

A ROBUST CONTROL FOR PERMANENT MAGNET SYNCHRONOUS GENERATOR ASSOCIATED WITH VARIABLE SPEED WIND TURBINE

Ahmed TAHRI Said HASSAINE

Ibn Khaldoun University, Tiaret, Algeria.

tahriahmed89@gmail.com, s_hassaine@yahoo.fr

Sandrine MOREAU

National School of Engineers of Poitiers, , poitiers, France

sandrine.moreau@univ-poitiers.fr

Abstract: *This paper presents a simple and robust control scheme of permanent magnet synchronous generators (PMSG) wind turbine with two full-scale controllable three phase converter connected to the grid. Our aim is to drive wind turbine at an optimal rotor speed in order to perform maximum power point tracking control of the wind generation system, therefore a nonlinear backstepping control is applied to the PMSG which is based on both feedback laws and Lyapunov theory. The PMSG wind turbine is integrated to the grid through three phase converter which is controlled by classical pi controller of the active and reactive power. The system performance and robustness is investigated using Matlab/simulink® with SimPowerSystems block for 2.5 kW PMSG wind turbine.*

Keywords: *Permanent magnet synchronous generator, backstepping control, three phase converter, wind turbine.*

1. INTRODUCTION

In nowadays the demand of electrical energy is growing rapidly, this increase has economic impact. If there is more demand for a product, while supply does not change much, the product will get more expensive. Most scientists think that production of energies from fossil fuels source like oil, coal and gas within time is going to vanish and causes environment pollution, Therefore, human kind is looking for alternative energy sources, like solar and wind. As a consequence the increase of Wind energy knew a big spread and significant growth. The annual average growth rate of installation of wind turbine is around 30% in the last decade. This number will be going to 12% of the global electricity consumption[1] by 2020 and this situation will make wind turbine a great subject of research

Wind turbine is all about reducing the cost to the minimum, maximizing the power, improving the quality of power and the contribution in protecting environment [2, 3, 4].

The wind energy conversion system has many diverse structures. The most promising of these structures is the variable-speed wind turbine with permanent magnet synchronous generator and full-scale controllable power converter [1], The reason behind our interest to such a subject is configuration which includes an elimination of DC excitation system, full controllability of the system for maximum wind power extraction and grid interface [2,3]. Hence, the efficiency and reliability of a full-converter PMSG wind turbine is assessed to be higher than a DFIG (Doubly Fed Induction Generator) wind turbine [5,6]

However, we should take into account that the performances of a PMSG system depend on the synchronous generator as well it depend on how it is controlled.

We propose in this paper a robust control of a typical PMSG wind turbine configurations based on a nonlinear backstepping control in order to improve the control of the conversion system that is traditionally controlled through conventional decoupled d-q vector control approach, this approach has some disadvantages presented in[7].

The backstepping technique is a systematic and recursive method for synthesizing nonlinear control laws. It uses the Lyapunov stability principle which can be applied to a large number of non-linear systems.

The basic idea of the backstepping control is to make the equivalent closed loop systems to low order subsystems in cascade which are stable within the significance of Lyapunov, which gives them the qualities of robustness and asymptotic global stability. In other words, it is a multi-step method, for each step of the process; a virtual control is generated to ensure the convergence of the system to its equilibrium state. This can be reached from

Lyapunov functions to ensure step by step the stabilizing of each synthesis step [8,9].

2. SYSTEM DESCRIPTION:

The proposed structure of a wind energy conversion system is composed of a wind turbine, a PMSG, two full-scale back-to-back PWM (pulse width modulation) converters and inductance filter, as it is shown in Fig 1, knowing that the system is connected to the power grid.

The modeling of each component is presented as following

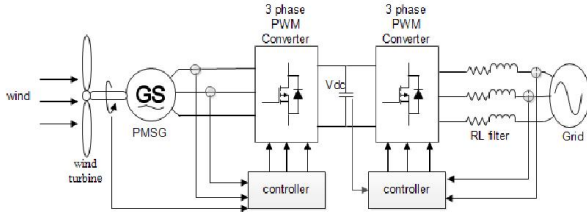


Fig 1: the wind energy conversion system

2.1. Wind turbine model:

The mechanical power extracted from the wind can be expressed as follows

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

Where P_w is the extracted power from the wind, ρ is the air density (kg/m^3), R is the blade radius (m), v is the wind speed (m/s) and C_p is the power coefficient which is a function of the pitch angle of rotor blades θ (deg) and of the tip speed ratio λ . The term λ is defined as

$$\lambda = \frac{w_w R}{v} \quad (2)$$

Where w_w is the wind turbine speed.

