ROBUST FUZZY SLIDING MODE CONTROLLER DESIGN FOR MOTORS DRIVES

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ABSTRACT
The synthesis algorithms of modern control theory and fuzzy logic have been studied to upgrade the performances of SMC. In this paper, Fuzzy sliding mode control, which takes the features of both SMC and FLC to overcome the disadvantage of chattering and enhancing the robustness of the controller, is presented. The fuzzy sliding mode controller is designed for a class of non linear dynamic systems to tackle the problems with model uncertainties, parameter fluctuations and external disturbances. By this design, the bounds of the uncertainties are not required to be known in advance, and the robust stability of closed loop system is analysed in the Lyapunov sense. A numerical example is simulated with the proposed algorithm, witch consists to control the synchronous motor speed. The simulation results show the effectiveness of the proposed control strategy with desired tracking accuracy and robustness.

Keywords: f*uzzy logic, sliding mode control, electrical motor drives.*

1. INTRODUCTION

Variable structure control (VSC) with sliding mode or sliding mode Control (SMC), is one of the effective non linear robust control approaches since it provides system dynamics with an invariance property to uncertainties once the system dynamics reach the sliding surface [1, 2, 3]. The main disadvantage of this approach is the high switching frequency of the control action or chattering that VSC system exhibit. Chattering is undesirable since it can excite the unmodeled high frequency dynamics in the non linear system control. Introducing a boundary layer (BL) is one of the most common techniques used, with the cost of an important degradation in tracking performance.

Fuzzy control has been an active research topic, since the work of Mamdani proposed in 1974 [4]. The concept of FLC is to utilize the qualitative knowledge of a system to design a practical controller; it is generally applicable to plants that are ill-modelled, but qualitative knowledge of experienced operators available for design. It is particularly suitable for those systems with uncertain or complex dynamics. In general, a fuzzy control algorithm consists of a set of heuristic decision rules and can be regarded as a nonmathematical control algorithm, in contrast to a conventional feedback control algorithm [5].

In recent years, some results of the fuzzy sliding mode control (FSMC) have been reported [5, 6]. To decrease the number of rules in the rule base, several authors have suggested using the way of a composite state to obtain a fuzzy sliding mode controller described in the previous work. The advantage of such controllers is that the number of rules required is reduced. Obviously, the FSMC is one of the reducible fuzzy rules methods. In general, since the FSMC combines both fuzzy control and sliding mode control principles, the performance of closed-loop system is superior to that using only one control theory.

In this study, a robust controller is derived through variable structure control (VSC). Al though the method of variable structure control can solve the above mentioned system, the drawback of the variable structure control is their chattering owing to the sliding control law that has to be discontinuous across the sliding surface. Chattering is undesirable because it involves high control activity and may excite high-frequency dynamics. So we apply the fuzzy control principle to overcome the drawback. Herein, what we want to demonstrate is that the FSMC can handle this chattering problem effectively by adjusting the control input near the sliding hyperplane. Mostly, the FSMC method is applied in tracking control of a non linear system.

The organization of this paper is as follows. In section 2, the system under study is stated, the modified SMC is described and its stability is guaranteed by Lyapunov theory. In section 3, the proposed fuzzy sliding mode controller is developed. In section 4, the vector control principle for synchronous motor drive is presented. In section 5, the proposed controller is used to control the synchronous motor speed, simulation results are given to show the effectiveness of this controller. Conclusion is summarized in the last section.

2. SLIDING MODE CONTROL

Consider a nonlinear system which can be represented by the following state space model in a canonical form [2, 7]:

$$\begin{aligned} x^{(n)}(t) &= f(x(t),t) + g(x(t),t)u + d(t) \\ y(t) &= x(t) \end{aligned} \tag{1}$$

where $x = \left[x(t)\ \dot{x}(t) ... \ x^{(n-1)}(t)\right]^T$ is the state vector, $f(x(t),\ t)$ and $g(x(t),t)$ are nonlinear functions, u is the control input, $d(t)$ is the external disturbances.

The objective of the control is to determine a control law $u(t)$ to force the system output $y(t)$ in (1) to follow a given bounded reference signal $y_d(t)$, that is, the tracking error $e(t) = y_d(t) - y(t)$ and its forward shifted values, defined as

$$e^{(i)}(t) = y_d^{(i)}(t) - y^{(i)}(t) = x_d^{(i)}(t) - x^{(i)}(t), \quad (i = 1, \ldots, n-1) \tag{2}$$

should be small.

The design of SMC involves two tasks. The first one is to select the switching hyperplane $s(x,t)$ to prescribe the desired dynamic characteristics of the controlled system. The second one is to design the discontinuous control such that the system enters the sliding mode $s(x,t) = 0$ and remains in it forever.

