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Advanced control of a permanent magnet synchronous generator for a wind turbine

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ABSTRACT

This article presents an improved vector control scheme based on super twisting continuous sliding mode for a permanent magnet synchronous generator integrated in a dual roror wind turbine system. To augment the energy effectiveness of wind systems, several research has recently been realized by different researchers and in various technologies fields. The field of machine control occupied a large part of this research as the objective was always to find the most optimal control solution. Two main objectives are targeted in this work. The first goal is to develop the vector control performance of the permanent magnet synchronous generator by using second order continuous sliding mode controller, which is known for their robustness and ability to reduce chattering phenomenon. The second objective of this work is to use a dual rotor wind turbine in order to increase the energy efficiency of the wind power system used. The obtained simulation results showed the efficacy of the techniques used.

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1. INTRODUCTION

In the last few decades, wind energy has experienced rapid development around the world compared to other kinds of renewable energy [1]. It went from a few tens of kW to hundreds of MW in a short time [2], [3]. Conventional wind turbine (WT) or mono rotor wind turbine (MRWT) with three blades and horizontal axis are the most widely used WTs in the world market today. The energy efficiency of the latter is around 40%. This characteristic is restricted by the limit of Betz which reaches a maximum of 59%. However, this limit is not insurmountable. Recent studies have been carried out to design more efficient WTs offering better power characteristics [4]. Among the proposed solutions we find the dual rotor wind turbine (DRWT). The latter, under development, can increase energy efficiency above the Betz limit (0.59). This type of wind turbines is used in this work. WT based on permanent magnet sunchronous generator (PMSG) is widely employed because their high effectiveness and suitable cost [3], [5]. However, the no need for a Gearbox and the excitation system on the one hand and the simplicity of the model of this machine and its adaptation to variable speed applications on the other hand, allows obtaining a WT of better quality and verycompetitive with other WTs. Nowadays, variable speed WTs occupy the large part of the WT market in the world [6], [7].

Indeed, the nature of the wind speed of a random nature has encouraged researchers and manufacturers to focus on this type of WT compared to fixed speed WTs.

Given the random nature of the wind, a maximum power point tracking (MPPT) control technique is necessary to capture the maximum of energy coming from the wind. Various research has been made recently by several researchers to improve this technique [8]. An MPPT command with proportionnal integral (PI) regulator is among the most used solutions currently used in several research. The synthesis of the parameters of this type of regulator that departs from the parameters of the system represents the weakest link of this type of regulator. Indeed, the variation of the parameters of the system makes the values of the gains of this regulator difficult to fix [9]. Several types of regulators have been proposed in literature to surpass the robustness drawback of the PI controller. In our work, a second order continuous sliding mode controller (SOCSMC) has been used for the speed control. This type of controller is known by its robustness, rapidity, and ability to reduce the phenomenon of Chattering compared to the conventional sliding mode controller (SMC) and even the second order sliding mode controller (SOSMC) [9].

The article is organised given as: the section 2 presents the system modelling. Section 2 is dedicated to the modeling of the PMSG-based DRWT system. In section 3 we briefly present the vector control (VC) method of the PMSG. The speed control using SOCSMC of the PMSG is the subject of section 4. Finally, sections 5 and 6 successively present the simulation results and the conclusion of the article.

2. THE SYSTEM MODELLING

2.1. The DRWT model

The system studied in this article is shown in Figure 1. It is composed of a DRWT driving a PMSG connected to the electrical grid through power converters providing electrical energy with adjustable characteristics. The modeling of the various organs of our system is carried out in the following sessions.