In literature review the power coefficient can be used in the form of look-up tables or in form of a function. The second approach is presented below, where the general function of the power coefficient is defined as a function of the tip-speed ratio λ and the blade pitch angle θ [10]

$$c_p(\lambda, \theta) = c_1 \left(c_2 \frac{1}{\beta} - c_3 \theta - c_4 \theta^x - c_5 \right) e^{-\frac{c_6}{\beta}} \quad (3)$$

Since this function depends on the wind turbine rotor type, the coefficients C_i ($i = 1, 2 \dots, 6$) and x is different for various turbines. we use the coefficients as in [11] which are: $c_1 = 0.5$, $c_2 = 116$, $c_3 = 0.4$, $c_4 = 0$, $c_5 = 5$, $c_6 = 21$ (x is not used because $c_4 = 0$). Additionally, the parameter β is also defined in different ways [7,8] For example, the parameter $\frac{1}{\beta}$ is defined as

$$\frac{1}{\beta} = \frac{1}{\lambda + 0.08\theta} - \frac{0.035}{1 + \theta^3} \quad (4)$$

2.2. Generator model

The mathematical model of the PMSG is established under the d and q axis synchronization reference frame [11]. It is simplified as

$$\frac{di_d}{dt} = -\frac{R_s}{L_d} i_d + w_e \frac{L_q}{L_d} i_q + \frac{1}{L_d} u_d \quad (5)$$

$$\frac{di_q}{dt} = -\frac{R_s}{L_q} i_q - w_e \left(\frac{L_d}{L_q} i_d + \frac{1}{L_q} \psi_f \right) + \frac{1}{L_q} u_q \quad (6)$$

Where subscripts d and q refer to the physical quantities that have been transformed into the $d - q$ synchronous rotating reference frame, R_s is the stator resistance [Ω], L_d and L_q are the inductances [H] of the generator on the d and q axis. ψ_f is the permanent magnetic flux [Wb] and w_e is the electrical rotating speed [rad/s] of the generator, defined as $w_e = w_g p$, where p is the number of pole pairs and w_g is the rotated speed of the generator.

The electromagnetic torque equation of PMSG is described by this equation:

$$T_e = \frac{3}{2} p \left((L_d - L_q) i_d i_q + i_q \psi_f \right) \quad (7)$$

The mechanical equation which connect the generator with the wind turbine is described by:

$$j_{eq} \frac{dw_g}{dt} = T_e + T_l - B_m w_g \quad (8)$$

Where T_l is the torque applied by the turbine to the generator. j_{eq} is the equivalent moment of inertia; and B_m is the viscous turn coefficient.

3. CONTROL STRATEGY

We have two methods to control the PMSG while the wind speed is variable. The first named Maximum Power Point Tracking (MPPT), its principle is to make the PMSG running at the speed corresponding to the maximum power point when wind speed is lower than the rated wind speed. While the second method makes the PMSG running around the rated power point by the torque angle controller when the wind speed is higher than the rated wind speed. The torque angle controller is similar to speed controller of generator, which is influenced by the power coefficient C_p [7].

Our control strategy of the wind energy converter system is divided in two parts, the first focuses on the control of PMSG by nonlinear backstepping controller relying on the MPPT through the PWM converter, and the second part focuses on the control of the active and reactive power injected to the grid, and also on the stabilization of the terminal voltage measured of the capacitor located between the PWM converters.

3.1. Control of the permanent magnet synchronous generator side converter

The control of PMSG is achieved by the nonlinear backstepping controller that is composed of two loops, the inner loop that control the stator current and the outer loop which control the PMSG speed, where the optimum speed reference w_g^* is given by the MPPT bloc as shown in Fig 2.

3.1.1.MPPT principle

The MPPT principle is to extract the maximum of power from the wind power, this can be only realized if the turbine operates at maximum C_p (i.e., at $C_{p_{opt}}$). Therefore, it is necessary to keep the tip-speed ratio λ at an optimum value λ_{opt} . From (2) to maintain this value it is essential to adjust the rotor speed to an optimum value (w_{opt}) in order to follow the change value when the wind varies.

