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A Proposed Direct Control Strategy for Space Vector PWM based Variable Speed IPM Wind Turbine

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ABSTRACT:

This paper proposes a direct control strategy for an interior permanent magnet synchronous generator-based variablespeedwind turbine. In this scheme, the requirement of the continuous rot or 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. 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.

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. 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.

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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. 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.

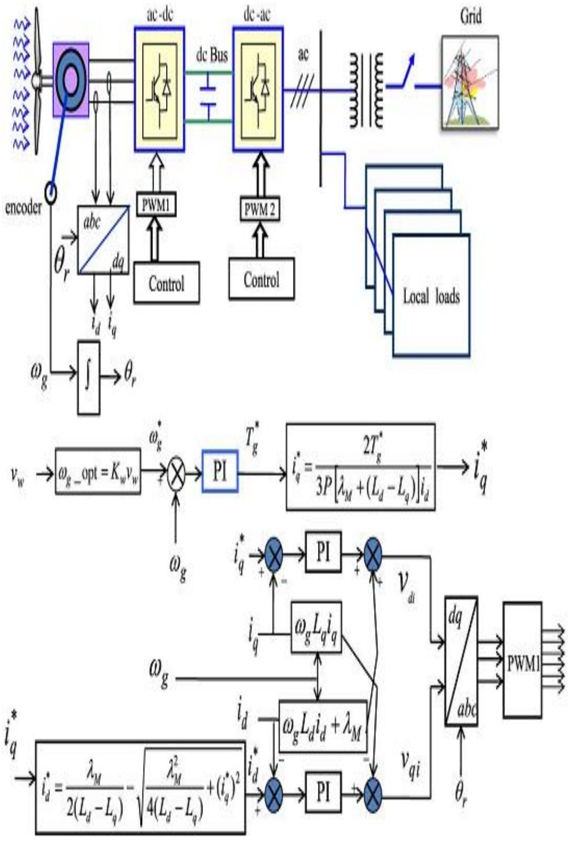

Fig. 1. Traditional vector control scheme for the IPM synchronous generator.

This method is inherently sensorless and have several advantages compared with the traditional indirect vector control scheme. 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.

WIND SYSTEMS:

GRID-connected wind electricity generation is showing the highest rate of growth of any form of electricity generation, achieving global annual growth rates in the order of 20 - 25%. It is doubtful whether any other energy technology is growing, or has grown, at such a rate. Global installed capacity was 47.6 GW in the year 2004 and 58.9 GW in 2005. Wind power is increasingly being viewed as a mainstream electricity supply technology. Its attraction as an electricity supply source has fostered ambitious targets for wind power in many countries around the world. Wind power penetration levels have increased in electricity supply systems in a few countries in recent years; so have concerns about how to incorporate this significant amount of intermittent, uncontrolled and non-dispatch able generation without disrupting the finely-tuned balance that network systems demand. Grid integration issues are a challenge to the expansion of wind power in some countries. Measures such as aggregation of wind turbines, load and wind forecasting and simulation studies are expected to facilitate larger grid penetration of wind power. In this paper simulation studies on grid connected wind electric generators (WEG) employing (i) Squirrel Cage Induction Generator (SCIG) and (ii) Doubly Fed Induction Generator (DFIG) have been carried separately. Their dynamic responses to disturbances such as variations in wind speed, occurrence of fault etc. have been studied, separately for each type of WEG.

Power from Wind

The power that can be captured from the wind with a wind energy converter with effective area Ar is given by [2]

