International Journal of Robotics and Automation (IJRA)
Vol. 7, No. 2, June 2018, pp. 87~95
ISSN: 2089-4856, DOI: 10.11591/ijra.v7i2.pp87-95

Nonlinear Adaptive Control for Wind Turbine Under Wind Speed Variation

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Article Info

Article history:

Received Jan 3, 2018
Revised Apr 12, 2018
Accepted Apr 26, 2018

Keyword:

ASMC
MPPT
PMSG
SMC
TANH

ABSTRACT

Wind turbines components work as nonlinear systems where electromechanical parameters change frequently [1], which makes nonlinear control an interesting solution to prevail good efficiency. SMC has been largely used in electrical power applications because it offers interesting features like robustness to parametric uncertainties and external disturbances, to conquer the biggest drawback of the SMC, adaptation strategy consists on updating the sliding gain and the turbine torque to contribute with some important characteristics such as chatter-free performance, heftiness, robustness and secure power system operation. Matlab tests are introduced and compared.

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1. INTRODUCTION

Nowadays, Wind Turbines have become one of the important topics and treated as a future technology because it's clean, free, reliable and it efficiency [2,3]. Thus, those factors became important topics in industry and research [4,5]. Accordingly, control approaches are required to fulfil ultimate performance. The PMSG-WT has been one of popular wind power systems [6] due to the simpler structure, robustness, lower maintenance costs, elimination of gearbox and high effectiveness [7,8]. Several methods are introduced to achieve maximum performances like the vector control theory accompanied by classical control techniques [9] but this controllers can serve a good performance only under ideal grid voltage conditions and can't handle the inaccuracies. Furthermore, these controllers may provide insufficient performance for different operating points. Therefore, papers have presented different control schemes like SMC [10-12], HOSMC [13-15], advance control techniques [16-18].

Due to the strong nonlinearities originated from the aerodynamics, nonlinear control methodologies gained attraction such us backstepping [19,20] because it's many features like high accuracy, fast dynamic response, stability and simplicity [21]. However, it can't handle parametric precariousness and exterior disturbances. Fortunately, SMC can conquer that problem because it's robust and respect parameters variations. Standard SMC it suffers two main deficiencies. First, chattering phenomenon which produced from the high-frequency switching that damage the performance and excites high frequency vibrations [22,23] to overthrown these problems, many authors proposed to modify the SMC law [24-26] like approximating the sign function by a high gain saturation function [27]. In an attempt to exploit the advantages of the SMC, an adaptive sliding mode controller is developed to track the rotor speed for maximum power the adaptation algorithms are developed, where the sliding gain is updated based on the sliding surface and its derivative, and the turbine torque, considered unknown by the controller, is developed by using the sliding mode control itself. The adaptive part constitutes the major contribution of this work. Results are presented and discussed to show that controllers as ASMC can improve performances of PMSG in terms of reference tracking, sensibility to perturbations and parameters variations. In this article: turbine model and the MPPT are in the section II. In part III, PMSG mathematical model is introduced. Section IV introduces SMC. In section V ASMC is proposed. At last, matlab results are given and debated.

2. TURBINE MODEL:

The power contained in kinetic energy form at a speed Vv, surfaceA1, is expressed by (1) [28]:

$$P_v = \frac{1}{2}\rho A_1 V_v^3 \tag{1}$$

Where ρ is the air density, but WT can regain just a part of that power as shown in (2):

$$P_v = \frac{1}{2}\rho\pi R^2 V_v^3 C_p \tag{2}$$

Where: Cp is power coefficient [24].The speed ratio λ introduced by (3):

$$\lambda = \frac{R\Omega_t}{V_v} \tag{3}$$

Where R: blades length, Ω_t : rotor speed. The theoretical extreme rate of Cp is Betz limit:

$$C_{p\_theo\_\max} = 0,593 = 59,3\%$$

The torque and power coefficient is represented in function of tip step ratio (λ) and the pitch angle (β) as shown in (4,5):

$$C_p = C_1\left(\frac{C_2}{\lambda_i} - C_3\beta - C_4\beta^{C_5} - C_6\right)\left(e^{C_7/\lambda_i}\right) \tag{4}$$

$$\lambda_i = \frac{1}{\lambda + C_8} \tag{5}$$

The slow shaft mechanical torque Ct is expressed by (6):

$$C_t = \frac{P_t}{\Omega_t} = \frac{\pi}{2\lambda}\rho R^3 v^2 C_p \tag{6}$$

Mechanical system: Mechanical model will be represented in Figure 1.

