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RESEARCH ARTICLE

MODELING OF IPM SYNCHRONOUS GENERATOR BY USING FUZZY LOGIC CONTROLLER UNDER VARIABLE SPEED

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ABSTRACT

This paper proposes a direct control strategy for an interior permanent magnet synchronous generator-based variable speed 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.

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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. Renewable energy is generally defined as energy that comes from resources which are naturally replenished on a human timescale such as sunlight, wind, rain, tides, waves and geothermal heat. Renewable energy replaces conventional fuels in four distinct areas: electricity generation, hot water/space heating, motor fuels, and rural (off grid) energy services. 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. At the national level, at least 30 nations around the world already have renewable energy contributing more than 30 percent of energy supply. National renewable energy markets are projected to continue to grow strongly in the coming decade and beyond 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. 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 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. 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

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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 and six switch vector-controlled PWM rectifiers. 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. Traditional vector control scheme, as shown in Fig. 1, is widely used in modern PMSG-based variable speed wind energy conversion system. In this scheme, the generator torque is controlled indirectly through current control. The output of the speed controller generates the d – and q –axes current references, which are in the rotor reference frame. The generator developed torque T_g 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.

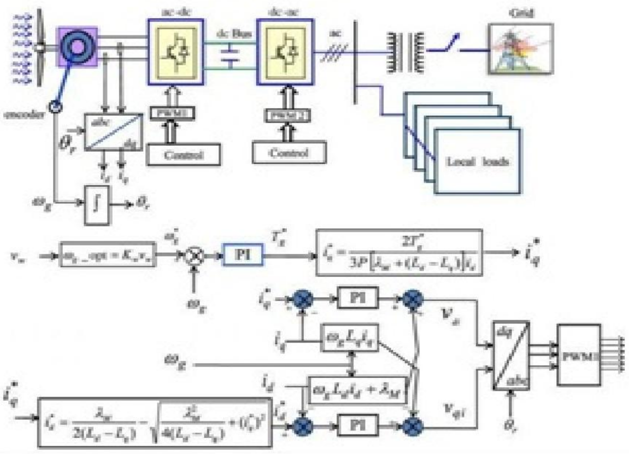

Fig. 1. Traditional vector control scheme for the IPM synchronous generator

Fuzzy logic controller

In this paper control is done by the fuzzy logic controller. The control scheme consists of a Fuzzy controller, a limiter, and a three phase sine wave generator for the generation of the internal structure of the control circuit. The control scheme consists of a Fuzzy controller, a limiter, and a three phase sine wave generator for the generation of reference currents and switching signals. The peak value of the reference current is estimated by regulating the DC link voltage. The actual capacitor voltage is compared with a set reference value. The error signal is then processed through a Fuzzy controller, which contributes to the zero steady error in tracking the reference current signal. A fuzzy controller converts a linguistic control strategy into an automatic control strategy, and fuzzy rules are constructed either by expert experience or with a knowledge database. Firstly, the input Error 'E' and the change in Error '4E' have been placed with the angular velocity to be used as the input variables of the fuzzy logic controller. Then the output variable of the fuzzy logic controller is presented by the control Current Imax. To convert these numerical variables into linguistic variables, the following seven fuzzy levels or sets are chosen: NB (negative big), NM (negative medium), NS (negative small), ZE (zero), PS (positive small), PM (positive medium), and PB (positive big) as shown in below Fig. 2.

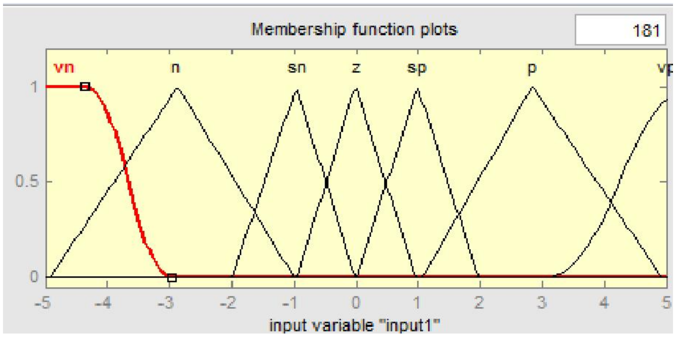

Fig. 2. Variable terms of error

Table 1. Output of fuzzy rules

D (%)		Derivative of error		
		Negative	**Zero**	**Positive**
Error	**VN**	VP	VP	VP
	N	SN	SN	VN
	SN	N	SN	VN
	Z	Z	Z	Z
	SP	SP	SP	P
	P	P	VP	VP
	VP	VP	VP	VP