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$$P = \frac{1}{2}\rho_{air} C_p A v_w^3 \qquad (1)$$

where ρair is the air mass density [kg/m3], vw is the wind speed and Cp is the so-called power coefficient which depends on the specific design of the wind converter and its orientation to the wind direction. Its theoretical maximum value is 16/27 = 0.593 (Betz limit). For a wind turbine with given blades it can be shown that the power coefficient Cp basically depends only on the tip speed ratio l, which equals the ratio of tip speed vt [m/s] over wind speed vw [m/s] and the so-called blade pitch angle q [deg]. This pitch angle is defined as the angle between the cord of the blade and the plane of the wind rotor. So, for a wind rotor with radius r, (1) can be rewritten as:

$$P = \frac{1}{2}\rho_{air} C_p(\lambda,\theta)\pi r^2 v_w^3 \qquad (2)$$

As an example, Fig. 2 shows the dependency of the power coefficient Cp on the tip speed ratio l and the blade pitch angle q for a specific blade. For this blade maximum energy capture from the wind is obtained for q =0 and l just above 6. To keep Cp at its optimal value for varying wind speed, the rotor speed should be proportional to the wind speed. In practice both constant l (variable speed) and constant speed operation is applied.

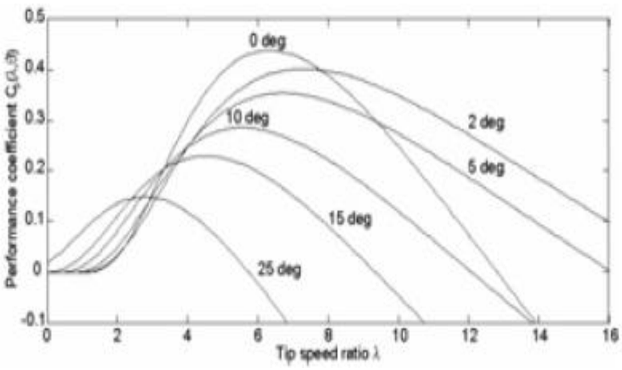

Fig:2 Power coefficient Cp as a function of tip speed ratio l and pitch angle q for a specific blade.

For on shore turbines, the blades are designed such that the optimal tip speed is limited to roughly 70 m/s. This is done because the blade tips cause excessive acoustical noise at higher tip speeds. For offshore turbines, the noise does not play an important role, and higher speeds are used leading to slightly higher optimal values of Cp. The relation between wind speed and generated power is given by the power curve, as depicted in Fig. 3. The power curve can be calculated from (2) where the appropriate value of l and q should be applied. In the power curve, four operating regions can be distinguished, that apply both to constant speed and variable speed turbines:

1 No power generation due to the low energy content of the wind.

2 Less than rated power generation. In this region, optimal aerodynamic efficiency and energy capture is aimed at. The wind speed at the boundary of region 2 and 3 is called the rated wind speed and all variables with the subscript rated refer to design values at this wind speed.

3 Generation of rated power, because the energy content of the wind is enough. In this region, the aerodynamic efficiency must be reduced, because otherwise the electrical system would become overloaded.

4 No power generation. Because of high wind speeds the turbine is closed down to prevent damage.

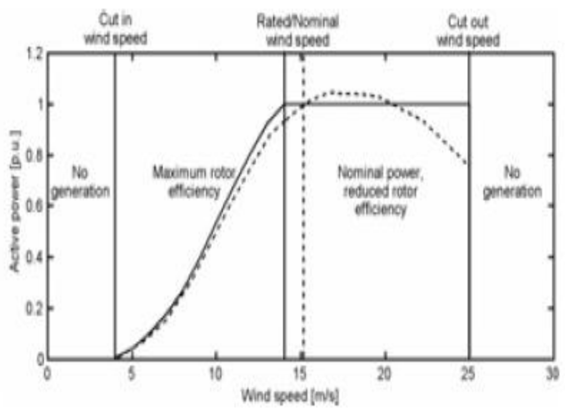

Fig:3 Typical power curve of a constant speed stall (dotted) and a variable speed pitch (solid) controlled wind turbine.

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Aerodynamic Power control:

In region 3 (and 4) the shaft power should be less then the available power from wind to prevent overloading of components. There are two main methods for limiting the aerodynamic efficiency in high wind speeds. With the first method one takes advantage of the aerodynamic stall effect. When the angle, at which the wind hits the blade ('angle of attack'), is gradually increased, then at a certain angle the airflow will no longer flow along the blade, but will become loose from the blade at the back side. Large eddy's will be formed that result in a drastic reduction of Cp (see Fig. 4).

