Chaos Control of Permanent Magnet Synchronous Generator via Sliding Mode Controller

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ABSTRACT:
In this paper a sliding mode control method by using state feedback on a permanent magnet synchronous generator (PMSG) is proposed. This system by Lyapunov exponents known as a chaotic system with unstable equilibrium points. Stability of this system using the proposed controller is proved by Lyapunov theory. Finally, the simulation results have shown that the mentioned controller converge chaotic system to zero. In addition, the controller is capable of tracking any desired point.

KEYWORDS: Chaos, Synchronous Motor, Sliding Mode.

1. INTRODUCTION

Wind power is one of the best replacement for nonrenewable energies which their source is about to finish. Now, the most important method in case of tracking the maximum power can be classified into three parts, optimal tip speed ratio method, hill climbing method and power curve control method. In [1], precise analysis of these methods is described. Briefly, the differences between these three methods can be expressed as follows, the measurement of wind speed and maximum power tracking techniques. The important challenge in the mentioned system is the leading measurement of wind turbine speed. In comparison with the fixed-speed types, the variable-speed wind turbine (VSWT) systems have a wide operation speed range somehow that provide 10%-15% higher energy capture from the wind turbine (WT) [12]. PMSG is one of the most important parts in the wind turbine, in order to achieve maximum power angular velocity must be controlled. So in this article PMSG control in wind turbines is the main subject which is discussed.

In recent years, the study of chaos in nonlinear systems has become popular for researchers. In 1963 Edward Lorenz found the first chaotic attractor in a three dimensional autonomous system while studying atmospheric convection [4], the most important feature is sensitivity to initial conditions [5]. Another important feature in chaotic dynamical system is the limited phase portrait [6]. Chaos in nonlinear systems is detectable by the Lyapunov exponent, which should be positive. The dynamical system will be hyperchaotic if the nonlinear differential equation has at least two positive Lyapunov exponents [7, 8]. Some application of chaotic systems is described in [9, 10]. In [1], a new ADHDP method based on Cloud RBF neural network is proposed to track the point of maximum wind power; in this method, the stability period is long. In [11] the predictive control method is introduced, which in this method overshoot is high. In some of these methods, the synchronous generator is considered as a nonlinear system [2, 3], however, there is a chaotic behavior in the model of permanent magnet synchronous generator. This paper is organized as follows: in section 2, analysis of the mathematical model of the PMSG and equilibrium points is performed. In section 3, a sliding mode controller is designed. Numerical simulations are given in section 4 to illustrate the performance of proposed method. Finally, conclusions are presented in section 5.

2. ANALYSIS MODEL OF THE PMSG

This section consists of two sub-sections for investigating the mathematical model of the chaotic synchronous generator, and analytical consideration of system stability and equilibrium point.

2.1. Mathematical Model and Behavior

The principle of maximum wind power tracking is expressed in [11]. Therefore, we will refer only to the original equation. By considering air gap PMSG and $L_q = L_d = L$, will have:

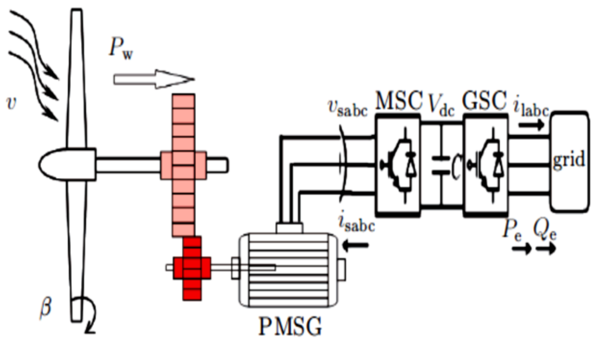

Fig.1. Scheme of a PMSG.

$$\begin{cases} \dfrac{d\omega}{dt'} = \dfrac{p}{J}(\varphi_f i_q + (L_d - L_q) i_d i_q) - \dfrac{f}{J}\omega - \dfrac{T_1}{J} \\ \dfrac{di_q}{dt'} = -\dfrac{R_s}{L_q} i_q + \dfrac{L_d}{L_q} p\omega i_d - \dfrac{p\varphi_f \omega}{L_q} + \dfrac{u_q}{L_q} \\ \dfrac{di_d}{dt'} = -\dfrac{R_s}{L_d} i_d + \dfrac{L_q}{L_d} p\omega i_q \dfrac{u_d}{L_d} \end{cases} \quad (1)$$

where u_q and u_d are the quadrature and direct axis stator control voltages, i_q and i_d are the quadrature and direct axis stator currents, L_q and L_d are the quadrature and direct axis stator inductance, p is the number of poles pairs, R_S is the stator resistance, φ_f is the rotor magnet flux linking the stator, T_L is the load torque, J is the rotor moment of inertia, f is the viscous friction coefficient, and t' is the time. A normalized model of PMSG system is derived from time scale transformation and linear affine transformation by Han Ho at el [13] that is $\tilde{t} = \dfrac{1}{\tau} t$. So,

