ROTOR SPEED CONTROL FOR THE PMSG WIND TURBINE SYSTEM USING DYNAMIC SURFACE CONTROL ALGORITHM

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Abstract: *This paper focuses on the design a controller for PMSG Wind turbine system bases on dynamic surface control (DSC). DSC is a new technique based on sliding mode control and backstepping which provides the ability to solve problems in backstepping controllers and avoids their drawbacks. The stability of the system is proved by using Lyapunov theory. The proposed controller was simulated in matlab/simulink and results expressed the efficiency of the controller.*

Keywords: Dynamic surface control; DSC; PMSG; Wind turbine; Backstepping.

I. INTRODUCTION

The wind is a free, clean, and inexhaustible type of energy, thus nowadays the wind turbine systems are widely used in many countries. The wind turbines convert the kinetic energy inside the wind turbine into mechanical power, which may be used for a generator can convert this mechanical power into electricity energy. Wind turbines exactly like the aircraft propeller blades and they can be classified as asynchronous or synchronous depending on rotor of the generator [1]. In the early stage, fixed-speed wind turbines and induction generators were often used in wind farms. However, with large-scale exploration and integration of wind sources, variable speed wind turbine generators, such as permanent magnet synchronous generators (PMSG) are emerging as the preferred technology [2].

Because of these widespread applications, the PMSG wind turbine system has got considerable attention from many researchers. Many different maximum power point tracking (MPPT) control strategies have been developed [3-4]. This control method calculates the optimal rotor rotation speed for varying wind speeds. However, these control strategies may not provide satisfactory performances due to the system nonlinearity of the PMSG. To improve the quality of the controller, Sliding Mode Control (SMC) is applied for MPPT in the wind energy conversion system with uncertainties in [5, 6]. In these papers, SMC strategy was applied for controlling electromagnetic torque in MPPT for PMSG system. In [7, 11] the authors applied an adaptive sliding mode control strategy for speed tracking problem, they designed the controller based on SMC, Backstepping Sliding Mode Controller (BSMC) to track the rotor speed for maximum power extraction.

Sliding Mode Control and Backstepping Sliding Mode Controller are considered as the popular techniques in nonlinear system design since the derived system control law and parameters adaptive law are able to make controlled system be global stable and robust. But there are some drawbacks of these algorithms. Sliding mode controller generates undesirable chattering phenomenon. In some specifical circumstances, it may damage actuators or sometimes make the system unstable. Besides, Backstepping technique has huge disadvantages that are an explosion of term and sensitive with disturbance. Specially the complex system, they may reduce the performance of the system. From the aforementioned problems, D. Swaroop et al. proposed DSC algorithm [8]. This method is not only inherited the advantages of both the above mechanisms but also rejected their weaknesses. A low pass filter was added in DSC' design that brought significant effect in

diminishing error in calculating and minimizing the amount of computation. Some researchers applied DSC to control of nonlinear systems [9-10].

In this paper, we propose a controller using DSC technique to adjust the rotation speed of roto tracking desired value from MPPT. By adding the low pass filter in design, calculating control signal is faster because of avoiding complexity arising in the operation. In addition, the stability of the closed-loop system is guaranteed by Lyapunov theory. The paper consists of 6 sections: The model of PMSG Wind turbine will be shown in section 2, section 3 is designing controller using DSC algorithm for this system, the simulation in Matlab/Simulink is in section 4 in order to show response of the system with the new controller, section 5 is conclusion and reference.

II. MODELING OF A PMSG WIND ENERGY CONVERSION SYSTEM

A model of PMSG Wind Energy Conversion is shown in fig.1. The system can be considered as two-part: generator side and electrical grid side. The generator side transforms wind power into mechanical energy through a wind turbine, then creates electrical energy by the PMSG generator. This study focuses on designing controller for generator side by analysing model of wind turbine and PMSG.

