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Sensorless Output Tracking Control for Permanent Magnet Synchronous Machine based on T-S Fuzzy Approach

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Abstract

The objective of our work presented in this paper is to control a permanent magnet synchronous machine (PMSM) using fuzzy models of Takagi-Sugeno (TS). the T-S fuzzy output tracking control will be presented. From the stability analysis results, we have some inspiration to deal with the output tracking response, and control input should satisfy constraint of generalized kinematics. Here we assume that all states are measurable. Control gains can be obtained by LMI numerical toolboxes. By the way, the speed tracking control problem for the PMSM using the feedback linearization methodology is introduced.. The simulations are performed under the MATLAB 6.5.

Keywords: fuzzy observer, PMSM, Sensorless, T-S fuzzy model, PDC, LMIs.

Introduction

The DC machines were the most used due to the simplicity of their control. However, these machines have a great problem of reliability and cost is relatively expensive. Recently, it was thought to replace them in many applications for synchronous machines, which have the advantage of being more robust, inexpensive and simple construction [1].

In recent years, thanks to its low operating costs, the scalar control has shown great efficiency [2]. It is to control the torque by controlling the amplitude of stator currents. To do this, the amplitude of the reference phase currents is generated by the proportional-integrator (PI) speed. However, this strategy control suffers from a major handicap. Indeed, its dynamic performance is limited due to the coupling between the flow and the electromagnetic torque. In addition, this method of control offers no way to reduce the flow of excitement generated by the magnet, which limits the speed at rated speed.

To remedy this problem, we have used the vector control [3] [4]. It is an approach control that is developed from the model of Park (d, q). Thus, it is to select and guide the repository (d, q) to linearize the best model of the machine, which makes the behavior of the permanent magnet synchronous machine similar to the DC machine.

Another approach has proven effective for nonlinear systems: The control based on fuzzy logic. Since the work of Lotfi Zadeh [13], fuzzy logic has been very successful not only in the context of modeling systems, but also within the control of complex nonlinear systems. Several applications using fuzzy systems have been developed in several areas of electrical engineering. The fuzzy models of Takagi-Sugeno [14], have the ability to approximate any nonlinear function, but do without the explicit models of the process. The control laws are commonly used for the fuzzy models of Takagi-Sugeno are nonlinear static state feedback called control PDC (Parallel Distributed Compensation) [15].

In this sense, the objective of our work is to control the PMSM via fuzzy models of Takagi-Sugeno, we will discuss the tracking control on T-S fuzzy model. The tracking control problem can be considered as a generalization of stabilization problem. We give the basic structure for output tracking control, whereas all states are temporarily assumed to be measurable.

Basic Fuzzy Tracking Control [16]

Consider a general nonlinear dynamic equation:

$$x(t) = f\big(x(t)\big) + g\big(x(t)\big)u(t) \quad (1)$$
$$y(t) = h\big(x(t)\big)$$
$$\overline{y}(t) = \varphi(x(t))$$

where $x(t) \in R^n$ is the state vector; $y, \overline{y} \in R^m$ are the measured output and controlled output (variables), respectively, $u(t) \in R^m$ is the control input vector; $f(x)$, $g(x)$, $h(x)$ and $g(x)$, and $\varphi(x)$ are nonlinear functions with appropriate dimensions. The measured output and controlled output may often be the same, but not always. The nonlinear system (1) can be expressed by the TS fuzzy system:

Rule i: IF z_1 is F_{1i} and ... and z_g is F_{1g}

THEN $\dot{x}(t) = A_i x(t) + B_i u(t), i = 1..r$

where $z_1 \sim z_g$ are the premise variables which would consist of the states of the system; F_{ji} $(j = 1,2, \dots g)$ are the fuzzy sets; r is the number of fuzzy rules; A_i and B_i are system matrices with appropriate dimensions.