In this paper, we use the sliding surface proposed par J.J. Slotine, as mentioned in appendix A-2,

$$s(x,t) = \left(\frac{d}{dt} + \lambda\right)^{n-1} e(t) \tag{3}$$

in which $e = x_d(t) - x(t)$, λ is a positive coefficient, and n is the system order.

It remains to be shown that the control law can be constructed so that the sliding surface will be reached. Then, a sliding hyperplane S can be represented as $s(x,t) = 0$.

The scalar $s(x,t)$ is defined as the distance to the sliding hyperplane S.

Consider a Lyapunov function:

$$V = \frac{1}{2}s^2 \tag{4}$$

From Lyapunov theorem we know that if $\dot{V}$ is negative definite, the system trajectory will be driven and attracted toward the sliding surface and remain sliding on it until the origin is reached asymptotically [8, 9]:

$$\dot{V} = s\,\dot{s} \tag{5}$$

The simplified 1st order problem of keeping the scalar $s(x,t)$ at zero can be achieved by choosing the control law $u(t)$. A sufficient condition for the stability of the system is

$$\frac{1}{2}\frac{\partial}{\partial t}s^2 \le -\eta|s| \tag{6}$$

where η is a positive constant.

(6) is called reaching condition or sliding condition. $s(t)$ verifying (6) is referred to as sliding surface, and the system's behaviour once on the surface is called sliding mode.

If the control input is so designed that the inequality (6) is satisfied, together with the properly chosen sliding hyperplan, the state will be driven toward the origin of the state space along the sliding hyperplane from any given initial state. This is the way of the SMC that guarantees asymptotic stability of the systems.

The process of sliding mode control can be divided in two phases, that is, the approaching phase and the sliding phase. The sliding mode control law $u(t)$ consists of two terms, equivalent term $u_{eq}(t)$, and switching term $u_s(t)$.

In the sliding phase, where $s(x,t) = 0$ and $\dot{s}(x,t) = 0$, the equivalent term $u_{eq}(t)$ is designed to keep the system on the sliding surface. In the approaching phase, where $s(x,t) \neq 0$, the switching term $u_s(t)$ is designed to satisfy the reaching condition (6).

While in sliding phase we have:

$$\dot{s}(x,t) = 0 \tag{7}$$

By solving the above equation formally for the control input, we obtain an expression for u called the equivalent control u_{eq}, which can be interpreted as the continuous control law that would maintain $\dot{s}(x,t) = 0$ if the dynamics were exactly known.

In order to satisfy sliding conditions (6) and to despite uncertainties on the dynamic of the system, we add a discontinuous term across the surface $s(x,t) = 0$, so the sliding mode control law $u(t)$ has the following form:

$$\begin{aligned} u &= u_{eq} + u_s \\ u_s &= -K_f \operatorname{sgn}(s(x,t)) \end{aligned} \tag{8}$$

where K_f is the control gain.

For a defined function φ :

$$\operatorname{sgn}(\varphi) = \begin{cases} 1, & if \ \varphi > 0 \\ 0, & if \ \varphi = 0 \\ -1, & if \ \varphi < 0 \end{cases} \tag{9}$$

The controller described by the equation (8) presents high robustness, insensitive to parameter fluctuations and disturbances [1, 2, 3, 7, 10], but it will have high-frequency switching (chattering phenomena) near the sliding surface due to sgn function involved. These drastic changes of input can be avoided by introducing a boundary layer with width ε [2, 3, 11, 12]. Thus replacing $\operatorname{sgn}(s(t))$ by $sat(s(t)/\varepsilon)$ in (8), we have

$$u = u_{eq} - K_f \ sat(s(x,t)/\varepsilon) \tag{10}$$

Where

$$\varepsilon > 0,$$

$$sat(\varphi) = \begin{cases} \operatorname{sgn}(\varphi) & if |\varphi| \ge 1 \\ \varphi & if |\varphi| < 1 \end{cases}.$$

3. FUZZY SLIDING MODE CONTROL

Sliding mode control (SMC) systems or variable structure control systems have been studied extensively to tackle problems of the nonlinear dynamic control systems.

A sliding mode control law is formulated using a Lyapunov approach to guarantee that the system state first reaches the prescribed sliding mode in finite time from any initial state, and then remains on it thereafter by a discontinuous control. However, since a discontinuous control action is involved, chattering due to the high gain and high speed switching control will take place and the steady-state performance will be degraded. The undesirable chattering may excite previously unmodelled system dynamics and damage actuators, resulting in unpredictable instability. Smoothing techniques such as the boundary layer approach have been employed to reduce its effects at the cost of giving concession from performance. In this paper, we will use the discontinuous component u of the sliding control law to develop the fuzzy logic control. We propose a design methodology of FLC based on SMC with fast self-tuning the dead zone parameters (boundary layer thickness) under parameter variations in the control object. This design is called fuzzy sliding mode control (FSMC). The FSMC takes the features of both SMC and FLC to overcome the disadvantage of chattering and enhance the robustness of the controllers. With this scheme, the stability and the robustness of the proposed fuzzy logic control algorithm are proved and ensured by the sliding mode control law. Then, the stability of the FSMC is guaranteed by Lyapunov theory.