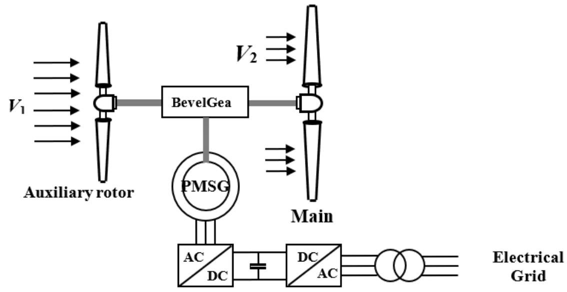

Figure 1. System presentation

The expressions of the kinetic powers of the wind through respectively the auxiliary and main rotor are expressed by (1):

$$P_1 = 0,5.\rho.\pi.R_1^2V_1^3,\ P_2 = 0,5.\rho.\pi.R_2^2V_2^3 \qquad (1)$$

where: ρ is the air density, (R_1, R_2) are the radius of the auxiliary and main rotor, (V_1, V_2) are the wind speed through the auxiliary and main rotor. The expressions of the powers captured by the auxiliary and main rotor are given by (2):

$$P_{c1} = C_p(\lambda_1).P_1,\ P_{c2} = C_p(\lambda_2).P_2 \qquad (2)$$

where the power coefficient Cp can be approximated as a relationship of tip-speed ratio λ and blade-pitch angle β (in degree) by the (3) [10].

$$C_p = (0.44 - 0,167\beta) \cdot sin\left[\frac{\pi(\lambda-3)}{15-0,3\cdot\beta}\right] - 0,0018 \cdot (\lambda - 3)\beta \qquad (3)$$

The tip-speed radio expressions (λ_1, λ_2) of the auxiliary and main rotor are given as (4):

$$\lambda_1 = \Omega_{t1}.R_1/V_1,\ \lambda_2 = \Omega_{t2}.R_2/V_2 \qquad (4)$$

where: Ω_{t1} and Ω_{t2} are respectively the mechanical speed of the auxiliary and main rotor. To have an optimal result, next simulations are carried with $\beta_1 = \beta_2 = 2°$ and $\lambda_1 = \lambda_2 = 8$ rad. The aerodynamic torque expressions of the auxiliary and main turbine are respectively exposed as (5).

$$T_1 = \frac{C_p \rho \pi R_1^2 V_1^3}{2\Omega_{t1}}, T_2 = \frac{C_p \rho \pi R_2^2 V_2^3}{2\Omega_{t2}} \quad (5)$$

2.2. The PMSG model

The PMSG model in Park reference frames is expressed as (6) [11], [12]:

$$\begin{cases} \frac{di_d}{dt} = -\frac{R}{L_d} i_d + \frac{L_q}{L_d} \omega i_q + \frac{1}{L_d} v_d \\ \frac{di_q}{dt} = -\frac{R}{L_q} i_q - \frac{L_d}{L_q} \omega i_d + \frac{1}{L_q} \omega \varphi_m + \frac{1}{L_q} v_q \end{cases} \quad (6)$$

where R is the stator resistance, (L_d, L_q) are the stator d-q inductances, (i_d, i_q) and (v_d, v_q) are respectively the d- and q-axis components of current and voltage, $\phi_m$is the permanentmagnet flux and ω is the rotor speed. The electromagnetic torque is given in the d-q synchronously rotating reference frame by (7) [13]:

$$T_{em} = \frac{3}{2} n_p \left((L_d - L_q) \cdot i_d i_q - \varphi_m i_q \right) \quad (7)$$

with n_p is the pole pairs number. The mechanical equation of the WT system is (8):

$$T_t = T_{em} + f_r \Omega + J \frac{d\Omega}{dt} \quad (8)$$

where T_t is the mechanical torque of the DRWT, T_{em} is the electromagnetic torque of the PMSG, J is the total inertia of the system and f_r is the coefficient of a viscous friction.

3. VECTOR CONTROL OF THE PMSG

The VC technique is used to establish a linear model and make the behavior of the synchronous machine analogous to that of a separately excited direct current machine which exhibits decoupling between torque and flux. If the current I_d is imposed equal to zero, and since the flux ϕ_m is constant, the torque will be linked directly to the current I_q as shown in (9) [14]:

$$T_{em} = -\frac{3}{2} n_p \varphi_m i_q \quad (9)$$

with the previous hypothesis ($i_d = 0$), two terms of compensation (u_d and u_q) are defined in order to decouple the system (6) as (10):

$$\begin{cases} u_d = L_q \omega i_q + v_d \\ u_q = -L_d \omega \varphi_m i_d - e_q + v_q \end{cases} \quad (10)$$

where,

$$\begin{cases} e_q = \omega \varphi_m \\ u_d = L_d \frac{di_d}{dt} + R i_d \\ u_q = L_q \frac{di_q}{dt} + R i_q \end{cases} \quad (11)$$

based on (6), two first-order transfer functions can be written as (12).