Tracking Control Design

For output tracking control, the control objective is required to satisfy:

$$\overline{y}(t) - r(t) \to 0 \; as \; t \to \infty$$

where $r(t)$ denotes the desired trajectory or reference signal. In order to convert the output tracking problem into a stabilization problem, we introduce a set of virtual desired variables x_d which are to be tracked by the state variables x. According to $\overline{y}(t) = \varphi(x(t))$, it is nature to require $r(t) = \varphi(x_d)$. First we can dene a T-S fuzzy representation of a nonlinear plant model as:

$$\dot{x}(t) = \sum_{i=1}^{r} h_i\big(z(t)\big)\{A_i x(t) + B_i u(t)\} \; (2)$$

Let $\tilde{x}\,(t) = x\,(t) - x_d(t)$ xd(t) denote the tracking error for the state variables. The time derivative of $\tilde{x}\,(t)$ yields:

$$\dot{\tilde{x}}\,(t) = \dot{x}\,(t) - \dot{x_d}(t)$$

$$\dot{\tilde{x}}\,(t) = \sum_{i=1}^{r} h_i\big(z(t)\big)\{A_i x(t) + B_i u(t)\} - \dot{x_d}(t)$$

$$\dot{\tilde{x}}\,(t) = \sum_{i=1}^{r} h_i\big(z(t)\big)A_i x(t) - \sum_{i=1}^{r} h_i\big(z(t)\big)A_i x_d(t) + \sum_{i=1}^{r} h_i\big(z(t)\big)B_i u(t)$$
$$+ \sum_{i=1}^{r} h_i\big(z(t)\big)A_i x_d(t) - \dot{x_d}(t) \; (3)$$

In (3), we assume the latter as follows:

$$\sum_{i=1}^{r} h_i\big(z(t)\big)B_i \tau = +\sum_{i=1}^{r} h_i\big(z(t)\big)A_i x_d(t) \; - \dot{x_d}(t) \; (4)$$

Using (4), then the tracking error system (3) is rewritten below:

$$\dot{\tilde{x}}(t) = \sum_{i=1}^{r} h_i\big(z(t)\big)\{A_i \tilde{x}(t) + B_i \tau(t)\} \; (5)$$

According to the above description, we can nd that the tracking control is similar to the stabilization problem. Then, our control purpose change to make the new state ~ $\tilde{x}(t) = 0$. In this situation, it is the same as the origin state x(t) track to our objective $x_d(t)$. Now a new fuzzy controller $\tau\,(t)$ is designed to deal with the tracking control systems as:

Controller Rule i: if $z_1(t)$ is F_{1i} and ... $z_g(t)$ is F_{gi}
then $\tau\,(t) = -K_i \tilde{x}(t), i = 1,2, \dots, r$

The inferred output of the PDC controller is determined by the summation:

$$\tau\,(t) = -\sum_{i=1}^{r} h_i\big(z(t)\big)\, K_i \tilde{x}(t) \; (6)$$

Using (6) in the tracking error system (5), we obtain the closed-loop system:

$$\dot{\tilde{x}}(t) = \sum_{i=1}^{r}\sum_{j=1}^{r} h_i(z(t))h_j(z(\,t))(\,G_{ij})\tilde{x}(t)\ (7)$$

where $G_{ij} = A_i - B_iK_j$

The exponential stability for system (7) is addressed below.

Stability Analysis
Theorem [17]: The fuzzy system (7) can be stabilized via the PDC controller, if there exists a common positive definite matrix X and M_i ($i\ = 1...r$) such that:

$$-XA_i^T + A_iX - M_i^TB_i^T + B_iM_i > 0, i$$
$$= 1,2 \ldots r\ - XA_i^T - A_iX - XA_j^T - A_jX + M_j^TB_i^T + B_iM_j + M_j^TB_i^T$$
$$+ B_jM_i \geq 0, i <\ (8)$$

Where

$$h_i(z(t))h_j(z(t)) \neq 0, t > 0, P = X^{-1}\text{and } K_i = M_iX^{-1}$$

The stability conditions for output tracking are same as thes tabilization problem. This means that the feedback gains K_i in (6) can be obtainedby directly solving stabilization problem. The main dierence of the control law (6) for output tracking from stabilization problem comes from $x\,(t) - x_d(t)$. In what follows, the virtual desired variables xd is to be discussed.

