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Blade Pitch Angle Control for a Direct Drive Wind Turbine Based DTC-PMSG

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***Abstract*—This paper describes a control strategy of a variable speed chain of a wind conversion based on a Permanent Magnet Synchronous Generator (PMSG). In fact, a control scheme for the generator side converter has been proposed. A Proportional-Integral (PI) pitch angle controller for a wind turbine have been designed in order to limit the wind power. Then, the principle of the DTC control dedicated to PMSG has been presented. Simulation results show that the proposed controller succeeds to keep the power at the desired limits. Thus, PI controllers are simple and suitable for blade pitch angle control.**

Keywords: Wind turbine, Pitch angle control, PI controllers, Permanent magnet synchronous generator.

I. Introduction

In recent years, the development of wind energy power systems has been increased rapidly as renewable and clean electricity sources without neglecting their cost competitiveness compared with conventional energy resources [1].

In other hand, the directly driven permanent magnet synchronous generator PMSG is receiving considerable attention thanks to several advantages as the simplicity, the robustness and the high reliability [2].

For permanent magnet synchronous wind power generator, the Direct torque control seems to be the best applied algorithm for wind turbine generator system thanks to the well dynamic torque response, the low complexity and its robustness [3].

There are two operating modes: fixed speed and variable speed modes. In fact, The variable speed operating mode offers several advantages as reducing audible noises, mechanical stresses, and it is the most suitable to extract the maximum power wind by changing the turbine rotor speed proportionally to the wind speed [4]. For variable-speed wind turbine, generated power can be divided into two control regions: the partial load region and the full load region. In the first region the wind speed is below rated value, the speed controller should adjust the rotor to extract the maximum of power. Above rated wind speed, the Pitch angle regulation is required to keep the generated power at the designed limit. This paper has focused on the design of a Proportional-Integral (PI) pitch angle control for a 2MW wind turbine.

The control block for the generator side converter involves three parts: the maximum power point tracking (MPPT), the pitch control and the Direct Torque Control (DTC). The control strategy of the wind system is presented in Fig. 1.

The paper is organised as follows. Section II describes the wind generation system. Section III provides a configuration of the control strategy for the generator side converter. Simulation results are given to verify controllers performance in Section IV.

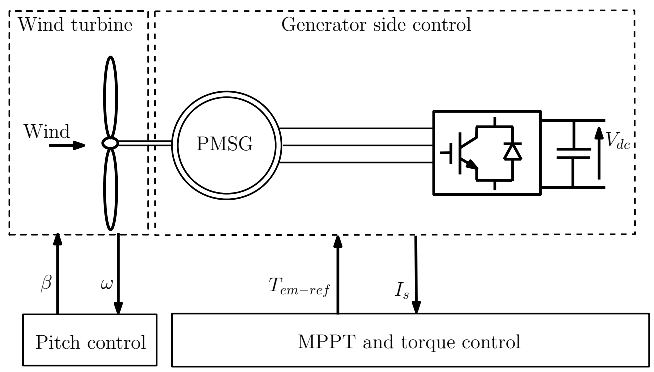

Fig. 1. Generator side control scheme of the direct drive wind turbine.

II. Wind generation system

A. Wind turbine modeling

The mechanical power extracted from the wind turbine, as proposed in [5], is as follows:

$$P_w = \frac{1}{2}\pi\rho C_p(\lambda,\beta)\ R^2 V_w^3 \quad (1)$$

where:
R: is the blade radius of the wind turbine (m)
ρ: represents the air density (in normal atmosphere it is 1.25 kg/m)
V: is the wind speed (m/s)
C_p: is the power coefficient which represents the aerodynamic efficiency of the turbine. It depends on the pitch angle β and the speed ratio λ which is given by :

$$\lambda = \frac{\Omega_t R}{V} \quad (2)$$

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where:
Ω_t: is the generator speed and the turbine radius (without gearbox
Several models for the power coefficient has been developed such as in [6] which approximates C_p by:

$$C_p(\lambda,\beta) = 0.22\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)e^{\frac{-12.5}{\lambda_i}} \tag{3}$$

with

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

Figure 2 shows the evolution of the power coefficient as a nonlinear function of the speed ratio λ and the pitch angle β. It obvious that the curve of the power coefficient is maximized for a tip-speed ratio value λ_{opt} when $\beta = 0$, and decreases significantly for an increment of β. Thus, we can determine the theoretical basis for the pitch angle control: the power coefficient can be adjusted by the pitch angle in order to keep the output power near the power rating.

