FUZZY CONTROLLER FOR AN IPM SYNCHRONOUS GENERATOR-BASED GEARLESS VARIABLE SPEED WIND TURBINE USING FUZZY LOGIC CONTROLLER

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ABSTRACT- In this paper we propose a new control strategy for an interior permanent magnet synchronous generator-based (IPMSG) variable speed wind turbine. In this scheme, the requirement of the continuous rotor position is eliminated as all the calculations are done in the stator reference frame. The direct control scheme with fuzzy logic controller (FLC) is simpler and can eliminate some of the drawbacks of traditional indirect vector control scheme. The proposed control scheme is implemented in MATLAB/SimPowerSystems and the results show that the Fuzzy controller can operate under constant and varying wind speeds. Finally, a sensorless speed estimator is implemented by using fuzzy logic controller, which enables the wind turbine to operate without the mechanical speed sensor. The simulation and experimental results for the sensorless speed estimator are presented. This scheme possesses advantages such as lesser parameter dependence and reduced number of controllers compared with the traditional indirect vector control scheme.

Index Terms— Direct control, interior permanent magnet (IPM) synchronous generator, sensorless speed estimator, variable speed wind turbine, Fuzzy logic controller (FLC)

INTRODUCTION

NOW a days the need for Renewable energy is increasing day by day, 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.[2] 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.[9] In international public opinion surveys there is strong support for promoting renewable sources such as solar power and wind power.[10] At the national level, at least 30 nations around the world already have renewable energy contributing more than 20 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 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 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.

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 - and –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 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 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 ‘ΔE’ 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.

Therefore, coordinate transformation is involved and a position sensor is, thus, mandatory for the torque loop. All these tasks introduce delays in the system. Also, the torque response under this type of control is limited by the time constant of stator windings. 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 (Ωr) 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.

Rule Base: The elements of this rule base table are determined based on the theory that in the transient state, large errors need coarse control, which requires coarse input/output variables, while in the steady state, small errors need fine control, which requires fine input/output variables. Based on this, the elements of the rule table are obtained as shown in below fig

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Fig.2. Mechanical power generated by the turbine as function of the rotor speed for different wind speeds.
II. WIND TURBINE MODEL AND MAXIMUM POWER EXTRACTION

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

$$P_m = 0.5 \rho AC_p(\lambda_r, \beta) X (V_w^3)$$

$$= 0.5 \rho AC_pX \left(\frac{w_mr^3}{\lambda_r}\right) \quad (1)$$

Where $\rho$ 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 ($\lambda_r$) and $\beta$ pitch angle (deg.), $w_m$ is the rotational speed of turbine rotor in mechanical (rad/s), and $R$ is the radius of the turbine (m). The tip speed ratio is given by

$$TSR = \lambda_r = \text{Rotor speed } \div \text{Wind speed} = \frac{w_m R}{v_w} \quad (2)$$

The wind turbine can produce maximum power when the turbine operates at maximum $C_p$ (i.e., at $C_{p\text{-opt}}$). Therefore, it is necessary to keep the rotor speed at an optimum value of the tip speed ratio $\lambda_{r\text{-opt}}$. If the wind speed varies, the rotor speed should be adjusted to follow the change. The target optimum power from a wind turbine is given by

$$P_{m\text{-opt}} = 0.5 \rho AC_{p\text{-opt}} \left(\frac{(w_{m\text{-opt}} R)}{\lambda_{r\text{-opt}}}\right)^3 \quad (3)$$

$$= k_{p\text{opt}} (w_{m\text{-opt}}) \quad (4)$$

Where

$$k_p = 0.5 \rho AC_{p\text{-opt}} \left(\frac{R}{\lambda_{r\text{-opt}}}\right)$$

And

$$w_{m\text{-opt}} = w_{g\text{-opt}} = \left(\frac{\lambda_{r\text{-opt}}}{R}\right) V_w \quad (5)$$

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

The optimum torque can be given by

$$T_{m\text{-opt}} = k_{\text{opt}} \left(w_{m\text{-opt}}\right)(t)^2 \quad (6)$$

The mechanical rotor power versus rotor speed for varying wind speeds is shown in Fig. 2. The optimum power curve ($p_{m\text{-opt}}$) 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).