Constraint of Generalized Kinematics

The remaining design for the output tracking is to determine $x_d(t)$ and then obtain the practical controller input u(t). To this end, we use the fact:

$$g(x) = \sum_{i=1}^{r} h_i(z(t))B_i$$

and rewrite (4) as the following compact form:

$$g(x)(u(t) - \tau(t)) = -A(x)x_d(t) + \dot{x_d}(t))\ (9)$$

where

$$A(x) = \sum_{i=1}^{r} h_i(z(t))A_i$$

From (9), the existence of the control input u(t) depends on the form of $g(x)$. Here, the input matrix $g(x)$ is assumed with full-column rank. If necessary, we can rearrange the coordinate frame in (1) such that:

$$g(x) = \begin{bmatrix} 0_{n-m} \\ ---- \\ B(x) \end{bmatrix} \; A(x) = \begin{bmatrix} A_{n-m} \\ ---- \\ A_m(x) \end{bmatrix} \; (10)$$

$$x_d(x) = \begin{bmatrix} x_{d_{n-m}} \\ ---- \\ x_{d_m}(x) \end{bmatrix}$$

where $0_{n-m} \in R^{(n-m)\times m}$ is a zero matrix and $B(x) \in R^{m\times m}$.Consequently, the condition (9) is with the following form:

$$\begin{bmatrix} 0_{n-m} \\ ---- \\ B(x)(u-\tau) \end{bmatrix} = \begin{bmatrix} \dot{x}_d(t)_{n-m} - A(x)_{n-m}x_d(t) \\ \dot{x}_d(t)_m - A_m(x)x_d(t) \end{bmatrix} \; (11)$$

As a result, the virtual desired variables are determined according to the following constraints:

$$r(t) = \varphi(x_d) \; (12)$$
$$\dot{x}(t)_{n-m} = A_{n-m}(x)x_d(t) \; (13)$$

where (12) rises from the output equation and (13) is due to (11). Also from (11),the practical control input:

$$u = -\sum_{i=1}^{r} h_i\big(z(t)\big)F_i\tilde{x} + B^{-1}(x) \; [\dot{x_d}(t)_m A_m(x)x_d]$$

Application on PMSM

By considering the classical simplifying assumptions, the dynamic model of the Permanent Magnet Synchronous Machine, in the synchronously d-q reference frame, can be described as [2]:

$$\begin{cases} \dfrac{d\omega}{dt} = \dfrac{3p}{2J}\phi_v i_q - \dfrac{1}{J}T_L - \dfrac{B}{J}\omega \\ \dfrac{di_q}{dt} = -\dfrac{R}{L}i_q + p\omega i_d + \dfrac{\phi_v}{L}p\omega + \dfrac{1}{L}u_q \\ \dfrac{di_d}{dt} = -\dfrac{R}{L}i_d + p\omega i_q + \dfrac{1}{L_d}u_d \end{cases} \; (14)$$

Where $\omega(t)$ is the rotor speed, (i_q, i_q) are the d-q axis stator currents, (u_q, u_d) are the d-q axis stator voltages. The load torque T_L is a known step disturbance. The motor parameters are: J the moment of inertia of the rotor, R the stator winding resistance,$(L_d = L_q = L)$ the d-q axis inductances, B the friction coefficient relating to the rotor speed, ϕ_v the flux linkage of the permanent magnets and p the number of poles pairs.

To transform the nonlinear model of the machine into a fuzzy linear Takagi-Sugeno model, the adopted method is to use a transformation on functions of one variable, as follows [17]:

Lemme: for $x \in [-b, a], a, b \in R^+$, conseder $f\ (x): R \to R$ a bounded function, then there are always two functions $w_1(x)$ and $w_2(x)$ and two scalars α and β verifying the following properties:

$$f(x) = \alpha . w_1(x) + \beta . w_2(x) \ (15)$$
$$w_1(x) + w_2(x) = 1, w_1(x) \geq 0, w_2(x) \geq 0$$

Proof: Considering that $f\ (x)$ bornée tel que:

$$f_{min} \leq f(x) \leq f_{max}$$

we can always write:

$$f(x) = \alpha . w_1(x) + \beta . w_2(x) \ (16)$$

whith

$$\alpha = f_{max}, \beta = f_{min}, w_1 = \frac{f(x) - f_{min}}{f_{max} - f_{min}},$$
$$and\ w_2 = \frac{f_{max} - f(x)}{f_{max} - f_{min}}$$