In the proposed fuzzy controller, totally 21 rules are formed and it shown in table 2. For example, if the error is positive and change in error is negative then the duty cycle will be positive. The rules formed process is called as fuzzification. After the fuzzification process, Defuzzification as a plant usually requires a non- fuzzy value of control, a defuzzification stage is needed. To compute the output modifies of the fuzzy logic controlled method is used and the fuzzy logic controller controls the switch in the inverter. In UPQC, the active power, reactive power, terminal voltage of the line and capacitor voltage are required to be maintained. In order to control these parameters, they are sensed and compared with the reference values. To achieve this, the membership functions of fuzzy controller.

U= -[Ae+(1-α)*C]

Where α is self –adjustable factor which can regulate the whole operation the defuzzification is performed which converts the fuzzified value into defuzzified value. It gives the final output value. The defuzzification is shown in Figure 3. 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 a n d implemented in this paper to estimate the speed without a mechanical sensor.

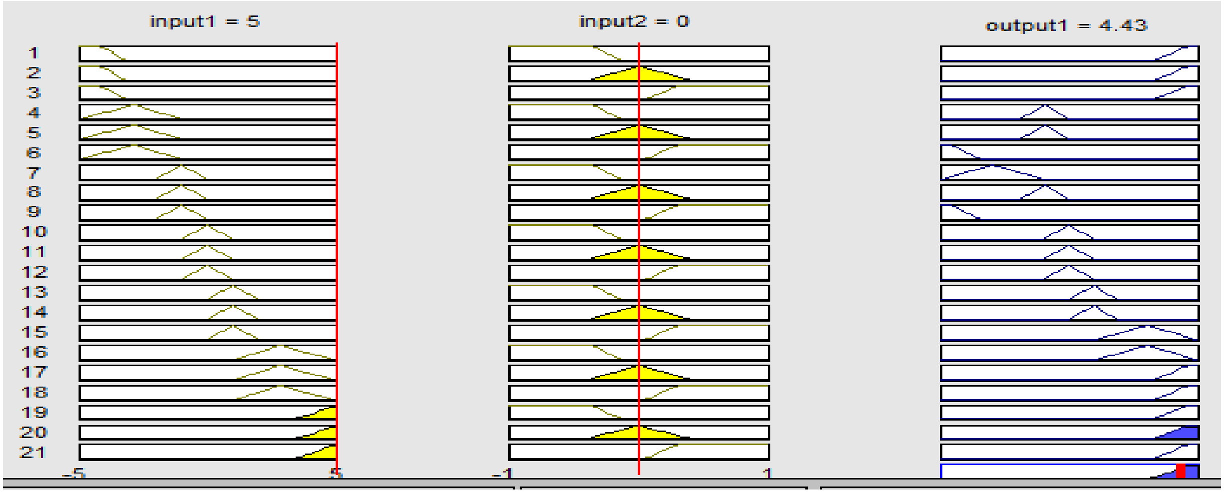

Fig. 3. Defuzzification

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 axis is orthogonal to q - axis, is usually used for analyzing the interior permanent magnet (IPM) synchronous machine. The d - and q – axes voltages of PMSG can be given by

$$v_d = -i_d R_s - \boldsymbol{\omega}_r \boldsymbol{\lambda}_q + p\boldsymbol{\lambda}_d \tag{1}$$

$$v_q = -i_q R_s + \boldsymbol{\omega}_{r\lambda_d} + p\boldsymbol{\lambda}_q \tag{2}$$