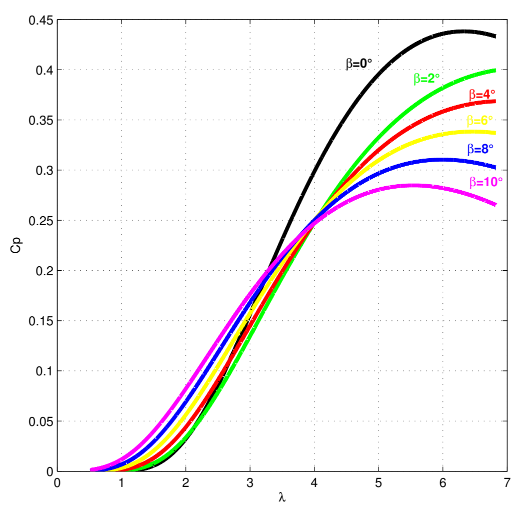

Fig. 2. Aerodynamic power coefficient variation C_p against the tip speed ratio λ and the pitch angle β

The aerodynamic torque can be calculated by the following equation [7]:

$$T_m = \frac{P_m}{\Omega_t} = \frac{C_p(\lambda,\beta)\rho\pi R^2 V^3}{\Omega_t} \tag{5}$$

B. PMSG modeling

The electrical model for the PMSG in the d-q reference can be expressed by [8]:

$$\frac{d\Phi_{sd}}{dt} = -R_s I_{sd} + \omega_s \Phi_{sd} + V_{sd} \tag{6}$$

$$\frac{d\Phi_{sq}}{dt} = -R_s I_{sq} - \omega_s \Phi_{sq} + V_{sq} \tag{7}$$

The components of the stator flux are described by [8]:

$$\Phi_{sq} = L_{sq} I_{sq} + \Phi_v \tag{8}$$

$$\Phi_{sd} = L_{sd} I_{sd} \tag{9}$$

where R_s is the stator winding's resistance, V_{sd}, V_{sq}, I_{sd} and I_{sq} are direct and quadrature voltage/current components, ω_s is the stator current frequency, Φ_v is the exciter flux of the PMSG.
The expression of the electromagnetic torque in the d-q reference is given by [8] :

$$T_{em} = \frac{3}{2}p\left(\Phi_{sd} I_{sq} - \Phi_{sq} I_{sd}\right) \tag{10}$$

where p is the pole pair number.
The dynamic equation of the wind turbine is given by:

$$J\frac{d\Omega_m}{dt} = T_m - T_{em} \tag{11}$$

where T_m is the mechanical torque given by the turbine, Ω_m is the machine speed and J is the total inertia.

III. Control strategy for the generator side

The direct-drive PMSG's is capable to work in different speed ranges. According to the wind speed, the wind turbine generator must be controlled to ensure both the efficiency and the safety of the system.

A. Maximum power point tracking (MPPT)

The aim of this strategy is to ensure a maximum power capture when the wind speed is below its rated value [7]. Figure 3 shows the characteristic of the generated power based on the mechanical speed. It is obvious that for each wind speed V there is one specific angular frequency for which the output power is maximum.
For each peak, there is an optimal speed ratio λ_{opt} which contributes to the power coefficient peak C_{pmax} .
For low wind speeds, β should be equal to 0 to make full the use of the wind energy .
The red curve in Fig. 3 represents the maximum power point tracking for different wind values .

