Control of chaos in the smooth-air-gap permanent magnet synchronous motor with sliding mode control

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Abstract: In this paper has investigated the chaos control scheme of Permanent Magnet Synchronous Motor using Sliding Mode Control (SMC) method. In order to make control of chaos in permanent magnet synchronous motor system, its smooth air-gap model is examined. Sliding Mode Control method consists of two sections. To simplify the directive of the stability of the controlled permanent magnet synchronous motor in the sliding mode, firstly adopted a special type of PI switching surface. Secondly the SM Controller is obtained to guarantee the occurrence of the PI switching surface. The effectiveness of the theoretical analysis is evaluated by numerical simulations. Thus, Numerical results show that the proposed method is verify and trustworthy.

Key words: Permanent Magnet Synchronous Motor, Sliding Mode Control, Nonlinear System, Chaos, Chaos Control, Nonlinear System

1. Introduction

Permanent magnet synchronous motors (PMSM) are of great need for industrial applications due to their high speed, high efficiency, high power density and large torque to inertia ratio. The secure and stable operation of the PMSM, which is an essential requirement of industrial automation manufacturing, has received considerable attention because its dynamic model is nonlinear. If chaos should be not suppressed or eliminated by a controller, the performance of Permanent Magnet Synchronous Motor (PMSM) decreases due to chaos. Therefore, chaos should be suppressed or eliminated.

Many researchers are endeavored for find new ways to suppress and control chaos more efficiently. So far many researchers have worked on different control methods to identify, suppress, synchronize and the control of the chaos phenomenon in PMSM [1–8]. For example see; Robust Linear Control, Synchronization and Controlling Chaos, Linear Feedback Anti-control, Nonlinear Feedback Control, Fuzzy Impulsive Control, Direct Adaptive Neural Control, Instantaneous Lyapunov Exponent Control, Controlling via Fuzzy Guaranteed Cost Controller.

In PMSM system, the external inputs (v_d, v_q, TL) are set to zero, then the PMSM system becomes an the unforced system. In fact, this system is equivalent well known Lorenz system by everyone. Usually, researchers have used and controlled this unforced system of PMSM [9-13]. In these control methods, the different types of SMC methods are used by the researchers. For example see; Quasi-Sliding Mode Control [9], nonlinear back-stepping control and sliding mode control [10], a sliding mode variable structure controller for chaotic control [11], T-S Fuzzy Design and Sliding-Mode Control [12], Sliding mode control for PMSM drive system [13].

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Additionally, Bitao Zhang, Youguo Pi is applied sliding mode control to Permanent Magnet Synchronous Motor Servo Drive [14].

Furthermore, chaos and its control has been studied in different electrical machines; for example, induction motor drives [15-18], DC motors and drives [19-24], step motors [25-26], synchronous reluctance motor drives [27], switched reluctance motor drives [28-29].

Sliding mode control method is especially preferred due to its capability to suppress disturbances and dynamic model uncertainties by many researchers [30-35]. Sliding-mode control (SMC) is known as a very effective way to control a system for its advantages, such as insensitivity to parameter variations, external disturbance rejection, and fast dynamic response. Consequently, SMC has been widely used in position and velocity control of dc and ac motor drives.

This paper contributes to the development of the SMC design for smooth air-gap PMSM. This paper is organized as follows. In the Section 2, the mathematical model of a smooth air-gap PMSM is given. SMC for chaos control of smooth air-gap PMSM is designed in Section 3. Some numerical simulations are illustrated to confirm the validity of the proposed method in Section 4. Finally, conclusions are given.

2. Mathematical Model of the Smooth-Air-Gap Permanent Magnet Synchronous Motor (PMSM)

In this section, the mathematical model of PMSM which have a similar the system of equation with the BLDCM is presented. The control of the PMSM has been conducted using similarity of the two systems.

A brushless DC motor is an electromechanical system. The equations of electrical and mechanical dynamics of a BLDCM can be described by Hemati [36] and Ge and Chang [23]. The system equations are transformed to a compact form through a single time-scale transformation. In this way, the equations in compact forms with a greatly reduced number of parameters are obtained as follow (1). For more details on modeling of PMSM and BLDCM may be found in ref. [1-8, 22- 23, and 37].

