SLIDING MODE BASED ADAPTIVE CONTROL OF CHAOS FOR PERMANENT MAGNET SYNCHRONOUS MOTORS

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Abstract - The paper presents the sliding mode based adaptive control (SMAC) of chaos for a permanent magnet synchronous motor (PMSM) subjected to parameter uncertainties and an external disturbance. A PMSM faces the chaos phenomenon when its parameters fall into a certain area. The sliding mode based adaptive control is developed to eliminate chaos and ensure the robust stability even when the system parameters are in the chaotic area and the external disturbance affects system dynamics. Finally, under the control actions, the chaos phenomenon can be driven to zero. The numerical simulation is carried out to demonstrate the perfect performance of the proposed control approach.

Key words - adaptive control; chaos control; chaos phenomenon; permanent magnet synchronous motor; sliding mode control.

Tóm tắt - Bài báo này trình bày kỹ thuật điều khiển thích nghi hỗn loạn dựa vào điều khiển trượt cho động cơ đồng bộ nam châm vĩnh cửu chịu tác động của tham số không chắc chắn và nhiễu loạn bên ngoài. Động cơ đồng bộ này trải qua sự hỗn loạn khi tham số của nó rơi vào một miền chắc chắn nào đó. Thuật toán điều khiển thích nghi được phát triển nhằm loại bỏ những dao động hỗn loạn và đảm bảo tính ổn định bền vững ngay cả khi tham số động cơ rơi vào vùng hỗn loạn và hệ thống chịu tác động của nhiễu loạn ngoài. Cuối cùng, dưới tác động của bộ điều khiển được phát triển, dao động hỗn loạn được lái về zero. Mô phỏng số được thực hiện để minh chứng cho khả năng thực thi tốt của giải pháp điều khiển đã được đề xuất.

Từ khóa - điều khiển thích nghi; điều khiển hỗn loạn; hiện tượng hỗn loạn; động cơ đồng bộ nam châm vịnh cửu; điều khiển trượt.

1. Introduction

Recently, a permanent magnet synchronous motor (PMSM) has become one of the popular motors used in industry applications because of its high performance and high efficiency. However, the PMSM model parameters, such as stator resistance and friction coefficient are difficult to be measured precisely. Moreover, a PMSM system has nonlinear dynamic states and express chaos behavior when system parameters fall into a certain area. The bifurcations and chaos control of the PMSM have been widely studied and discussed with modern nonlinear theory in recent years [1-4]. However, the chaos phenomenon in PMSM driver system is highly unexpected for its applications because it also severely influences the performance of controlled motor.

For the above reasons, to suppress and eliminate the chaos phenomenon of PMSM system is important to the PMSM applications and also widely studied in previous research [3-7]. Up to now, the chaos suppression of PMSM and its speed/position control are still popular study fields in control issues. Therefore, the pioneer researchers proposed many control technologies, such as feedback-control [5], nonlinear feedback [6], time-delay feedback control [7] and sliding mode control [8, 9] to achieve the control goals in earlier works. However, those research denoted the $d-q$ axis stator inductances as the same value to simplify the complexity in study fields, also called smooth-air-gap permanent magnet synchronous motor. Furthermore, the real $d-q$ axis stator inductances in PMSM system are limited to production manufacturers and also infected by environment conditions which will be unequal and are called non-smooth-air-gap permanent magnet synchronous motors. Consequently, the chaos suppression problem is an important issue to realize a real non-smooth-air-gap PMSM system. One of studies that discuss the control problems for a real non-smooth-air-gap PMSM system can be found in [10].

The aim of this paper is to develop sliding mode based adaptive control (SMAC) of chaos suppression for non-smooth-air-gap PMSM system with unknown system parameters. First, the switch surface is proposed to ensure the stability of controlled PMSM in the sliding mode. Consequently, based on the switching surface, the adaptive control is derived to guarantee the occurrence of the sliding motion. Attached to the adaptive scheme, the limitations of known system parameters and the prior unknown disturbance are also released. Moreover, a single controller with adaptive scheme is proposed for reducing the cost and complexity for controller implementation. The proposed method is verified by numerical simulation results, and illustrates its effectiveness explicitly.

