ROBUST CONTROL OF A VARIABLE-SPEED WIND TURBINE WITH VARIABLE PITCH CONTROL AND STRATEGY MPPT CONTROL BASED ON A PMSG

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ABSTRACT

In this paper, we present a performance study of a variable-speed wind turbine with variable pitch control and sensorless control strategy used MPPT based on a Permanent Magnet Synchronous Generator (PMSG). This paper first proposes the PITCH angle control which is the most common means for adjusting the aerodynamic torque of the wind turbine when wind speed is above rated speed, is applied. control strategy used Maximum Power Point Tracking (MPPT) below the rated speed, which corresponds to low and high wind speed, and the maximum energy can be captured from the wind. The control scheme is tested for three real profiles of wind speed and for two reference wind powers. The effectiveness of the proposed control strategy is evaluated by simulation results.

Key Words: *PMSG, Maximum Power Point Tracking (MPPT), Pith Control.*

NOMENCLATURE

Symbols :

$V_w(t)$	The instantaneous wind speed	p	Number of pole pair
$V_{wa}(t)$	Average wind speed	$v_{d,q,a,b,c}$	Stator voltages in the reference frame
$V_{wr}(t)$	Ramp component	τ	Time constant
$V_{wg}(t)$	Gust component	ξ	Damping coefficient
$V_{wt}(t)$	Turbulence component	Ω_{ref}	Reference speed
P_e	Power wind	ρ	Air density
R_e	The turbine radius	v	Wind speed
A	The turbine blade sweep area	$C_p(\lambda, \beta)$	Coefficient of power
Ω_t	The wind turbine	β	Blade pitch angle
λ_i	Initial Speed ratio	β_{ref}	Reference blade pitch angle
λ_{opt}	Optimum tip speed ratio		

1. INTRODUCTION

The development in the use of renewable energy is becoming the key solution to the serious energy crisis and environment pollution now. Among various kinds of renewable energy, wind energy is by far the fastest growing energy for its free availability, environmental friendliness, policy fostering, and the maturity of turbine techniques, and it has become a research focus and priority all over the world [14].

Wind Generation Systems (WGS) are currently taking a great interest in renewable energy systems [15]. This is mainly due to the high cost of fossil fuels and the need for clean energy sources. Although in the case of wind energy some places are not suitable for fully take advantage of this energy.

Currently wind energy can be used under various schemes, that is, primary source with storage systems provide energy in remote locations, as primary energy source with conventional sources to inject energy into a grid; In small power wind generation systems ranging from *1 kW* to *50 kW*, permanent magnet synchronous generators (PMSG) are preferred to other electrical machines [15]. Moreover, compared with an induction generator, a PMSG has the advantages of a higher efficiency, due to the absence of rotor losses and lower no-load current below the rated speed; and its decoupling control performance is much less sensitive to the parameter variations of the generator.

The wind turbine can be operated at the maximum power operating point (MPPT) for various wind speeds by adjusting the shaft speed optimally to achieve maximum efficiency at all wind velocities [1]-[2], [4]. Pitch angle regulation is required in conditions above the rated wind speed when the rotational speed is not kept constant. Small changes in pitch angle can have a dramatic effect on the power output [3].

In this study, we present a control strategy of a variable pitch wind turbine based on a Permanent Magnet Synchronous Generator (PMSG). This control strategy, without measurement of wind speed, permit to operate at maximum power or at controlled power and presents a robust control system for variable-speed, variable-pitch wind turbines with direct-drive permanent magnet synchronous generator**.**
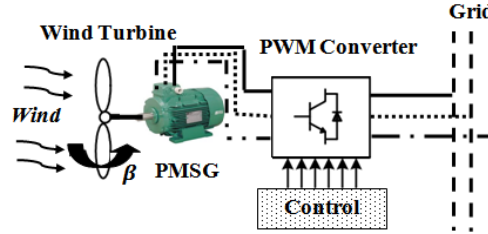

Figure 1. Block diagram of a wind turbine equipped with PMSG.

Further on, the mechanical components of the Wind Turbine System (WTS) that are the wind turbine rotor, drive train as well as the pitch control and the electrical components that are the synchronous generator and the Voltage Source Converter (VSC) will be briefly presented.