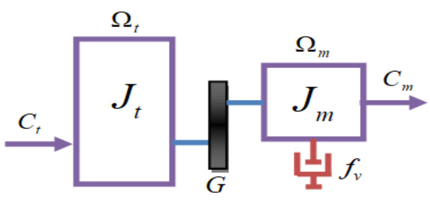


Figure 1. Mechanical model

Where: Jt: the turbine inertia, while Jm: generator inertia, G: gearbox ratio. The generator speed and the fast shaft torque as shown in (7-9):

$$\Omega_m = G\Omega_t \tag{7}$$

$$C_m = C_t / G \tag{8}$$

Next,

$$C_m - C_{em} = \left(\frac{J_t}{G^2} + J_m \right) \frac{d\Omega_m}{dt} + f_v \Omega_m \tag{9}$$

3. PMSG MATHEMATICAL MODEL:

PMSG mathematical model in the dq reference as shown in (10-11) [29]:

$$U_d = R_s I_d + L_d \frac{di_d}{dt} - L_q i_q \omega_r \tag{10}$$

$$U_q = R_s I_q + L_q \frac{di_q}{dt} + \left(L_d i_d + \phi_m \right) \omega_r \tag{11}$$

Thus, (10) - (11) can be indicated by (12-13):

$$\frac{di_d}{dt} = -\frac{R_s}{L_d} i_d + \frac{L_q}{L_d} \omega_r i_q - \frac{1}{L_d} U_d \tag{12}$$

$$\frac{di_q}{dt} = -\frac{R_s}{L_q} i_q - \frac{L_d}{L_q} \omega_e i_d - \frac{1}{L_q} U_q + \frac{1}{L_q} \phi_m \omega_r \tag{13}$$

The motion equation as shown in (14-15):

$$C_{em} - C_r = J \frac{d}{dt} \omega_r + f_v \omega_r \tag{14}$$

$$J = \frac{J_{turbine}}{G^2} + J_g \tag{15}$$

Rotational speed as shown in (16):

$$\frac{d\omega_r}{dt} = \frac{1}{J} \left(C_m - C_{em} - f \omega_r \right) \tag{16}$$

Where: Cr is the load torque J is total inertia, ωr is mechanical speed.

4. THE SLIDING MODE CONTROL

The advantage of this approach is its simplicity and robustness in spite of system unpredictability and exterior disturbances, furthermore it needs relatively less information about the system and also is insensitive to the parametrical changes plus it doesn't need the mathematical models accurately like classical controllers but needs the range of parameter changes for ensuring sustainability and condition satisfactory [25, 30-32]. The SMC goes through three steps:

Choice of surface

Sliding surface as shown in (17):

$$S = \omega_r - \omega_{ref} \;,\; S_1 = i_q - i_{qref} \;,\; S_2 = i_d - i_{dref} \tag{17}$$

The derivative of (17) as shown in (18):

$$\dot{S} = \dot{\omega}_r - \dot{\omega}_{ref} \;,\; \dot{S}_1 = \dot{i}_q - \dot{i}_{qref} \;,\; \dot{S}_2 = \dot{i}_d - \dot{i}_{dref} \tag{18}$$

By substituting (ω_r , i_q and i_d) in (18), we get (19):

$$\begin{cases} \dot{S} = \dfrac{1}{J}\left(C_m - C_{em} - f\,\omega_r\right) - \dot{\omega}_{ref} \\ \dot{S}_1 = -\dfrac{R_s}{L_q} i_q - \dfrac{L_d}{L_q}\omega_e i_d - \dfrac{1}{L_q}U_q + \dfrac{1}{L_q}\phi_m \omega_r - \dot{i}_{qref} \\ \dot{S}_2 = -\dfrac{R_s}{L_d} i_d + \dfrac{L_q}{L_d}\omega_r i_q - \dfrac{1}{L_d}U_d - \dot{i}_{dref} \end{cases} \tag{19}$$

Convergence condition:
The stability of the SMC is estimated by adopting Lyapunov function as shown in (20).

$$V = \frac{1}{2} S^2 \tag{20}$$

The derivative of (20) as shown in (21):

$$\dot{V} = S\,\dot{S} \prec 0 \tag{21}$$

Calculation of control laws:
Control law has the following form (22),

$$U = U_{eq} + U_n \tag{22}$$

Where U is the control vector, U_{eq} is the equivalent control vector, we acquire it by considering that $\dot{S}(x) = 0$. U_n Is the switching part of control and it’s defined by (23):

$$U_n = k \tanh(S) \tag{23}$$

Control structure is (24):

$$\begin{cases} C_{em} = C_m - f\,\omega_r - J\,\dot{\omega}_{ref} + Jk\tanh(S) \\ U_q = -R_s i_q - L_d \omega_e i_d + \phi_m \omega_r - L_q\,\dot{i}_{qref} + k_1 \tanh(S_1) \\ U_d = -R_s i_d + L_q \omega_r i_q - L_d\,\dot{i}_{dref} + k_2 \tanh(S_2) \end{cases} \tag{24}$$

Where (k, k1, k2) are the sliding gain. However, the latter generates on sliding surface, a phenomenon called chattering, which is generally undesirable because it adds to the spectrum control high frequency components as indicate Figure 2, In an attempt to minimize the chattering we will use the hyperbolic tangent function (tanh) which will make the control signal smoother.

