Power Control of Permanent Magnet Synchronous Generator Directly Driven by Wind Turbine

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***Abstract*—In order to smooth the wind turbine generated power, this paper proposes a new direct torque control (DTC) scheme for the permanent magnet synchronous generator (PMSG). The control strategy combines the technique of DTC and the variable pitch control algorithm. Considering the variation of wind speed, the PMSG side converters are used to achieve maximum wind energy capture and power smoothing, while the grid-side converter regulates DC-link voltage, injects the generated power into the AC network. The employed control strategy provides an optimal control solution for wind turbine with the PMSG.**

***Index Terms*—DTC, PMSG, power control, maximum wind energy capture**

I. Introduction

Recent years have witnessed rapid development and increasing applications of wind power as an attractive clean electricity source. Compared to conventional thermal or hydraulic electric power generation, wind power generation has advantages including no need for fuel burning, being friendly to the environment. On the other hand, Permanent magnet synchronous generator directly driven gets more and more application thanks to many advantages such as high reliability, high efficiency, low cost and predominant performance.

Control strategies of wind power generator are divided into two categories: field oriented control and direct torque control (DTC). Direct torque control has several advantages such as less parameter-dependent, easy control and essentially less sensor. Substantial research already exists obtaining the accurate information of speed and rotor position in Ref. [1]-[4]. Although the adaptive control technique and the sliding mode observer have been used to achieve sensor-less control in Ref. [2]-[4], these method had several disadvantages such as high computational requirement for the position observers and high parameter dependence. DTC strategy was extended naturally to the PMSG wind power application. Stationary torque response of this system realizes high operational reliability in Ref. [5]. The torque limiter enhanced this system's loading capability to achieve the goal of MPPT strategy in Ref. [6], [7].

Both maximum wind energy capture and power smoothing are the goals of controlling the PMSG for different wind condition. To adjusting the duty ratio of frequency converter, the system realized MPPT under low wind speed in Ref. [8]. The system operated at rated power mode using pitch control in high wind situation. However, the power fluctuation that caused by lag action of stationary components is still a problem. Estimation of optimal rotate speed and power feedback has used to realize maximum wind energy capture in Ref. [9], [10]. In these studies, these controls do not take into account the different wind speed conditions.

By static coordinate mathematical model of direct-driven permanent magnet synchronous generator, maximum wind energy capture and power smoothing control worked respectively under low and high wind speed condition. Based on direct torque control, a power smoothing control of permanent magnet synchronous generator directly driven by wind turbine were proposed in this paper. Experimental results from 2.0MW model confirm the validity of the design procedure and the effectiveness of the control method.

II. Wind Generation System

A. Wind Turbine Model

The mechanical power extracted from the wind can be expressed as follow:

$$P_m = \frac{1}{2} C_p \rho \pi r^2 v^3 \tag{1}$$

$$\lambda = \frac{\omega r}{v} = \frac{2\pi r n}{60 v} \tag{2}$$

where ρ is the air density (kg/m^3), r is the blade radius (m), ω is the wind speed (rad/s), C_p (λ, β) is utilization factor of wind power with a maximum value is about 0.5, and it could be expressed as:

$$C_p = 0.22(116\frac{1}{\eta} - 0.4\beta - 5)e^{-12.5\frac{1}{\eta}} \tag{3}$$

$$\frac{1}{\eta} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{4}$$

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where β is the pitch angle, λ is the tip speed ratio. The wind turbine mechanical torque output T_m is given by:

$$T_m = P_m / \omega \tag{5}$$

Therefore, a generic equation is used in order to model the mechanical power based on the modeling turbine characteristics described as:

$$P_m = \frac{1}{2} C_p \rho \pi R^2 \left(\frac{\pi R}{30\lambda}\right)^3 \cdot n^3 \tag{6}$$

Equation (6) shows that the mechanical power is a function of the rotational speed for any particular wind speed.

B. Modeling of PSMG

First it makes the following assumptions:

- Linear magnetic circuit;
- Completely symmetrical three-phase windings;
- Ignoring the cogging;
- Excluding core loss.