1.1.   Wind turbine Modelling

A wind turbine is a mechanical device that converts kinetic energy into mechanical energy which then is converted to electrical energy by coupling a generator to the wind turbine. There are two main categories of wind turbine: Horizontal Axis Wind Turbine (HAWT) and Vertical Axis Wind Turbine (VAWT). HAWT is horizontal, approximately parallel to the ground. These turbines have evolved from the traditional "Dutch" windmill used for grain grinding [8].

The mechanical behavior of the wind turbine follows eq (2). The amount of maximum power that can be extracted from the wind turbine and fed to the PMSG is governed by the following equation:

$$P_e = \frac{1}{2} \rho A v^3 C_p (\lambda, \beta) \qquad (1)$$

where ρ (*1.225 kg.m⁻³*) is the air density, $A = \pi R_e^2$ the turbine blade sweep area (*m²*), with R_e (m) is the turbine radius, v (*m.s⁻¹*) is the wind speed and $C_p (\lambda, \beta)$ is the power coefficient which represents the aerodynamic efficiency of the turbine and also depends on speed ratio λ and the pitch angle β.

For any particular value of wind velocity the parameters other than the aerodynamic coefficient would be a constant. In such a scenario we find that [8] :

$$P_e \propto C_p (\lambda, \beta) \qquad (2)$$

Tip Speed Ratio is the ratio between the product of generator speed and radius of the wind turbine to the wind velocity [8] :

$$\lambda = \frac{R_e \, \Omega_t}{v} \qquad (3)$$

Low value of λ or high value of λ means most of the air pass through the air gap and least energy captured by the wind turbine. Hence there exists an optimal λ point such that where wind turbine has the most energy efficiency [12], [5].

with Ω_t is the mechanical turbine speed (*rad/s*).

A generic equation is used to model the coefficient of power conversion $C_p (\lambda, \beta)$ based on the modeling turbine characteristics described in [10] as:

$$C_p (\lambda, \beta) = \frac{1}{2} \left(\frac{116}{\lambda_i} - 0.4 \, \beta - 5 \right) e^{-\left(\frac{21}{\lambda_i} \right)} \qquad (4)$$

$$\lambda_i = \left(\frac{1}{\lambda + 0.08 \, \beta} - \frac{0.035}{\beta^3 + 1} \right) \qquad (5)$$

The coefficient of power conversion and so the power extracted are maximum at a certain value of tip speed ratio called optimum tip speed ratio λ_{opt}. For this reason, the maximum value of $C_p (\lambda, \beta)$, that is $C_{pmax} (\lambda, \beta) = 0.45$, is achieved max for $\lambda_{opt} = 5.1$ and for $\beta = 0°$ [6]. Moreover, any change in the wind speed or the rotor velocity induces change in the tip speed ratio leading to power coefficient variation. Consequently, the output power of the wind turbine generator is affected. $P_t = \frac{1}{2} \rho A v^3 C_{p \, max} (\lambda_{opt}, \beta) \qquad (6)$

This power is maximized at the particular rotational velocity for various wind and it's obligatory to keep the rotor velocity at an optimum value of the tip speed ratio λ_{opt} . As a result, the variable speed wind energy converter system can operate at the peak of the $P_{turbine}$ curve when the wind velocity changes and the maximum power is extracted

continuously from the wind (MPPT control) [8]-[7]. The mechanical torque produced by the turbine is expressed as follows[6] : $\quad C_t = \frac{1}{2} \rho \pi R_e^3 v^2 C_m (\lambda, \beta)$ $\qquad$ (7)

$C_m (\lambda, \beta)$ Is the torque coefficient : $\qquad C_m (\lambda, \beta) = \frac{c_p (\lambda, \beta)}{\lambda}$ $\qquad$ (8)

1.2. *Mechanical shaft modeling*

The mechanical system is represented by the following equation: $\quad J_T \frac{d\Omega_t}{dt} = C_t - C_{em} - f \Omega_t$ $\qquad$ (9)

where J_T (*kg.m²*) is the total inertia which appears on the shaft of the generator, C_t (*N.m*) is the mechanical torque, C_{em} (*N.m*) is the electromagnetic torque applied to the PMSG rotor, and f (*N.m.s.rad⁻¹*) is a viscous friction coefficient [11],[9].