III. IPM SYNCHRONOUS GENERATOR MODEL

The machine model in dq 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. The d- and q-axes voltages of PMSG can be given by

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

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

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

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

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

The torque equation of the PMSG can be written as

$$T_g = -\frac{3}{2} P (\lambda_d i_q - \lambda_q i_d)$$

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

In (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, Fig.2. Mechanical power generated by the turbine as function of the rotor speed for different wind speeds. $R_s$ is the stator resistance, $V_w$ is the rotor speed in rad/s, $L_m$ is the magnet flux, $P$ is the number of pole pairs, $p$ and is the operator $\frac{d}{dt}$. Fig. 3 shows the dq model of IPM synchronous generator. The first term in the torque equation (11) is the excitation torque that is produced by the interaction of permanent magnet flux and $i_q$. 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, 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

$$
i_d^* = \frac{2 L_d}{2 L_d - L_q} - \sqrt{\frac{L_d}{L_d - L_q}} + \left(i_q^*\right)^2$$

$$i_q^* = \frac{L_M}{2(L_d - L_q)} - \sqrt{-\frac{L_d}{L_d - L_q}} + \left(i_d^*\right)^2$$

**IV. 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. 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. 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 band width.

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 flux, stator current, and stator voltage. These relationships are shown in Fig. 5 as rotor flux ($\delta_d$) reference, stator flux (xy) reference, and stationary (DQ) reference frames. The angle between the stator and rotor flux linkages $\delta$ is the load angle if the stator resistance is neglected. In the steady state, $\delta$ 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 $\delta$ between the stator flux vector and the rotor flux vector.

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

$$\lambda_D = -\int (V_d - i_d R_s)dt$$

$$\lambda_Q = -\int (V_q - i_q R)dt$$

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

![4. Proposed direct control scheme for the IPM generator side converter](image)
The stator voltage vector for a three-

voltage vectors can

be expressed as

degree apart from each other, as in Fig. 7. These eight

torsional

torsional

\[
V_s(s_a, s_b, s_c) = V_d \left( S_a + S_b e^{j2\pi/3} + S_c e^{j4\pi/3} \right)
\]

(20)

Where \(V_d = 2/3 \cdot V_{dc}\) and \(V_{dc} = \text{dc link voltage}\)

Fig. 6. Rectifier connected to IPM synchronous generator

Fig. 7. Available stator voltage vectors

A. Control of Amplitude of Stat or Flux

Linkage

The stator flux linkage in the stationary reference

torsional

torsional

frame can be given as

\[
\lambda_s = \int (V_s - i_s R_s) dt
\]

(21)

Equation (21) can written as

\[
\lambda_s = \frac{V_d}{s} - R_s \int i_s dt
\]

(22)

Equation (22) implies that the tip of the stator flux

linkage vector \(\lambda_s\) 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 \(\Theta_1\) to \(\Theta_6\) 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 \(\lambda_s\). For instance,

voltage vectors \(V_2\) and \(V_3\) are selected to increase or

decrease the amplitude of \(\lambda_s\), respectively, when \(\lambda_s\)

TABLE I

SIX-VECTOR SWITCHING TABLE FOR CONVERTER

<table>
<thead>
<tr>
<th>(\lambda)</th>
<th>(\tau)</th>
<th>(V_{1(10)})</th>
<th>(V_{1(01)})</th>
<th>(V_{1(00)})</th>
<th>(V_{1(11)})</th>
<th>(V_{1(100)})</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tau = 1)</td>
<td>( \tau = 1)</td>
<td>( \tau = 0)</td>
<td>( \tau = 0)</td>
<td>( \tau = 0)</td>
<td>( \tau = 0)</td>
<td>( \tau = 0)</td>
</tr>
</tbody>
</table>

In the stationary reference frame, the stat or flux link

age phasor is given by

\[
|\lambda_s| = \sqrt{\lambda_D^2 + \lambda_Q^2} \quad \text{and} \quad \delta = \tan^{-1}\left(\frac{\lambda_Q}{\lambda_D}\right)
\]

(16)

And the electromagnetic torque is given by

\[
T_g = -\frac{3}{2} P (\lambda_D i_Q - \lambda_Q i_D)
\]

(17)

The torque equation in term s of and generator

parameters is given by [24]

\[
T_g = -\frac{3P|\lambda_s|}{4L_d L_q} \left( 2\frac{L_m}{L_q} s \sin \delta \right) - |\lambda_s| (I_Q - I_d) \sin 2\delta
\]