The dimensionless mathematical model of BLDCM can be described by the following differential equations:

$$\left.\begin{aligned} \dot{x}_1 &= v_q - x_1 - x_2.x_3 + \rho.x_3 \\ \dot{x}_2 &= v_d - \delta.x_2 + x_1.x_3 \\ \dot{x}_3 &= \sigma(x_1 - x_3) + \eta.x_1.x_2 - T_L \end{aligned}\right\} \tag{1}$$

where, vq=0.168, ρ=60, vd =20.66, δ=0.875 η=0.26 TL=0.53 σ =4.55

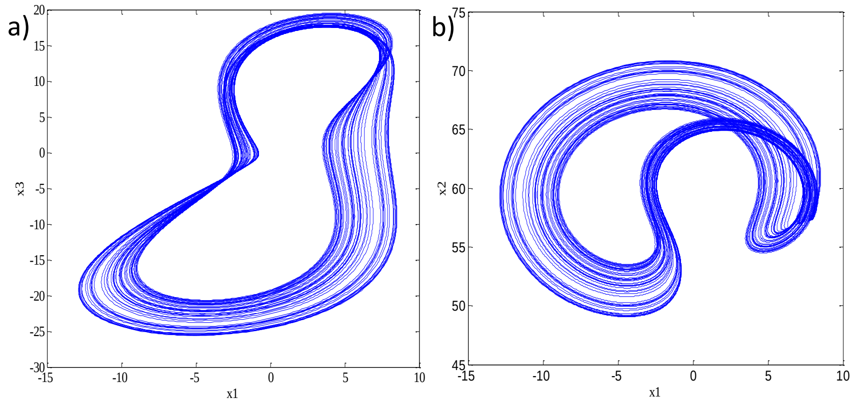

Fig. 1. σ = 4.55 for phase portraits for uncontrolled BLDCM system. a) $x_1 - x_3$, b) $x_2 - x_3$

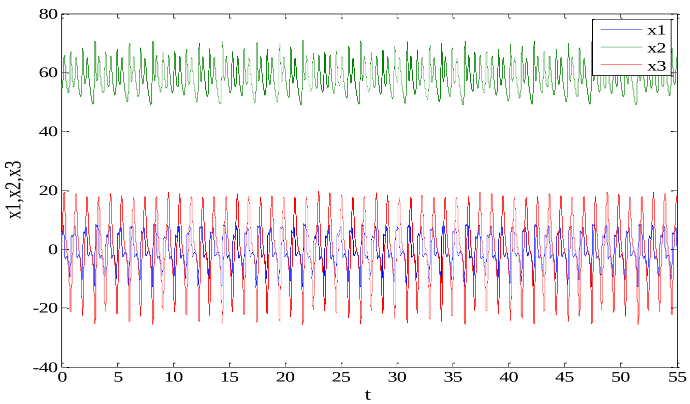

Fig. 2. σ = 4.55 for time series for uncontrolled BLDCM system.

The dynamic model of a PMSM, which is based on the d-q axis, is described as follows (Li et al., [38]).

$$\left.\begin{aligned} \dot{i_q} &= \frac{1}{L_q}\left[v_q - R_1 i_q - w(L_d i_d + \varphi_r)\right] \\ \dot{i_d} &= \frac{1}{L_q}\left[v_d - R_1 i_d - w L_d i_q\right] \\ \dot{w} &= \frac{1}{J}\left[n_p \varphi_r i_q + n_p\left(L_d - L_q\right) i_q i_d - T_L - \beta w\right] \end{aligned}\right\} \quad (2)$$

where $i_{d,} i_q$ and w are state variables denoting currents and motor angular frequency, respectively; v_d and v_q are direct- and quadrature-axis stator voltage components, respectively; J is the polar moment of inertia; T_L is external load torque; β is the viscous damping coefficient; R_1 is stator winding resistance; L_d and L_q are the direct- and quatrature- axis stator inductors, respectively; φ_r is permanent-magnet flux; n_p is the number of pole-pairs.