We follow the development established in [6] and show that a particular fuzzy controller is an extension of an SMC with a boundary layer [3, 13]. We will use the discontinuous component u_s of the sliding control law (8) to develop the fuzzy logic control.

$$u = u_{eq} + u_f \tag{11}$$

where u_f is the output of the fuzzy control block.

Fig. 1 shows the general structure of the fuzzy sliding mode control (FSMC) where X is the variable of control. In this work, X can be the angular speed, s the sliding surface defined by equation (3), and the plant the machine object of control.

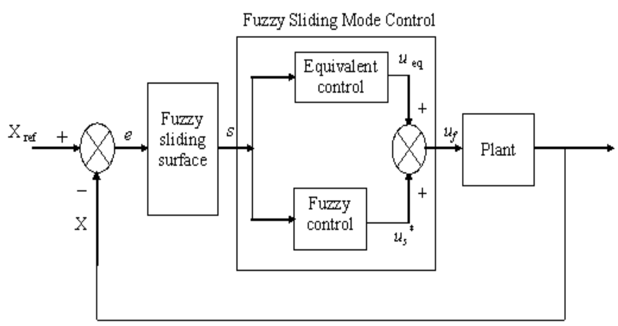

Fig. 1 The bloc diagram of the fuzzy sliding mode control (FSMC).

Suppose the fuzzy controller in this article is constructed from the following IF-THEN rules:

Rule 1: if s is NB, then u_f is BIGGEST,

Rule 2: if s is NM, then u_f is BIGGER,

Rule 3: if s is NS, then u_f is BIG,

Rule 4: if s is ZR, then u_f is MEDIUM,

Rule 5: if s is PS, then u_f is SMALL,

Rule 6: if s is PM, then u_f is SMALLER

Rule 7: if s is PB, then u_f is SMALLEST

Or equivalently

Rule (i): if s is F_s^i, then u_f is $F_{u_f}^i$, i =1,…,5.

Here NB is negative big, NM is negative medium, NS is negative small, ZR is zero, PB is positive big, PM is positive medium and PS is positive small. NB, NM, NS …, SMALLER, SMALLEST are labels of fuzzy sets and their corresponding membership functions are depicted in Fig. 3 and Fig. 4, respectively.

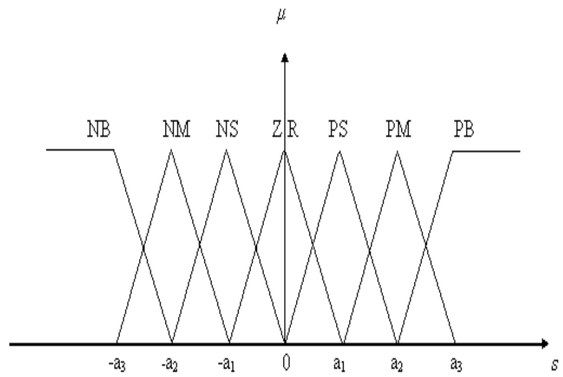

Fig. 2 Membership functions for input s.

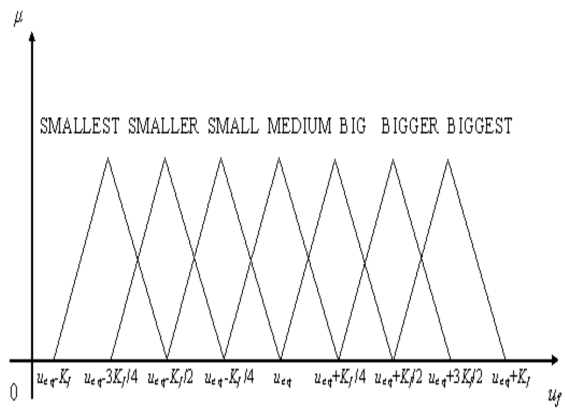

Fig. 3 Membership functions for output u.

Let X and Y be the input and output space of the fuzzy rules. For any arbitrary fuzzy set F_x in X, each rule R^i can determine a fuzzy set $F_x o R^i$ in Y. Use the sup-min compositional rule of inference [14, 15, 16]:

$$\mu_{F_x o R^i}\left(u_f\right) = \sup_{s\in X}\left[\min\left[\mu_{F_x}(s), \min\left[\mu_{F_x^i 0}(s), \mu_{F_{u_f}^i}\left(u_f\right)\right]\right]\right] \tag{12}$$