The optimal value of the aerodynamic power should be set to the following expression :

$$P_{opt} = \frac{1}{2}C_{pmax}(\lambda_{opt})\rho S V^3 \tag{12}$$

Then, the value of the reference electromagnetic torque is adjusted to this expression [7]:

$$T_{em-ref} = k_{opt}\Omega_{opt}^2 \tag{13}$$

$$k_{opt} = \frac{1}{2}C_{pmax}\rho\pi R^2\left(\frac{R}{\lambda_{opt}}\right)^3 \tag{14}$$

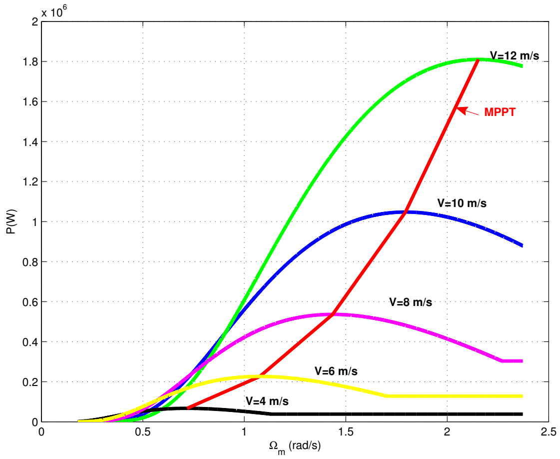

Fig. 3. Characteristic of the generated power versus the mechanical speed for different wind speed values.

B. *Pitch Control Synthesis*

When the wind speed is greater than the rated value, and the MPPT is still applied, the power generated by the system will be above its rated value, which increases the electrical stresses on the power processing device and the PMSG.

Therefore, it is necessary to control properly the blade angle of the wind turbine to keep constant the delivered power.

According to [9], the rotor speed, the power and the torque control can be used to regulate the pitch angle. In this paper the power deviation from its reference has been considered.

Below the rated wind speed, the pitch angle is set to the optimum value 0° and the pitch control is inactive.

In contrast, when the wind speed is above the rated wind, the error between the reference power and the output power of the PMSG is sent to a PI controller which results a reference pitch angle β_{ref} to the pitch angle controller block.

In order to put the blade into the desired position, a pitch actuator consists of a mechanical system which can be assumed as a first order dynamic system as follows [10] :

$$\frac{\beta}{u_\beta} = \frac{k_0}{1+\tau s} \tag{15}$$

k_0 is a proportional gain and τ is the time constant of the orientation system of the blade.

This pitch actuator could not respond immediately and it is limited by the actuation speed. Therefore, it is necessary to include a pitch rate to get more realistic responses. According to industrial recommendations, the pitch rate is adjusted to $10°/s$.

Thus the complete model of the pitch control system is shown in Fig.4.

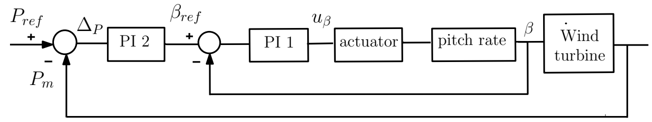

Fig. 4. Block diagram of the Pitch angle PI controller

Determination of PI parameters:

The first PI controller provides the adequate control of the pitch angle β. It's transfer function is :

$$\frac{u_\beta}{\beta_{ref}-\beta} = k_{p1}\left(1+\frac{1}{T_{i1}s}\right) \tag{16}$$

where k_{p1} and T_{i1} are the proportional gain and the time constant of the first PI controller,respectively.

The synthesis of this PI can be done using the compensation method and leading to a closed loop system (input β_{ref} and output β) two times faster than the open loop one. This yields:

$$k_{p1} = \frac{2}{k_0} \;,\quad T_{i1} = \tau \tag{17}$$

Then, the transfer function of the closed loop system (input β_{ref} and output β) is:

$$\frac{\beta}{\beta_{ref}} = \frac{1}{1+\frac{\tau}{2}s} \tag{18}$$

The transfer function of the second controller of the system (input P_{re} and output P_{em}) is:

$$\frac{\beta_{ref}}{\Delta P} = k_{p2}\left(1+\frac{1}{T_{i2}s}\right) \tag{19}$$

with:

$$\Delta P = P_{ref} - P_m \tag{20}$$

k_{p2} and T_{i2} are the proportional gain and the time constant of the second PI controller.