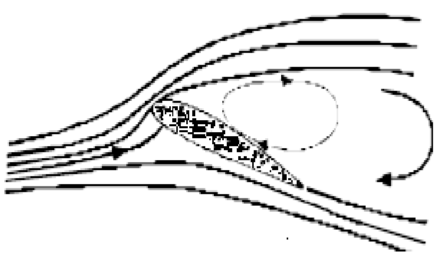

Fig. 4. Stalled flow around an aerofoil .

MODELING OF PROPOSED THORY

Wind Turbine Model and Maximum Power Extraction:

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

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

where is the air density ( ), is the wind speed in m/s, is the blade swept area ( ), is the power coefficient, which is a function of tip speed ratio ( ) and pitch angle (deg.), is the rotational speed of turbine rotor in mechanical (rad/s), and is the radius of the turbine (m).

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

The wind turbine can produce maximum power when the turbine operates at maximum (i.e., at). Therefore, it is necessary to keep the rotor speed at an optimum value of the tip speed ratio. 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

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

Where

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

And

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

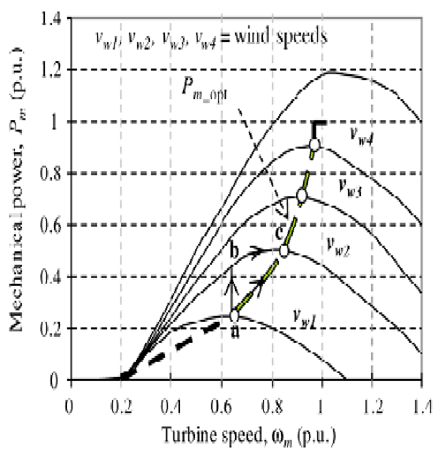

Fig.5 Mechanical power generated by the turbine as a function rotor speed for different speed The optimum torque can be given by

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

The mechanical rotor power versus rotor speed for varying wind speeds is shown in Fig. 5. The optimum power curve ( ) is also shown in Fig. 5, 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. 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).

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IPM SYNCHRONOUS GENERATOR MODEL

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

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

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

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

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

$$\lambda_q = -L_q i_q. \qquad (10)$$

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), , , , , , and 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. 7 shows the model of IPM synchronous generator. The first

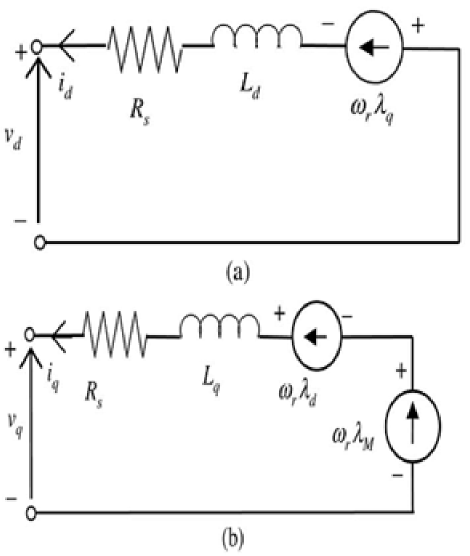

Fig.6 dq model of IPM synchronous generator (a) d axis equivalent circuit (b) q axis equivalent circuit

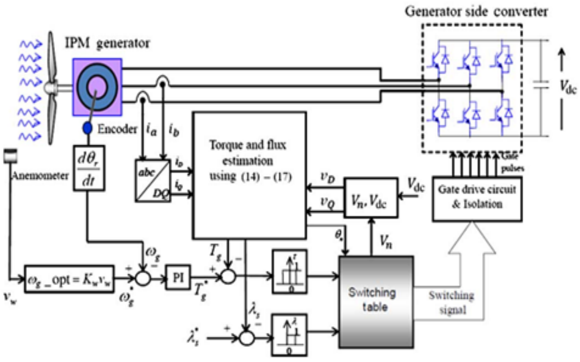

Fig.7 Proposed direct control scheme for IPM generator side converter

Term in the torque equation (11) is the excitation torque that is produced by the interaction of permanent magnet flux and is independent of . The second term is the reluctance torque that is proportional to the product of 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.