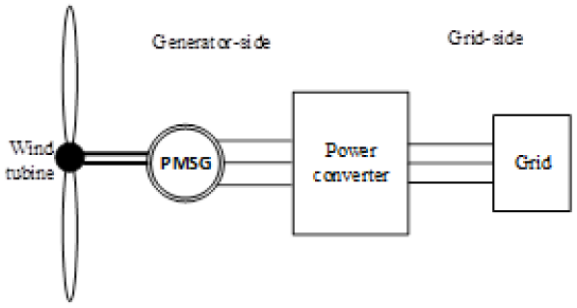


Figure 1. *The PSMG wind turbine system.*

2.1. Modeling of Wind Turbine

The energy and power of wind in considered environment can be expressed by the following equations:

$$E_w = \frac{1}{2}mv^2 = \frac{1}{2}(\rho Avt)v^2 = \frac{1}{2}\rho Atv^3, \quad (1)$$

$$P_w = \frac{E_w}{t} = \frac{1}{2}\rho Av^3 = \frac{1}{2}\rho\pi R^2 v^3. \quad (2)$$

Where:

E_w: The wind' kinetic energy,

P_w: The wind' kinetic power,

ρ : The air destiny,

A: The area that the wind passes through,

v : The velocity of the wind,

R: The radius of the wind turbine.

In actually, the mechanical power generated by turbine is a part of that power and the relation between potential wind and mechanical power coefficient C_p:

$$C_p = \frac{P_m}{P_w} \quad (3)$$

Where P_m is mechanical power generated through wind turbine. Refer to as Betz's limit, the maximum of the output coefficient is 59.26%. Actually, this coefficient is in a range from 25 to 45%, and it can be express as follows [11]:

$$C_p = c_1\left(c_2\frac{1}{\lambda_i} - c_3\beta - c_4\right)e^{-\frac{c_5}{\lambda_i}}, \tag{4}$$

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

Where λ is the tip speed ratio, β is the blade pitch angle, $c_1 = 0.5$, $c_2 = 116$, $c_3 = 0.4$, $c_4 = 5$ and $c_5 = 21$.

From (2) and (3), the output power from the wind turbine is written as:

$$P_m = \frac{1}{2}\rho\pi R^2 C_p v^3 \tag{5}$$

For each wind speed, we have an optimal value of rotor rotation speed to achieve the maximum output power. The algorithm that calculates this optimal speed is called by Maximum Power Point Tracking (MPPT) [4]. When β is maintained as a constant, with optimal value of the generator's rotor rotation speed generated through MPPT, we get an optimal value of output coefficient C_{p-opt} as follows:

$$C_{p-opt} = C_p\left(\lambda_{opt}, \beta\right),$$

$$\lambda_{opt} = \frac{\omega_{m-opt} R}{v}.$$

The output power from wind turbine can be considered as mechanical power and can be expressed through rotation speed and torque as:

$$P_m = T_m \omega_m \tag{6}$$

Where T_m is wind turbine's mechanical torque, and ω_m is the turbine's rotor rotation speed. From equation (5) and (6), we get the formula to calculate mechanical torque as following:

$$T_m = \frac{\rho\pi R^2 C_p v^3}{2\omega_m}$$

2.2. Modeling of PMSG

The PMSG kinetic equation (in dq frame through dq transformation) is shown below [10]:

$$\frac{di_d}{dt} = -\frac{R}{L}i_d + P\omega_m i_q + \frac{1}{L}u_d, \tag{7}$$

$$\frac{di_q}{dt} = -\frac{R}{L}i_q - P\omega_m i_d + \frac{1}{L}P\psi_m\omega_m + \frac{1}{L}u_q. \tag{8}$$

Where:

i_d : The d-axis current,

i_q : The q-axis current,

u_d : The input voltage for the stator's d-axis,

u_q : The input voltage for the stator's q-axis,

R : The resistance,

L : The inductance

ψ_m : The magnetic flux of the PMSG

The dynamic equation of the generator side is:

$$T_m - T_e - F\omega_m = J\frac{d\omega_m}{dt} \tag{9}$$

Where:

F : The viscous friction coefficient,

J : The total inertia,

T_e : The electromagnetic torque, that can be expressed as a product of q-axis current and the magnetic flux of the PMSG as following:

$$T_e = 1.5P\psi_m i_q \tag{10}$$

From equation (9) and (10), we obtain:

$$\frac{d\omega_m}{dt} = \frac{1}{J}\left(T_m - 1.5P\psi_m i_q - F\omega_m\right) \tag{11}$$

From (7), (8) and (11), the whole generator side's model is:

$$\begin{aligned}
\frac{d\omega_m}{dt} &= -\frac{1}{J}1.5P\psi_m i_q - \frac{F}{J}\omega_m + \frac{1}{J}T_m, \\
\frac{di_q}{dt} &= -\frac{R}{L}i_q - P\omega_m i_d + \frac{1}{L}P\psi_m\omega_m + \frac{1}{L}u_q, \\
\frac{di_d}{dt} &= -\frac{R}{L}i_d + P\omega_m i_q + \frac{1}{L}u_d.
\end{aligned} \tag{12}$$

III. CONTROLLER DESIGN

In this section, from the system's model in section 2, a control is proposed base on DSC controller and the stability of closed-loop system is analyzed.

3.1. Dynamic Surface controller

The following example expresses the DSC approach for the nonlinear system:

$$\begin{cases} \dot{x}_1 = x_2 + f(x_1) \\ \dot{x}_2 = u \end{cases}$$

Where the function $f(x)$ is non-Lipschitz nonlinearity and assumed completely known.

Defining the first error valuable:

$$Z_1 = x_1 - x_{1r} \tag{13}$$

Choosing Lyapunov candidate for Z_1:

$$V_1 = \frac{1}{2}Z_1^T Z_1 \tag{14}$$

Differentiating (14) gives:

$$\dot{V}_1 = Z_1^T \dot{Z}_1 = Z_1^T \left(x_2 + f\left(x\right) - \dot{x}_{1r} \right)$$

Choosing $\bar{x}_{2r} = -f\left(x\right) + \dot{x}_{1r} - k_1 Z_1$, where k_1 is a positive gain, thus $V_1 \le 0$ or x_1 will be driven to x_{1r} by x_{2r}.

The Signal $\bar{x}_{2r}$ determined above is a virtual signal. At this step, a low pass filter is added, x_{2r} track to $\bar{x}_{2r}$ through this filter as:

$$\begin{cases} \tau \dot{x}_{2r} + x_{2r} = \bar{x}_{2r} \\ x_{2r}\left(0\right) = \bar{x}_{2r}\left(0\right) \end{cases}$$

The control signal u will drive $x_2 \to x_{2r}$. Defining sliding surface:

$$S_2 = x_2 - x_{2r} \tag{15}$$

Taking time derivative of (15), we obtain:

$$\dot{S}_2 = u - \dot{x}_{2r} \tag{16}$$

From (16), that is easy to choose u so that $S_2 \dot{S}_2 \le 0$.

3.2. Dynamic Surface controller for PMSG Wind turbine system

The algorithm's purpose is keeping rotation speed of turbine's rotor and q-axis current at the desired value. The controller is generated by DSC method presented above. This section focuses specifically on steps to design DSC controller for PMSG Wind turbine system. This following design steps:

Step 1: Defining tracking variables below:

$$Z_\omega = \omega_m - \omega_{mr}, \tag{17}$$

$$Z_q = i_q - \alpha_r, \tag{18}$$

$$Z_d = i_d - i_{dr}. \tag{19}$$

Where ω_{mr} is the reference speedfrom MPPT. The ideal is using virtual control signal α_r generated through backstepping technique in order to $Z_\omega \to 0$. Then, calculating control signals by sliding mode method such that $Z_{q,}\, Z_{\mathrm{d}}$ asymptotically stable.