It can be further simplified by supposing F_x as a fuzzy singleton, i.e., only at its support $s = \alpha$, $\mu_{F_x}(s) = 1$ otherwise $\mu_{F_x}(s) = 0$, then (12) becomes

$$\mu_{F_x o R^i}(u_f) = \min\left[\mu_{F_x^i}(\alpha), \mu_{F_{u_f}^i}(u_f)\right] \tag{13}$$

and the deduced membership function $F_{u_f}^d$ of the consequences of rules is

$$\mu_{F_{u_f}^d}(u_f) = \max\left[\mu_{F_x o R^1}(u_f), \ldots, \mu_{F_x o R^5}(u_f)\right] \tag{14}$$

The crisp output u_c is obtained by the center-of-area defuzzifier:

$$u_c = \frac{\int u_f \mu_{F_{u_f}^d}(u_f) du_f}{\int \mu_{F_{u_f}^d}(u_f) du_f} \tag{15}$$

4. SYNCHRONOUS MOTOR

4.1. Machine equations

The dynamic model of synchronous motor in d-q frame can be represented by the following equations [17, 18]:

$$\begin{aligned} v_{ds} &= R_s\, i_{ds} + \frac{\mathrm{d}}{\mathrm{d}t}\phi_{ds} - \omega\,\phi_{qs} \\ v_{qs} &= R_s i_{qs} + \frac{\mathrm{d}}{\mathrm{d}t}\phi_{qs} + \omega\,\phi_{ds} \\ v_f &= R_f\, i_f + \frac{\mathrm{d}}{\mathrm{d}t}\phi_f \end{aligned} \tag{16}$$

The mechanical equation of synchronous motor can be defined by:

$$J\frac{\mathrm{d}}{\mathrm{d}t}\Omega = T_e - T_L - B\Omega \tag{17}$$

Where the electromagnetic torque is given in d-q frame:

$$T_e = p(\phi_{ds} i_{qs} - \phi_{qs} i_{ds}) \tag{18}$$

In which:

$$\Omega = \frac{\mathrm{d}}{\mathrm{d}t}\theta \tag{19}$$

$$\theta = \int \Omega\, dt \tag{20}$$

$$\omega = \frac{\mathrm{d}}{\mathrm{d}t}\theta_e = p\,\Omega \tag{21}$$

$$\theta_e = p\theta \tag{22}$$

The flux linkage equations are:

$$\begin{aligned} \phi_{ds} &= L_{ds} i_{ds} + M_{fd}\, i_f \\ \phi_{qs} &= L_{qs} i_{qs} \\ \phi_f &= L_f\, i_f + M_{fd}\, i_{ds} \end{aligned} \tag{23}$$

where R_s – stator resistance, R_f – field resistance, L_{ds}, L_{qs} – respectively direct and quadrature stator inductances, L_f – field leakage inductance, M_{fd} – mutual inductance between inductor and armature, ϕ_{ds} and ϕ_{qs} – respectively direct and quadrature flux, ϕ_f – field flux, T_e – electromagnetic torque, T_L – external load disturbance, p – pair number of poles, B – is the damping coefficient, J – is the moment of inertia, ω – electrical angular speed of motor. Ω – Mechanical angular speed of motor, θ – mechanical rotor position, θ_e –electrical rotor position.

4.2. Description of the system

The schematic diagram of the speed control system under study is shown in Fig. 4. The power circuit consists of a continuous voltage supply which can provided by a six rectifier thyristors and a three phase GTO thyristors inverter whose output is connected to the stator of the synchronous machine. The field current i_f of the synchronous machine, which determines the field flux level is controlled by voltage v_f. The parameters of the synchronous machine are given in the Appendix A-1.

The self-control operation of the inverter-fed synchronous machine results in a rotor field oriented control of the torque and flux in the machine. The principle is to maintain the armature flux and the field flux in an orthogonal or decoupled axis. The flux in the machine is controlled independently by the field winding and the torque is affected by the fundamental component of armature current i_{qs}. In order to have an optimal functioning, the direct current i_{ds} is maintained equal to zero [14, 15].

Substituting (23) in (18), the electromagnetic torque can be rewritten for $i_f = \mathit{constant}$ and $i_{ds} = 0$ as follow:

$$T_e(t) = \lambda i_{qs}(t) \tag{24}$$

where $\lambda = pM_{fd}\, i_f$.

