and flux are controlled using two hysteresis controllers and by selecting optimum converter switching modes, as shown in Fig. 4. 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 [20]. 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 [21], [24]. 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 PWM modulator [20]. 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. 5 as rotor flux (λ_r) reference, stator flux (λ_s) reference, and stationary (D) 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, δ is constant corresponding to a load torque and both stator and rotor fluxes rotate at the synchronous speed. In the transient operation, δ 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 [20]. In direct torque and flux control scheme, the stator flux linkage is estimated by integrating the difference between the input voltage and the voltage drop across the stator resistance, as given by

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

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

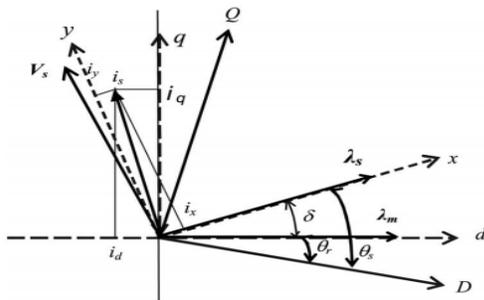


Fig. 5. Stator and rotor flux linkages in different reference frames.

In the stationary reference frame, the stator flux linkage phasor is given by

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

and the electromagnetic torque is given by

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

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

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

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:

$$V_s = \frac{2}{3} (v_a - v_b e^{j\frac{2\pi}{3}} + v_c e^{j\frac{4\pi}{3}}) \quad (19)$$

where the phase “a” axis is taken as the reference position and v_a, v_b, v_c are the instantaneous values of line to neutral voltages. In Fig. 6, the ideal bidirectional switches represent the power switches with their antiparallel diodes. The primary voltages v_a, v_b, v_c are determined by the status of these three switches (S_a, S_b, S_c and their antiparallel diodes). Therefore, there are six nonzero voltage vectors $V_1, V_2, V_3, V_4, V_5, V_6$ and two zero voltage vectors V_7, V_8 . The six nonzero voltage vectors are 60° apart from each other, as in Fig. 7. These eight voltage vectors can be expressed as

$$V_s(s_a s_b s_c) = V_D \left(s_a - s_b e^{j\frac{2\pi}{3}} + s_c e^{j\frac{4\pi}{3}} \right) \quad (20)$$

Where $V_D = \frac{2}{3} V_{dc}$ and V_{dc} = dc link voltage

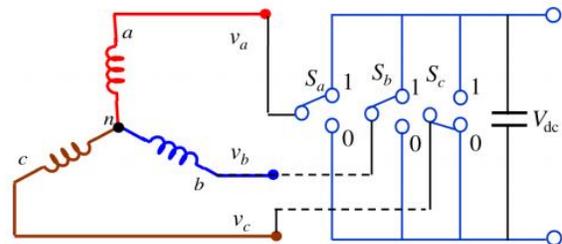


Fig. 6. Rectifier connected to IPM synchronous generator

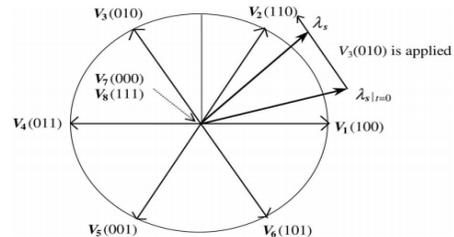


Fig. 7. Available stator voltage vectors.

A. Control of Amplitude of Stator Flux Linkage The stator flux linkage in the stationary reference frame can be given as

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

Equation (21) can be written as

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

Equation (22) implies that the tip of the stator flux linkage vector will move in the direction of the applied voltage vector if the stator resistance is neglected, as shown in Fig. 7. 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. In Fig. 8, 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 v_1 and v_2 are selected to increase or decrease the amplitude of, respectively, when λ_s is in region θ_1 and the stator flux vector is rotating in counter clockwise direction. In this way, the amplitude of λ_s can be controlled at the required value by selecting the proper voltage vectors. How the voltage vectors are selected for keeping λ_s within a hysteresis band is shown in Fig. 8 for a counter clockwise direction of λ_s . The hysteresis band here is the difference in radii of the two circles in Fig. 8. To reverse the rotational direction of λ_s , voltage vectors in the opposite direction should be selected.