The system of equations representing the MSAP can be written as:

$$\dot{x} = A(\omega)x + Bu + \Delta(t) \ (17)$$

whith $x = [\omega \quad i_q \quad i_d]^T, u = [u_q \quad u_d]^T$

$$A(\omega) = \begin{bmatrix} \frac{3p}{2J}\phi_v i_q - \frac{B}{J}\omega \\ -\frac{R}{L} i_q - p\omega i_d - \frac{p\phi_v}{L}\omega \\ p i_q \omega - \frac{R}{L} i_d \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 \\ \frac{1}{L} & 0 \\ 0 & \frac{1}{L} \end{bmatrix}$$

$$\Delta = \begin{bmatrix} -\frac{1}{J} T_L \\ 0 \\ 0 \end{bmatrix}$$

Introducing plant rule of fuzzy model:

Plant Rule 1: if $z_1(t)$ is F_{11}

$$\dot{x}(t) = A_1 x(t) + B_1 u(t) + \Delta_1(t)$$

Plant Rule 2: $z_1(t)$ is F_{12} THEN

$$\dot{x}(t) = A_2x(t) + B_2u(t) + \Delta_2(t)$$

F_{12} and F_{11} are fuzzy sets. The premise variable $z_1(t)$ is $\omega(t)$ and is assumed to be bounded.

$$\omega \in [d, D]$$

The corresponding membership functions are:

$$F_{11} = h_1, F_{12} = h_2$$

Where

$$F_{11} = \frac{\omega - d}{D - d} \; et \; F_{12} = \frac{D - \omega}{D - d}$$

The subsystem matrices are:

$$A_1 = \begin{bmatrix} \frac{B}{J} & \frac{3p\phi_v}{2J} & 0 \\ -\frac{p\phi_v}{L} & -\frac{R}{L} & -pD \\ 0 & pD & -\frac{R}{L} \end{bmatrix}$$

$$A_2 = \begin{bmatrix} \frac{B}{J} & \frac{3p\phi_v}{2J} & 0 \\ -\frac{p\phi_v}{L} & -\frac{R}{L} & -pd \\ 0 & pd & -\frac{R}{L} \end{bmatrix}$$

$$B_1 = B_2 = \begin{bmatrix} 0 & 0 \\ \frac{1}{L} & 0 \\ 0 & \frac{1}{L} \end{bmatrix}, \Delta_1 = \Delta_2 = \begin{bmatrix} -\frac{1}{J}T_L \\ 0 \\ 0 \end{bmatrix}$$

The virtual desired variables x_d are needed to satisfy (9), which is rewritten below:

$$g(x)\big(u(t) - \tau(t)\big) = -A(x)x_d(t) + \dot{x_d}(t) \; (18)$$

Then we obtain the following matrix form

$$\begin{bmatrix} 0 & 0 \\ \frac{1}{L_s} & 0 \\ 0 & \frac{1}{L_s} \end{bmatrix}\big(u(t) - \tau(t)\big) = -\begin{bmatrix} -\frac{B}{J} & \frac{3P\phi_v}{2J} & 0 \\ -\frac{p\phi_v}{L_s} & -\frac{R_s}{L_s} & -p\omega \\ 0 & p\omega & \frac{R_s}{L_s} \end{bmatrix}\begin{bmatrix} \omega_d \\ i_{qd} \\ i_{dd} \end{bmatrix} + \begin{bmatrix} \dot{\omega_d} \\ \dot{i_{qd}} \\ \dot{i_{dd}} \end{bmatrix}$$

The second index word d denotes the desired states. According to the first equation, it follows that:

$$\dot{\omega_d} = -\frac{B}{J}\omega_d + \frac{3p\phi_v}{2J} i_{qd}$$

which induces that:

$$i_{qd} = \left(\dot{\omega_d} + \frac{B}{J}\omega_d\right)\frac{2J}{3p\phi_v} \dot{i_{qd}} = \left(\ddot{\omega_d} + \frac{B}{J}\dot{\omega_d}\right)\frac{2J}{3p\phi_v}$$

Then, from the second and the third equations, we can obtain the control input:

$$u_q = p\phi_v\omega_d + R_s i_{qd} + L_s\frac{d}{dt}\left(i_{qd}\right) + L_s p\omega i_{dd} + \tau_q$$
$$u_d = -pL_s\omega i_{qd} + R_s i_{dd} + L_s\frac{d}{dt}(i_{dd}) + \tau_d \quad (19)$$