This paper is organized as follows. Section 2 describes the mathematical model of a non-smooth-air-gap PMSM and the chaos phenomenon. In Section 3, the SMAC is designed and proven to guarantee the occurrence of the sliding motion on the stable switching surface. In Section 4, the numerical simulation confirms the verification and feasibility of the proposed method. Finally, conclusions are illustrated in Section 5.

2. System Description and Problem Formulation

2.1. Mathematical model of an non-smooth air gap PMSM

The mathematical formation of PMSM system with non-smooth air gap can be illustrated as follows [1-3]:

$$\begin{aligned}
\dot{i}_d(t) &= \frac{-R_1 i_d(t) + L_q i_q(t) w(t) + u_d}{L_d} \\
\dot{i}_q(t) &= \frac{-R_1 i_d(t) + L_d i_d(t) w(t) + \psi_r w(t) u_q}{L_d} \\
\dot{w}(t) &= \frac{n_p \psi_r i_q(t) + n_p (L_d - L_q) i_d(t) i_q(t) - \beta w(t) + T_L}{J}
\end{aligned} \tag{1}$$

where $w(t)$, $i_d(t)$ and $i_q(t)$ are denoted to the state variables of angle speed, direct and quadrature $(d-q)$ axis currents respectively. In reference [11], the state $w(t)$ can be measured directly while the states, $i_d(t)$ and $i_q(t)$, are calculated by the $d-q$ transformation. u_d and u_q are the transformed $d-q$ axis stator voltage components, respectively. J is the polar moment of inertia, and β is the viscous friction coefficient. R_1, L_d and L_q are the stator resistance and stator inductances. T_L is the transformed external load torque. The permanent-magnet flux and the number of pole pairs are represented as ψ_r and n_p. In references [1-3], the external inputs of system (1) are set to zero, i.e. $T_L = u_d = u_q = 0$, we rewrite the dynamic states with the Affine transformation and Time-scaling transformation as follows:

$$\begin{aligned}
\dot{\tilde{i}}_d(t) &= -\tilde{i}_d(t) + \tilde{i}_q(t)\tilde{w}(t) \\
\dot{\tilde{i}}_q(t) &= -\tilde{i}_q(t) - \tilde{i}_d(t)\tilde{w}(t) + \gamma\tilde{w}(t) \\
\dot{\tilde{w}}(t) &= \sigma\left(\tilde{i}_q(t) - \tilde{w}(t)\right) + \varepsilon\tilde{i}_d(t)\tilde{i}_q(t)
\end{aligned} \tag{2}$$

where σ, γ and ε are operating parameters of motor so that $\sigma > 0$, $\gamma > 0$ and $\varepsilon > 0$. $\tilde{w}(t)$, $\tilde{i}_d(t)$ and $\tilde{i}_q(t)$ are state variables which respectively represent the angle speed, direct and quadrature $(d-q)$ axis currents in dimensionless form. After that, the dynamic state in system (2) will be represented by $x = \left[\tilde{i}_d(t) \quad \tilde{i}_q(t) \quad \tilde{w}(t)\right]^T$, and re-defined in the following dynamic equations.

$$\begin{aligned}
\dot{x}_1(t) &= -x_1(t) + x_2(t)x_3(t) \\
\dot{x}_2(t) &= -x_2(t) - x_1(t)x_3(t) + \gamma x_3(t) \\
\dot{x}_3(t) &= \sigma\left(x_2(t) - x_3(t)\right) + \varepsilon x_1(t)x_2(t)
\end{aligned} \tag{3}$$

Figure 1 and Figure 2 show the chaos phenomenon of system (3) in the case: $\sigma = 5.46$; $\gamma = 20$; $\varepsilon = 0.6$, with initial states $x_1(0) = 2$, $x_2(0) = 5$ and $x_3(0) = 3$.