1.3. *Permanent Magnet Synchronous Generators (PMSG) Model*

The equivalent circuit of the permanent magnet synchronous generator [10] , the electric equations of the PMSG are described by (10) :

$$\begin{cases} \frac{di_d}{dt} = - \frac{R_s}{L_d} i_d + i_q \frac{L_q}{L_d} \Omega_t + \frac{1}{L_d} u_d \\ \frac{di_q}{dt} = - \frac{R_s}{L_q} i_q - \Omega_t \left(L_d i_d + \frac{1}{L_q} \varphi_f \right) + \frac{1}{L_q} u_q \end{cases} \quad (10) \qquad C_{em} = \left(p . \varphi_f . i_q \right) \qquad (11)$$

where L_q and L_d are the inductances of the generator on the q and d axis, i_d and i_q are the equivalent current of the d and q axis; R_s is stator phase resistance; Ω_t is the electrical angular speed, $\Omega_t = p \Omega$, p is the number of pole pairs; φ_f is the flux of the permanent magnets; v_d and v_q are components of $d - q$ axes [12].

2. CONTROL STRATEGY

2.1. *Variable Pitch Angle Control*

The pitch control is an essential method for controlling the amount of power generated by the variable speed wind turbine. Its function is to limit the output power for winds above rated values, by varying the pitch angle of the rotor blades. The pitch controller can have up to three states. It can be in one of them at a given time depending on the wind speed intensity. The pitch mechanism was built based on the power profile for a typical large wind turbine [13].

To not degrading the machine, it is necessary to limit its speed. This speed limit will be obtained using the pitch angle β_{ref}. When the rotational speed of the turbine exceeds a speed Ω_t, the control will give the order to increase the pitch angle to reduce the turbine torque C_t.

$$\begin{cases} \beta_{ref} = \beta_0 = 1 \quad for \quad 0 < \Omega_w < \Omega_t \\ \beta_{ref} = \frac{\Delta\beta}{\Delta\Omega} (\Omega_w - \Omega_t) + \beta_0 \quad for \quad \Omega_w > \Omega_t \end{cases} \quad (12)$$

The sensitivity and accuracy of pitch have a great influence on the output power. Variable pitch actuator model can be achieved by the hydraulic device or motor drive system, and can be expressed by one order inertial link [12]:

$$\tau_b \dot{\beta} = \beta_{ref} - \beta \qquad (13)$$

s is the Laplace operator and τ_b is the response time constant of pitch angle β is the actual pitch angle; β_{ref} is a given pitch angle [12]. The chosen pitch control method is illustrated in Figure 2b, where the difference between power reference and power measured gives the error signal. The error signal is input to the *PI* controller [13].

2.2. *Maximum Power Point Tracking (MPPT) Control*

The MPPT controller is used to generate the reference speed command which will enable the wind turbine generator to extract maximum power at different wind speeds. Thus, when the wind velocity changes, the speed of PMSG is controlled to follow the maximum power point trajectory and the optimum rotational speed of the generator can be simply estimated as follows [10] : $\quad \Omega_{t\_opt} = \frac{v \lambda_{opt}}{R}$ $\qquad$ (14)

The maximum extracted power of the wind turbine generator is given as :

$$P_{MPPT} = \frac{\rho A R^3 C_{p\,max} (\lambda,\beta)}{2 \lambda_{opt}^3} \Omega_t^3 = K \Omega_t^3 \qquad (15)$$