The - and -axes current references can be expressed as

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

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

RESULTS:

Performance of the traditional indirect vector control scheme: (a) wind speed,(b) –axis current and its reference,(c) –axis current and its reference,and (d) speed reference and measured speed.

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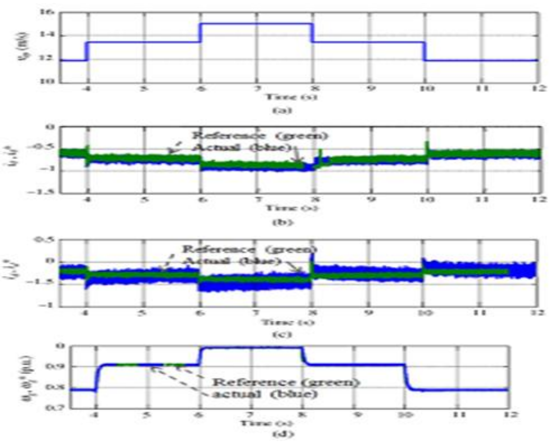
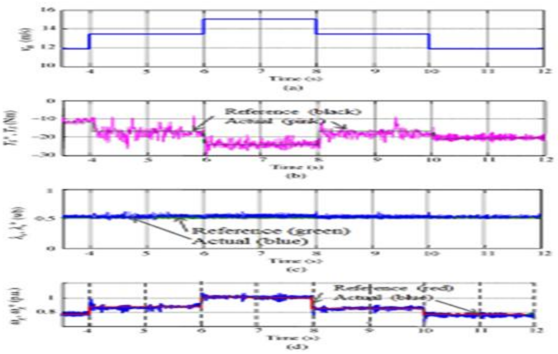
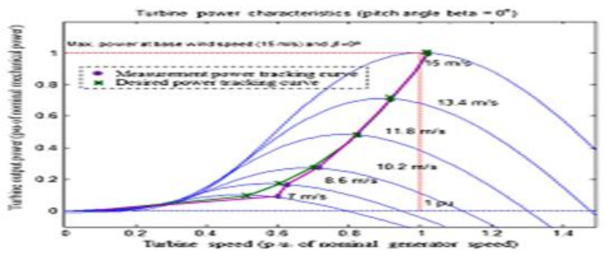


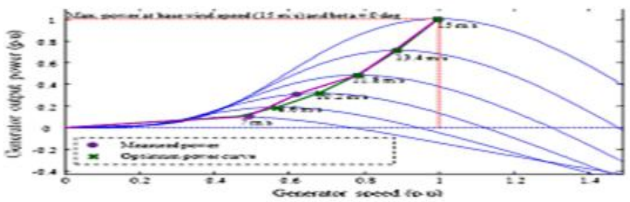
Performance of the direct control scheme:(a)wind speed,(b)torque and its reference, (c) flux linkage and its reference, and (d) speed reference and measured.



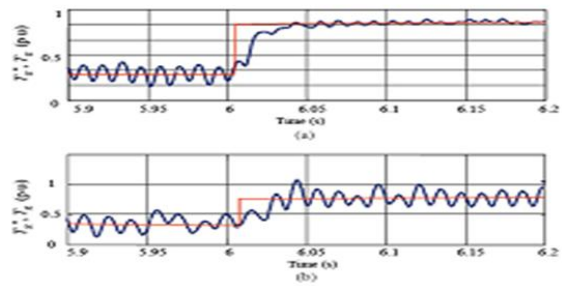
Maximum power extraction with indirect vector control.



Maximum power extraction with direct control scheme.



Comparison of torque responses: (a) torque response under vector control scheme and (b) torque response under direct control scheme.



CONCLUSION:

In this paper I proposed a sensorless direct 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. 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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