2.2. Problem formulation

Consider the PMSM system shown in (3), the control goal is to suppress the chaotic behavior of system subject to the external disturbance $\rho(t) \in R$. Without loss of generality, the external disturbance is bounded, i.e. $|\rho(t)| < \delta \in R^+$. We have introduced the single control input $u(t) \in R$ in system (3) as follows:

$$\begin{aligned}
\dot{x}_1(t) &= -x_1(t) + x_2(t)x_3(t) \\
\dot{x}_2(t) &= -x_2(t) - x_1(t)x_3(t) + \gamma x_3(t) \\
\dot{x}_3(t) &= \sigma\left(x_2(t) - x_3(t)\right) + \varepsilon x_1(t)x_2(t) + \rho(t) + u(t)
\end{aligned} \tag{4}$$

In this paper, a sliding mode based adaptive controller (SMACer) is designed for resulting states of PMSM with disturbance driven to zero so that the chaos phenomenon can be eliminated. Consequently, there are two major phases to be completed to achieve the control goal for PMSM. First, it has to select an appropriate switching surface for the system (4) so that the motion on the sliding manifold defined in following section can slide to original point. In other words, the system states will be suppressed to zero. Second, it needs to design a SMACer so that the existence of the sliding manifold can be guaranteed.

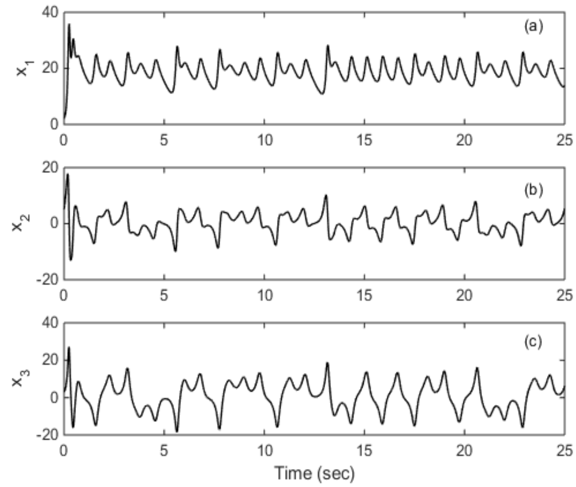

Figure 1. *The dynamic states of PMSM system with non-smooth air gap*

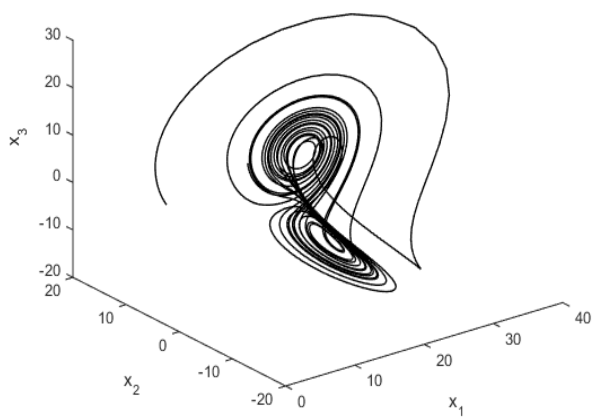

Figure 2. *The chaos attractor of PMSM system with non-smooth air gap*

3. Sliding Mode based Adaptive Control Design

In the following steps, the SMAC method will be illustrated to complete the above major phases. At first, the switching surface is defined as below:

$$s(t) = cx_2(t) + x_3(t) \tag{5}$$

where $s(t) \in R$ and $c > 0$ are design parameters which can be determined easily. It is known that when the system (4) operates in the sliding mode, the equation (5) satisfies the following equation:

$$s(t) = cx_2(t) + x_3(t) = 0 \tag{6}$$

Therefore, by equations (4) and (6), the following sliding mode dynamic can be obtained as

$$\begin{aligned}
x_3(t) &= -cx_2(t) \\
\dot{x}_1(t) &= -x_1(t) + x_2(t)x_3(t) \\
\dot{x}_2(t) &= -x_2(t) - x_1(t)x_3(t) + \gamma x_3(t) \\
\dot{x}_3(t) &= \sigma\left(x_2(t) - x_3(t)\right) + \varepsilon x_1(t)x_2(t) + \rho(t) + u(t)
\end{aligned} \tag{7}$$