In the same conditions, it appears that the v_{ds} and v_{qs} equations are coupled. We have to introduce a decoupling system, by introducing the compensation terms emf_d and emf_q in which

$$\begin{aligned} emf_d &= \omega L_{qs} i_{qs}, \\ emf_q &= -\omega L_{ds} i_{ds} - \omega M_{af}\, i_f. \end{aligned} \tag{25}$$

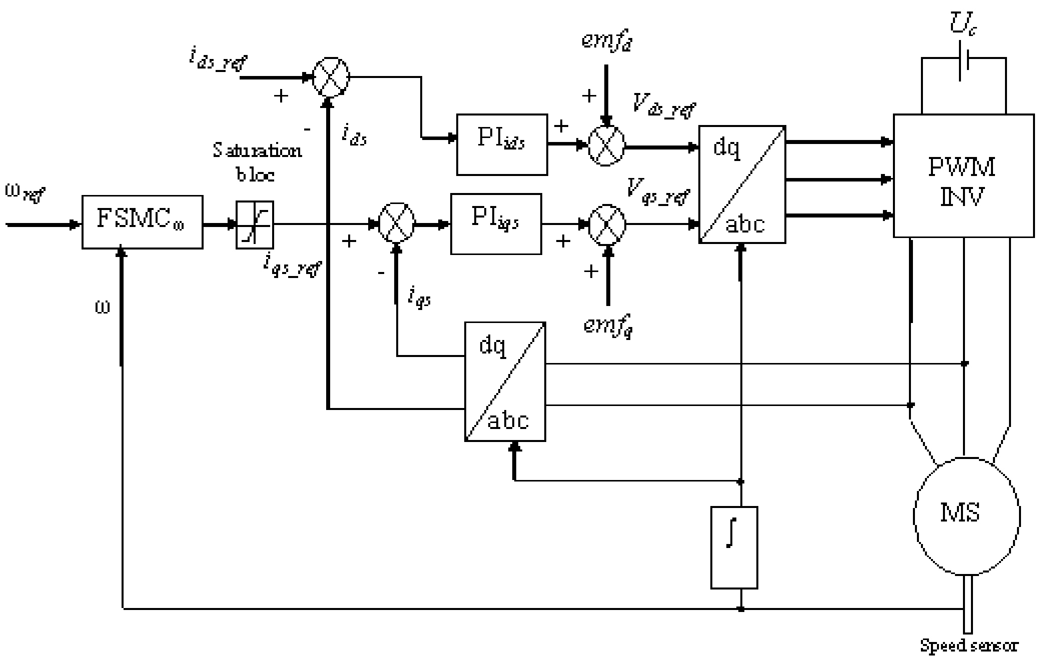

Fig. 4 System configuration of Field-Oriented Synchronous Motor.

Fig. 4 shows the schematic diagram of the speed control of synchronous motor using fuzzy sliding mode control.

The blocks $FSMR_\omega$, PI_{id} et PI_{iq} are régulators, the first one is the fuzzy sliding mode controller for speed, the second is the proportional integral (PI) regulator for direct current and the third is the PI regulator for the quadrature current. To avoid the appearance of an inadmissible value of current, a saturation bloc is used.

4.3. Voltage inverter

The power circuit of a three-phase bridge inverter using six switch device is shown in Fig. 5. The dc supply is normally obtained from a utility power supply through a bridge rectifier and LC filter to establish a stiff dc voltage source [14].

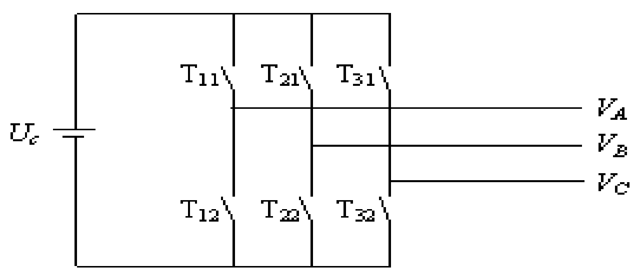

Fig. 5 Voltage inverter.

The switch T_{ci} $(c \in \{1, 2, 3\},\ i \in \{1, 2\})$ is supposed perfect. The simple inverter voltage can be presented by logical function connexion in matrix form as [7, 19, 20]

$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}\begin{bmatrix} F_{11} \\ F_{21} \\ F_{31} \end{bmatrix} U_c, \tag{26}$$

where the logical function connexion F_{c1} is defined as: $F_{c1} = 1$ if the switch T_{c1} is closed, $F_{c1} = 0$ if the switch T_{c1} is opened, U_c is the voltage feed inverter.

5. SIMULATION AND RESULTS

5.1. Results and comments

To show the fuzzy sliding mode performances we have simulated the system described in Fig. 4. The simulation of the starting mode without load is done, followed by reversing of the reference $\omega_{ref} = \pm 100$ rad/s at t_3=2s,

The load (T_L) is applied in two periods:

1. The reference $\omega_{ref} = +100$ rad/s, the load ($T_L = +8$Nm) is applied at $t_1 = 1$ s and eliminated at $t_2 = 1.5$ s
2. The reference $\omega_{ref} = -100$ rad/s, the load ($T_L = -8$Nm) is applied at $t_4 = 3$ s and eliminated at $t_5 = 3.5$ s.

The simulation is realized using the SIMULINK software in MATLAB environment.

Fig. 6 shows the performances of the fuzzy sliding mode controller.

The control presents the best performances, to achieve tracking of the desired trajectory and to reject disturbances. The current is limited in its maximal admissible value by a saturation function. The decoupling of torque-flux is maintained in permanent mode.