$$\begin{cases} \frac{i_d}{u_d} = \frac{1}{L_d s + R} \\ \frac{i_q}{u_q} = \frac{1}{L_q s + R} \end{cases} \quad (12)$$

Two PI (integral proportional) regulators are used to control, separately the two currents i_d and i_q. The same for the mechanical speed regulating loop and based on (8), another PI controller is used for its regulation. According to (8), the transfer function of the mechanical speed is given by (13).

$$\Omega = (T_t - T_{em})\frac{1}{Js+f_r} \quad (13)$$

Figure 2 illustrates the VC scheme of the PMSG integrated in a DRWT. In fact, the speed controller takes as input the difference between the reference speed Ω^* and the one measured. Where Ω^* is obtained by λ expression as shown in (4).

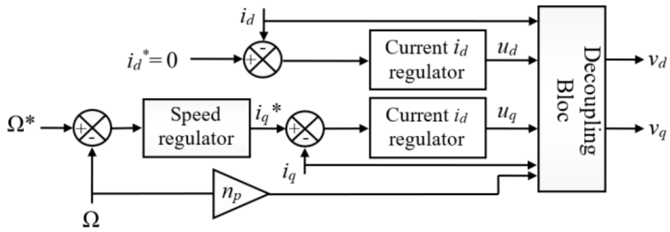

Figure 2. Control scheme

4. SECOND ORDER CONTINUOUS SLIDING MODE CONTROL OF THE PMSG

Conventional SMC is known by its performances especially the simplicity of synthesis and the robustness. Indeed, the major problem of this command lies in the presence of the chattering phenomenon which can cause serious damage to the mechanical portion of rotating machines by vibrations on the electromagnetic torque [15]. Several solutions are proposed in the literature to mitigate and/or eliminate this undesirable phenomenon [16]-[23]. Newly devlopped, SOCSMC is well appropriate because has preferred qualities, such as robustness versus uncertainties. In addition, it can decrease chattering and offers better transient features than the other high order sliding mode [24], [25]. The employed control law used in our article is presented by [26]:

$$u(t) = -l_1|S|^{a_1}\mathrm{sgn}(S)\cdots - -l_n\left|S^{(n-1)}\right|^{a_n}\mathrm{sgn}(S^{(n-1)}) - v \quad (14)$$

where v is determined by (15)-(16) and the constants a_1, a_2,..., a_n satisfy (17). In addition l_1, l_2,..., l_n are scalar coefficients determined such that the n[th] order polynomial $p^n+l_np^{n-1}+...+ l_2p+l_1$ is Hurwitz.

$$v(t) = k \cdot |S|^{1/2}\mathrm{sgn}(S) + v_1(t) \quad (15)$$

$$\dot{v}_1(t) = \alpha \cdot \mathrm{sgn}(S) \quad (16)$$

$$a_{i-1} = \frac{a_i a_{i-1}}{2a_{i+1} - a_i}, i = 2, \dots, n \quad (17)$$

The aim of the SOCSMC is to control the mechanical speed of the PMSG. The proposed controller, which is designed to control rotor speed of the PMSG is exposed in Figure 3. The SOCSM speed controller designed to generate the desired electromagnetic torque (T_{em}^*) as shown in (18):

$$T_{em}^* = -l|S_\Omega|^a\mathrm{sign}(S_\Omega) - k \cdot \mathrm{sign}|S_\Omega|^{1/2} + \int \alpha \cdot \mathrm{sign}(S_\Omega) \quad (18)$$

where the speed error $S\Omega = \Omega * -\Omega$ is the surface, and the gain k must check the stability conditions [27]:

$$k_1 > \frac{A_M}{B_m}, k_2 \geq \frac{4A_M}{{B_m}^2} \cdot \frac{B_M(K_1 + A_M)}{B_m(K_1 - A_M)} \quad (19)$$

with $\boldsymbol{A_M} \geq |\boldsymbol{A}|$ and $\boldsymbol{B_M} \geq \boldsymbol{B} \geq \boldsymbol{B_m}$ are superior and inferior bounds of A and B in the second derivative of y.