Step 2: Determining virtual control

Proposing Lyapunov candidate function as:

$$V_\omega = \frac{1}{2} Z_\omega^{\,2} \tag{20}$$

Taking time derivative of (20) gives:

$$\dot{V}_\omega = Z_\omega \dot{Z}_\omega = Z_\omega \left(\dot{\omega}_m - \dot{\omega}_{mr} \right)$$

From (12) and (18), rewrite $\dot{V}_1$ as:

$$\dot{V}_\omega = Z_\omega \left(-\frac{1}{J} 1.5 P \psi_m \left(Z_q + \alpha_r \right) - \frac{F}{J} \omega_m + \frac{1}{J} T_m - \dot{\omega}_{mr} \right) \tag{21}$$

Choose α_r as:

$$\alpha_r = -\frac{1}{1.5P\psi_m}F\omega_m + \frac{1}{1.5P\psi_m}T_m - \frac{J}{1.5P\psi_m}\dot{\omega}_{mr} + \frac{J}{1.5P\psi_m}k_1 Z_\omega \quad (22)$$

Where k_1 is a positive gain. Assuming Z_q will be driven to zero, we obtain:

$$\dot{V}_\omega = -k_1 Z_1^{\,2} \le 0$$

Step 3: Calculating the control signals by slidding mode controller put the final hypothesis.

At this step, control signals u_q and u_d are chosen to drive Z_q and Z_d to zero. From (7) and (8), rewrite the kinetic equation of PMSG as:

$$\dot{\underline{q}} = C\underline{q} + D + M\underline{u} \quad (23)$$

Where:

$\underline{q} = \begin{bmatrix} i_q \\ i_d \end{bmatrix}$ is the current vector,

$\underline{u} = \begin{bmatrix} u_q \\ u_d \end{bmatrix}$ is the control vector,

$C = \begin{bmatrix} -\frac{R}{L} & -P\omega_m \\ P\omega_m & -\frac{R}{L} \end{bmatrix}$, $D = \begin{bmatrix} \frac{P\psi_m\omega_m}{L} \\ 0 \end{bmatrix}$, $M = \begin{bmatrix} \frac{1}{L} & 0 \\ 0 & \frac{1}{L} \end{bmatrix}$

$\underline{q}_r = \begin{bmatrix} \alpha \\ i_{dr} \end{bmatrix}$ is desired value of current vector, where α is signal tracking to α_r through filter $\tau\dot{\alpha} + \alpha = \alpha_r$ with constant time τ is very small and $\alpha(0) = \alpha_r(0)$.

Define sliding surface as:

$$S = \underline{q} - \underline{q}_r \quad (24)$$

Differentiating S gives:

$$\dot{S} = \dot{\underline{q}} - \dot{\underline{q}}_r = C\underline{q} + D + M\underline{u} - \dot{\underline{q}}_r \quad (25)$$

The control signal $\underline{u}$ includes two components: $\underline{u}_{eq}$ will drive sliding surface to zero and $\underline{u}_{sw}$ will keep surface at zero value. So control signal can be rewritten as:

$$\underline{u} = \underline{u}_{eq} + \underline{u}_{sw} \quad (26)$$

From (25), that easy to get $\underline{u}_{eq}$ as:

$$\underline{u}_{eq} = M^{-1}\left(C\underline{q} + D - \dot{\underline{q}}_r\right) \quad (27)$$

In order to make $S \to 0$, we need signal $\underline{u}_{sw}$ so that $S\dot{S} < 0$. So we choose $\underline{u}_{sw}$ as:

$$\underline{u}_{sw} = -M^{-1}k_2 \text{sign}(S) \quad (28)$$

Where k_2 is a positive gain. From these above equations, we obtain control signal that guarantees $Z_q \to 0$ and $Z_d \to 0$ as following:

$$\underline{u} = M^{-1}\left(C\underline{q} + D - \underline{\dot{q}}_r - k_2 \text{sign}(S)\right) \quad (29)$$