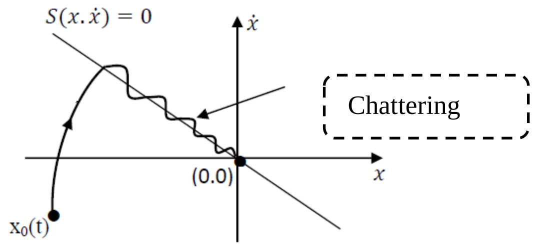


Figure 2. Chattering Phenomenon.

5. ADAPTIVE SLIDING MODE CONTROLLER

To bring the rotor speed as quickly as possible to it reference and improve the system's response, the time sliding gain k(t) is adapted. The control law (24) becomes (25):

$$C_{em} = C_m - f\,\omega_r(t) - J\,\dot{\omega}_{ref}(t) + Jk(t)\tanh(S) \tag{25}$$

The gain adaptation as shown in (26):

$$k(t) = \int aS\tanh(S)\,dt \tag{26}$$

Where, α is a positive adaptation rate. The torque control law has the following expression (27):

$$C_{em} = \hat{C}_m - f\,\omega_r(t) - J\,\dot{\omega}_{ref}(t) + Jk(t)\tanh(S) \tag{27}$$

Where $\hat{C}_m$ is an estimate of the reflected wind turbine torque. The closed loop dynamics of system (16) and the control law (27) is expressed as shown in (28):

$$\dot{S} = k\tan(S) + \frac{1}{J}\tilde{C}_m \tag{28}$$

Where $\tilde{C}_m = C_m - \hat{C}_m$ is the torque tracking error. $\tilde{C}_m$ must be carried out to reach zero using adaptive estimation of C_m .Let us impose a first-order dynamics to the torque error as shown in (29):

$$\dot{\tilde{C}}_m + c_0\tilde{C}_m = 0\ ,\ \ c_0 \succ 0 \tag{29}$$

Using the expression of C_m and the assumption that $\dot{C}_m = 0$, (29) is reorganized as (30):

$$\dot{\hat{C}}_m = c_0\left(C_m - \hat{C}_m\right) = c_0\left(C_{em} + f\,\omega_r + J\,\dot{\omega}_{ref}\right) - c_0\hat{C}_m \tag{30}$$

Then, the torque control law (27) is substituted into (30) yielding to (31):

$$\dot{\hat{C}}_m = c_0 J\left(\dot{\omega}_r + \dot{\omega}_{ref}\right) + c_0 Jk\tanh(S) \tag{31}$$

Integrating (31), the torque estimation becomes (32):

$$\dot{\hat{C}}_m = c_0 J S(t) + c_0 J \int k(t) \tanh(S(t)) \tag{32}$$

To control the stator current components, a field orientation approach is implemented, where the required components of the converter voltage vector are derived from controllers to track $i_d^* = 0$ and i_q^* carried out from the decoupling turbine-generator, the torque generator is simplified as shown in (33-34):

$$C_{em} = \frac{3}{2} p \phi_m i_q \tag{33}$$

Therefore, i_{qs}^* is:

$$i_q^* = \frac{2}{3 p \phi_m} C_{em}^* \tag{34}$$

Where, C_{em}^* is carried out from (27).

6. SIMULATION RESULTS

In this section, simulation tests have been performed with the help of Matlab to prove the efficiency of the controller reference tracking. In order to evaluate the control strategy proposed in this paper, a change in wind speed is applied as presented in Figure 3, 4, 5, 6, 7, dan 8.

Figure 4 shows that the rotational speed response converges perfectly to its reference track and following the maximum power. The currents id - iq are depicted in Figures 5 and 6, respectively. It can be seen that the direct and quadrature currents tracks almost perfectly there references which indicate that the ASMC has a good dynamic response, the active power is shown in (7-a). Furthermore, (7-b) shows that the reactive power is approximately zero. Although wind variation, pitch control has a rapid angle respond and minimum power ripples. The mechanical speed of the turbine represented in Figure. 4 is obtained according to angle variation in (8-a). We can notice that the dynamic response of the active power and reactive power under ASMC control is fast and have smooth control signals.