$$\begin{cases} \dfrac{d\tilde{\omega}}{dt} = \sigma(\tilde{i}_q - \tilde{\omega}) + \varepsilon \tilde{i}_d \tilde{i}_q - \tilde{T} \\ \dfrac{d\tilde{i}_q}{dt} = -\tilde{i}_q + \tilde{\omega}\tilde{i}_d + \gamma\tilde{\omega} + \tilde{u}_q \\ \dfrac{d\tilde{i}_d}{dt} = -\tilde{i}_d + \tilde{\omega}\tilde{i}_q + \tilde{u}_d \end{cases} \quad (2)$$

Where $\varepsilon = \dfrac{pbL_d^2 k^2 (\mathrm{L}_q - \mathrm{L}_d)}{JR_s^2}$, $\gamma = \dfrac{\varphi_f}{k\,\mathrm{L}_q}$,

$\sigma = \dfrac{fL_q}{R_s J}$, $\mathrm{t} = \dfrac{R_s}{L_q} t'$, and $b = \dfrac{L_q}{L_d}$, $k = \dfrac{fR}{pL_q \varphi_f}$

$\tilde{i}_d = \dfrac{L_d p \varphi_f}{fR_s} i_d$, $\tilde{T} = \dfrac{L_q^2}{JR_s^2} T_1$ and $\tilde{i}_q = \dfrac{L_q p \varphi_f}{fR_s} i_q$,

$\tilde{\omega} = \dfrac{L_q}{R_s}\omega$, $\tilde{u}_d = \dfrac{1}{R_s k} u_d$, $\tilde{u}_q = \dfrac{1}{R_s k} \tilde{u}_q$.

The behavior of PMSG state variables with initial conditions $[\tilde{\omega}_0 \quad \tilde{i}_{q0} \quad \tilde{i}_{d0}]^T = [5 \quad 5 \quad 5]^T$ and fixed parameters values $\varepsilon = 0.21$, $\gamma = 20$, $\sigma = 5.45$ and $\tilde{T} = 0, \tilde{u}_d = 0, \tilde{u}_q = 0$ are shown in Fig.2. as can be seen, PMSG has a comprehensive not locally stability. Fig.3 shows the phase space of PMSG. Also, Fig .4 shows Lyapunov exponent over time. It can be seen that there is always a positive Lyapunov exponent. Therefore, we conclude that a permanent magnet synchronous generator with its parameters will be chaotic.

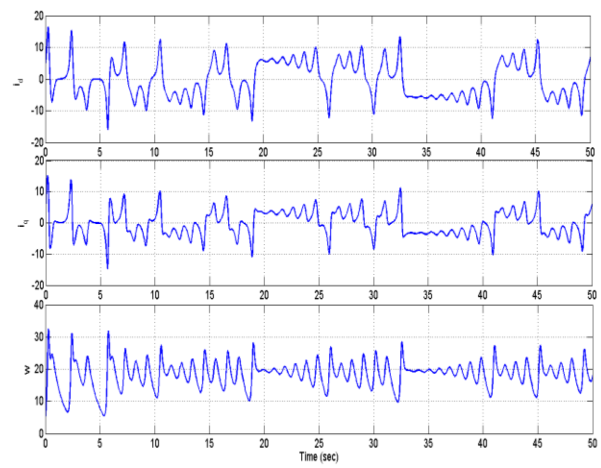

Fig.2. State variable of the PMSG chaotic at the time.

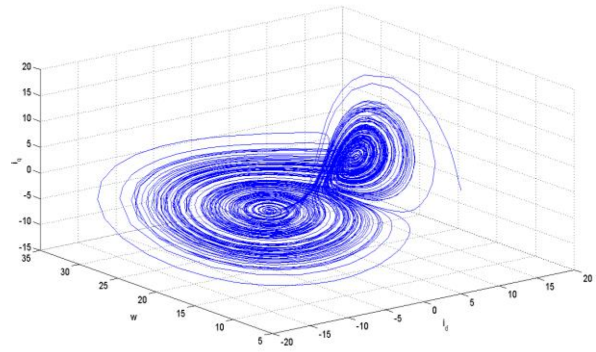

Fig.3. Phase space on the PMSG chaotic.