$$\frac{d^2y}{dt^2} = A(x,t) + B(x,t)\frac{du}{dt} \quad (20)$$

5. SIMULATION RESULTS

In this part, a numeric simulation by MATLAB/Simulink was performed on a 1.5 MW PMSG integrated on a DRWT. Tables 1 and 2 give respectively the parameters of the DRWT and those of the PMSG. The results obtained are shown in Figures 3(a)-(h) and Figure 4. A random wind speed profile was used to simulate a scenario like reality.

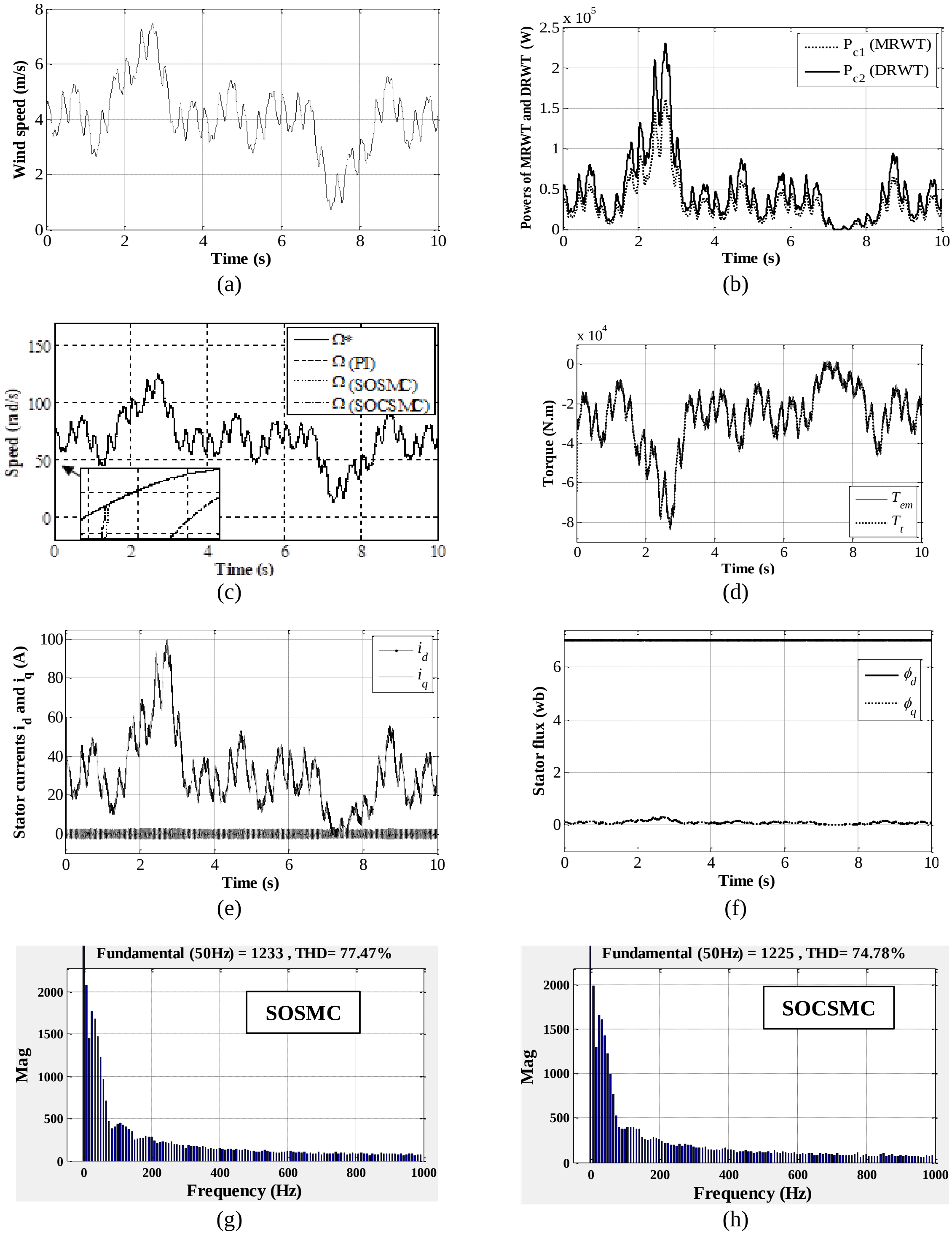

Figure 3. Reference tracking test: (a) wind spped, (b) active powers of MRWT and DRWT, (c) mechanical spped (d) electromagnetic torque, (e) stator currents, (f) stator fluxes, (g) THD on the torque curve using SOSMC, and (h) THD on the torque curve using SOCSMC

According to the results obtained, the first remark that can be observed clearly in Figure 3(b) is that the DRWT produces a higher power than that produced by a MRWTthis proves the efficiency of this WT technology. For the speed curve (Figure 3(a)), we clearly note that the two new regulators by sliding mode used (SOSMC and SOCSMC) have given a good result with respect to the classic PI especially on the rapidity side and static error. A comparison between the two controllers by sliding mode used with the attenuation of the chattering phenomenon showed that the SOCSMC controller is very better compared to that SOSMC, and this is shown by a THD on the curve of the electromagnetic torque (Figures 3(g)-(h)). For the other curves, we note that the field orientation has been successfully completed, such as the direct component of the flux is zero is that of quadrature takes the nominal value (Figure 3(f)). For stator currents, the direct component of these currents is zero while the other takes