As a result, the MPPT controller computes the optimum speed of PMSG Ω_{t_opt} and by regulating the wind turbine generator speed in different wind velocities the maximum power P_{MPPT} $(P_{Turbine\_max})$ max is extracted. Also, if the wind speed reached the nominal value of wind turbine generator, the system of Pitch Angle controller enters in operation to prevent wind turbine damage from excessive wind speed [10].
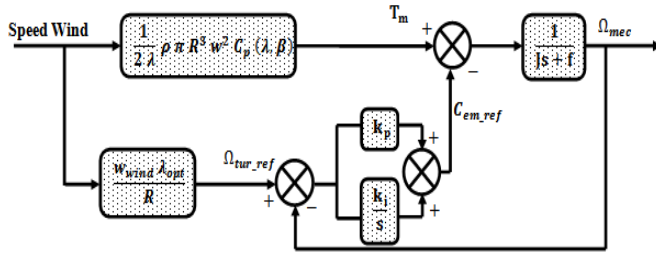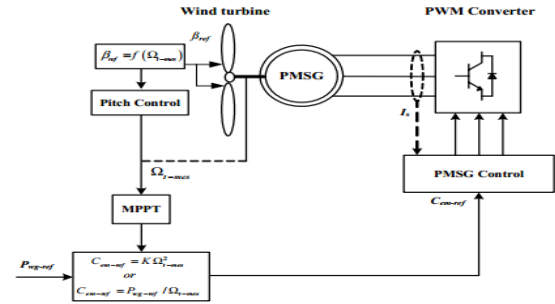
Figure 2. Power MPPT.

Figure 3. global control structure of the wind generator.

3.   SIMULATION RESULTS

To validate the turbine model, we used three types of wind : a low wind with an average speed of ± *6 m/s*, a medium wind with an average speed of ± *9 m/s* and a high wind with an average speed *of ± 12 m/s*. The figure 5 shows the three real profiles of wind speed considered in the simulations.

A. Low Wind
$$V_w(t) = 6 + 0.2\, sin(0.1047\, t) + 2\, sin(0.2665\, t) + sin(1.293\, t) + 0.2\, sin(3.6645\, t) \qquad (16)$$

B. Medium Wind
$$V_w(t) = 9 + 0.2\, sin(0.1047\, t) + 2\, sin(0.2665\, t) + sin(1.293\, t) + 0.2\, sin(3.6645\, t) \qquad (17)$$

C. High Wind
$$V_w(t) = 12 + 0.2\, sin(0.1047\, t) + 2\, sin(0.2665\, t) + sin(1.293\, t) + 0.2\, sin(3.6645\, t) \qquad (18)$$
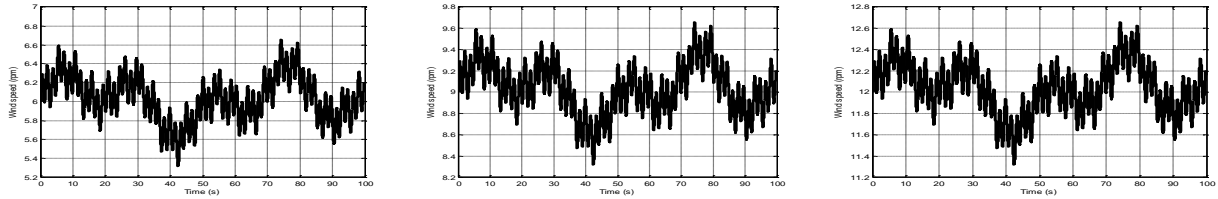

Figure 4. Speed wind turbine (low,medium, high).

3.1.   Simulation Results (Control of Wind Turbine)

To show the principle of power control of the wind generator, its behaviour subjected to two different reference wind powers : a reference power fixed at   *15 kW* and another fixed at *150 kW*, will be illustrated using numerical simulations carried under the Matlab-Simulink. The Figures 5 and 6 show the simulation results when the reference power turbine is fixed *15 kW*. The figures 7 and 8 show the simulation results when the reference power turbine is fixed at *150 kW*.

We present for each reference wind power and with the three profiles of wind speed (low, medium, high) the mechanical turbine speed, the pitch angles, the turbine torque, the generated powers MPPT, and the reference electromagnetic torque, C_p, the pitch angles, courante, voltages. The wind speed shape presented in Fig. 5 was used to test the whole wind turbine simulation.

The Figures 7 and 8 the low wind, and for the two reference powers *15 kW* and *150 kW*, the simulation results are identical because the maximum power which we can extract from the wind generator is less than the reference wind power. When the wind speed steps are applied, an overshoot and small oscillation in the mechanical and electromagnetic torques may be observed. These overshoots and oscillations are mainly due to the drive train. As it may be seen at the instant of 2 [s] when the wind speed increases from 5 to 12 [m/s].

A similar phenomenon may be observed when the reference speed is decreased the mechanical energy stored in form of kinetic energy in the moving parts of the WTS is converted into electrical energy. As a result of decreasing the reference speed during the transient actually the electrical power is higher than the mechanical power.