From equations (1) and (2) The optimum power of a wind turbine is written as:

$$P_{w_{opt}} = \frac{1}{2} \rho \pi R^2 C_{p_{opt}} \left(\frac{w_{opt}}{\lambda_{opt}} \right)^3 \quad (9)$$

Where $w_{opt} = \frac{\lambda_{opt}}{R} v$ and $w_g^* = w_{opt} * G_r$ where G_r is the Gear ration of the wind turbine

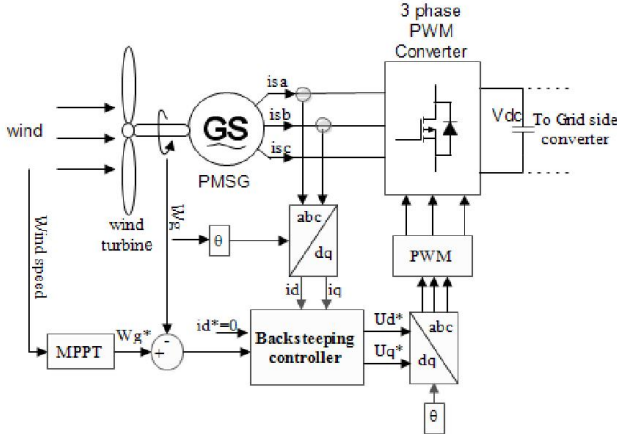


Fig 2: Overall diagram of proposed control system of PMSG

3.1.2.Nonlinear Backstepping Control Design of PMSG

The objective of the nonlinear backstepping controller is to track the speed of PMSG with the choice of appropriate regulated variables. Its design procedure has the following steps:

a) Direct current controller:

We define the direct current error as:

$$e_d = i_d^* - i_d \quad (10)$$

where i_d is the d-axis stator current and i_d^* its reference .

We define the variable ε_d as

$$\varepsilon_d = e_d + K_{d1} \int_0^t e_d dt \quad (11)$$

Where $\varepsilon_d' = K_{d1} \int_0^t e_d$

With K_{d1} a twining gain.

Consider the following Lyapunov function

$$V_d = \frac{1}{2} \varepsilon_d^2 + \frac{1}{2} \varepsilon_d'^2 \quad (12)$$

This function is always positive and if its derivative is always negative, then the error will be stable and tend towards zero. The derivative of the function is written as

$$\begin{aligned} \dot{V}_d &= \varepsilon_d \frac{d\varepsilon_d}{dt} + \varepsilon_d' \frac{d\varepsilon_d'}{dt} \\ &= \varepsilon_d \left[\frac{de_d}{dt} + K_{d1} e_d \right] + \varepsilon_d' K_{d1} e_d \\ &= \varepsilon_d \left[\frac{di_d^*}{dt} - \frac{di_d}{dt} + K_{d1} (i_d^* - i_d) \right] + \varepsilon_d' K_{d1} (i_d^* - i_d) \end{aligned} \quad (13)$$

By replacing $\frac{di_d}{dt}$ from (5) we acquire

$$\dot{V}_d = \varepsilon_d \left[\frac{di_d^*}{dt} + \frac{R_s}{L_d} i_d - w_e \frac{L_q}{L_d} i_q - \frac{1}{L_d} u_d \right] + \varepsilon_d K_{d1} (i_d^* - i_d) + \varepsilon_d' K_{d1} (i_d^* - i_d) \quad (14)$$

We define ψ_1 as

$$\psi_1 = \frac{di_d^*}{dt} + \frac{R_s}{L_d} i_d - w_e \frac{L_q}{L_d} i_q - \frac{1}{L_d} u_d \quad (15)$$

Equation (14) turns out to be

$$\begin{aligned} \dot{V}_d &= \varepsilon_d \psi_1 + \varepsilon_d K_{d1} (i_d^* - i_d) + \varepsilon_d' K_{d1} (i_d^* - i_d) \\ &= \varepsilon_d \psi_1 + (\varepsilon_d + \varepsilon_d') K_{d1} (i_d^* - i_d) \end{aligned} \quad (16)$$

Where $(i_d^* - i_d) = \varepsilon_d - \varepsilon_d'$ therefore

$$\begin{aligned} \dot{V}_d &= \varepsilon_d \psi_1 + K_{d1} (\varepsilon_d + \varepsilon_d') (\varepsilon_d - \varepsilon_d') \\ &= \varepsilon_d \psi_1 + K_{d1} (\varepsilon_d^2 - \varepsilon_d'^2) \\ &= \varepsilon_d \psi_1 + K_{d1} \varepsilon_d^2 - K_{d1} \varepsilon_d'^2 \end{aligned} \quad (17)$$