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

$$\boldsymbol{\lambda}_d = -L_{did} + \boldsymbol{\lambda}_M \tag{3}$$

$$\boldsymbol{\lambda}_q = -L_{qiq} \tag{4}$$

The torque equation of the PMGG can be written as

$$T_g = \frac{-3}{2}\mathrm{P}\,(\boldsymbol{\lambda}_{Miq} - \boldsymbol{\lambda}_{qid}) = \frac{-3}{2}\mathrm{P}\,(\boldsymbol{\lambda}_{Miq} + (L_d - L_q)_{idiq} \tag{5}$$

In(1)–(5), v_d,v_q, i_d, i_q, L_d and $L_q$are the -and –axes stator voltages, currents, and inductances, respectively, is the stator resistance, is the rotor speed in rad/s, is the magnet flux, is the number of pole pairs, and is the operator. Fig. 5 shows the model of IPM synchronous generator.

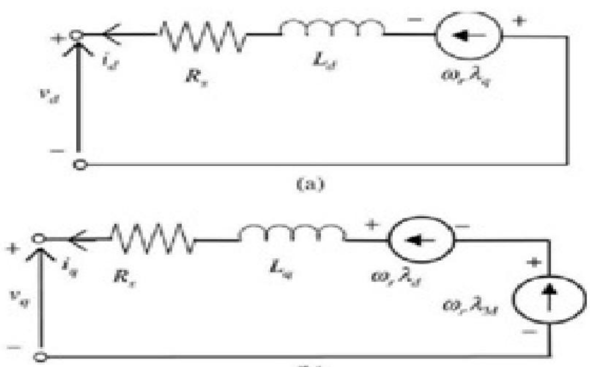

Fig.4. $d_q$model of IPM synchronous generator: (a) d-axis equivalent circuit and (b) q -axis equivalent circuit

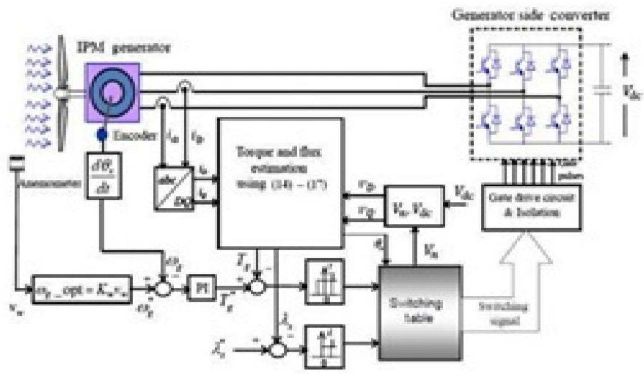

Fig.5. Proposed direct control scheme for the IPM generator side converter

Term in the torque equation (5) 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 q - and d -axes current references can be expressed as

$$i_q^* = \frac{2T_g^*}{3p[\boldsymbol{\lambda}_M + (Ld - Lq)]} \tag{6}$$

$$i_d^* = \frac{\boldsymbol{\lambda}_M}{2(Ld - Lq)} - \sqrt{\frac{\boldsymbol{\lambda}_M^2}{4(Ld-Lq)} + (i_q^{*2})} \tag{7}$$

Proposed topology – direct control scheme for IPM synchronous generator

The direct control scheme for IPM synchronous generator is shown in Fig. 6. 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. 6. 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. The required switching-voltage vectors can be selected by using a switching voltage vector lookup table, as shown in Table 1. 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 rise 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. 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. The optimal switching logic is based on the mathematical spatial relationships of stator flux, rotor fluxd_q, stator current, and stator voltage. These relationships are shown in Fig.6 as rotor reference, stator flux (xy) reference, and stationary reference frames. The angle between the stator and rotor flux linkages (δ) 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, 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 δ between the stator flux vector and the rotor flux vector.