an image of the electromagnetic torque, which reflects the theory treated before Figure 3(e). A robustness test on the control techniques used with an increase of 50% of the moment of inertia showed that this variation has no effect on the two controllers by sliding mode used, whereas the response of the PI controller presents an effect very clear of this variation on the mechanic speed curve (Figure 4). According to all these results, it can be concluded that a DRWT based on a PMSG with a SOCSMC controller represents an effective system for the production of electricity.

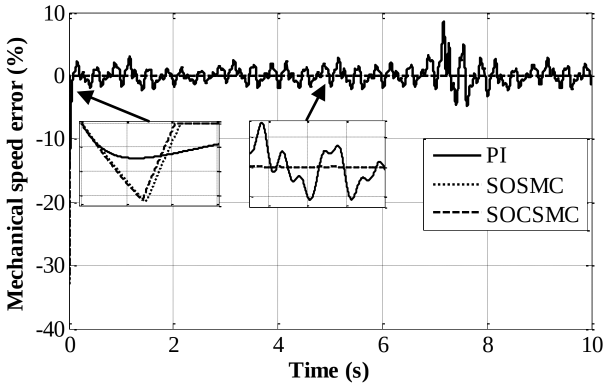

Figure 4. Error curves of PI, SOSMC and SOCSMC (robustness test)

Table 1. The DRWT parameters

Parameters	value	Unity
Rated power	1.5	MW
R_1	13.2	m
R_2	25.5	m
J	4.87×10^6	$Kg.m^2$

Table 2. The PMSG parameters

Parameters	value	Unity
Rated power	1.5	MW
R	3.174	mΩ
L_d	3.07	mH
L_q	3.07	mH
ϕ_m	7.0172	wb
n_p	80	
f_r	200	N.m.s/rad

6. CONCLUSION

In this article, an advanced control scheme of a PMSG-based DRWT system has been presented. Energy efficiency has been improved by the use of the new turbine. In addition, and in order to improve system control performance, a SOCSMC has been used. The latter is used for the speed control of the PMSG, as it has exceeded the convenient disadvantages the conventional PI controller, especially the great dependence of their gains at the system settings.The controller used also has the capacity to decrease the effect of chattering phenomenon that represents the major inconvenience of the conventional SMC. The simulation results obtained confirmed the theoretical study carried out in the previous sessions.

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