A Lyapunov function is defined as follows

$$V(t)=\frac{1}{2}\left(x_1^2(t)+x_2^2(t)\right) \tag{8}$$

The differential equation of (8) can be written directly as below:

$$\begin{aligned}\dot{V}(t)&=x_1(t)\dot{x}_1(t)+x_2(t)\dot{x}_2(t)\\&=-x_1^2(t)-x_2^2(t)+\gamma x_2(t)x_3(t)\end{aligned} \tag{9}$$

By applying $x_3(t)=-cx_2(t)$, we get the following result

$$\dot{V}(t)=-x_1^2(t)-\left(1+c\gamma\right)x_2^2(t)\le 0 \tag{10}$$

From Lyapunov sense, if the design parameter $c>0$ is satisfied, $\dot{V}(t)\le 0$ and the stability of (10) should be guaranteed asymptotically as $\lim_{t\to\infty}V(t)=0$. Therefore, by Eq. (8), $x_1(t)$ and $x_2(t)$ should converge to zero at $t\to\infty$. Moreover, $x_3(t)$ also converges to zero by Eq. (6). Meanwhile, an appropriate switching surface is completely designed. From the above analysis, we find that the unknown system parameters and external disturbance will not affect the stability of the controlled system (7) if $s(t)=cx_2(t)+x_3(t)=0$. In other words, if the controlled system is in the sliding manifold, the state dynamic equations are robust and insensitive to the variation of system parameters and external disturbance. Therefore, to achieve our control goal, the next step is to design an SMAC scheme to drive the system trajectories onto the switching surface $s(t)=0$. To ensure the appearance of the sliding mode, a SMACer is proposed as

$$\begin{aligned}u(t)&=c\left(x_2(t)+x_1(t)x_3(t)\right)+u_a(t);\\u_a(t)&=-\xi\begin{pmatrix}\hat{\gamma}(t)\left|cx_3(t)\right|\\+\hat{\sigma}(t)\left|x_2(t)-x_3(t)\right|\\+\hat{\varepsilon}(t)\left|x_1(t)x_2(t)\right|\\+\hat{\delta}(t)+w\end{pmatrix}sign\left(s(t)\right)\end{aligned} \tag{11}$$

where $w>0$, $\xi>1$, $c>0$. The adaptive laws are

$$\begin{aligned}&\dot{\hat{\gamma}}(t)=\left|cx_3(t)\right|\left|s(t)\right|, && \hat{\gamma}(0)=\hat{\gamma}_0\\&\dot{\hat{\sigma}}(t)=\left|x_2(t)-x_3(t)\right|\left|s(t)\right|, && \hat{\sigma}(0)=\hat{\sigma}_0\\&\dot{\hat{\varepsilon}}(t)=\left|x_1(t)x_2(t)\right|\left|s(t)\right|, && \hat{\varepsilon}(0)=\hat{\varepsilon}_0\\&\dot{\hat{\delta}}(t)=\left|s(t)\right|, && \hat{\delta}(0)=\hat{\delta}_0\end{aligned} \tag{12}$$

where $\hat{\gamma}_0$, $\hat{\sigma}_0$, $\hat{\varepsilon}_0$ and $\hat{\delta}_0$ are the positive and bounded initial values of $\hat{\gamma}(t)$, $\hat{\sigma}(t)$, $\hat{\varepsilon}(t)$ and $\hat{\delta}(t)$, respectively.