Since the rotor is magnet in PMSM $i_{dd} = 0$, We obtained the following form:

$$u_q = p\phi_v\omega_d + R_s i_{qd} + L_s\dot{i_{qd}} + \tau_q$$
$$u_d = -pL_s\omega i_{qd} + \tau_d$$

where τ_q, τ_d are new controller to be designed via LMI approach. The inferred output of the PDC controller is determined by the summation:

$$\tau = -\sum_{i=1}^{2} h_i F_i(x - x_d)$$

where $\tau = [\tau_q\ \tau_d]^T$, $x = [\omega\ i_q\ i_d]^T$, $x_d = [\omega_d\ i_{qd}\ i_{dd}]^T$

Simulation Results

The control gains K_1, K_2 are obtained by solving LMIs (8). In LMI numerical toolboxes, using the motor parameters [19] and setting the nonlinear term $\omega \in [d, D]$, with $D = 50, d = 0$, we obtained P, K_1, and K_2 as follows

$$P = \begin{bmatrix} 3.1 & -10.8 & 0.4 \\ -10.8 & 1755.5 & -66.7 \\ 0.4 & -66.7 & 204.1 \end{bmatrix}$$
$$K_1 = \begin{bmatrix} -0.6160 & -2.5490 & 0.1030 \\ 0.0826 & -10.6374 & -3.8083 \end{bmatrix}$$
$$K_2 = \begin{bmatrix} -0.6182 & -2.1635 & 0.0884 \\ 0.0204 & -1.6938 & -4.1936 \end{bmatrix}$$

In $d - q$ axis frame, simulation results are shown in Fig. 1, Fig. 2 and Fig. 3. They are the traces of the ω_d, ω speed, i_{qd}, i_q current, and i_{dd}, i_d current. for the initial conditions $[30rd/s, 0.5A, 0.5A]^T$and the desired speed:

$$\omega_d(t) = 25\, sin\, t + 25$$

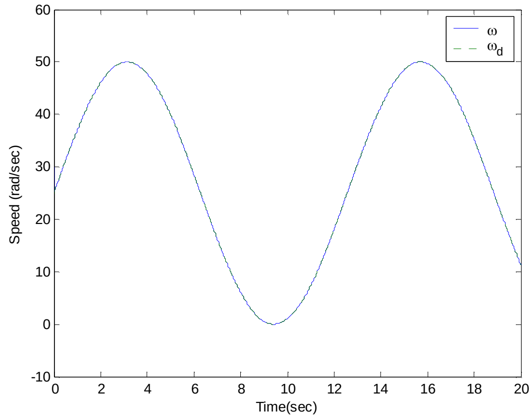


Figure 1: Time response for ω_d and ω for $d-q$ axis control

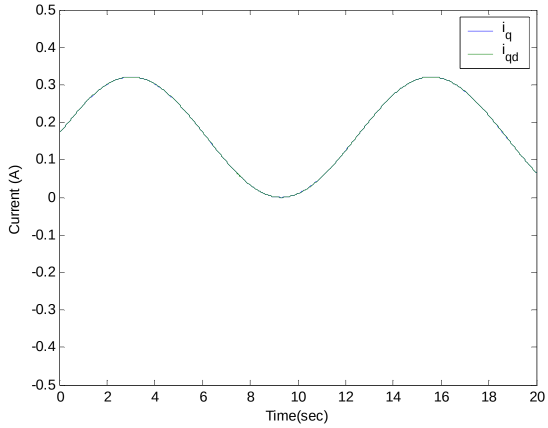


Figure 2: The response of current i_{qd} and i_q for $d-q$ axis control

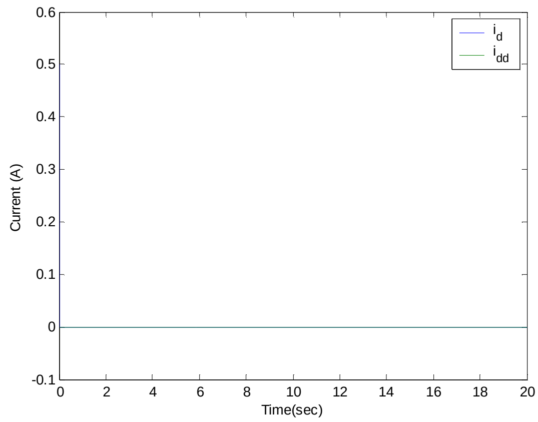
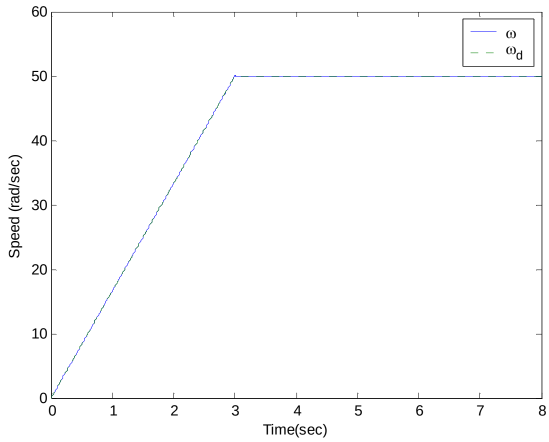


Figure 3: The response of current i_{dd} and d for $d-q$ axis control

In $d-q$ axis frame, simulation results are shown in Fig. 4, Fig. 5 and Fig. 6. They are the traces of the ω_d, ω speed, i_{qd}, i_q current, and i_{dd}, i_d current. for the initial conditions $[0rd/s, 0A, 0A]^T$ and the desired speed:

$$\omega_d(t) = \begin{cases} \frac{50}{3} t \; rad/sec, t < 3 \\ 50 \; rad/sec, t \geq 3 \end{cases}$$



Time (s)

Figure 4: Time response for $\boldsymbol{\omega_d}$, $\boldsymbol{\omega}$ for $\boldsymbol{d-q}$ axis control

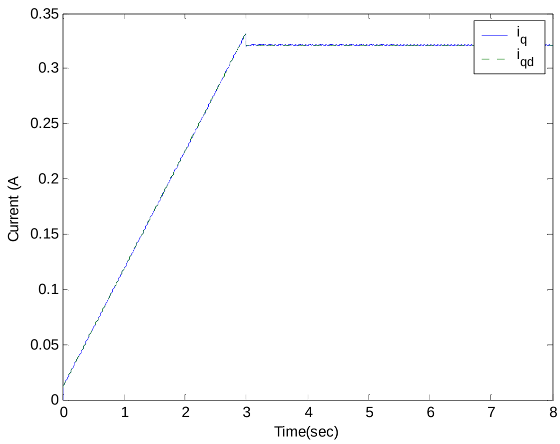


Figure 5: Time response for i_{qd} and i_q for $d-q$ axis control

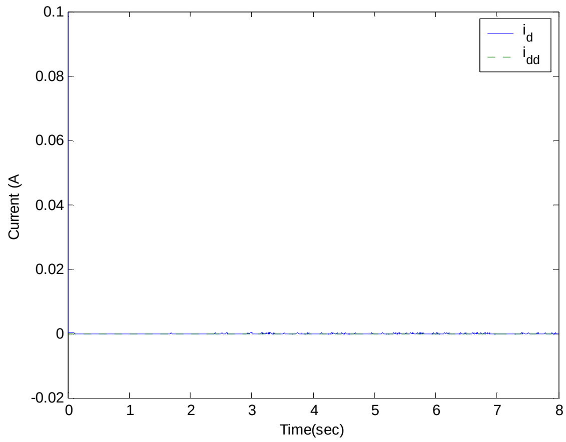


Figure 6: Time response for i_d *and* i_{dd} for $d-q$ axis control

Interpretation of Results

We have shown by two separate simulations that the trajectories of the system follow the desired trajectories. The first simulation concerns a desired speed, whose function is: $\omega_d(t) = 25\sin 0.5t + 25$, the second is that it thee another desired angular velocity, whose function is:

$$\omega_d(t) = \begin{cases} \frac{50}{3} t \; rad/sec, t < 3 \\ 50 \; rad/sec, t \geq 3 \end{cases}$$

Conclusion

In this paper, we studied the Sensorless Output Tracking Control problem based on T-S Fuzzy Approach, the state feedback we used a control law of type PDC.