Table 2. Six-vector switching table for converter

Sector		1	2	3	4	5	6
$C_\emptyset = -1$	$c_\tau = -1$	V_2	V_3	V_4	V_5	V_6	V_1
	$c_\tau = 0$	V_7	V_0	V_7	V_0	V_7	V_0
	$c_\tau = +1$	V_6	V_1	V_2	V_3	V_4	V_5
$C_\emptyset = +1$	$c_\tau = -1$	V_3	V_4	V_5	V_6	V_1	V_2
	$c_\tau = 0$	V_0	V_7	V_0	V_7	V_0	V_7
	$c_\tau = +1$	V_5	V_6	V_1	V_2	V_3	V_4

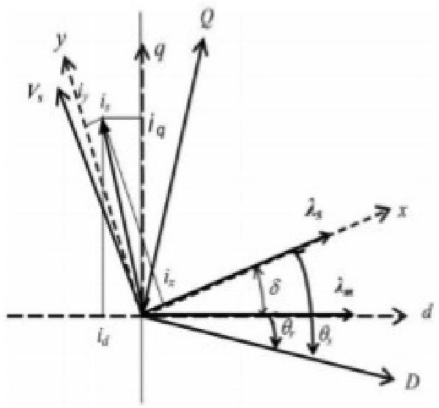

Fig.6. Stator and rotor flux linkages in different reference frame

Proposed topology – control of stator flux linkage by selecting proper stator voltage vector

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

$$v_s = \frac{2}{3}\left(v_a + v_b e^{\frac{j\pi 2}{3}} + v_c e^{\frac{j\pi 4}{3}}\right) \quad (8)$$

Where the phase axis is taken as the reference position and is the instantaneous values of line to neutral voltages. In Fig.7, the ideal bidirectional switches represent the power switches with their ant parallel diodes. The primary voltages and are determined by the status of these three switches. Therefore, there are six nonzero voltage vectors $V_1(100)$, $V_2(110)$, ……….and $V_6(101)$ and two zero voltage vectors $V_7(000)$ and V_8.(111) The six nonzero voltage vectors are 60 apart from each other, as in Fig.8. These eight voltage vectors can be expressed as

$$v_s(s_a, s_b, s_c) = v_D\left(s_a + s_b e^{\frac{j\pi}{3}} + s_c e^{j4\pi/3}\right) \quad (9)$$

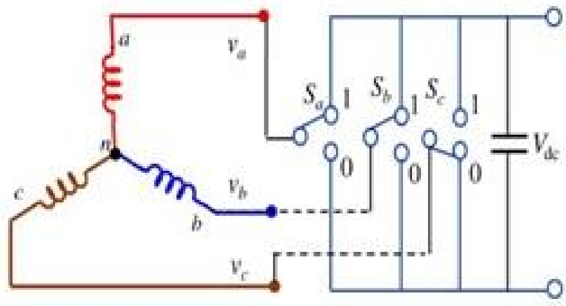

Fig. 7. Rectifier connected to IPM synchronous generator

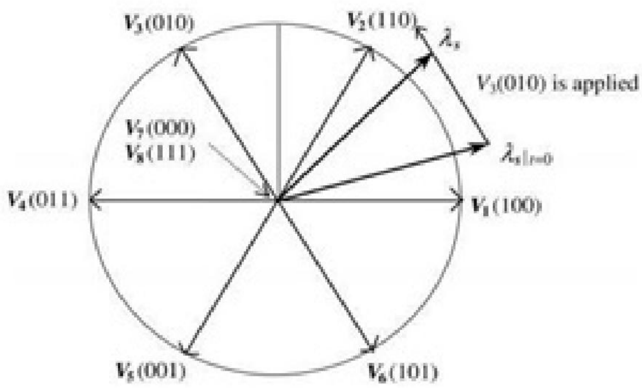

Fig. 8. Available stator voltage vectors

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. 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 stator flux 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. 9. To reverse the rotational direction of, voltage vectors in the opposite direction should be selected.