Theorem 1. For the controlled system (4), if this system is controlled by controller (11) with adaptive law (12), the system trajectories will converge to the sliding surface so that $s(t)=0$.

Before proving Theorem 1, the Barbalat's lemma should be introduced first as below

Lemma 1. (Barbalat's lemma [12]) If $w:R\to R$ is as uniformly continuous function for $t\ge 0$ and if $\lim_{x\to\infty}\int_0^t w(\lambda)d\lambda$ exists and is finite, then lim $\lim_{x\to\infty}w(t)=0$.

Proof. Let

$$\begin{aligned}\phi_\gamma(t)&=\gamma-\hat{\gamma}(t)\\\phi_\sigma(t)&=\sigma-\hat{\sigma}(t)\\\phi_\varepsilon(t)&=\varepsilon-\hat{\varepsilon}(t)\\\phi_\delta(t)&=\delta-\hat{\delta}(t)\end{aligned} \tag{13}$$

where $\phi_\gamma(t)$, $\phi_\sigma(t)$, $\phi_\varepsilon(t)$, $\phi_\delta(t)\in R$ .It is assumed that γ, σ, ε and δ are unknown positive constants. Thus the following expression holds

$$\begin{aligned}\dot{\phi}_\gamma(t)&=-\dot{\hat{\gamma}}(t)\\\dot{\phi}_\sigma(t)&=-\dot{\hat{\sigma}}(t)\\\dot{\phi}_\varepsilon(t)&=-\dot{\hat{\varepsilon}}(t)\\\dot{\phi}_\delta(t)&=-\dot{\hat{\delta}}(t)\end{aligned} \tag{14}$$

Consider the following Lyapunov function candidate

$$V(t)=\frac{1}{2}\left(s^2(t)+\phi_\sigma^2(t)+\phi_\varepsilon^2(t)+\phi_\gamma^2(t)+\phi_\delta^2(t)\right) \tag{15}$$

Then taking the derivative of $V(t)$ with respect to time will get

$$\begin{aligned}\dot{V}(t)&=s(t)\dot{s}(t)+\phi_\sigma(t)\dot{\phi}_\sigma(t)+\phi_\varepsilon(t)\dot{\phi}_\varepsilon(t)\\&\quad+\phi_\gamma(t)\dot{\phi}_\gamma(t)+\phi_\delta(t)\dot{\phi}_\delta(t)\\&=s(t)\left(c\dot{x}_2(t)+\dot{x}_3(t)\right)+\phi_\sigma(t)\dot{\phi}_\sigma(t)\\&\quad+\phi_\varepsilon(t)\dot{\phi}_\varepsilon(t)+\phi_\gamma(t)\dot{\phi}_\gamma(t)+\phi_\delta(t)\dot{\phi}_\delta\\&=s(t)\begin{pmatrix}\gamma cx_3(t)+\sigma\left(x_2(t)-x_3(t)\right)\\+\varepsilon x_1(t)x_2(t)+\rho(t)+u_a(t)\end{pmatrix}\\&\quad+\phi_\sigma(t)\dot{\phi}_\sigma(t)+\phi_\varepsilon(t)\dot{\phi}_\varepsilon(t)\\&\quad+\phi_\gamma(t)\dot{\phi}_\gamma(t)+\phi_\delta(t)\dot{\phi}_\delta(t)\\&\le\gamma\left|cx_3(t)\right|\left|s(t)\right|+\sigma\left|x_2(t)-x_3(t)\right|\left|s(t)\right|\\&\quad+\varepsilon\left|x_1(t)x_2(t)\right|\left|s(t)\right|+\left|\rho(t)\right|\left|s(t)\right|\\&\quad+\left|u_a(t)\right|\left|s(t)\right|+\phi_\sigma(t)\dot{\phi}_\sigma(t)+\phi_\varepsilon(t)\dot{\phi}_\varepsilon(t)\\&\quad+\phi_\gamma(t)\dot{\phi}_\gamma(t)+\phi_\delta(t)\dot{\phi}_\delta(t)\\&\le-\left(\xi-1\right)\begin{pmatrix}\hat{\gamma}(t)\left|cx_3(t)\right|\\+\hat{\sigma}(t)\left|x_2(t)-x_3(t)\right|\\+\hat{\varepsilon}\left|x_1(t)x_2(t)\right|\\+\hat{\delta}(t)\end{pmatrix}\left|s(t)\right|\\&\quad-\xi w\left|s(t)\right|\end{aligned} \tag{16}$$