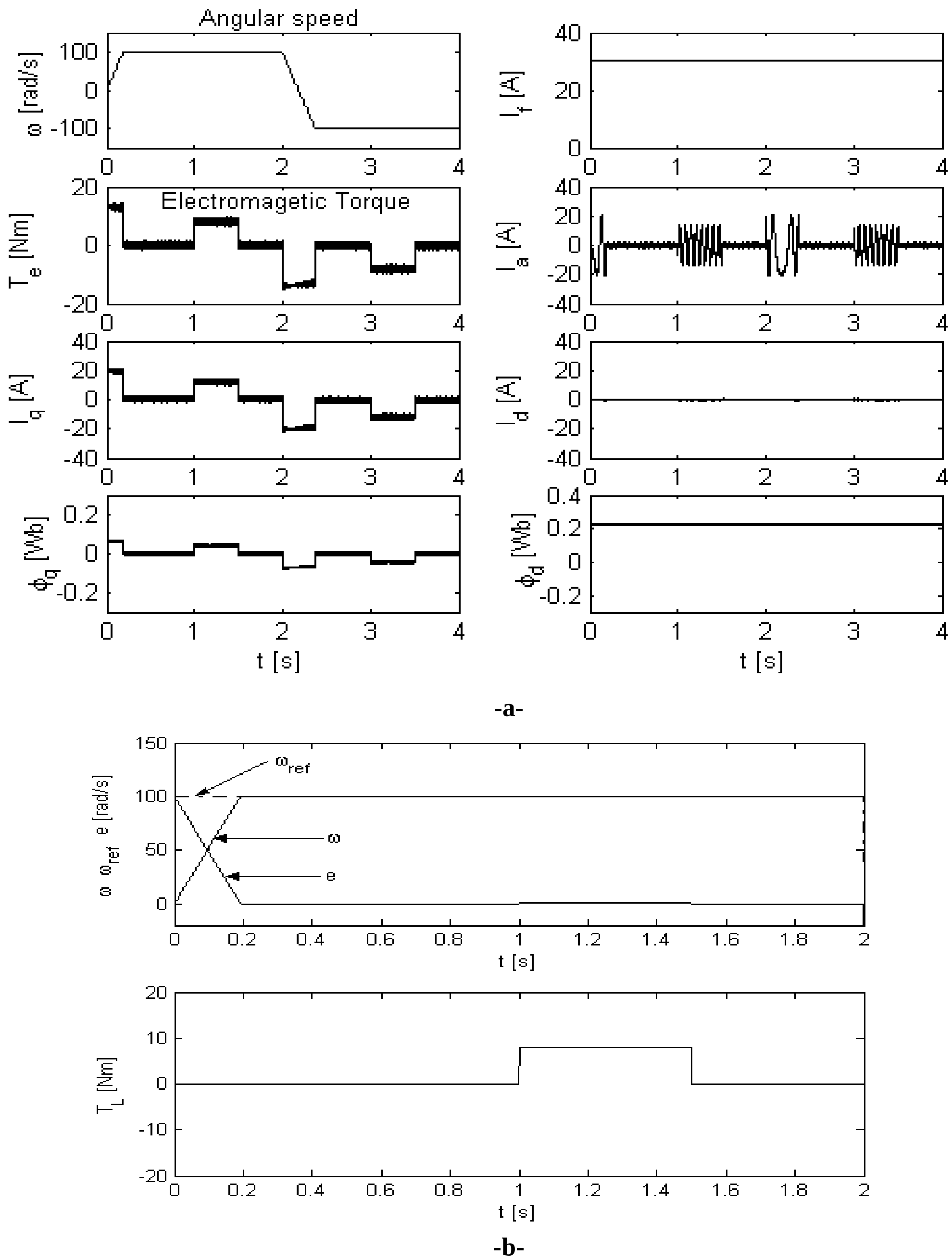

Fig. 6 Simulation results of speed control with fuzzy sliding mode control: a- performances of the system, b- speed tracking error.

5.2. Robustness

In order to test the robustness of the used method we have studied the effect of the parameters uncertainties on the performances of the speed control.

To show the effect of the parameters uncertainties, we have simulated the system with different values of the parameter considered and compared to nominal value (real value).

Three cases are considered:

1. The moment of inertia (±50%).
2. The stator and rotor resistances (+50%).
3. The stator and rotor inductances (+20%).

To illustrate the performances of control, we have simulated the starting mode of the motor without load, and the application of the load ($T_L = +8\text{Nm}$) at the instance $t_1 = 2$ s and it's elimination at $t_2 = 3$ s; in presence of the variation of parameters considered (the moment of inertia, the stator and rotor resistances, the stator and rotor inductances) with speed step of +100 rad/s.