According to the assumptions above, we establish the mathematical model of PMSM in the α-β axis rotating coordinate system in a series of equations that include the flux, mechanical motion and torque.

The PMSG mathematical model is described in the α-β reference system as follows:

$$\frac{d\psi_s}{dt} = -i_s R_s + u_s \tag{7}$$

where, R_s is the stator resistance and the expression for the electromagnetic torque can be described as:

$$T_e = 1.5 p_n (\psi_{s\alpha} i_{s\beta} + \psi_{s\beta} i_{s\alpha}) \tag{8}$$

And p_n denotes the number of pole pairs. In addition, the dynamic equation of the wind turbine is given as:

$$T_m = T_e + B\omega + J\frac{d\omega}{dt} \tag{9}$$

where J is the total inertia, B is the viscous friction coefficient and T_m is the mechanical torque developed by turbine.

III. Control Strategy for Generator Side Converter

A. Pitch Control

Pitch control system meets the optimal relation between mechanical power absorbed by wind generator and rotor speed. When the wind speed is below the rated value, the pitch angle will track the maximum power point. If the wind speed is above the rated value, the pitch angle will limit the power output of wind generators to prevent mechanical damage of them caused by overload.

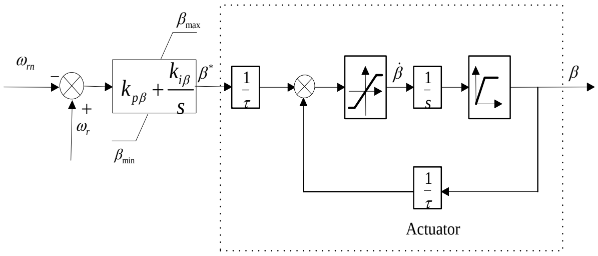


Figure 1. Variable-pitch control.

As shown in Fig. 1, the proposed controller is based on the speed deviation from its reference value $\Delta\omega_r$:

$$\begin{cases} \beta^* = \Delta\omega(k_{p\beta} + k_{i\beta} / s) \\ \Delta\omega_r = \omega_r - \omega_{rn} \end{cases} \tag{10}$$

where $k_{p\beta}$ and $k_{i\beta}$ are the proportional and integral gains respectively, ω_{rn} is rated speed of generator.

The pitch actuator is a hydraulic or electromechanical device that allows rotating the turbine blades around their longitudinal axis. The implementation of reliable control strategies is possible mostly through pitch control in commercial wind turbines. In this paper, we model the pitch actuator as a first-order dynamic system with amplitude and rate saturation as shown in Fig. 1. We noted that these saturation limits vary depending on the type of the actuating device, as well as the turbine power. In the linear region, the dynamics of the actuator is represented by:

$$\dot{\beta} = -\frac{1}{\tau}\beta + \frac{1}{\tau}\beta^* \tag{11}$$

where, τ is the time constant of the actuator, β and β^* are the actual and desired pitch angles. For the purpose of the present study, we have assumed that β can change from -2 to 30 degrees and varies at a maximum rate of ± 10 °/s.

In fact, the pitch actuators generally present a hard constraint on their speed response besides the natural amplitude saturation. To reduce the effects of fatigue loads, the amplitude and rate saturation limits of the pitch actuator should not be reached during normal operation of the turbine. For instance, high frequency load mitigation, as well as power smoothing demands fast and large corrections to the pitch angle that might cause fatigue damage to some mechanical devices. These limitations should be considered in the controller design procedure to avoid the high activity of the pitch actuators, since it could not only damage the pitch actuators but also cause unstable modes of operation.

B. Maximum Wind Energy Capture

Any change in the rotor speed converts the tip-speed ratio leading to power coefficient variation. In this way, it is unavoidable that this variation will affect generated power. Thus the vintage change in rotor speed can provide best tip-speed ratio leading to maximum generated power. According to power capture, most studies regard the tip-speed ratio control; proper speed feedback control and mountain-climb searching algorithm in Ref. [7].