Since $\xi>1$, $\hat{\gamma}>0$, $\hat{\sigma}>0$, $\hat{\varepsilon}>0$ and $\hat{\delta}>0$, we obtain the following inequality.

$$\dot{V}(t) \le -(\xi - 1)\begin{pmatrix} \hat{\gamma}(t)\left|cx_3(t)\right| \\ +\hat{\sigma}(t)\left|x_2(t)-x_3(t)\right| \\ +\hat{\varepsilon}\left|x_1(t)x_2(t)\right| \\ +\hat{\delta}(t) \end{pmatrix}\left|s(t)\right| \\ -\xi w\left|s(t)\right| \\ \le -\xi w\left|s(t)\right| \tag{17}$$

Integrating the above equation from zero to t, it yields

$$V(0) \ge V(t) + \int_0^t \xi w\left|s(\tau)\right| d\tau \ge \int_0^t \xi w\left|s(\tau)\right| d\tau \tag{18}$$

Taking the limit as $t \to \infty$ on both sides to eq. (18).

$$\lim_{x\to\infty}\int_0^t \xi w\left|s(\tau)\right| d\tau \le V(0) < \infty \tag{19}$$

Thus according to Barbalat's lemma, we obtain

$$\lim_{x\to\infty} \xi w\left|s(t)\right| = 0 \tag{20}$$

Since $w > 0$, implies $s(t) = 0$ when $t \to \infty$. Hence the proof is achieved completely.

4. Numerical simulation

In this section, the numerical simulation results are presented to demonstrate the effectiveness of the proposed SMAC method. The simulation program are coded and executed with the software of MATLAB. The non-smooth-air-gap PMSM system parameters are organized as follows: $\sigma = 5.46$; $\gamma = 20$; $\varepsilon = 0.6$. The initial states of system (4) are $x_1(0) = 2$, $x_2(0) = 5$ and $x_3(0) = 3$ and the external disturbance is defined as $\rho(t) = 0.3\sin(2t)$.

As the SMAC method in mentioned in Section 3, the proposed design steps are illustrated as follows:

Step 1: According to (5), the design parameter selects $c = 1 > 0$ to result in a stable sliding mode. Therefore the switching surface equation (5) becomes

$$s(t) = x_2(t) + x_3(t) \tag{21}$$

Step 2: From (11), SMACer is obtained as

$$u(t) = c\left(x_2(t) + x_1(t)x_3(t)\right) + u_a(t); \\ u_a(t) = -\zeta\begin{pmatrix} \hat{\gamma}(t)\left|cx_3(t)\right| \\ +\hat{\sigma}(t)\left|x_2(t)-x_3(t)\right| \\ +\hat{\varepsilon}(t)\left|x_1(t)x_2(t)\right| \\ +\hat{\delta}(t)+w \end{pmatrix} sign\left(s(t)\right) \tag{22}$$

where $w = 2 > 0$, $\xi = 2 > 1$. And the adaptive laws are

$$\begin{aligned} \dot{\hat{\gamma}}(t) &= \left|cx_3(t)\right|\left|s(t)\right|, & \hat{\gamma}(0) &= 0.01 \\ \dot{\hat{\sigma}}(t) &= \left|x_2(t)-x_3(t)\right|\left|s(t)\right|, & \hat{\sigma}(0) &= 0.01 \\ \dot{\hat{\varepsilon}}(t) &= \left|x_1(t)x_2(t)\right|\left|s(t)\right|, & \hat{\varepsilon}(0) &= 0.01 \\ \dot{\hat{\delta}}(t) &= \left|s(t)\right|, & \hat{\delta}(0) &= 0.01 \end{aligned} \tag{23}$$