We assume that

$$\psi_1 = -K_1 \varepsilon_d \quad (18)$$

Then

$$\dot{V}_d = -K_1 \varepsilon_d^2 + K_{d1} \varepsilon_d^2 - K_{d1} \varepsilon_d'^2 \quad (19)$$

Therefore, the condition to ensure that the derivative is still negative, is :

$$K_1 > 0 \text{ and } K_1 > K_{d1}$$

Where K_1 is parameter introduced by the backstepping method, which must always be positive and greater than K_{d1} to attain the stability criteria of Lyapunov function; Thus the virtual control is asymptotically stable. Besides, this parameter can influence the dynamics of regulation.

The control input u_d can be found by solving the constraint in (18). So, by replacing ψ_1 from equation (15) in equation (18) we get

$$\frac{di_d^*}{dt} + \frac{R_s}{L_d} i_d - w_e \frac{L_q}{L_d} i_q - \frac{1}{L_d} u_d = -K_1 \varepsilon_d \quad (20)$$

Then, the control input u_d making $\dot{V}_d \leq 0$ is found as

$$u_d = -K_1 L_d \varepsilon_d + L_d \frac{di_d^*}{dt} + R_s i_d - w_e L_q i_q \quad (21)$$

b) Speed control:

The control objectives are mainly to make the speed error converge to zero asymptotically. The definition of the speed error is as follows:

$$e_w = w_g^* - w_g \quad (22)$$

And the derivative according to the time is:

$$\frac{de_w}{dt} = \frac{dw_g^*}{dt} - \frac{dw_g}{dt} \quad (23)$$

According to (7) and (8), (23) is writing as:

$$\frac{de_w}{dt} = \frac{dw_g^*}{dt} - \frac{1}{j_{eq}} \left(\frac{3}{2} p \left((L_d - L_q) i_d i_q + i_q \psi_f \right) + T_l - B_m w_g \right) \quad (24)$$

In order to make the speed error tends to zero, Lyapunov function is defined as

$$V_2 = \frac{1}{2} e_w^2 \quad (25)$$

The derivative of this function is as

$$\dot{V}_2 = e_w \frac{de_w}{dt} \quad (26)$$

To guarantee that the derivative is still negative, we choose:

$$\frac{de_w}{dt} = -K_2 e_w \quad (27)$$

Where K_2 is a positive design parameter. That achieves global asymptotic stability of the speed tracking.

So according to (20) and (24), we can write the following equation:

$$\frac{dw_g^*}{dt} - \frac{1}{j_{eq}} \left(\frac{3}{2} p \left((L_d - L_q) i_d i_q + i_q \psi_f \right) + T_l - B_m w_g \right) = -K_2 e_w \quad (28)$$

From The equation (28) the virtual controls should be the signal i_q in order to achieve our control

objectives. So it provides references for next step of the backstepping design, which is essentially to make the signal i_q behave as desired.

Therefore the desired quadratic current i_q^* is

$$i_q^* = \frac{2j_{eq}}{3p\psi_f} \left(K_2 e_w + \frac{dw_g^*}{dt} - \frac{T_l}{j_{eq}} + \frac{B_m}{j_{eq}} w_g \right) \quad (29)$$

c) Quadratic current error

Let us define the quadratic current error as

$$e_q = i_q^* - i_q \quad (30)$$

$$\varepsilon_q = e_q + K_{d2} \int_0^t e_q dt \quad (31)$$

Where $\varepsilon'_q = K_{d2} \int_0^t e_q dt$

With K_{d2} a twining gain.

Consider the following Lyapunov function

$$V_q = \frac{1}{2} \varepsilon_q^2 + \frac{1}{2} \varepsilon'_q{}^2 \quad (32)$$

The derivative of the function is written as

$$\begin{aligned} \dot{V}_q &= \varepsilon_q \frac{d\varepsilon_q}{dt} + \varepsilon'_q \frac{d\varepsilon'_q}{dt} \\ &= \varepsilon_q \left[\frac{de_q}{dt} + K_{d2} e_q \right] + \varepsilon'_q K_{d2} e_q \\ &= \varepsilon_q \left[\frac{di_q^*}{dt} - \frac{di_q}{dt} + K_{d2} (i_q^* - i_q) \right] + \varepsilon'_q k_{d2} (i_q^* - i_q) \end{aligned} \quad (33)$$