Owing to proper speed feedback control, some part especially the characteristic of wind turbine and air-flow measuring device has been simplified. According to the characteristic of wind turbine and rotor speed, the computed rated value would send into PI. When the wind turbine speed is close to the operation rotor speed, the PI can swiftly adjust the output current to the rated value without variation. Compare with wind capture method, feedback control replaces the relation between wind speed and output power to the relation between rotor speed and output power. The control can make wind turbine working at optimum level and improve the efficient of whole system totally ignoring that the characteristic of wind turbine. Nevertheless, C_p and λ_{opt} are the required parameter. Moreover, for wind turbine under rated level, the power point is difficult to estimate in Ref. [9]. In order to fix the problem, the proper speed feedback control converts to power feedback control until output power exceeds rated power.

The active power output of a wind energy conversion system can be written as:

$$P_e = u_{s\alpha} i_{s\alpha} + u_{s\beta} i_{s\beta} \tag{12}$$

Considering core loss of stator:

$$P_{cu} = (i_{s\alpha}^2 + i_{s\beta}^2) R_s \tag{13}$$

Ignoring iron loss and mechanical loss, power may be written as:

$$\begin{aligned} P_m &= P_e + P_{cu} \\ &= (u_{s\alpha} + i_{s\alpha} R_s) i_{s\alpha} + (u_{s\beta} + i_{s\beta} R_s) i_{s\beta} \end{aligned} \tag{14}$$

Further, through (1) and (14), the optimum reference speed of the wind turbine rotor can be simply estimated as follows:

$$\omega_r^* = \sqrt[3]{2 P_m \lambda_{opt}^3 / \rho \pi R^5 C_{p\max}} \tag{15}$$

The optimum reference speed ω_r^* is the speed which corresponds to optimum tip speed ratio λ_{opt}. In order to have maximum possible power, the turbine should always operate at optimum tip speed ratio λ_{opt}. This is possible by controlling the rotational speed of the turbine so that it always rotates at the optimum speed of rotation.

C. Power Control

According to (3) and (4), the performance coefficient of the turbine is a function of the pitch angle. As a result, it's possible that the generated power is controllable by regulating the pitch angle if the tip speed ratio is the constant. To compare with fixed pitch control, the conventional strategy that is always working together with less power control has not attractive advantages.

In this paper, the proposed pitch control smoothes the extracted power when wind speed is below the rated value. Fig. 2 shows the perfect power curve. In fact, the practical power curve has relative loss. The constant speed control minimizes pitch angle for capture the maximum wind power. In contrast, the variable speed control can act for low wind speeds and obtain the optimal tip speed ratio by pitch angle strategy. In other words, the variable speed control gets more power than the constant speed control for same wind speed.

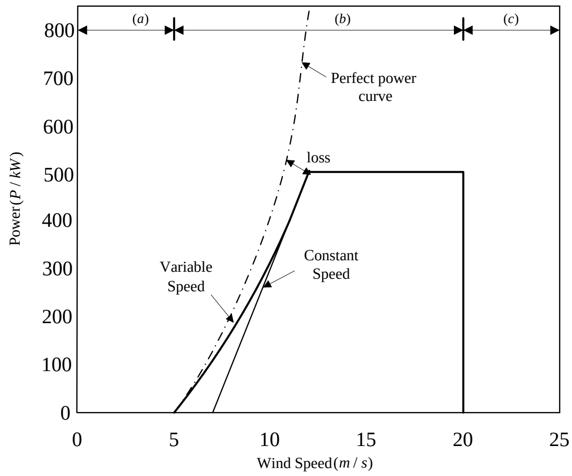


Figure 2. Relation by wind speed and power.

The typical power controls regions of wind turbine are shown in Fig. 2. The turbine starts operating when the wind speed exceeds cut-in wind speed. The power captured by the turbine increases with the wind speed increasing. At the set point of wind speed, the generating power reaches the rated power of the turbine. If the wind speed continues to rise, the generator output power remains constant at the design limit. Due to safety consideration, the turbine is shut down at speeds exceeding cut-out wind speed.