Fig. 7 shows the tests of robustness realized with the fuzzy sliding mode control for different values of the moment of inertia. Fig. 8 shows the system response realized with the fuzzy sliding mode control for different values of stator and rotor resistances.

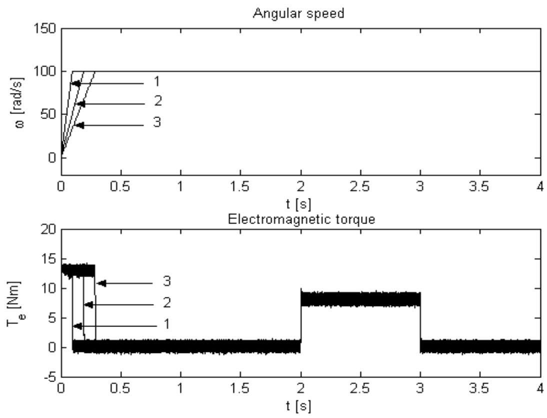

Fig. 7 Test of robustness for different values of the moment of inertia: 1) – 50%, 2) nominal case, 3) +50%.

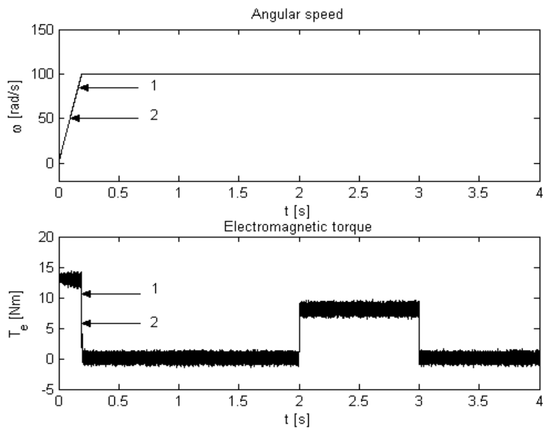

Fig. 8 Test of robustness for different values of stator and rotor resistances: 1) nominal case, 2) +50%.

Fig. 9 shows the tests of robustness realized with the fuzzy sliding mode control for different values of stator and rotor inductances.

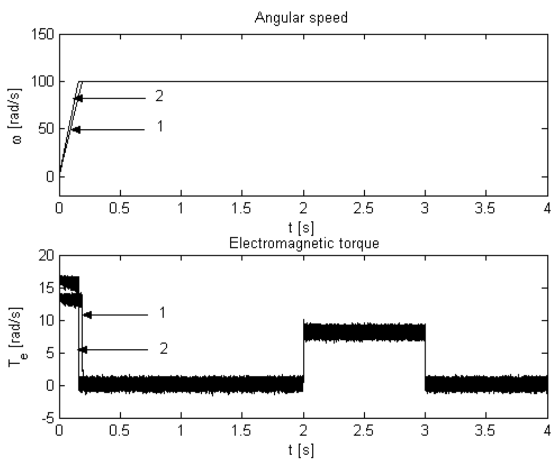

Fig. 9 Test of robustness for different values of stator and rotor inductances: 1) nominal case, 2) +20%.

For the robustness of control, a decrease or increase of the moment of inertia *J*, the resistances or the inductances doesn't have any effects on the performances of the technique used (Fig. 8 and Fig. 9). An increase of the moment of inertia gives best performances, but it presents a slow dynamic response (Fig. 7). The fuzzy sliding mode control gives to our controller a great place towards the control of the system with unknown parameters.

6. CONCLUSION

The paper describes a new approach to robust speed control for synchronous motor. It's develops a simple robust controller to deal with parameters uncertain and external disturbances and takes full account of system noise, digital implementation and integral control. The control strategy is based on SMC and FLC approaches. The FSMC has the advantage in handling the chattering phenomena and in reducing the number of the fuzzy rules.

The simulation results show that the proposed controller is superior to SMC in eliminating chattering phenomena and with higher tracking precision. It appears from the response properties that it has a high performance in presence of the plant parameters uncertain and load disturbances. It is used to control system with unknown model. The control of speed by FSMC gives fast dynamic response with no overshoot and zero steady-state error. The decoupling, stability and convergence to equilibrium point are verified.

APPENDIX

A.1 - Three phases SM parameters:
Rated output power 3HP, Rated phase voltage 60V, Rated phase current 14 A, Rated field voltage v_f=1.5V, Rated field current i_f =30A, Stator resistance R_s =0.325Ω, Field resistance R_f =0.05Ω, Direct stator inductance L_{ds} =8.4 mH, Quadrature stator inductance L_{qs}=3.5 mH, Field leakage inductance L_f=8.1 mH, Mutual inductance between inductor and armature M_{fd}=7.56mH, The damping coefficient B=0.005 N.m/s, The moment of inertia J =0.05 kg.m^2, Pair number of poles p=2.