By replacing $\frac{di_q}{dt}$ from the equation (6) we obtain

$$\begin{aligned} \dot{V}_q &= \varepsilon_q \left[\frac{di_q^*}{dt} + \frac{R_s}{L_q} i_q + w_e \left(\frac{L_d}{L_q} i_d + \frac{1}{L_q} \psi_f \right) - \right. \\ &\quad \left. \frac{1}{L_q} u_q \right] + \varepsilon_q K_{d1} (i_q^* - i_q) + \varepsilon'_q k_{d2} (i_q^* - i_q) \end{aligned} \quad (34)$$

We set

$$\psi_2 = \frac{di_q^*}{dt} + \frac{R_s}{L_q} i_q + w_e \left(\frac{L_d}{L_q} i_d + \frac{1}{L_q} \psi_f \right) - \frac{1}{L_q} u_q \quad (35)$$

Equation (34) turns into

$$\begin{aligned} \dot{V}_q &= \varepsilon_q \psi_2 + \varepsilon_q K_{d1} (i_q^* - i_q) + \varepsilon'_q k_{d2} (i_q^* - i_q) \\ &= \varepsilon_q \psi_2 + (\varepsilon_q + \varepsilon'_q) K_{d2} (i_q^* - i_q) \end{aligned} \quad (36)$$

Where $(i_q^* - i_q) = \varepsilon_q - \varepsilon'_q$ then

$$\begin{aligned} \dot{V}_q &= \varepsilon_q \psi_2 + K_{d2} (\varepsilon_q + \varepsilon'_q) (\varepsilon_q - \varepsilon'_q) \\ &= \varepsilon_q \psi_2 + K_{d2} (\varepsilon_q^2 - \varepsilon'^2_q) \\ &= \varepsilon_q \psi_2 + K_{d2} \varepsilon_q^2 - K_{d2} \varepsilon'^2_q \end{aligned} \quad (37)$$

We assume that

$$\psi_2 = -K_3 \varepsilon_q \quad (38)$$

Then

$$\dot{V}_q = -K_3 \varepsilon_q^2 + K_{d2} \varepsilon_q^2 - K_{d2} \varepsilon_q'^2 \quad (39)$$

Therefore, the condition to make sure that the derivative is still negative, is

$$K_3 > 0 \text{ And } K_3 > K_{d2}$$

Where K_3 is parameter introduced by the backstepping method. The control input u_q can be found by solving the constraint (38). So, by replacing ψ_2 from equation (35) in equation(38)we get

$$\frac{di_q^*}{dt} + \frac{R_s}{L_q} i_q + w_e \left(\frac{L_d}{L_q} id + \frac{1}{L_q} \psi_f \right) - \frac{1}{L_q} u_q = -K_2 \varepsilon_q \quad (40)$$

Then, the control input u_d making $\dot{V}_q \leq 0$ is given by

$$u_q = -K_2 L_q \varepsilon_q + L_q \frac{di_q^*}{dt} + R_s i_q + w_e (L_d id + \psi_f) \quad (41)$$

After obtaining the u_d and u_q control signals; they are turned into three phases referential by means of the inverse Park transformation and are given as a reference to the PWM block (pulse width modulation) in order to generate the Converter signals pulse as shown in Fig 2.

Thus the consequential closed loop system is asymptotically stable; therefore, all the variable errors ed, eq and e_w will converge to zero asymptotically. Consequently the id current will converge to its reference ($i_d^* = 0$) and the speed will converge also at its reference. So, the desired control objective of speed tracking for the PMSG is indeed achieved by the proposed nonlinear backstepping control scheme.

3.2. Control of the grid side converter

The role of the grid side converter control is to adjust the DC (Direct Current) line voltage to the desired value, and ensure that the output voltage converter has a similar amplitude and frequency with the grid, but the main role of this control is to control the active and reactive power.

3.2.1.DC line modeling and control

The dc line is the capacitor located between the converters; its function is to keep the DC voltage stable, the model of the dc line is expressed as:

$$\frac{C dV_{dc}}{dt} = i_s - i_g \quad (42)$$

Where V_{dc} is the DC line voltage, i_s is the current of DC-line at the generator side and i_g is the courant

of DC line at the grid side, C is the capacity of DC-line capacitor.