The transformed model of PMSM can be described as a set of equations in the following in the dimensionless form:

$$\left.\begin{aligned} \frac{d\tilde{\imath}_q}{d\tilde{t}} &= \tilde{v}_q - \tilde{\imath}_q - \tilde{\imath}_d.\tilde{w} + \rho.\tilde{w} \\ \frac{d\tilde{\imath}_d}{dt} &= \tilde{v}_d - \tilde{\imath}_d + \tilde{\imath}_q.\tilde{w} \\ \frac{d\tilde{w}}{d\tilde{t}} &= \sigma\left(\tilde{\imath}_q - \tilde{w}\right) + \eta.\tilde{\imath}_q.\tilde{\imath}_d - \tilde{T}_L \end{aligned}\right\} \tag{3}$$

$$\rho = \frac{n_p\varphi_r^2}{R_1\beta}, \sigma = \frac{L_q\beta}{R_1 J}, \tilde{v}_q = \frac{n_p L_q \varphi_r v_q}{R_1^2\beta}, \ \tilde{v}_d = \frac{n_p L_q \varphi_r v_d}{R_1^2\beta}, \eta = \frac{L_q\beta^2(L_d - L_q)}{n_p L_d J \varphi_r^2}, \tilde{T}_L = \frac{L_q^2 T_L}{R_1^2 J}, n_p = 1$$

For simplicity, the following notations are introduced, $x_1 = \tilde{\imath}_q$, $x_2 = \tilde{\imath}_d$, $x_3 = \tilde{w}$. By using these notations, the dimensionless mathematical model of PMSM can be described by the following differential equations (4). For the simplicity and the equations of PMSM to make different from BLDC motor equations, we here only studied the dynamic characteristics of the smooth-air-gap PMSM (in this model, $L_d = L_q = L$, so $\eta = 0$). Thus, in order to take control of chaos in permanent magnet synchronous motor system, smooth air-gap model of the permanent magnet synchronous motor is obtained as follows.

So, the dimensionless mathematical model of smooth air-gap PMSM as (4) becomes:

$$\left.\begin{aligned} \dot{x}_1 &= \tilde{v}_q - x_1 - x_2.x_3 + \rho.x_3 \\ \dot{x}_2 &= \tilde{v}_d - x_2 + x_1.x_3 \\ \dot{x}_3 &= \sigma(x_1 - x_3) - \tilde{T}_L \end{aligned}\right\} \tag{4}$$

where $\tilde{\imath}_d$ and $\tilde{\imath}_q$ are the transformed direct- and quadrature-axis stator currents respectively: $\tilde{w}$ is transformed angular speed of the motor; $\tilde{v}_d$ and $\tilde{v}_q$ are transformed direct- and quadrature axis stator voltage components, respectively; $\tilde{T}_L$ is the transformed external load torque; σ and ρ are system parameters.

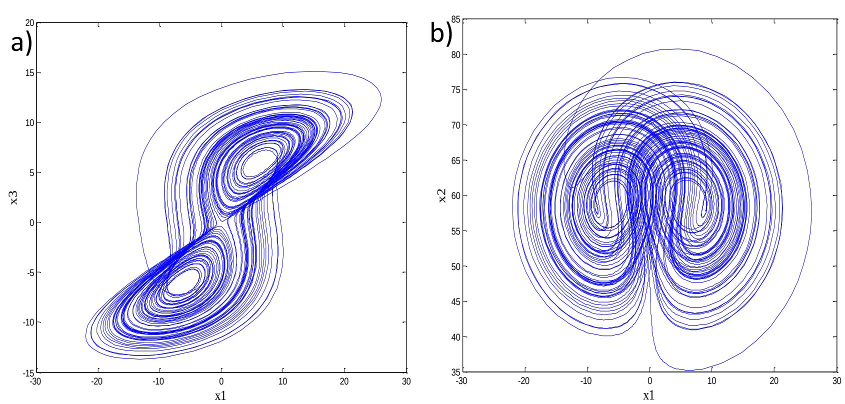

Fig. 3. $\sigma = 4.55$ for phase portraits for uncontrolled PMSM system. a) $x_1 - x_3$, b) $x_2 - x_3$