(18)

V. 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:

\[
V_s = \frac{2}{3} \left( V_a + V_b e^{j2\pi/3} + V_c e^{j4\pi/3} \right)
\]

(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 anti parallel diodes. The primary voltages \(V_a\), \(V_b\), \(V_c\) are determined by the status of these

three switches \((s_a, s_b, s_c)\). Therefore, there are

six nonzero voltage vectors \(V_1(100), V_2(110)\), \(V_3(010), V_4(001), V_5(101), V_6(111)\). The six nonzero voltage vectors are 60

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

Fig. 5. Stator and rotor flux linkages in different reference frames.
is in region \( \Theta_s \) and the stator flux vector is rotating in counter clockwise direction.

In this way, the amplitude of \( \lambda_s \) can be controlled at the required value by selecting the proper voltage vectors. How the voltage vectors are selected for keeping \( \lambda_s \) within a hysteresis band is shown in Fig. 8 for a counter clockwise direction of \( \lambda_s \). The hysteresis band here is the difference in radii of the two circles in Fig. 8. To reverse the rotational direction of \( \lambda_s \), voltage vectors in the opposite direction should be selected. For example, when \( \lambda_s \) is in region and \( \Theta_s \) is rotating in the clockwise direction the voltage vectors pair and are selected to reverse the rotation of \( \lambda_s \) [20], [24] for the torque. The six-vector switching table for controlling both the amplitude and rotating direction of \( \lambda_s \) is shown in Table I and is used for both the directions of operations. In Table I, \( \lambda \) and \( T \) are the outputs of the hysteresis controllers for Flux linkage and torque, respectively. If \( \lambda=1 \), then the actual flux linkage is smaller than the reference value. The same is true for the torque. \( O_1-O_4 \) are the region numbers for the stator flux linkage positions.

VI. 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 DQ-axes variables. 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 (T,\( \lambda \) ) 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 DQ reference frame and without any co-ordinate transformation.

A. Flux Linkage and Torque Estimation

The DQ-axes flux linkage components \( \lambda_{d(K)} \) and \( \lambda_{q(K)} \) at the K th sampling instant can be calculated as

\[
\lambda_{d(K)} = T_s [-V_{d(K-1)} + R_s \lambda_{d(K-1)} + \lambda_{d(K-1)}] \quad (23)
\]

\[
\lambda_{q(K)} = T_s [-V_{q(K-1)} + R_s \lambda_{q(K-1)} + \lambda_{q(K-1)}] \quad (24)
\]

Where \( T_s \) is the sampling time, the variables with subscript \( K \) are their values at the \( K \) th sampling instant, and the variables with \( K-1 \) are 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 \( V_d \) and \( V_q \) axes voltages for the applied voltage vectors.

The amplitude of the stator flux linkage is calculated from

\[
|\lambda_{s(K)}| = \sqrt{\lambda_{d(K)}^2 + \lambda_{q(K)}^2}
\]

And

\[
\Theta_s = \tan^{-1}\left(\frac{\lambda_{q(K)}}{\lambda_{d(K)}}\right) \quad (25)
\]
The developed torque is calculated from

\[ T_{g(k)} = -\frac{3}{2} \left( p \lambda_{D(k)} i_{Q(k)} - \lambda_{Q(k)} i_{D(k)} \right) \]  

(26)

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

\[ T_{g(k)} = -\frac{3P |\lambda_{S(k)}|}{4L_dL_q} \left[ 2 \lambda_{m} L_q \sin(\delta_{(k)}) \right] \]

\[ - |\lambda_{S(k)}| \left( L_q - L_d \right) \sin 2(\delta_{(k)}) \]  

(27)

<table>
<thead>
<tr>
<th>( V_1 )</th>
<th>( V_2 )</th>
<th>( V_3 )</th>
<th>( V_4 )</th>
<th>( V_5 )</th>
<th>( V_6 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_D )</td>
<td>( V_D )</td>
<td>( 0.5V_D )</td>
<td>( -0.5V_D )</td>
<td>( -0.5V_D )</td>
<td>( 0.5V_D )</td>
</tr>
<tr>
<td>( V_Q )</td>
<td>0</td>
<td>0.886</td>
<td>( V_D )</td>
<td>0.886</td>
<td>0.88</td>
</tr>
</tbody>
</table>