The general power strategy turns speed control to power control. At the same time, variable-pitch system acts under power signal of generator for high wind speeds. The output power is not satisfactory by changing the pitch on their speed response for variable wind speeds. For mega-watt level wind turbines, mechanical power will be much greater than the rated power of the generator, which will inevitably lead to the rise of the generator speed when the wind speed reach the rated wind and exceed it.

IV. DESIGN OF GENERATION SYSTEM

A. Power Smoothing and Smoothing Coefficient

In order to restrain the power fluctuation, this paper proposes a new smooth method, it achieves by simultaneously changing pitch and speed. Using the proposed method, the wind speed is between the cut-in speed and cut-out speed. In contrast, using the conventional method, the wind speed reaches the cut-out speed or cut-in speed.

Due to the randomness and clearance of wind generation, it is unavoidable that the power will affect power grid. It is certain that the power fluctuations will affect the power quality seriously and can be a threat to the safe and stable operation of the power system. In order to characterize the smoothness of the active power output, the smoothing coefficient γ is defined:

$$\gamma = \frac{\int_{t-\sigma}^{t} \left| \frac{dP_g}{dt} \right| dt}{\sigma} \tag{16}$$

where P_g is active power value, σ is integral region. If the γ curve is getting smaller, it means that the active power to the grid is smoother than others.

B. Double Mode Power Control of the System

For DTC PMSG, the power control is double mode control. The control diagram of PMSG is shown in Fig. 3.

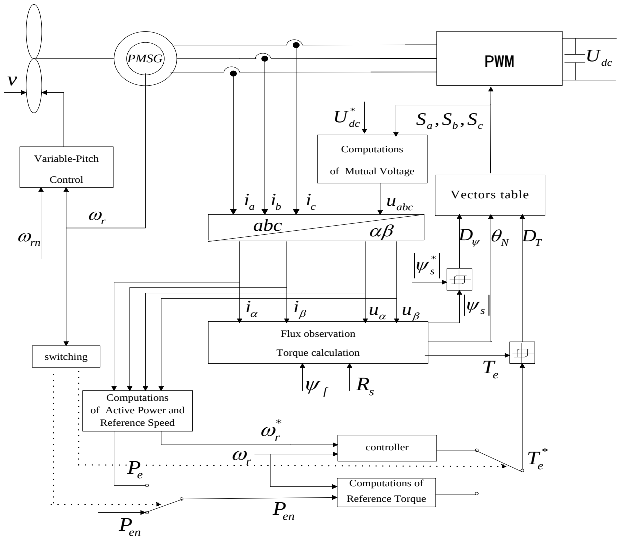


Figure 3. Power control scheme of DTC-PMSG.

DTC technique has been proposed for calculations and controls stator flux linkage and torque of PMSM directly to achieve high dynamic performance in the stator coordinate system. Stator voltage in stationary α-β is obtained from the switching states and the DC bus voltage U_{dc}. Stator current $i_{s\alpha}$ and $i_{s\beta}$ are the components of i in the α-β axis and it can be obtained from the phase current sampling values i_a , i_b and i_c through Clark Coordinate Inverse Transformation. Then $\psi_{s\alpha}$, $\psi_{s\beta}$ and T_e could be estimated by $i_{s\alpha}$, $i_{s\beta}$, $u_{s\alpha}$ and $u_{s\beta}$. This system contains three closed control loop that are the speed loop, the flux linkage loop and the torque loop. For the speed loop, the input is $\Delta\omega_r$. The output is T_e^* and it is the set value of torque loop. The reference values of the stator flux ψ^* and of the torque T_e^* are compared with the value of the actual stator flux ψ and with the value of the actual torque T_e respectively. The errors of torque and flux that exist between the reference and feedback values are inputs to the bang-bang controllers.