In the incapacity to provide the P_{ref} it is thus an operating at maximum power which is shown in figures 6, 7 and 8. The blades are at their optimal angle, and the power coefficient is maximum $C_{pmax} = 0.45$. And illustrate that the wind generator can, at times, to produce the reference wind power P_{ref}. We thus observe an operating at constant power at P_{ref}.
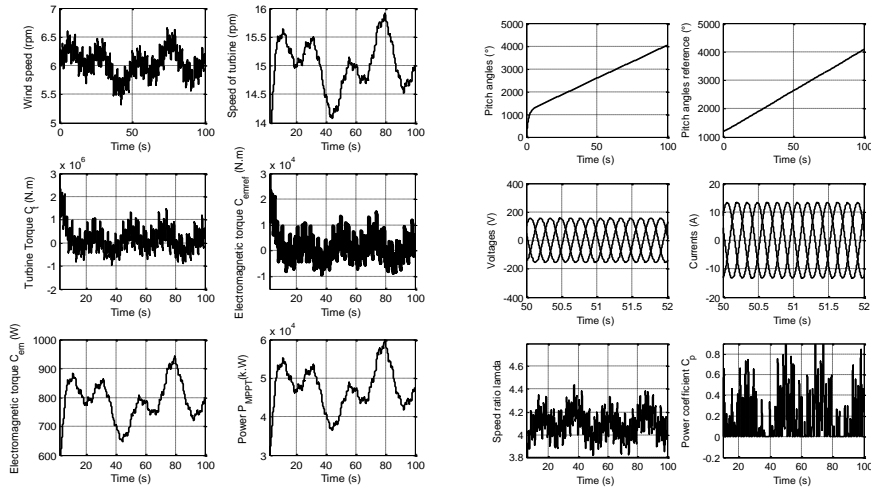
Figure 6. Simulation of a variable speed wind turbine under a low wind and $P_{ref} = 15$ kW.
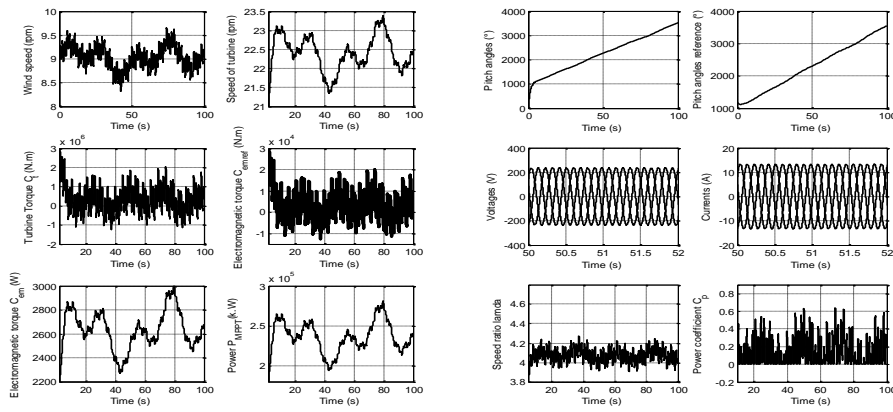

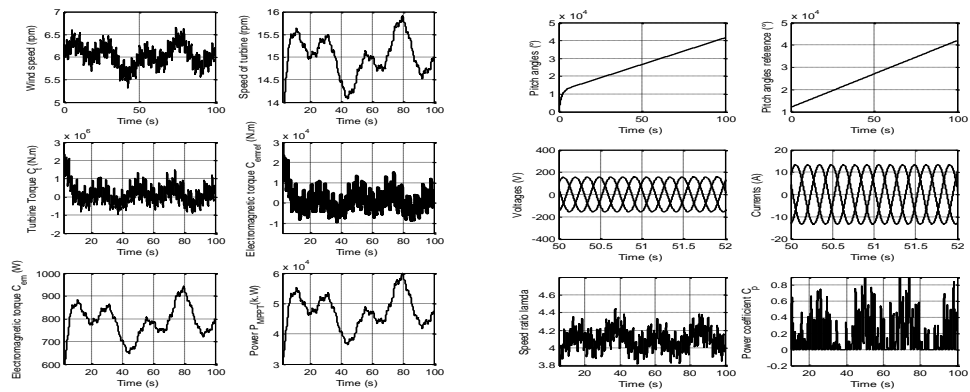Figure 5. Simulation of a variable speed wind turbine under a medium wind and $P_{ref} = 15$ kW.