The above control formula uses the conventional sliding surface by using signum function, this schedule brings robustly stability for the system under effecting external disturbance. However, the signum function generates phenomenal "chatterring" that will reduce the quality of the system. We propose relacing signum function by satlins function as:

$$y = \text{sat}(x) <=> \begin{cases} y = -1 \text{ if } x \le -1 \\ y = x \text{ if } -1 < x < 1 \\ y = 1 \text{ if } x \ge -1 \end{cases}$$

Satlins function will reduce phenomenal "chattering" and make responses of system more smoothly. The final control signal is :

$$\underline{u} = M^{-1}\left(C\underline{q} + D - \underline{\dot{q}}_r - k_2 \text{sat}(S)\right) \quad (30)$$

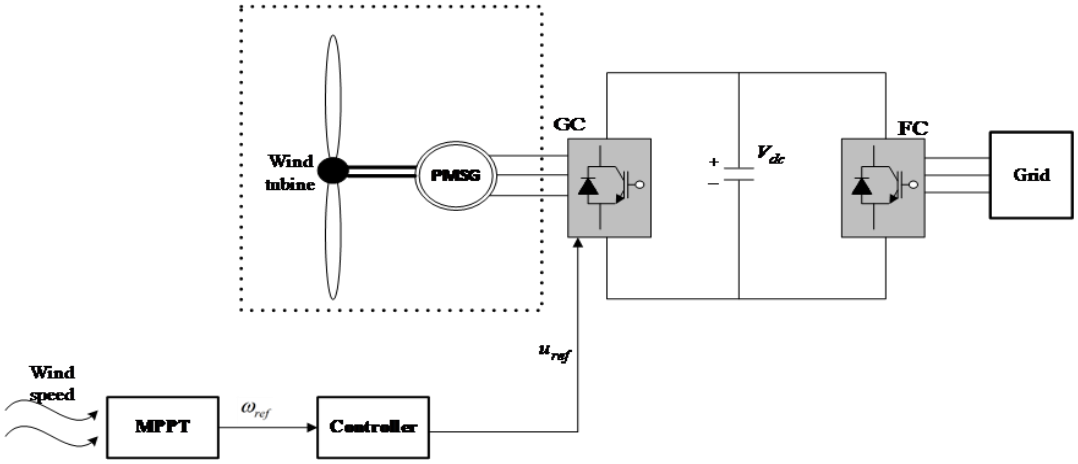


Figure 2. *Structure of control system.*

IV. SIMULATION RESULTS

In this section, the efficiency of the proposed controller is investigated through a numerical simulation, the simulation model of the controller and the wind turbine system are built and calculated in Matlab application. To adequately examine the performance of the proposed controller, the reference rotor speed obtained from MPPT algorithm is suddenly changed from the initial value 70 (rad/s) to the final value 75 (rad/s), that is shown in the fig.3.

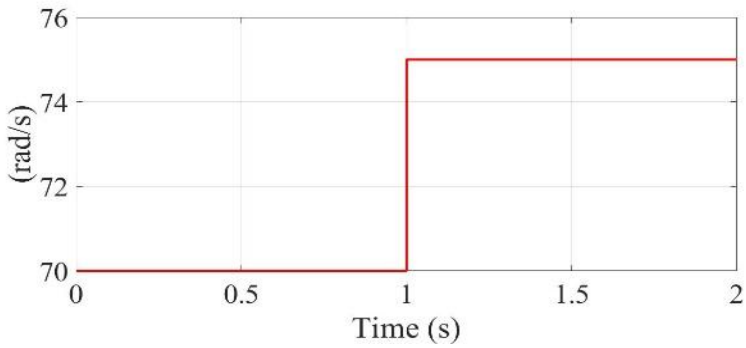


Figure 3. *The reference robot speed.*

The system parameters and the designed controller gains are presented as the following table:

Table 1. *The parameters of the system and the controller.*

The PMSG wind turbine system
R=0.15(Ω) ; L=5.3(mH) ; φ=1.314(wb) J=100(kg.m^2) ; F=10(Nms/rad) ; P=4
Dynamic surface control
$k_1 = 100;\ k_2 = 1000;\ k_3 = 10$

The external disturbance shown in fig.4, which exerts on the input signal to evaluate the robustness of the proposed method. By incorporating the DSC technique, the design procedure of the controller becomes simpler than that result from a traditional backstepping method. In [11], the control law used the integrator backstepping, the derivative of the desired virtual control signal $\dot{i}_{qr}$ would have to appear in $\underline{u}$ that leads to the control signal would be more complex. The differentiation would be sharper for the higher dimension system. In the following figures, we compare the performance of the DSC controller to that of Backstepping Sliding Mode Controller (BSMC).

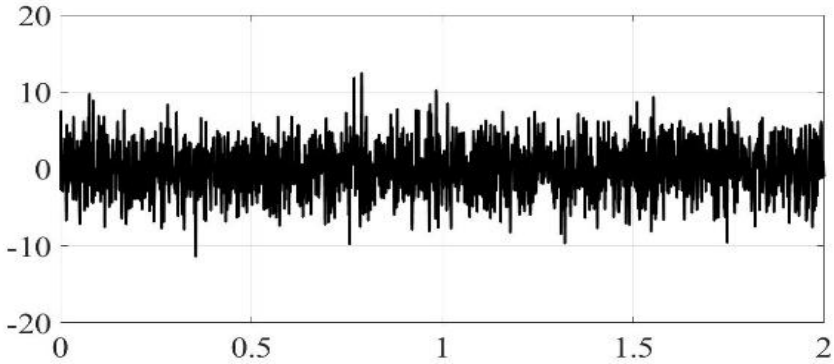


Figure 4. *External disturbance.*

The system responses are presented in figs.5-7:

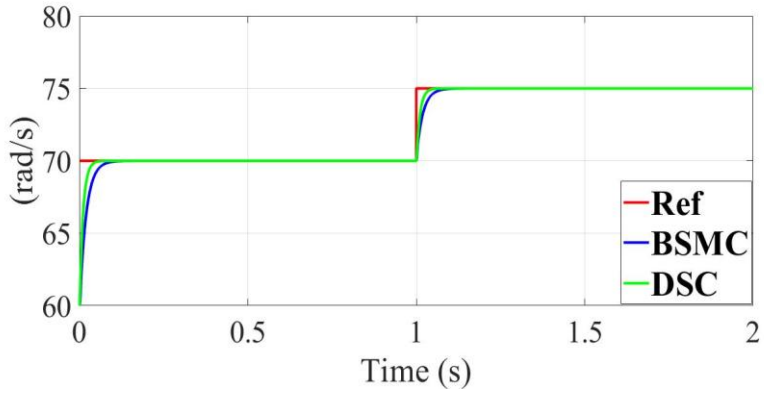


Figure 5. *The rotor speed responses.*

As the simulation results, the displacement of the wind turbine rotor speed and the currents are shown in figs.5-7 respectively. In fig.5, it can be seen that the mechanical velocity of the generator controlled with two presented methods tracks its reference, successfully with converge to the desired value in a short time roughly 0.1s. Both proposed controllers show the good performance of diminishing the vibration at a steady state, in which the DSC law demonstrates the better effectiveness of reducing the settling time of the system in comparison with the BSMC scheme.