Let us suppose that the converter is ideal i.e. does not consume power; the voltage of the capacitor is written as

$$C \frac{dV_{dc}}{dt} = \frac{P_s}{V_{dc}} - i_g \quad (43)$$

Where P_s is the output power of generator. We can write it as

$$P_s = 3V_s i_s = V_{dc} i_{dc} \quad (44)$$

We rephrase it as

$$P_s = \frac{3}{2} E_{max} I_{max} = V_{dc} i_{dc} \quad (45)$$

Where V_s is the voltage of generator side and E_{max} is its amplitude, I_{max} is the amplitude of the generator current, and i_{dc} is the current through the capacitor.

The control block diagram of the DC-line is presented in Fig 3

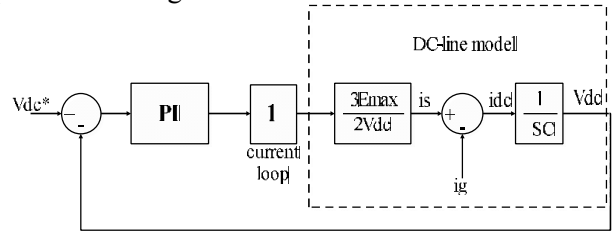


Fig 3: diagram of the loop control of DC-line

In this loop control, the current loop is considered to be fast than the voltage loop. We suppose it as equal to 1.

The PI controller is designed with the pole placement method.

3.2.2.Control of active and reactive power

The dynamic model of the grid connection when selecting a reference frame rotating synchronously with the grid voltage space vector is

$$u_{gd} = -R_g i_{gd} - \frac{L_g di_{gd}}{dt} + w_{gr} L_g i_{gq} + e_{gd} \quad (46)$$

$$u_{gq} = -R_g i_{gq} - \frac{L_g di_{gq}}{dt} - w_{gr} L_g i_{gd} \quad (47)$$

Where R_g and L_g are the resistance and inductance respectively of the filter, this latter is located between the converter and the grid. u_{gd} and u_{gq} are the inverter voltage components, w_{gr} is the electrical angular velocity of the grid.

If the reference frame is oriented along the supply voltage, the grid voltage vector is

$$u = u_{gd} + j0 \quad (48)$$

Then active and reactive power goes through the grid side converter, it is written as:

$$P = \frac{3}{2} u_{gd} i_{gd} \quad (49)$$

$$Q = \frac{3}{2} u_{gd} i_{gq} \quad (50)$$

The active and reactive power control is achieved in two loops, by controlling direct and quadrature current components[13] as shown in Fig 4.

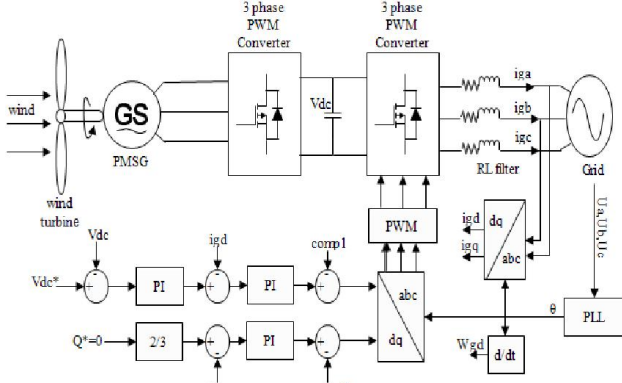


Fig 4 Overall diagram of proposed control system of the grid side converter

In Fig 4, θ is the electrical angle of the grid, it is extracted with the PLL (phase locked loops), and $comp1 = w_{gr} L_g i_{gq} + e_{gd}$; $comp2 = w_{gr} L_g i_{gd}$ are the compensation terms

The first channel controls the dc voltage which is used to provide to the d-axis current reference for active power control. This assures that all the power coming from the PMSG converter is instantly transferred to the grid through the converter.

The second channel controls the reactive power by setting the q-axis current reference to the current control loop similar to the previous one. The current controllers will provide a voltage reference for the converter that is compensated by adding rotational EMF (Electromotive Force) compensation terms. All controllers are PI and are tuned using the pole placement method.

The loop control of the direct and quadrature current is shown in Fig 5.

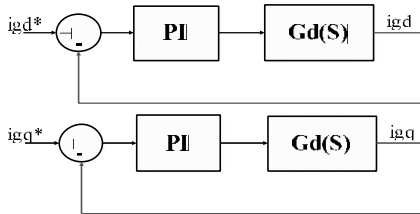


Fig 5 diagram of loop control of direct and quadrature current

$$\text{Where } G_d(s) = \frac{1}{L_g d \cdot s + R_g} \text{ and } G_q(s) = \frac{1}{L_g q \cdot s + R_q}$$

are the transfer functions of the filter that connects the converter to the grid.