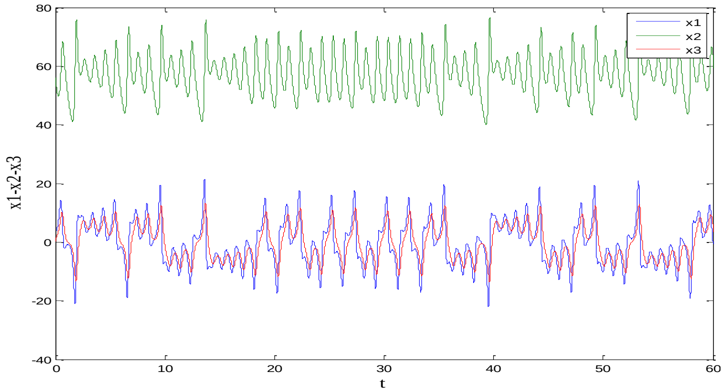

Fig. 4. σ = 4.55 for time series for uncontrolled PMSM system.

3. Sliding Mode Control Design For Chaos Control of in Smooth Air-Gap a PMSM

Suggested smooth air-gap a PMSM chaotic system is described in equation (5). Thus the controlled chaotic system of smooth air-gap a PMSM is attained as follows:

$$\begin{aligned} \dot{x}_1 &= v_q - x_1 - x_2.x_3 + \rho.x_3 + u_1 \\ \dot{x}_2 &= v_d - x_2 + x_1.x_3 + u_2 \\ \dot{x}_3 &= \sigma(x_1 - x_3) - T_L + u_3 \end{aligned} \tag{5}$$

where, $\tilde{v}_q$= 0.168, $\tilde{v}_d$ = 20.66, $\tilde{T}_L$= 0.53, ρ= 60, σ = 4.55, η= 0 (in smooth air-gap: $L_d = L_q = L$), u_1, u_2, u_3 are control signals.

$$e = x\text{-}\ x_d \tag{6}$$

where e =$[e_1\ e_2\ e_3]^T$ is the tracking error vector. The error dynamics may be written as below:

$$\dot{e} = \dot{x}\text{-}\ \dot{x}_d = Ax + Bg + Bu - \dot{x}_d \tag{7}$$

where A is the system matrix, B is the control matrix, and g represents the system nonlinearities plus parametric uncertainties in the system. The control problem is to get the state x= $[x_1\ x_2\ x_3]^T$ to track a specific time varying state x_d= [xd_1 xd_2 xd_3]T in the presence of nonlinearities.

$$A = \begin{bmatrix} -1 & 0 & \rho \\ 0 & -1 & 0 \\ \sigma & 0 & -\sigma \end{bmatrix}; \qquad B = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}; \qquad g = \begin{bmatrix} v_q - x_2.x_3 \\ v_d + x_1.x_3 \\ -T_L \end{bmatrix}$$

Now, a time varying proportional plus integral (PI) sliding surface s (e, t) ∈ R3 is defined by the scalar equation s = s (e, t) as

$$s = Ke - \int_0^t K(A - BL)e(\tau)d\tau \tag{8}$$

where K∈R3x3, which must satisfy det(KB) ≠ 0, is a gain matrix, and L ∈ R3x3, which must have a stable A-BL, is a gain matrix, namely, the eigenvalues λ_i (i=1,2,3) of the matrix A-BL are negative (λ_i |< 0). It is well known that when the system operates in the sliding mode, the sliding surface and its derivative must satisfy s = ṡ = 0 [39, 40]. The equations may be written as below:

$$\dot{s} = KBg + KBLe + KBu + KAx_d - K\dot{x}_d = 0 \tag{9}$$

Since KB is non-singular, the equivalent control in the sliding mode is given by

$$u_{eq}= -[\, \hat{g} + Le\,] - (KB)^{-1}\, [\, KAx_d - K\dot{x}_d\,] \tag{10}$$

where g is not exactly known, but guessed as ĝ, and the estimation error on g is presumed to be restricted by some known function G such that ∥ g - ĝ ∥ ≤ G. In addition, it reveals that the stability of systems in the sliding motion can be guaranteed just by selecting an appropriate matrix L using any pole assignment method. To ensure the achievement of the reaching condition indicated in equation (9), a control law is proposed as:

$$u = u_{eq} - (KB)^{-1}[\varepsilon + \| KBG \|]sign(s) \tag{11}$$

where $\varepsilon > 0$.

4. Numerical Simulations for Chaos Control of in smooth air-gap a PMSM

In this section, the permanent magnet synchronous motor systems with smooth air-gap are controlled to a chaotic orbit by a SM controller. Numerical simulations are applied to confirm the effective and the feasible of the proposed control method.

Equation (5) is rewritten with the numerical values as follows:

$$\left.\begin{aligned} \dot{x}_1 &= 0{,}168 - x_1 - x_2.x_3 + 60.x_3 + u_1 \\ \dot{x}_2 &= 20{,}66 - x_2 + x_1.x_3 + u_2 \\ \dot{x}_3 &= 4{,}55.(x_1 - x_3) - 0{,}53 + u_3 \end{aligned}\right\} \tag{12}$$

where A, B and g matrices are gained as follows:

$$A = \begin{bmatrix} -1 & 0 & 60 \\ 0 & -1 & 0 \\ 4.55 & 0 & -4.55 \end{bmatrix}; \qquad g = \begin{bmatrix} 0.168 - x_2x_3 \\ 20{,}66 + x_1x_3 \\ -0.53 \end{bmatrix}; \qquad B = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Here, the gain matrix K is chosen as K = diag (1, 1, 1) such that KB = diag (1, 1, 1) is nonsingular. The desired eigenvalues of the matrix A-BL are taken as P = [-5 -5.001 -5.0001].

The gain matrix L is found as follows by using the pole placement method:

$$L = \begin{bmatrix} 4 & 0 & 60 \\ 0 & 4{,}1260 & 0 \\ 4{,}55 & 0 & 0{,}451 \end{bmatrix}.$$

As a result, the matrix K(A-BL) is computed as K(A-BL) = diag (-5, -5.001, -5.0001). The PI switching surfaces are obtained as follows:

$$\left.\begin{aligned} s_1 &= e_1 + \int_0^t 5e_1(\tau)d\tau \\ s_2 &= e_2 + \int_0^t 5.001e_2(\tau)d\tau \\ s_3 &= e_3 + \int_0^t 5.0001e_3(\tau)d\tau \end{aligned}\right\} \quad (13)$$

For this numerical simulation, the initial points of the system are employed as $[x_1(0), x_2(0), x_3(0)] = [3.63, 56.02, 0.29]$. The constant controller coefficient ε is selected as ε<1. The reference states xd_1, xd_2, xd_3 are selected as $xd_1 = xd_2 = xd_3 = x_d$. Therefore, the control signals may be attained as:

$$\left.\begin{aligned} u_1 &= [-4e_1 + 60e_3 - 59x_d + \dot{x}_d + x_2x_3 - \mathrm{sign}(s_1)(\varepsilon + |x_2x_3 - 0.168|) - 0.168] \\ u_2 &= [-4.0016e_2 + x_d + \dot{x}_d - x_1x_3 - \mathrm{sign}(s_2)(\varepsilon + |x_1x_3 + 20.66|) - 20.66] \\ u_3 &= [-0.4501e_3 - 4.55e_1 + \dot{x}_d - \mathrm{sign}(s_3)(\varepsilon + |0.53|) + 0.53] \end{aligned}\right\} \quad (14)$$

The reference states are taken as $x_d = 0$, and the state vectors x_1, x_2, and x_3 converge to zero quickly after control signals are activated at the time t=0 as shown in Fig 5. Fig. 5(a) shows state vectors x_1, x_2, x_3, Fig. 5(b) shows control signals u_1, u_2, u_3. The reference states are taken as xd = 1sin(2.4t), and the state vectors x_1, x_2, and x_3 converge to xd quickly after control signals are activated at the time t=0 as shown in Fig 6. Fig. 6(a) shows state vectors x_1, x_2, x_3, Fig. 6(b) shows control signals u_1, u_2, u_3.