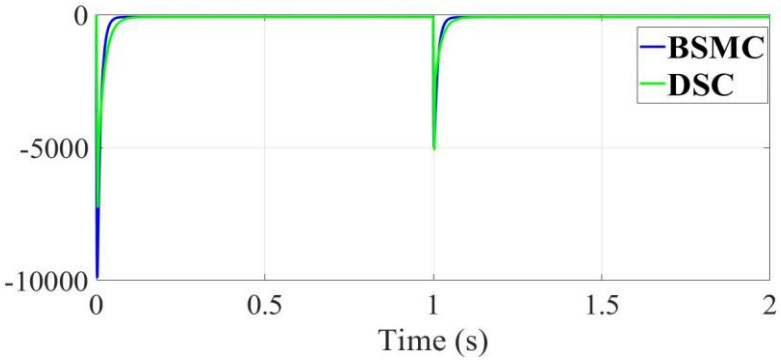


Figure 6. *The q-axis current responses.*

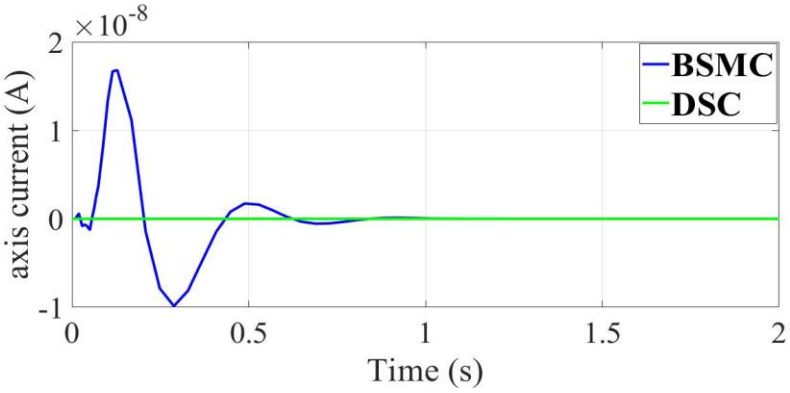


Figure 7. *The d-axis current responses.*

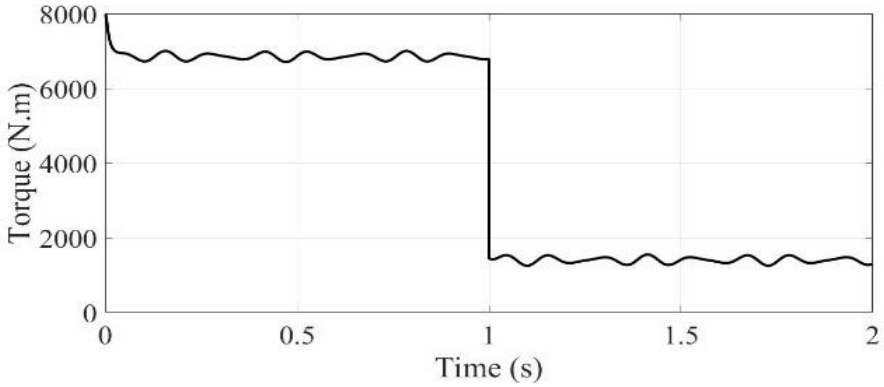


Figure 8. *The torque input with external disturbance.*

The d- and q- axis currents is illustrated in figs.6-7, meanwhile, the q-axis current i_q is chosen as a virtual control signal, these output signals of DSC and BSMC laws are the unremarkable difference and also ensure the performance of the errors system converge to

a neighborhood about 0, meanwhile, the current i_d track the reference value with the tracking errors are approximately 0.

Fig.8 describes the mechanical torque with the impact of the external disturbance.

V. CONCLUSION

This paper has presented the modeling the PMSG wind turbine system and the controller scheme for the system. The controller is designed based on the DSC method, the significant difference of DSC procedure in comparison with the integrator backstepping is the low-pass filter, which reduces the explosion of term. However, both controllers are able to ensure the effectiveness of the system under the effect of the external disturbance, thus the DSC can be recommended for nonlinear systems with high accuracy.

REFERENCES

[1]. P. Kundur, N. J. Balu, and M. G. Lauby, *"Power system stability and control"*. McGraw-hill New York, 1994.