4. SIMULATION RESULTS

Our control strategy of the wind energy conversion system studied previously is investigated using Matlab/simulink® with SimPowerSystems block.

The system performance and robustness is evaluated for the PMSG system parameters shown in Table 1 and the wind turbine parameters shown in Table 2. The main measurements include speed, torque, three-phase voltage, and stator current.

The controller has as input, the speed reference extracted from the MPPT block, the direct and quadrature stator current and also the torque applied by the wind turbine on the PMSG.

Table 1 PMSG system parameter

Parameter	Value	Units
Rated power	2.5	kW
Rated line current	11	A
Rated speed	3000	r/m
Mutual inductance in q-axis L_q	7.5	mH
Mutual inductance in d-axis L_d	7.5	mH
Stator resistance, R_s	0.45	Ω
Number of pole pairs p	3	
Permanent magnet flux ψ_f	0.52	Wb
viscous friction B_m	0.017	Nm/rad/s

Table 2: wind turbine parameters

Parameter	Value	Units
Air density ρ	1.22	Kg/m^3
Gear ratio G_r	6	
Rotor radius R	3	M
Maximum power coefficient C_p	0.4412	
Equivalent inertia(turbine +generator) J_{eq}	0.042	Kg.m^2

In order to test robustness of the proposed control system, we assumed the wind speed profile as it is shown in Fig 6, it varies between 4 to 9m/s.

The speed response of the backstepping controller shows a better tracking characteristics, as shown in Fig 7 in which the speed tracking controller operates in a critical variable situation, the response time of the PMSG speed is very short approximately 20ms, there is no overshoot and no steady state error.

The wind conversion system operates at maximum puissance as shown in Fig 8 which means that the power coefficient is around the maximum value ($C_{p_{max}} = 0.41$).

The Fig 9 shows the electromagnetic torque produced by the PMSG.

We observe from Fig 10 and Fig 11 that the currents in the d-axis and q-axis follow perfectly their references in a good performance, this insure that the backstepping controller have great robustness. We noticed that there is a shattering phenomena in the current and the torque , caused by the commutation frequency (15 kHz) of the converter.

The DC-line voltage is maintained around their reference (400 V) with no steady state error as shown in Fig 12

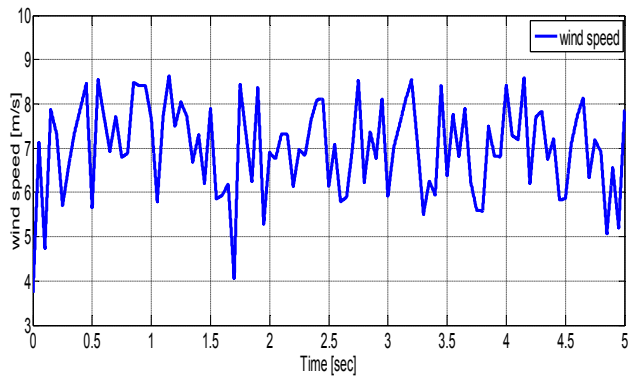


Fig 6 wind speed profile

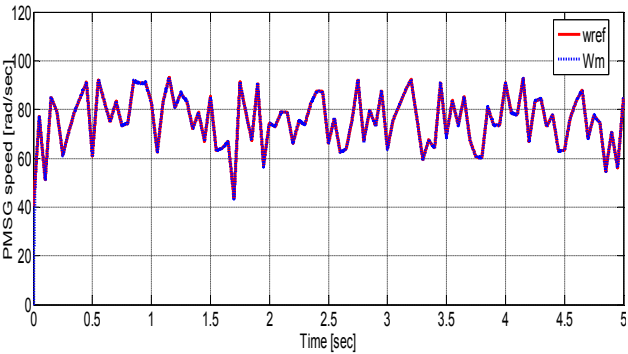


Fig 7: PMSG speed (blue) and its reference (red)