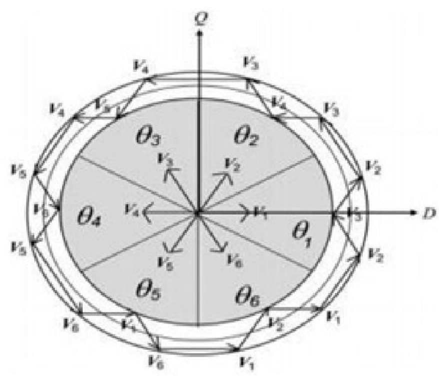

Fig. 9. Control of the amplitude of stator flux linkage

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. 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 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, 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, 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.

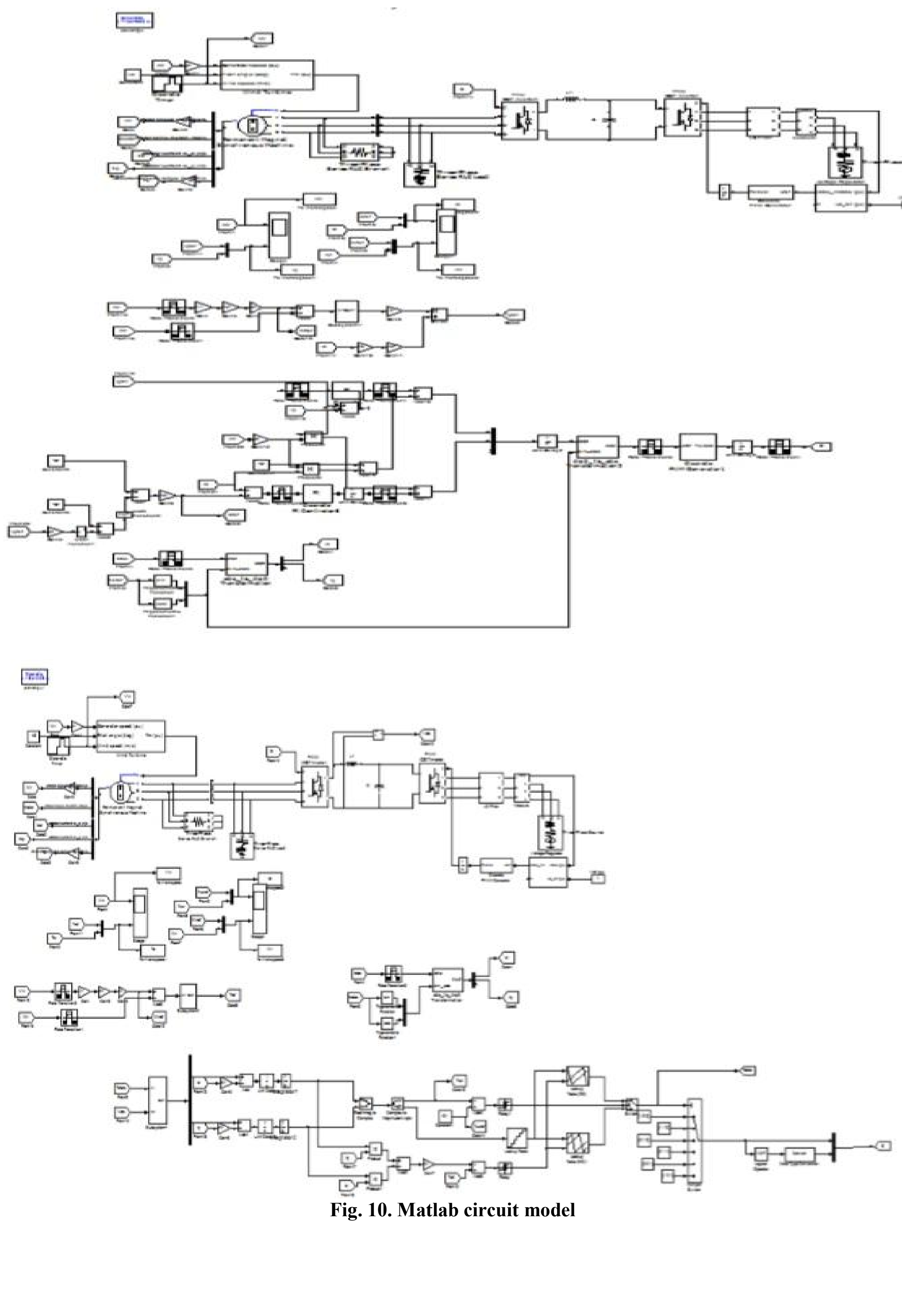

Fig. 10. Matlab circuit model

Table 3. Parameter 0f IPM Synchronous Generator

Rated Power	4.8 KW
Rated Torque	34.9 NM
Rated Speed	1280/1600 rpm
Rated Voltage	400/480 V rms
Rated Current	8.1A rms
Magnetic flux linkage	0.52572wb
d - axis inductance (L_d) per phase	18.247mH
q -axis inductance (L_q) per phase	49.249mH
Stator Resistance	1.60Ω
Number of poles	6
Rotor inertia	0.0049 kg-m^2
Static frication	0.637 N-m
Viscous damping	0.237 m/k rpm

The electromagnetic torque is controlled by controlling the direction of rotation of, according to the torque equation. For counter clockwise operations, 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. The six-vector switching table for controlling both the amplitude and rotating direction of is shown in Table 1 and is used for both the directions of operations. In Table 1, 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.