PMSG works at speed control mode when the wind speed is blow based speed. This control mode obtains reference speed ω_r^* by stator voltage and stator current. In order to achieve the input of torque loop, adopt speed deviation $\Delta\omega_r$ is the given value of proportional integral (PI) controller. With the increasing of wind speed, the given electromagnetic torque T_e^* is replaced by T_e when the active power of PSMG is up to rated power P_{en} .And the expression for T_e can be described as:

$$T_e = P_{en} / \omega_r \tag{17}$$

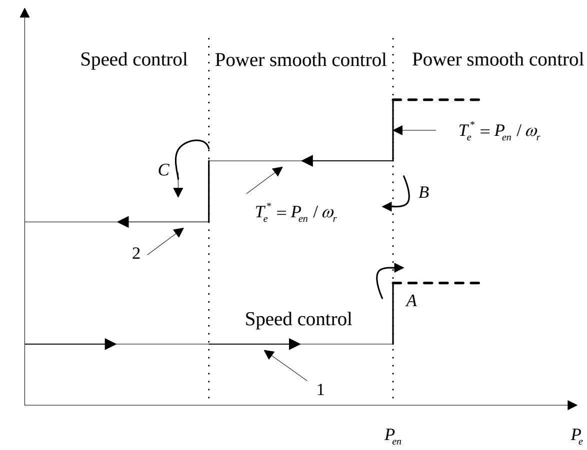


Figure 4. Switching strategy.

The rule of switch, are:

- If the rotor speed ω_r is not equal to reference speed ω_r^* from MPPT control ($\Delta\omega_r \neq 0$), the system remains at power control mode when active power P_e of generator is lower than rated value P_{en} (e.g. the section between B and C in Fig. 4). At the same time, the electromagnetic torque is

$$T_e = P_{en} / \omega_r \tag{18}$$

- When the rotor speed equals the set value ($\Delta\omega_r = 0$), the power control mode turns into speed control mode (e.g. the point C in Fig. 4.). And the electromagnetic torque value at this time is the initial value of output signal of PI at speed control mode. At speed control mode, the situation ($\Delta\omega_r = 0$) appears in steady or overshoot state. The electromagnetic torque remains unchanged at the same time in Ref. [11].

V. Simulation Results

All the simulations are performed in the FAST/Simulink interface in MATLAB. In the Table I, it lists the parameters of the 2MW wind turbine using in this paper. And Fig. 5 shows the waveform of wind speed, which considers variation in wind speed. On the other hand, if the wind speeds are up the rated wind speed and exceed it, the operation of the pitch angle control follows too.

TABLE I. PARAMETERS OF THE DTC-PMSG SYSTEM

Parameters	Values
The wind turbine radius/m	35
The optimal power coefficient	0.438
The optimal tip speed ratio	6.3
Air mass density/(kg / m^3)	1.25
Rated power/MW	2
Rotational inertia/ ($kg \cdot m^2$)	70000
Rated voltage/V	690
Rated current /A	1700
Pole pairs	145
Rated speed/(rad/s)	2.16
Stator resistance Ω	0.006
Stator inductance/mH	0.3

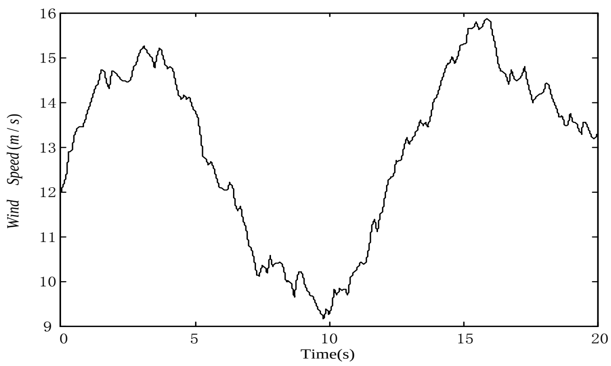


Figure 5. Wind speed profile.

The stator flux locus of PMSG is shown in Fig. 6. It is clearly shown that the stator flux follows its expecting predetermined path. Its trajectory is a circle in the stationary reference frame. The torque ripple is deduced theoretically.