Then we applied this approach to permanent magnet synchronous machine, we found that all the trajectories of the system are part of the desired trajectories

Parametres De La Machine

$R_s = 4.55\,\Omega$
$L_s = 11.6\,mH$
$J = 6.36e - 4\,Kg \cdot m^2$
$B = 6.11e - 3\,N \cdot m \cdot sec/rad$
$\phi_v = 0.317\,V \cdot sec/rad$
$P = 2\,pairs$

Nouns Explaining

PMSM: Permanent Magnet Synchronous Motors
PDC: Parallel Distributed Compensation

T-S fuzzy: Takagi-Sugeno fuzzy
LMIs: Linear Matrix Inequalities

References

[1] Z. Boulbair, Mise en œuvre d'une commande sans capteur d'une machine synchrone à aimants permanents, Mémoire de Magistère, Ecole Polytechnique de l'Université de Nantes, 2002.

[2] G. Grellet et G. Clerc, Actionneurs électriques, Eyrolles, France, 1996.

[3] B. Nahid-Mobarakeh, Commande vectorielle sans capteur mécanique des machines synchrones à aimants: Méthodes, convergence, robustesse, Identification en ligne des paramètres, Thèse de Doctorat, Institut National Polytechnique de Lorraine, Université de Nancy, 2001.

[4] A. Benchaib, S. Poullain, J. L. Thomas and J. C. Alacoque, "Discrete-time field-oriented control for SM-PMSM including voltage and current constraints", IEEE International, Electric Machines and Drives Conference, Vol. 2, pp. 999-1005, 2003.

[5] C. Y. Du and G. R. Yu, "Optimal PI Control of a Permanent Magnet Synchronous Motor Using Particle Swarm Optimization", Proceedings of the Second International Conference on Innovative Computing, Information and Control, pp. 255, Washington, 2007.

[6] Y. Ming, G. Yang, X. Dian-Guo and Y. Yong, "On-line Self tuning of PI Controller for PMSM Drives Based on the Iterative Learning Control", IEEE 20th Annual, Applied Power Electronics Conference and Exposition, Vol. 3, pp. 1889-1893, 2005.

[7] X. Dongemei, Q. Daokui and X. Fang, "Design of H_∞ Feedback Controller and IP-position Controller of PMSM Servo System", IEEE Transactions on Industrial Electronics, Vol. 48, No. 6, pp. 1098-1108, 2001.

[8] I. C. Baik, K. H. Kim and M. J. Youn, "Robust nonlinear speed control of PM synchronous motor using boundary layer integral sliding mode control technique", IEEE Transactions on Control Systems Technology, Vol. 8, No. 1, pp. 47-54, 2000.

[9] I. C. Baik, K. H. Kim and M. J. Youn, "Robust nonlinear speed control of PM synchronous motor using adaptive and sliding mode control techniques", IEEE Proceedings, Electric Power Applications, Vol. 145, No. 4, pp. 369-376, 1998.

[10] A. Kaddouri, Étude d'une commande non linéaire adaptative d'une machine synchrone â aimants permanents, Thèse de Doctorat, Université Laval Québec, 2000.

[11] A. Isidori, Nonlinear Control Systems: an Introduction, Springer-Verlag, 1989.

[12] M. Fliess, J. Lévine, P. H. Martin and P. Rouchon, "Flatness and defect of nonlinear systems: introductory theory and examples", International journal of control, Vol. 61, pp. 1327-1361, 1995.

[13] L. Zadeh, "Outline of a new approach to the analysis of complex systems and decision processes", IEEE Transactions on Systems Man and Cybernetics, Vol. 3, pp. 28-44, 1973.

[14] T. Takagi and M. Sugeno, "Fuzzy identification of systems and its applications to modeling and control", IEEE Transactions on Systems Man and Cybernetics, Vol. 115, pp. 116-132, 1985.

[15] K. Tanaka, T. Hori and H. O. Wang, "New parallel distributed compensation using time derivative of membership functions: a fuzzy Lyapunov approach", Proceeding of the control and decision conference, Orlando, Florida, Vol. 4, pp. 3942-3947, 2001.

[16] G. Zhu, L. Dessaint, O. Akhrif and A. Kaddouri, "Speed tracking control of apermanent-magnet synchronous motor with state adn load torque observer" IEEE Trans. Ind. Electron., vol. 47, pp. 346-355, Apr. 2000.

[17] Y. Morère, Mise en œuvre de lois de commande pour les modèles flous de type Takagi Sugeno, Thèse de Doctorat, Université de Valenciennes et du Hainaut Cambrésis, 2001.