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 3. Table 1 is used for switching the converter. 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 s for the torque and speed control loops is 10 and 100μs, respectively. For comparisons, the traditional vector-controlled scheme shown in Fig. 1 has also been implemented in MATLAB /Sim Power Systems using the same IPM synchronous generator. MATLAB/Sim Power Systems wind turbine model is used in this work. The input to the wind turbine model is wind speed and the output is torque

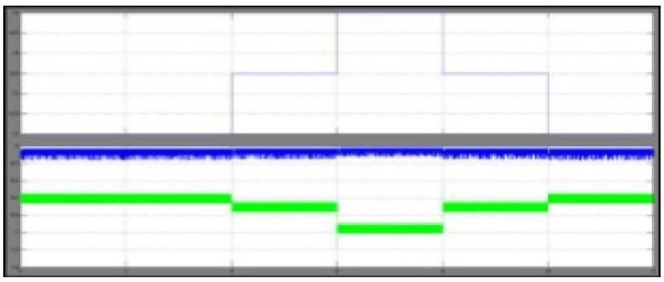

Fig. 11. Performance of the traditional indirect vector control scheme: (a) wind speed, (b) q-axis current and its reference

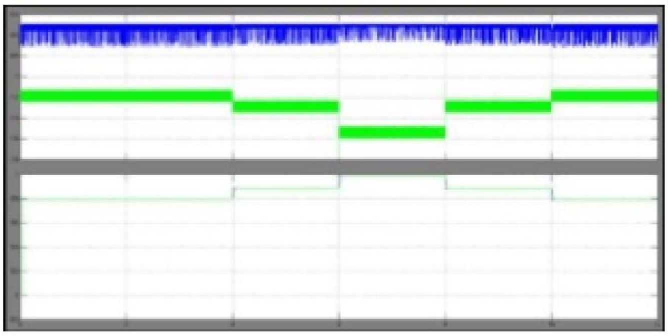

Fig 12. (c) d-axis current and its reference, and (d) speed reference and measured speed

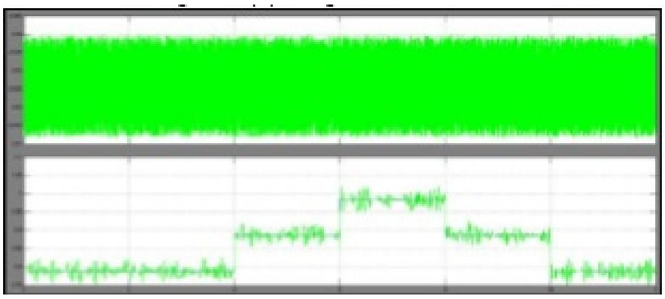

Fig. 13. Flux linkage and its reference, and (d) speed reference and measured

Conclusion

This paper proposed Modeling of IPM Synchronous Generator by Using Fuzzy Logic Controller Under variable Speed, 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. 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.

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