**TABLE II**

DQ-AXES VOLTAGES (\( V_D = \frac{2}{3} V_{dc} \))

**ABOUT FUZZY LOGIC CONTROLLER**

A fuzzy inference system (or fuzzy system) basically consists of a formulation of the mapping from a given input set to an output set using fuzzy logic. This mapping process provides the basis from which the inference or conclusion can be made. A fuzzy inference process consists of the following steps:

**Step 1:** Fuzzification of input variables
**Step 2:** Application of fuzzy operator (AND, OR, NOT) in the IF (antecedent) part of the rule
**Step 3:** Implication from the antecedent to the consequent (THEN part of the rules)
**Step 4:** Aggregation of the consequents across the rules
**Step 5:** Defuzzification

The crisp inputs are converted to linguistic variables in fuzzification based on membership function (MF). An MF is a curve that defines how the values of a fuzzy variable in a certain domain are mapped to a membership value \( \mu \) (or degree of membership) between 0 and 1. A membership function can have different shapes. The simplest and most commonly used MF is the triangular-type, which can be symmetrical or asymmetrical in shape. A trapezoidal MF has the shape of a truncated triangle. Two MFs are built on the Gaussian distribution curve: a simple Gaussian curve and a two-sided composite of two different Gaussian distribution curves. The bell MF with a flat top is somewhat different from a Gaussian function. Both Gaussian and bell MFs are smooth and non-zero at all points. The implication step helps to evaluate the consequent part of a rule. There are a number of implication methods in the literature, out of which Mamdani and TS types are frequently used. Mamdani proposed this method which is the most commonly used implication method. In this, the output is truncated at the value based on degree of membership to give the fuzzy output.

Takagi-Sugeno-Kang method of implication is different from Mamdani in a way that, the output MFs is only constants or have linear relations with the inputs. The result of the implication and aggregation steps is the fuzzy output which is the union of all the outputs of individual rules that are validated or “fired”. Conversion of this fuzzy output to crisp output is defined as defuzzification. There are many methods of defuzzification out of which Center of Area (COA) and Height method are frequently used. In the COA method (often called the center of gravity method) of defuzzification, the crisp output of particular variable \( Z \) is taken to be the geometric center of the output fuzzy value \( \mu_{out}(Z) \) area, where this area is formed by taking the union of all contributions of rules whose degree of fulfillment is greater than zero. Here in this scheme, the error \( e \) and change of error \( ce \) are used as numerical variables from the real system. To convert these numerical variables into linguistic variables, the following seven fuzzy levels or sets are chosen as:
NB (negative big), NM (negative medium), NS (negative small), ZE (zero), PS (positive small), PM (positive medium), and PB (positive big)

The fuzzy controller is characterized as follows:

- Seven fuzzy sets for each input and output.
- Triangular membership functions for simplicity.
- Fuzzification using continuous universe of discourse.
- Implication using Mamdani's 'min' operator.
- Defuzzification using the 'height' method.

VII. RESULTS AND DISCUSSIONS

The direct control scheme for IPM synchronous generator based variable speed wind turbine shown in Fig. 4 is implemented in MATLAB/SimPowerSystems 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. A smaller hysteresis bandwidth can reduce ripples in torque. The sampling times for the torque and speed control loops are 10 and 100μs, respectively. For comparisons, the traditional vector-controlled scheme shown in Fig. 1 has also been implemented in MATLAB/SimPowerSystems using the same IPM synchronous generator.

MATLAB/SimPowerSystems wind turbine model is used in this work. The input to the wind turbine model is wind speed and the output is torque

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power</td>
<td>4.7 kw</td>
</tr>
<tr>
<td>Rated torque</td>
<td>34.8Nm</td>
</tr>
<tr>
<td>Rated speed</td>
<td>1280/1600 rpm</td>
</tr>
<tr>
<td>Rated voltage</td>
<td>400/480 V rms</td>
</tr>
<tr>
<td>Rated current</td>
<td>8.1 A rms</td>
</tr>
<tr>
<td>Magnetic flux linkage</td>
<td>0525723 Wb</td>
</tr>
<tr>
<td>d-axis inductance(L_d) per phase</td>
<td>18.237mH</td>
</tr>
<tr>
<td>q-axis inductance(L_q) per</td>
<td>49.239 mH</td>
</tr>
</tbody>
</table>

Fig. 9 shows the performance of the indirect vector control of IPM synchronous generator-based variable speed wind turbine. The q- and d-axes currents and their references are shown in Fig. 9(b) and (c), respectively, and the wind speed in Fig. 9(a). It is seen that q- and d-axes currents follow their references quite well and regulate the generator current under different wind speeds. As shown in Fig. 9(d), the speed controller is able to regulate the speed for varying wind speeds.
Fig. 9. Performance of the traditional indirect vector control scheme:
(a) wind speed, (b) q-axis current and its reference, (c) d-axis current and its reference, and (d) speed reference and measured speed.