The synthesis of the second PI controller is also done using the compensation method and leading to a closed loop system (input P_{ref} and output P_m) faster or having the same dynamics than the open loop system (η times faster). This is due to the fact that function $P_m = f(\beta)$ is nonlinear. We can approximate:

$$\frac{\Delta P_m}{\Delta\beta} = k_2 \simeq 10^6 \tag{21}$$

The transfer function of the open loop system input P_{ref} and output P_m) is expressed by :

$$\frac{P_m}{P_{ref}-P_m} = k_{p2}\left(1+\frac{1}{T_{i2}s}\right) \times \frac{k_2}{1+\frac{\tau}{2}s} \tag{22}$$

This yields:

$$k_{p2} = \frac{\eta}{k_0} \;,\quad T_{i2} = \frac{\tau}{2} \tag{23}$$
$$1 < \eta \leq 0$$

C. Direct Torque Control Synthesis

The Direct Torque Control DTC is the most applied algorithm for PMSG control [11], [12].
The basic principle of this approach is the control of the three inverter states by the estimation of the stator flux linkage and the electromagnetic torque compared with their reference values. In fact, it selects one of the six voltage vectors generated by a voltage source inverter to keep the flux and torque within the limits of two hysteresis bands [12].
Figure 5 shows the block diagram of the DTC dedicated to the PMSG, for which each block is detailed below.

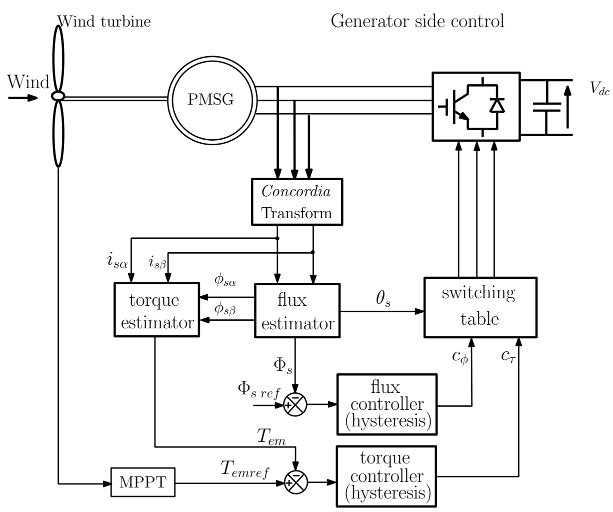

Fig. 5. Block diagram of DTC control

Let's start with the generator currents and follow the signal to the voltage source inverter output.
Current transformation
In a drive system, the generator is operated with its neutral point floating [12], that is :

$$i_a + i_b + i_c = 0 \quad (24)$$

The i_{abc} current is transformed to i_{dq} by the Park transformation [13]:

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 2 & -1 & -1 \\ 0 & -\sqrt{3} & -\sqrt{3} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (25)$$

Flux and Torque estimators
After that currents / voltages should be transformed to the stationary reference axes α and β which are expressed by [13] :

$$V_{s\alpha} = \sqrt{\frac{2}{3}} U_{dc}\left[S_a - \frac{1}{2}(S_b + S_c)\right] \quad (26)$$

$$V_{s\beta} = \sqrt{\frac{1}{2}} U_{dc}(S_b - S_c) \quad (27)$$

The stator-voltage space vector V_s is computed using the dc-link voltage U_{dc} and the inverter switch gating signals S_a, S_b, and S_c. The stator-current space vector is derived from measured currents i_a, i_b and i_c [14]:

$$i_{s\alpha} = \sqrt{\frac{2}{3}} i_{sa} \quad (28)$$

$$i_{s\beta} = \sqrt{\frac{1}{2}} (i_{sb} - i_{sc}) \quad (29)$$

Then, the stator flux vector can be estimated by:

$$\Phi_s = \int (v_s - R_s i_s) dt \quad (30)$$

$$|\Phi_s| = \sqrt{\phi_{s\alpha}^2 + \phi_{s\beta}^2} \quad (31)$$

$$\theta_s = \arctan\frac{\phi_{s\beta}}{\phi_{s\alpha}} \quad (32)$$

where

$$\phi_{s\alpha} = \int (v_{s\alpha} - R_s i_{s\alpha}) dt \quad (33)$$

$$\phi_{s\beta} = \int (v_{s\beta} - R_s i_{s\beta}) dt \quad (34)$$

Φ_s is the stator flux vector, $|\Phi_s|$ is the amplitude of the stator flux and R_s is the stator resistance.