According to the designed SMAC (14) with the adaptive laws (15), the simulation results in Figure 3 show the corresponding $s(t)$ and SMAC controller response. The system response states are shown in Figure 4. Figure 5 shows the adaptation parameters. From the simulations, the SMAC response state converges to $s(t) = 0$ and the PMSM system responses also converge to zero. Thus the proposed SMAC works effectively and the non-smooth-air-gap PMSM system with initial states factually suppresses the chaos phenomenon when the system's parameters and external disturbance are fully unknown.

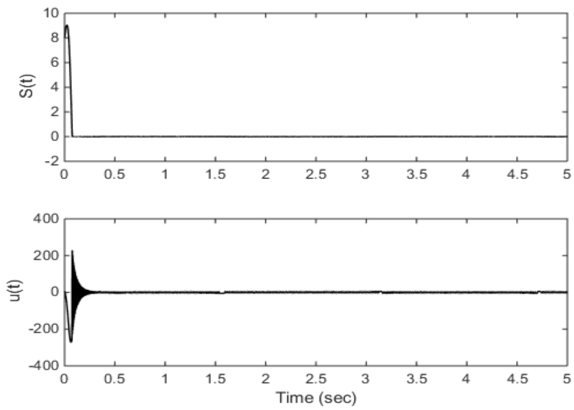

Figure 3. *Time responses of* $s(t)$ *and* $u(t)$

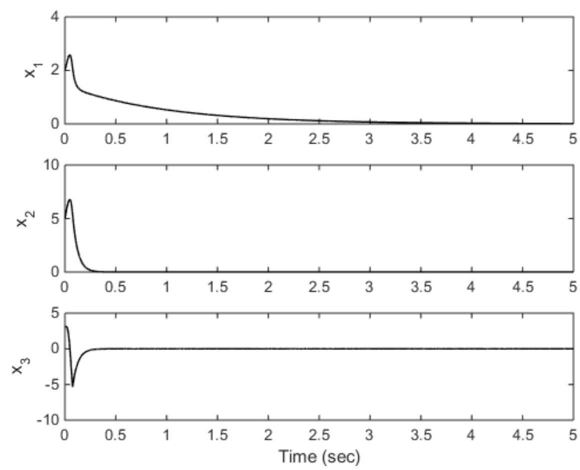

Figure 4. *System response states for the controlled PMSM system*

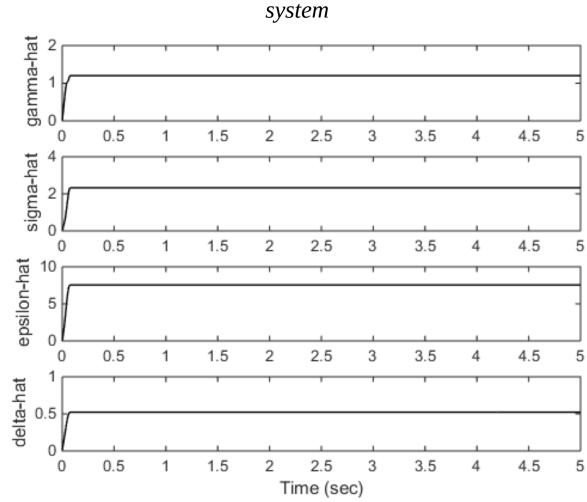

Figure 5. *Time responses for the adaptation parameters*

5. Conclusions

In this paper, an adaptive control scheme is proposed for non-smooth-air-gap PMSM system with unknown parameters and external disturbance. A robust adaptive sliding mode controller has been proposed to eliminate the chaos phenomenon of PMSM system. Numerical simulations are illustrated, and verify the validity of the proposed method.

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