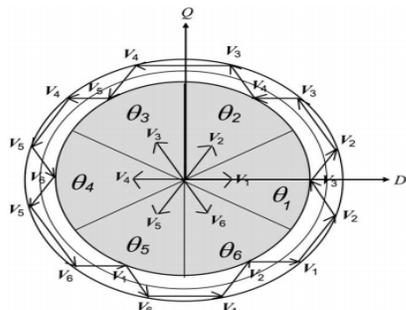


Fig. 8. Control of the amplitude of stator flux linkage

For example, when λ_s is in region θ_1 and is rotating in the clockwise direction the voltage vectors pair v_1 and v_2 are selected to reverse the rotation of λ_s [20], [24]. B. Control of Rotation of The effect of two nonzero voltage vectors and is more complicated. It is seen from (22) that λ_s 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, λ_s will change even when the zero voltage vectors are applied, since magnet flux continues to be supplied by the rotor and it will rotate with the rotor. In other words, λ_s 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 [20], [24]. The electromagnetic torque is controlled by controlling the direction of rotation of λ_s , according to the torque equation (18). 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, λ_s is rotated all the time and its rotational direction is determined by the output of the hysteresis controller for the torque [20], [24]. The six-vector switching table for controlling both the amplitude and rotating direction of λ_s is shown in Table I and is used for both the directions of operations. In Table I, v_1 and v_2 are the outputs of the hysteresis controllers for flux linkage and torque, respectively. If λ_s is smaller than the reference value. The same is true for the torque. θ_1 through θ_6 are the region numbers for the stator flux linkage positions.

IMPLEMENTATION OF DIRECT CONTROL SCHEME FOR IPM SYNCHRONOUS GENERATOR-BASED WIND TURBINE

The direct control scheme for IPM synchronous generator is shown in Fig. 4, where the switching scheme used is shown in Table I. The three-phase variables are transformed into stationary axes variables.

TABLE-II

DQ-AXES VOLTAGES ($V_D = 2/3V_{dc}$)

	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	$0.886V_D$	$0.886V_D$	0	$-0.886V_D$	$-0.886V_D$

As shown in Fig. 4, torque error and flux error are the inputs to the flux hysteresis comparator and torque hysteresis comparator, respectively. The outputs of the hysteresis comparators (λ_{s_err} and T_{err}) are the inputs to the voltage-switching selection lookup table. As shown in Fig. 4, this scheme is not dependent on generator parameters except the stator resistance. Moreover, all calculations are in the stator reference frame and without any co-ordinate transformation.

A. Flux Linkage and Torque Estimation

The d -axis flux linkage components and at the k th sampling instant can be calculated as

$$\lambda_D(k) = -T_s \int (-v_{D(k-1)} + i_{D(k)} R_s) + \lambda_D(k-1) \quad (23)$$

$$\lambda_Q(k) = -T_s \int (-v_{Q(k-1)} + i_{Q(k)}R_s) + \lambda_D(k-1) \quad (24)$$

where T_s is the sampling time, the variables with subscript are their values at the k th sampling instant, and the variables with $(k-1)$ are the previous samples. The $i_{d(k)}$ and $i_{q(k)}$ axes currents can be obtained from the measured three-phase currents and the $v_{d(k)}$ and $v_{q(k)}$ axes voltages are calculated from the measured dc-link voltages. Table II shows $i_{d(k)}$ and $i_{q(k)}$ axes voltages for the applied voltage vectors. The amplitude of the stator flux linkage is calculated from

$$|\lambda_s(k)| = \sqrt{\lambda_{D(k)}^2 + \lambda_{Q(k)}^2} \text{ and } \theta_s = \angle \tan^{-1} \left(\frac{\lambda_{Q(k)}}{\lambda_{D(k)}} \right) \quad (25)$$

The developed torque is calculated from

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

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

$$T_g(k) = -\frac{3P|\lambda_s(k)|}{4L_d L_q} \times [2\lambda_M L_q \sin\{\delta_{(k)}\} - |\lambda_s(k)| (L_d - L_q) \sin 2\delta_{(k)}] \quad (27)$$

IV. FUZZY LOGIC

In FLC, basic control action is determined by a set of linguistic rules. These rules are determined by the system. Since the numerical variables are converted into linguistic variables, mathematical modeling of the system is not required in FC. The FLC comprises of three parts: fuzzification, inference engine and defuzzification. The FC is characterized as; i. seven fuzzy sets for each input and output. ii. Triangular membership functions for simplicity. iii. Fuzzification using continuous universe of discourse. iv. Implication using Mamdani's „min“ operator. v. Defuzzification using the „height“ method