The electromagnetic Torque T_{em} is evaluated by:

$$T_{em} = p(\phi_{s\alpha} i_{s\beta} - \phi_{s\beta} i_{s\alpha}) \quad (35)$$

Hysteresis controllers
The electric torque and the magnitude of the calculated stator flux are compared with there references by hysteresis comparators.

Outputs of the comparators are fed to a switching table shown in Tab. I to select an appropriate converter voltage vector [15], [16]. This table determines the voltage vector to apply based on the position of the stator flux and the required changes in the torque.

There are six equally spaced voltage vectors, in voltage source converter, having the same amplitude and two zero voltage vectors.

Figure 7 shows the voltage vectors in every sector, which are selected from the eight possible switches configurations based on Tab. I.

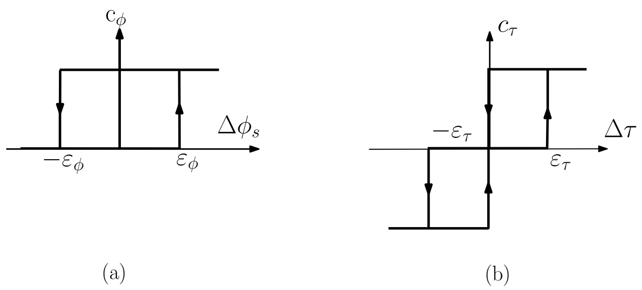

Fig. 6. (a) 2-level flux hysteresis regulator. (b) 3-level torque hysteresis regulator.

TABLE I
SWITCHING TABLE.

c_τ	1	0	-1	1	0	-1
c_ϕ	1	1	1	0	0	0
N_1	V_5	V_0	V_3	V_6	V_7	V_2
N_2	V_6	V_7	V_4	V_1	V_0	V_3
N_3	V_1	V_0	V_5	V_2	V_7	V_4
N_4	V_2	V_7	V_6	V_3	V_0	V_5
N_5	V_3	V_0	V_1	V_4	V_7	V_6
N_6	V_4	V_7	V_2	V_5	V_0	V_1

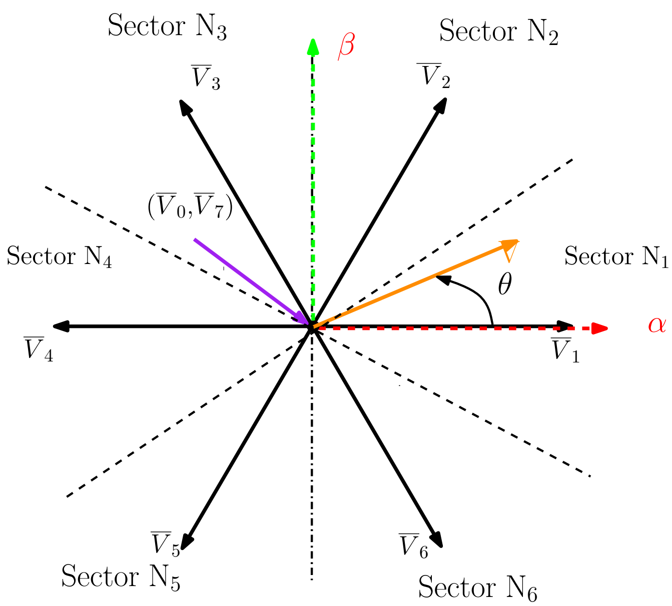

Fig. 7. Switching-voltage space vectors.

Voltage source inverter
The voltage vector of the three-phase voltage inverters is represented as follows [16]:

$$\vec{V} = \sqrt{\frac{2}{3}} U_{dc}\left(S_a + S_b e^{\frac{j2\pi}{3}} + S_c e^{\frac{j4\pi}{3}}\right) \tag{36}$$

where U_{dc} is the bus voltage. S_a, S_b and S_c are three-phase inverter switching functions, which can take a logical value of either 1 (ON) or 0 (OFF).