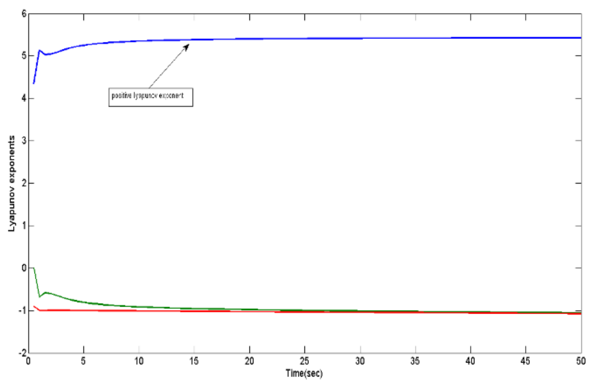

Fig.4. Lyapunov exponent PMSG.

2.2. Equilibrium Points and Stability

In order to obtain the system equilibrium points, derivatives in equation (2) needs to be considered with zero value, thus

$$\begin{cases} \sigma(\tilde{i}_q - \tilde{\omega}) + \varepsilon \tilde{i}_q \tilde{i}_d - \tilde{T} = 0 \\ -\tilde{i}_q + \tilde{\omega}\tilde{i}_d + \gamma\tilde{\omega} + \tilde{u}_q = 0 \\ -\tilde{i}_d + \tilde{\omega}\tilde{i}_q + \tilde{u}_d = 0 \end{cases}$$

(3)

Obviously, an equilibrium point of this system is zero $[\tilde{\omega}_{eq} \quad \tilde{i}_{qeq} \quad \tilde{i}_{deq}]^T = [0 \quad 0 \quad 0]^T$. The Jacobian matrix can be obtained as follows.

$$Jac = \begin{bmatrix} -1 & \tilde{\omega} & \tilde{i}_q \\ -\tilde{\omega} & -1 & \tilde{i}_d + \gamma \\ 0 & \tilde{\omega} & \tilde{i}_q \end{bmatrix}_{|\tilde{\omega} = \tilde{i}_q = \tilde{i}_d = 0} \tag{4}$$

Finally, the linear matrix is obtained as follows by replacing equilibrium points in the equation.

$$Jac = \begin{bmatrix} 5.45 & -5.45 & 0 \\ 20 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix},$$

By calculating eigenvalues of the Jacobian matrix, we have eigenvalues $[-13.89 \quad 7.44 \quad -1]$. So we can see that the system has unstable equilibrium points.

3. DESIGN OF SLIDING MODE CONTROLLER

In this section designing procedure of the proposed controller is described. Sliding mode control technique is an efficient method for nonlinear systems. The sliding mode controller design involves two steps: First, select the proper sliding surface and then obtaining control law .Finally, stability of the system with the proposed controller is proved by use of candidate Lyapunov function. By control in here means controlling the behavior of the system state variables, where, the mathematical function is added to differential equations to converge it to the desired behavior. Therefore, equation (2) must be rewritten in the form:

$$\begin{cases} \dfrac{d\tilde{\omega}}{dt} = \sigma(\tilde{i}_q - \tilde{\omega}) + \varepsilon \tilde{i}_d \tilde{i}_q + u_1 \\ \dfrac{d\tilde{i}_q}{dt} = -\tilde{i}_q + \tilde{\omega}\tilde{i}_d + \gamma\tilde{\omega} + u_2 \\ \dfrac{d\tilde{i}_d}{dt} = -\tilde{i}_d + \tilde{\omega}\tilde{i}_q + u_3 \end{cases} \tag{5}$$

Where, u_1, u_2, u_3 are mathematical function or control inputs. By considering error vectors such as:

$$e_i = x_i - x_i^*, \qquad i = 1,2,3 \tag{6}$$

Where, $x_i, x_i^* (i = 1,2,3)$ are state variables of the chaotic system and set points, respectively. In other words $\lim_{t \to \infty} |e_i(t)| = 0, \quad i = 1,2,3$. By deriving from Eq. (6),

$$\dot{e}_i = \dot{x}_i - \dot{x}_i^*, \qquad i = 1,2,3 \tag{7}$$

And tracking the constant desired x_i^* in PMSG we have $\dot{x}_i^* = 0$. By determining of the sliding surface as follow:

$$s_i = c_i e_i + \int_0^t d_i e_i(\tau)\,\mathrm{d}\tau, \qquad i = 1,2,3 \tag{8}$$

Where $c_i, d_i (i = 1,2,3) \in \mathrm{R}$ are constant. Sliding mode control law can be obtained from:

$$s_i = c_i e_i(t) + \int_0^t d_i e_i(\tau)\,\mathrm{d}\tau, = 0 \quad i = 1,2,3 \tag{9}$$

$$\dot{s}_i = c_i \dot{e}_i(t) + d_i e_i(t) = 0 \quad i = 1,2,3 \tag{10}$$

Theorem 1. By solving the equation (10), the control law is given:

$$\begin{aligned} u_1 &= -\sigma(\tilde{i}_q - \tilde{\omega}) - \varepsilon \tilde{i}_d \tilde{i}_d - \frac{d_1}{c_1} e_1 + \lambda_1 \frac{s_1}{|s_1 + \mu_1|} \\ u_2 &= +\tilde{i}_q - \tilde{\omega}\tilde{i}_d - \gamma\tilde{\omega} - \frac{d_2}{c_2} e_2 + \lambda_2 \frac{s_2}{|s_2 + \mu_2|} \\ u_3 &= \tilde{i}_d - \tilde{\omega}\tilde{i}_q - \frac{d_3}{c_3} e_3 + \lambda_3 \frac{s_3}{|s_3 + \mu_3|} \end{aligned} \tag{11}$$