[2]. J. Slootweg and W. Kling, *"Aggregated modeling of wind parks in power system dynamics simulations,"* in 2003 IEEE Bologna Power Tech Conference Proceedings, vol. 3, 2003, p. 6 pp.

[3]. R. Chedid, F. Mrad, and M. Basma, *"Intelligent control of a class of wind energy conversion systems,"* IEEE Transactions on Energy Conversion, vol. 14, no. 4, 1999, pp. 1597-1604.

[4]. A. Z. Mohamed, M. N. Eskander, and F. A. Ghali, *"Fuzzy logic control based maximum power tracking of a wind energy system,"* Renewable energy, vol. 23, no. 2, 2001, pp. 235-245.

[5]. F. Delfino, F. Pampararo, R. Procopio, and M. Rossi, *"A feedback linearization control scheme for the integration of wind energy conversion systems into distribution grids,"* IEEE systems journal, vol. 6, no. 1, 2011, pp. 85-93.

[6]. E. Ghaderi, H. Tohidi, and B. Khosrozadeh, *"Maximum power point tracking in variable speed wind turbine based on permanent magnet synchronous generator using maximum torque sliding mode control strategy,"* Journal of Electronic Science Technology, vol. 15, no. 4, 2017, pp. 391-399.

[7]. A. Merabet, R. Beguenane, J. S. Thongam, and I. Hussein, *"Adaptive sliding mode speed control for wind turbine systems,"* in IECON 2011-37th Annual Conference of the IEEE Industrial Electronics Society, 2011, pp. 2461-2466: IEEE.

[8]. Swaroop, D., et al, *"Dynamic surface control for a class of nonlinear systems,"* IEEE transactions on automatic control, vol. 45, no. 10, 2000, pp. 1893-1899.

[9]. B. Xu, Z. Shi, C. Yang, and F. Sun, *"Composite neural dynamic surface control of a class of uncertain nonlinear systems in strict-feedback form,"* IEEE Transactions on Cybernetics, vol. 44, no. 12, 2014, pp. 2626-2634.

[10]. J. Yu, P. Shi, W. Dong, B. Chen, C. Lin, and l. systems, *"Neural network-based adaptive dynamic surface control for permanent magnet synchronous motors,"* IEEE transactions on neural networks, vol. 26, no. 3, 2014, pp. 640-645.

[11]. Y. Errami, A. Obbadi, S. Sahnoun, M. Benhmida, M. Ouassaid, and M. Maaroufi, *"Design of a nonlinear backstepping control strategy of grid interconnected wind power system based PMSG,"* in AIP Conference Proceedings, 2016, vol. 1758, no. 1, p. 030053: AIP Publishing.

TÓM TẮT

THIẾT KẾ BỘ ĐIỀU KHIỂN BÁM TỐC ĐỘ CHO HỆ THỐNG TUA BIN GIÓ PMSG SỬ DỤNG THUẬT TOÁN DYNAMIC SURFACE CONTROL

Bài báo đề xuất thiết kế một bộ điều khiển dựa trên Dynamic Surface Control (DSC) cho hệ thống tua bin gió PMSG bám tốc độ đã đặt trước. Bộ điều khiển DSC được xây dựng dựa trên bộ điều khiển trượt và kĩ thuật backstepping, tính ổn định của hệ thống được chứng minh dựa vào tiêu chuẩn ổn định Lyapunov. Các kết quả mô phỏng khẳng định tính đúng đắn của bộ điều khiển được đề xuất, với các kết quả đạt được mở ra khả năng ứng dụng của bộ điều khiển trong thực tế.

Keywords: Thuật toán Dynamic surface control; DSC; PMSG; Tua bin gió; Kỹ thuật backstepping.

Nhận bài ngày 02 tháng 01 năm 2020
Hoàn thiện ngày 08 tháng 7 năm 2020
Chấp nhận đăng ngày 03 tháng 8 năm 2020

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