IV. Simulation Results

Parameters of the turbine and the PMSG used in simulation works are presented in Tab.II.

TABLE II
TURBINE AND PMSG PARAMETERS

wind turbine parameters	PMSG parameters
P=2MW	P_{nom}=2.02MW
N_m=24rpm	U_{dc}=1.75KV
J_{tot}=6.02 10^6	R_s= 32 m Ω
D= 75m	L_{sd}=2.7 mH
3 blades	L_{sq}=1.7 mH
Variable Speed	p = 32

Simulation results are presented in figures 8 and 9. . The wind speed profile used for simulation is given in 8.a.

- Figure 8.b shows that the output power remains constant if the wind speed is higher than the rated value, which shows good performances of the pitch control.
- Referring to Fig. 8.c and Fig. 8.d, it is obvious that the electromagnetic torque and the flux follow their reference values with tolerable ripples.
- Figure 9.a shows two control regions of the power: the MPPT control operation and the pitch control operation. The turbine starts operating when the wind speed exceeds cut-in wind speed 5 m/s then the MPPT algorithm ensures a maximum power capture. At the set point of wind speed, the generating power reaches the rated wind power turbine which is equal to 2MW, the pitch angle control intervenes to keep the power constant .
- Figure 9.b shows the curve of the pitch angle versus the wind speed. It is obvious that under the rated wind speed, the pitch angle is equal to 0° which makes the full the use of the wind energy. At the rated wind speed, the blade angle changes with the change of the wind speed in order to maintain the power at the design limit 2MW.

V. Conclusion

In this paper, a PI control design scheme for the control of the blade pitch angle of a wind turbine based PMSG-DTC has been proposed. This controller is the key part of variable-speed wind turbine system which allows the turbine to capture the maximum wind power and maintains the amplitude and the frequency of the output power. Moreover, the modeling of a Permanent magnet synchronous generator controlled by the DTC technique has been illustrated. Simulation results show the effectiveness of the employed control strategy.

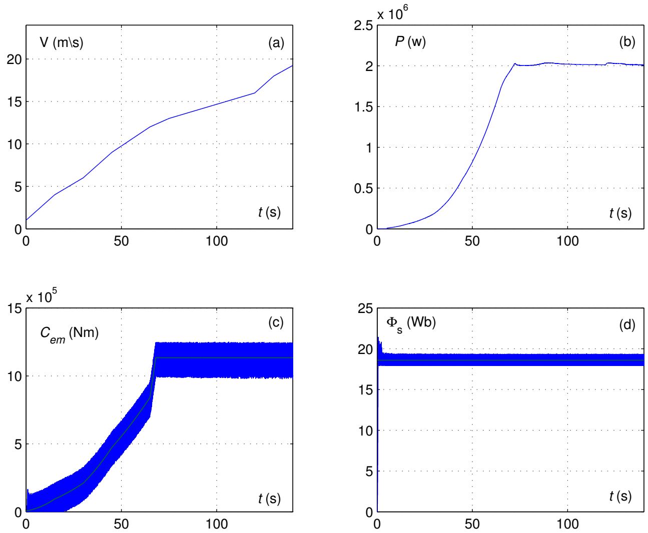

Fig. 8. Dynamic behavior of the PMSG under DTC strategy: (a) wind speed profile, (b) mechanical power, (c) electromagnetic torque and (d) stator flux.

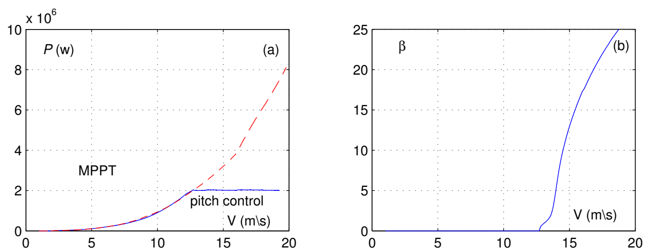

Fig. 9. (a) MPPT and pitch control zones. (b) Variation of the pitch angle versus wind speed

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