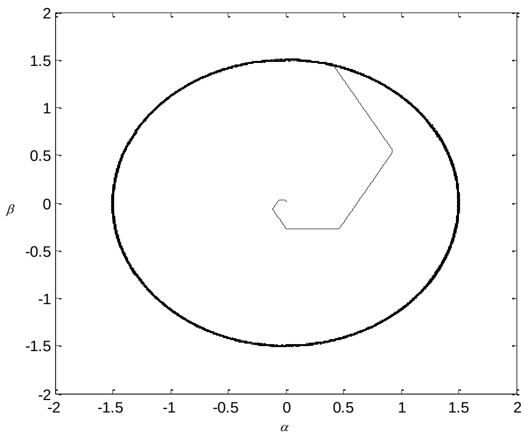
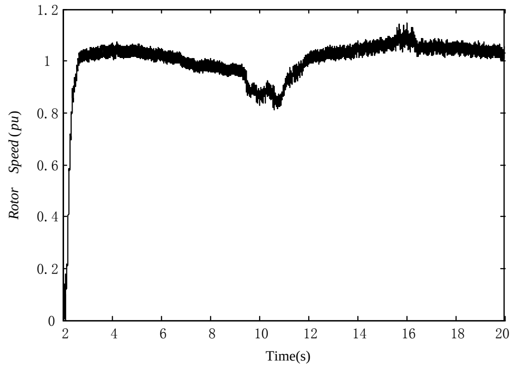
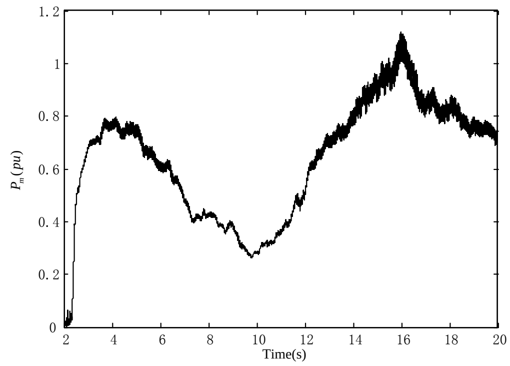


Figure 6. Stator flux trajectory.

Fig. 7 shows the rotor speed and generated mechanical power. The result show variation in the mechanical power extracted when the incoming winds are different for each time section. If the wind speed is lower than the rated speed, the rotor speed and the mechanical power is lower than the optimum of the wind turbine.



(a) generator speed



(b)Mechanical Power of Wind Turbine

Figure 7. Simulation results of double -model control strategy.

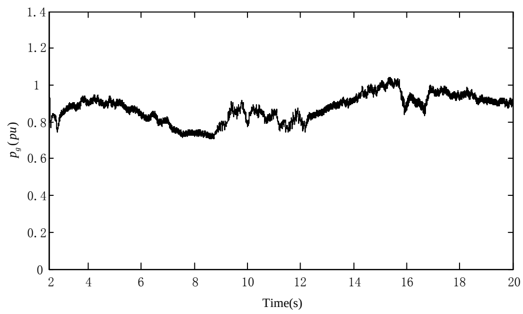


Figure 8. Grid-side active power.

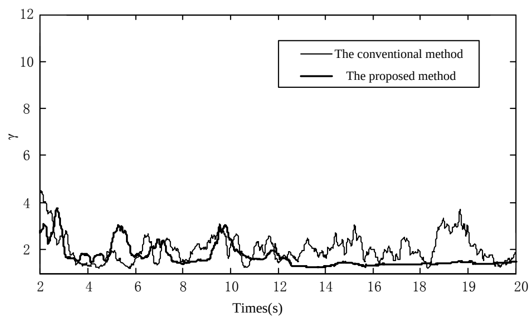


Figure 9. γ curve of systems.

The total power that the system generated is shown in Fig. 8. According to Fig. 9, while in the system using the proposed method, the active grid power becomes smoother and its γ-value is low compared to the system with the conventional method. Two mode switched pitch control for wind turbine cause a smooth output power. This proves the effectiveness of the established controller.

VI. CONCLUSIONS

This paper presents a novel direct torque control scheme for wind turbine based on grid connected permanent magnet synchronous generator. In variable-speed wind power generation systems, this control has proven to be an important element in extracting power from the wind which adjusts the generator speed and adopts the wind speed. Thus, wind turbine can't only capture the maximum wind power, but also can maintain the frequency and amplitude of the output power. Simulation results show clearly that the employed control strategy provides an optimal control solution based on permanent magnet synchronous generator.

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