Proof. The proof is carried out using the Lyapunov stability theory. To establish the sliding mode dynamics (6) using Lyapunov theory [14] considering the positive definite Lyapunov candidate function as;

$$V = \frac{1}{2}(s_1^2 + s_2^2 + s_3^2) \tag{12}$$

The continuous first partial derivative of (9), and law controller (8),

$$\begin{aligned} \dot{V} &= s_1\dot{s}_1 + s_2\dot{s}_2 + s_3\dot{s}_3 \\ &= s_1(\sigma(\tilde{i}_q - \tilde{\omega}) + \varepsilon \tilde{i}_d \tilde{i}_q + u_1) \\ &\quad + s_2(-\tilde{i}_q + \tilde{\omega}\tilde{i}_d + \gamma\tilde{\omega} + u_2) \\ &\quad + s_3(-\tilde{i}_d + \tilde{\omega}\tilde{i}_q + u_3) \end{aligned} \tag{13}$$

By substituting the controller Eq.11 into Eq. 13 will be:

$$\dot{V} = \lambda_1 s_1^2 + \lambda_2 s_2^2 + \lambda_3 s_3^2 \tag{14}$$

Where, $\dot{V} < 0$ if $c_i, d_i (i = 1,2,3) > 0$ and $\lambda_i (i = 1,2,3) < 0$.

4. NUMERICAL SIMULATION

In this section, MATLAB software is used for simulation. By solving the differential equation (10), under the proposed controller (11), numerical simulation results can be determined. The initial values of chaotic PMSG are set as $\begin{bmatrix}\omega_0 & i_{q0} & i_{d0}\end{bmatrix}^T = \begin{bmatrix}3 & 3 & 3\end{bmatrix}^T$, and the proposed controller parameters are set as $c_i = d_i = 1, (i = 1,2,3)$, $\lambda_i = -0.8 (i = 1,2,3)$, and $\mu_i = 0.01 (i = 1,2,3)$. The numerical response simulation results are depicted in Fig. 5.

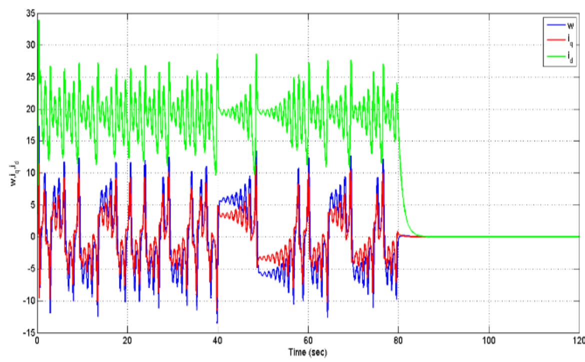

Fig.5. The stable chaotic PMSG.

In Fig.5, the controller is activated in t=80sec. The chaotic PMSG stability has happened in about 5 seconds. Fig. 6 shows stable chaotic PMSG and capability of tracking any desired angular velocity in the generator.

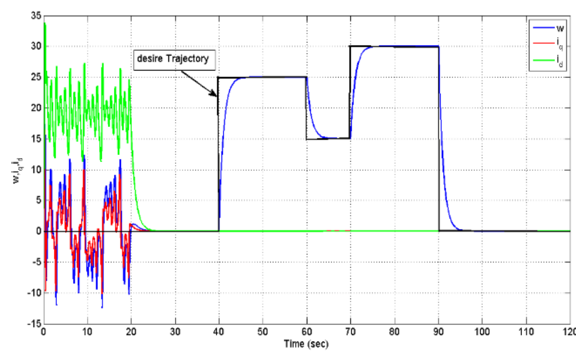

Fig.6. the stability and tracking of chaotic PMSG.

5. CONCLUSION

In this paper the mathematical model of PMSG is described. Chaos in the system model was proved by calculating and determining the Lyapunov exponent.

Model and state variables behavior of PMSG is very similar to the Lorenz system experiment. In this paper, a terminal sliding mode control method is introduced. By selecting a sliding surface which is dependent on system state variables, the controller is designed and proved its stability by Lyapunov theory. Based on simulation results, the speed of convergence in PMSG state variables is controlled with its parameters.

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