Performance of Direct Torque and Flux Control Scheme

Fig. 10 shows the performance of direct control scheme for IPM synchronous generator-based variable speed wind turbine. Fig. 10(a)–(d) shows the wind speed, torque response, flux linkage response, and speed response, respectively. As shown in Fig. 10(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. 10(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. 10. Performance of the direct control scheme:
(a) wind speed, (b) torque and its reference, (c) flux linkage and its reference, and (d) speed reference and measured.

Maximum Power Extraction at Variable Wind Speed

Figs. 11 and 12 show the maximum power extraction at different wind speeds under indirect vector control and direct torque and flux control scheme, respectively. In both control schemes, the measured power can track the optimum power curve quite well and extract the maximum power at different wind speeds. The deviations between the measured and optimum values are within 2%.
Performance Comparison

It is seen from Figs. 9 to 12 that direct torque and flux control scheme shows similar performance to indirect vector control scheme. No rotor position is required with direct control scheme as all the calculations are done in static or reference frame. In indirect vector control, the rotor position is required as all the calculations are done in the rotor reference frame. The direct control scheme possesses several advantages compared to the indirect vector control scheme such as lesser parameter dependence, torque and flux control without rotor position, and proportional-integral (PI) controller which reduces the associated delay in the controllers. However, it can be seen that the torque response from the proposed direct control scheme has fluctuations, as shown in Figs. 10(b) and 13, which introduces speed ripples. This fluctuation in angular velocity can cause dynamic vibration in the power train. Some methods to minimize the torque/speed ripples in IPM machines have been proposed in the literature [25], [26], which need to be considered in future research. Table IV shows the comparison of indirect vector control and direct control schemes.

<table>
<thead>
<tr>
<th>Indirect vector control</th>
<th>Direct torque and flux control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Encoder is always needed for coordinate transformation</td>
<td>No Encoder is always needed for coordinate transformation</td>
</tr>
<tr>
<td>PW modulator</td>
<td>Switching logic</td>
</tr>
<tr>
<td>Three PI controllers difficult to tune them</td>
<td>Only one PI controller for speed easy to tune</td>
</tr>
<tr>
<td>A number of generator parameters are required</td>
<td>Only stator resistance is required less parameters needed</td>
</tr>
</tbody>
</table>

Table IV: Comparison of indirect vector control and direct control schemes

VIII. 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. As shown in Fig. 14, the generator speed is measured by measuring the position using position sensor (encoder). However, the existence of the position sensor adds several disadvantages, such as: 1) increased number of connections between generator and its controller; 2) reduced reliability and robustness; 3) increased cost; 4) susceptibility to noise and vibration; 5) additional friction; and 6) design complexity of generator [21]. Therefore, 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, as shown in Fig. 14, 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 \( T_{g(k)} + \delta_{(k)} \), which after differentiation gives the speed signal. The proposed speed estimator is thus based on the following steps and inputs [21].

1) Estimate the stator flux linkage using (25). 2) Calculate the actual developed torque from (26). The torque angle 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. The sensorless speed estimator is very simple and software calculation burden is light. No extra sensor is needed for the estimation of the stator flux position. The variation of the angle \( \delta \) is taken into account and therefore, the rotor flux position can be calculated without large error in transient. The assumption of nearly constant stator and rotor flux linkages is eliminated. Figs. 15 and 16 show the simulation and experimental results for sensorless speed estimator, respectively. It is seen that the estimated speed follows the actual speeds quite well with little error. Table IV shows the comparison between the indirect vector control and direct control schemes.

**IX. CONCLUSION**

This paper proposed a sensorless direct control strategy for an IPM synchronous generator-based variable speed wind turbine. It is done with the help of fuzzy logic controller (FCL). 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. 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


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