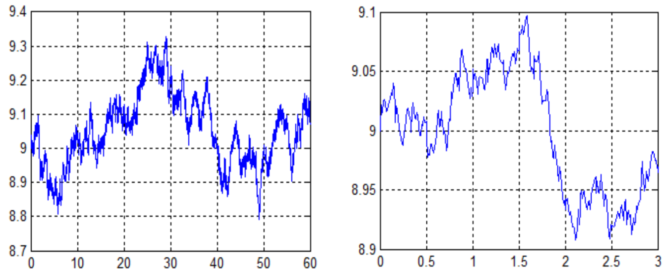


Figure 3. Wind speed

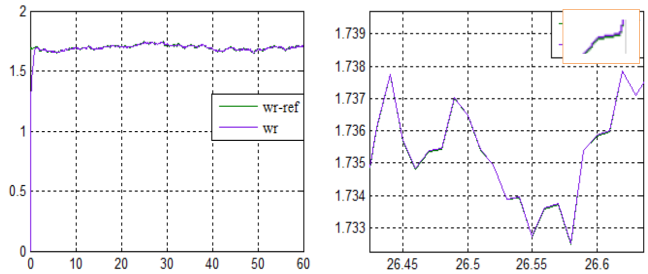


Figure 4. Rotational speed ωr

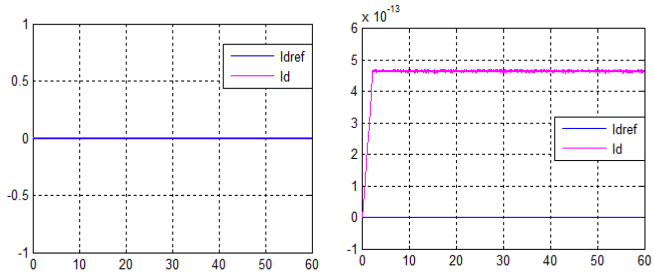


Figure 5. Direct current Id

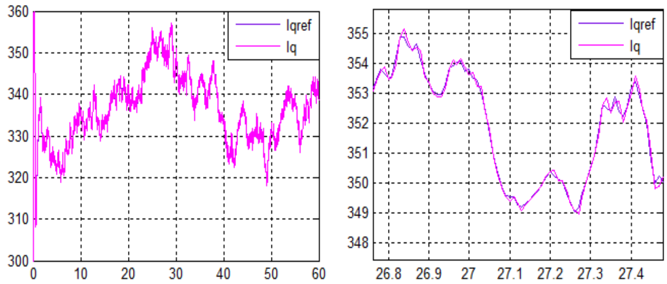
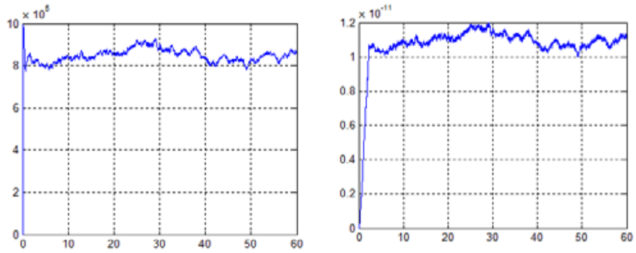
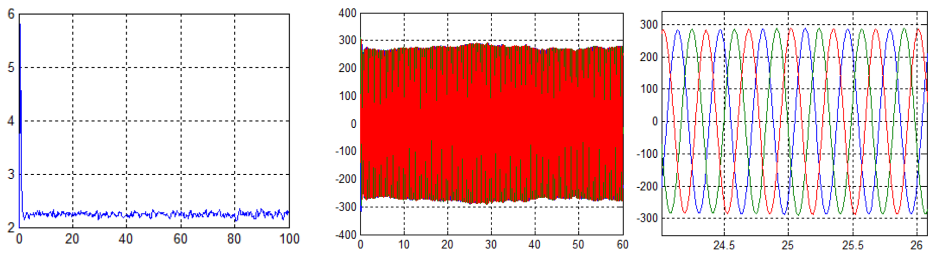


Figure 6. Quadrature current Iq



(a) (b)

Figure 7. a-Active power b-Reactive power



(a) (b)

Figure 8. a-Pitch angle b-Stator courant

7. CONCLUSION

This paper was devoted to modelling, control and simulation of a wind turbine used the PMSG running at variable speed, A pitch angle controller has been added to regulate the electric power, it allows to lower the excess power and keep it constant to ensure the continuity of the production of electrical energy, simulation results indicate that the ASMC provides a notable efficiency, since it permits to track the optimum power quickly despite the speed wind changing, external disturbances and the parametric variations. On the other hand, the stator power quantities provided show smooth waveforms, with good tracking indices. Consequently, undesirable mechanical stresses and the chattering in the case of SMC are avoided.

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