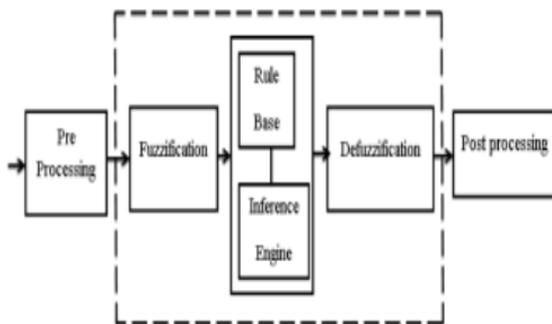


Fig.3 Fuzzy Logic Controller

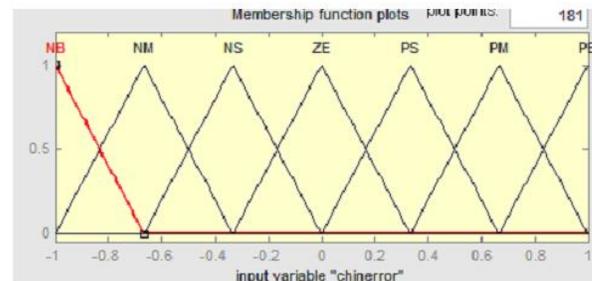
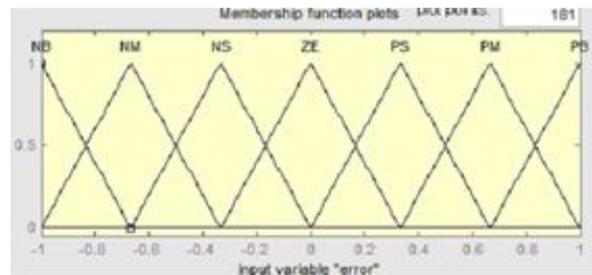
Fuzzification:

Membership function values are assigned to the linguistic variables, using seven fuzzy subsets: NB (Negative Big), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium), and PB (Positive Big). The partition of fuzzy subsets and the shape of membership $CE(k)$ $E(k)$ function adapt the shape up to appropriate system. The value of input error and change in error are normalized by an input scaling factor

Change In Error	Error						
	NB	NM	NS	Z	PS	PM	PB
NB	PB	PB	PB	PM	PM	PS	Z
NM	PB	PB	PM	PM	PS	Z	Z
NS	PB	PM	PS	PS	Z	NM	NB
Z	PB	PM	PS	Z	NS	NM	NB
PS	PM	PS	Z	NS	NM	NB	NB
PM	PS	Z	NS	NM	NM	NB	NB
PB	Z	NS	NM	NM	NB	NB	NB

Table1. Fuzzy Rules

In this system the input scaling factor has been designed such that input values are between -1 and +1. The triangular shape of the membership function of this arrangement presumes that for any particular $E(k)$ input there is only one dominant fuzzy subset. The input error for the FLC is given as



MEMBERSHIP FUNCTIONS

Interference Method:

Several composition methods such as Max–Min and Max-Dot have been proposed in the literature. In this paper Min method is used. The output membership

function of each rule is given by the minimum operator and maximum operator. Table 1 shows rule base of the FLC.

Defuzzification:

As a plant usually requires a non-fuzzy value of control, a defuzzification stage is needed. To compute the output of the FLC, „height“ method is used and the FLC output modifies the control output.

THE MEMBERSHIP FUNCTION EDITOR:

The Membership Function Editor shares some features with the FIS Editor. In fact, all of the five basic GUI tools have similar menu options, status lines, and Help and Close buttons. The Membership Function Editor is the tool that lets you display and edit all of the membership functions associated with all of the input and output variables for the entire fuzzy inference system. Fig.6 shows the Membership Function Editor.

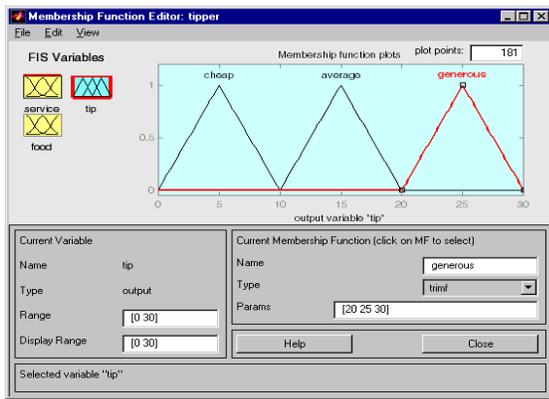


fig.. The updated Membership Function Editor Now that the variables have been named, and the membership functions have appropriate shapes and names, you're ready to write down the rules.

V. MATLAB CIRCUIT MODEL

The direct control scheme for IPM synchronous generator based variable speed wind turbine shown in Fig. 4 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.