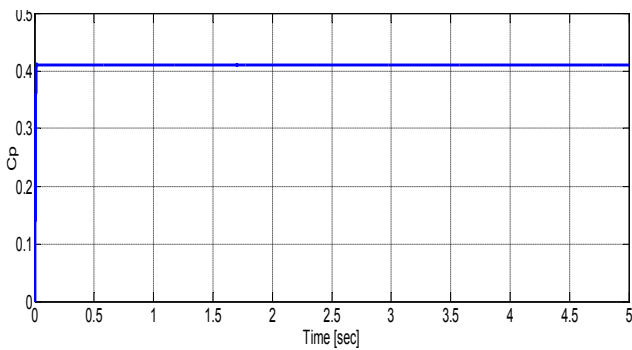


Fig 8: the power coefficient cp

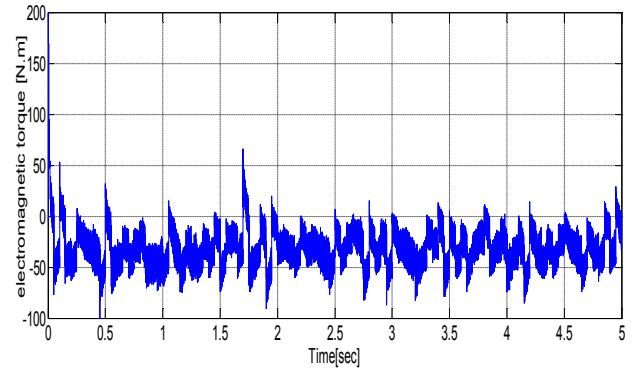


Fig 9 PMSG electromagnetic torque

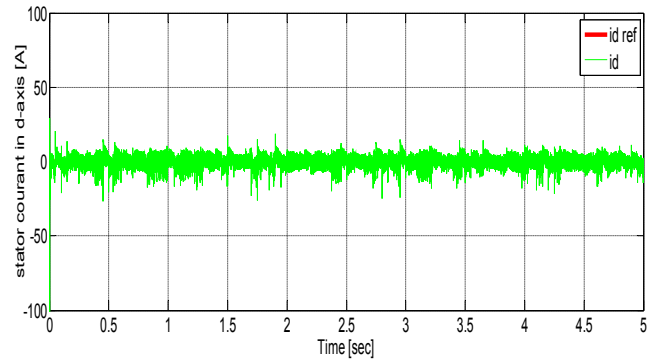


Fig 10 PMSG stator courant in d-axis (green) and its reference (red)

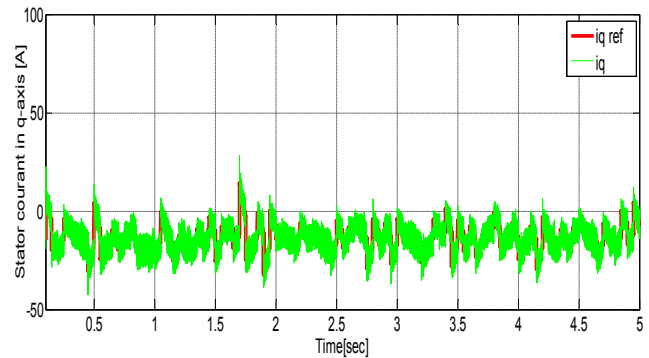


Fig 11 PMSG stator courant in the q-axis (green) and its reference (red)

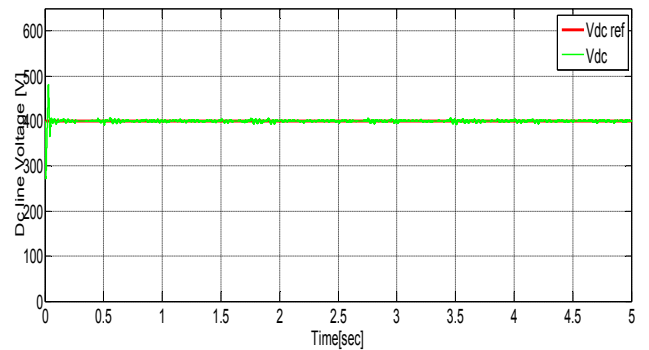


Fig 12: the DC-line voltage (green) and its reference (red)

5. CONCLUSION

In this paper, a robust nonlinear control approach of a PMSG associated with wind turbine and integrated to the grid has been presented to improve the reliability and efficiency of the wind energy conversion system.

This design is based on a nonlinear backstepping strategy which guarantees the robust performances and gives satisfactory results.

Simulation results prove the effectiveness of our strategy as regards robust stability and transient performances and ability to track the maximum power from the wind power when exciting the system with a variable wind speed.

Finally, as a further improvement of the proposed strategy, it will be interesting to combine the proposed backstepping controller with a nonlinear observer in order to estimate the PMSG speed and parameters. Also it will be interesting to apply our approach in a fault operation mode.

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