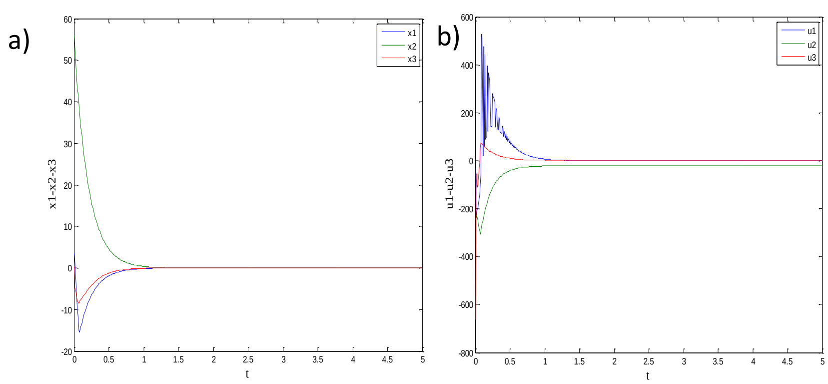

Fig. 5. σ = 4.55 and x_d = 0 for controlled PMSM system with SMC after t=0s,
(a) Time response (b) Applied control signals

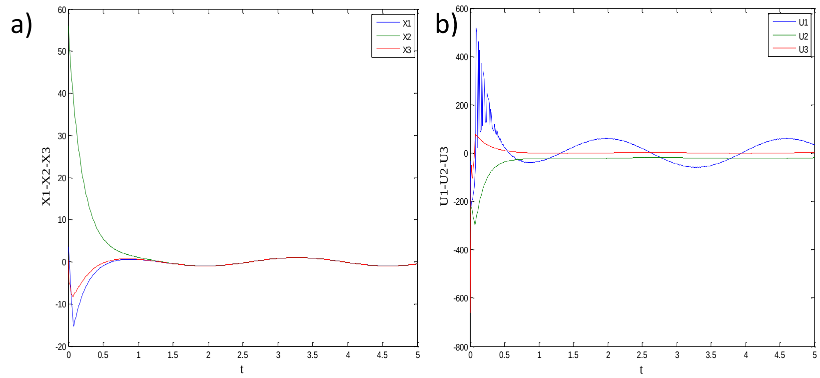

Fig. 6. σ = 4.55 and x_d = sin (2.4t) for controlled BLDCM system with SMC after t=0s,
(a) Time response, (b) Applied control signals

In this section, based on the above analysis, the permanent magnet synchronous motor systems with smooth air-gap are controlled to a chaotic orbit by a SM controller. Numerical simulation shows that the control method is effective and feasible.

5. Conclusions

In this paper, an effective control technique has been suggested to stabilize chaos PMSM chaotic system. A sliding mode control law is applied by using a PI switching surface. So, it is found the stability of the error dynamics in the sliding mode that easily ensured by the PI switching surface. Designed SMC controller is rather satisfactory to a nonlinear controller to eliminate the undesirable chaotic oscillations. Several simulations results are presented. The simulation results indicate that the proposed control scheme works well. The control scheme was able to stabilize the chaotic PMSM around user-defined set-points. In addition, the control was able to induce chaos on the stable PMSM. Related figures in Figs. 5(a) and 6(a) are shown control of states vectors for different references. Figures 5(b) – 6(b) are shown control signals providing the control of states vectors. In this paper, proposed S.M. Controller can be performed in similar D.C Machines. Finally, numerical simulations are provided to show the effectiveness of proposed method. The reaching results are satisfied in view of.

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