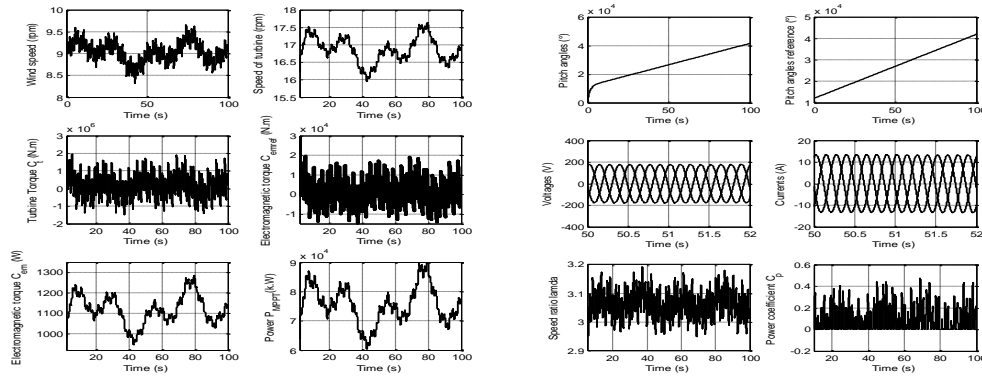Figure 6. Simulation of a variable speed wind turbine under a low wind and $P_{ref} = 150$ kW .

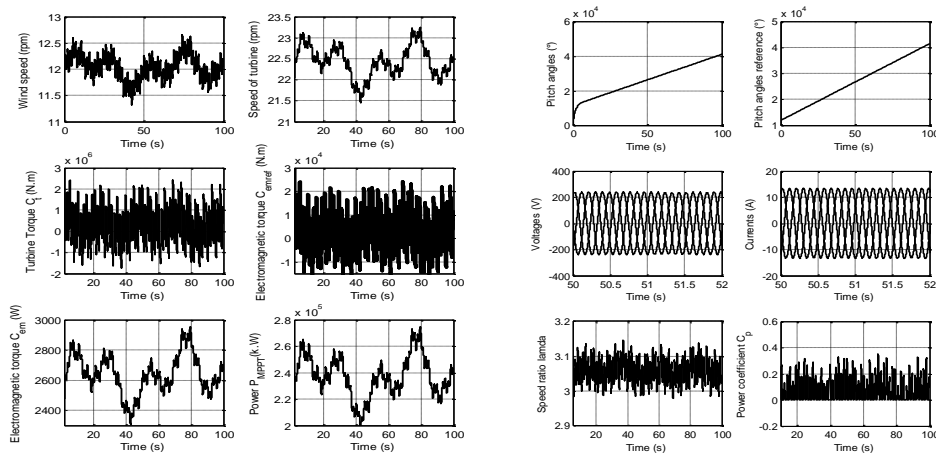Figure 7. Simulation of a variable speed wind turbine under a medium wind and $P_{ref} = 150$ kW.

Figure 8. Simulation of a variable speed wind turbine under a high wind and $P_{ref} = 150$ kW .

4.   CONCLUSION

This paper a performance study of a variable-speed wind turbine with variable pitch control MPPT control based on a Permanent Magnet Synchronous Generator (PMSG). To control the wind generator power, two operating modes were applied : an operating at maximum power which permit to extract the wind power maximum (MPPT), and an operating at constant power which is used to limit the turbine speed at its nominal value in the case of high wind (Pitch angle control).

The concept of MPPT has been presented in terms of the adjustment of the PMSG rotor speed according to instantaneous wind speed and limitation by Pitch Angle strategy for high wind speed. This control scheme is tested for three real profiles of wind speed and for two reference wind powers. It can easily be simulated with the help a software like Matlab-Simulink. As prospects for this work, we will associate to this wind generator, a flywheel energy-storage systems, to be able to take part in the management of the power grid. Finally, simulation results show clearly that the proposed control.

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