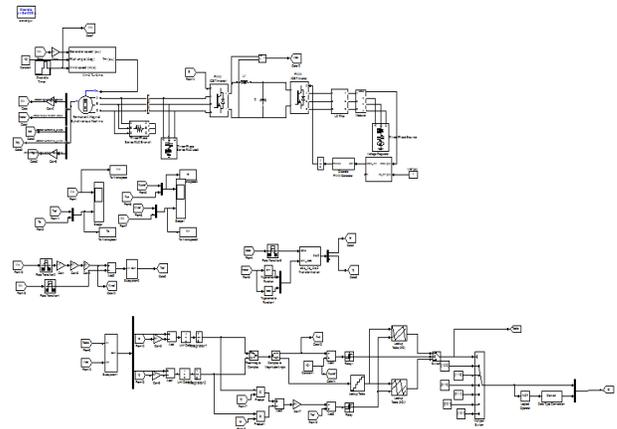
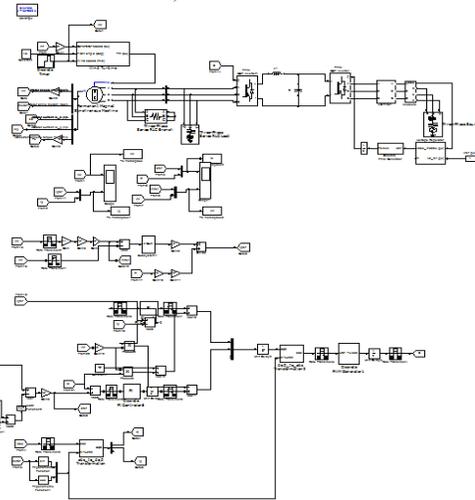


TABLE III
PARAMETER OF IPM SYNCHRONOUS GENERATOR

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 (<i>L_d</i>) per phase	18.237 mH
<i>q</i> -axis inductance (<i>L_q</i>) per phase	49.239 mH
Stator resistance	1.56 Ω
No. of poles	6
Rotor inertia	0.0049 kg·m ²
Static friction	0.637 N·m
Viscous damping	0.237 N·m/krpm

VI. SIMULATION RESULTS

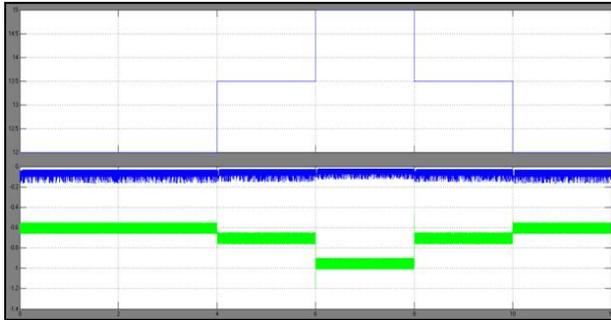


Fig. 9. Performance of the traditional indirect vector control scheme: (a) wind speed, (b) q-axis current and its reference

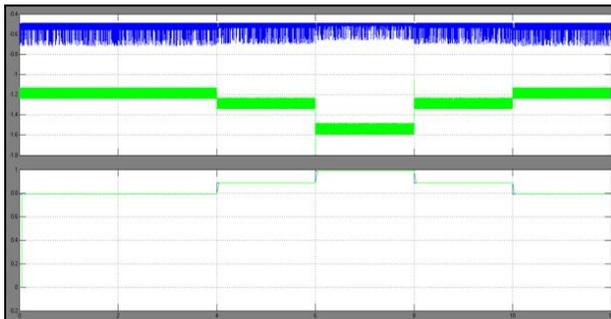


Fig. 9 :(c) d-axis current and its reference, and (d) speed reference and measured speed

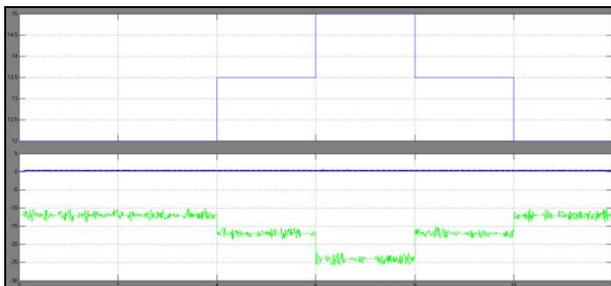


Fig. 10. Performance of the direct control scheme: (a) wind speed, (b) torque and its reference

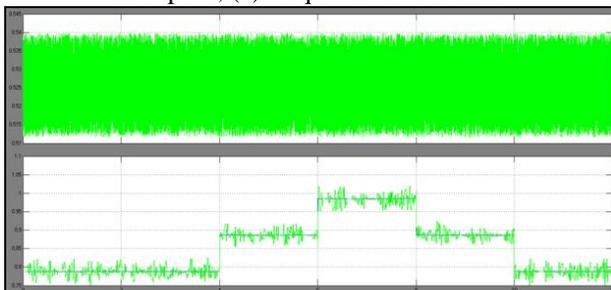


Fig. 10. (c) flux linkage and its reference, and (d) speed reference and measured.

VII. 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 sensor-less speed estimator are presented, and the results show that the estimator can estimate the generator speed quite well with a very small error.

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