A.2 - Sliding surface

Let:

$$e = [e_1(t)\ e_2(t) \ldots\ e_n(t)]^T = \left[e(t)\ \dot{e}(t) \ldots\ e^{(n-1)}(t)\right]^T \in R \quad (27)$$

Where: $e(t) = x_d(t) - x(t)$

For system (1), a sliding surface in the space of the tracking error vector s(*x*, *t*) can be defined by

$$s(x,t) = ce \quad (28)$$

where $c = [c_1\ c_2 \ldots c_{n-1}\ 1]$, c_i , (i=1,…, (n-1))are coefficients of Hurwtizian polynomial.

The sliding hyperplan S can be represented as

$$s(x,t) = c_1 e(t) + c_2\, \dot{e}(t) + \ldots + e^{(n-1)}(t) = 0 \quad (29)$$

The scalar s(x, t) of (28) is defined as the distance to the sliding hyperplan S.

The dynamic behaviour of (1) without disturbances on the sliding surface (29) will be stable if the coefficient of

Hurwitzian polynomial (c_i) are chosen such that the root of (29) are in the open left half plane.

J. J. Slotine proposed a particular surface where the surface can be written in following form

$$s(x,t) = \left(\frac{d}{dt} + \lambda\right)^{n-1} e(t) \qquad (30)$$

In which $e = x_d(t) - x(t)$, λ is a positive coefficient, and n is the system order.

The dynamic behavior of (1) without disturbances on the sliding surface is

$$s(t) = \left(\frac{d}{dt} + \lambda\right)^{n-1} e(t) = 0 \qquad (31)$$

and will be stable if the roots of (31) are in the open left-half plane.

REFERENCES

[1] V. I. Utkin. Variable structure system with sliding modes. IEEE Trans. on Automatic Control, vol. AC-22, April 1977, 210–222.

[2] J. J. E. Slotine, W. Li. Applied nonlinear control. Prentice Hall, USA, 1998.

[3] K. J. Astrom, B. Wittenmark. Adaptive control. Addison-Wesley, 1989.

[4] E.H. Mamdani. Applications of fuzzy algorithms for simple dynamic plants. Proc. IEE 121, 1974, 1585–1588.

[5] Fang-Ming Yu, Hung-Yuan Chung, Shi-Yuan Chen. Fuzzy sliding mode controller design for uncertain time-delayed systems with nonlinear input. Fuzzy Sets Syst., vol. 140, 2003, 359–374.

[6] S. W. Kim, J. J. Lee. Design of a fuzzy controller with fuzzy sliding surface. Fuzzy Sets Syst., vol. 71, 1995, 359–367.

[7] Ji Chang Lo, Ya Hui Kuo. Decoupled fuzzy sliding mode control. IEEE Trans. on Fuzzy Systems, vol. 6, N°3, August 1998.

[8] H. Bühler. Réglage par mode de glissement. Traité d'électricité, 1ère édition, presses polytechnique romandes, Lausanne, 1986.

[9] C. Namuduri and P. C. Sen. A servo-control system using a self-controlled synchronous motor (SCSM) with sliding mode control. IEEE Trans. on Industry Application, vol. IA-23, N°2, March/April 1987.

[10] V. I. Utkin. Sliding modes and their application in variable structure system. MIR, Moscow, 1978.

[11] S. Y. Yi, M. J. Chung. Systematic design and stability analysis of a fuzzy logic controller. Fuzzy Sets Syst., vol. 72, 1995, 271–298.

[12] H. K. Khalil. Non linear system. MacMillan, New York, 1992.

[13] G. C. Hwang, S. C. Lin. A stability approach to fuzzy control design for non linear systems. Fuzzy Sets Syst., vol. 48, 1992, 279–287

[14] M. N. Cirstea, A. Dinu, J.G. Khor, M. McCormick. Neural and Fuzzy Logic Control of Drives and Power Systems, Newnes, Oxford, 2002.

[15] J. T. Spooner, M. Maggiore, R. Ordonez, K. M. Passino. Stable adaptative control and estimation for nonlinear system, Neural and fuzzy approximator techniques. Willey-Interscience, 2002.

[16] B. K. BOSE. Expert System, Fuzzy logic, and neural network Applications in power Electronics and motion control. Proceedings of the IEEE, Vol. 82, NO. 8 August 1994, 1303-1321.

[17] B. K. Bose. Power electronics and AC drives. Prentice Hall, Englewood Cliffs, Newjersey, 1986.

[18] G. Sturtzer, E. Smigiel. Modélisation et commande des moteurs triphasés. édition Ellipses, 2000.

[19] J. P. Cambronne, Ph. Le Moigne, J. P. Hautier. Synthèse de la commande d'un onduleur de tension. Journal de Physique III, France, 1996, 757–778.

[20] M. Abid, Y. Ramdani, A. Bendaoud, A.. Meroufel. Réglage par mode glissant d'une machine asynchrone sans capteur mécanique. Rev. Roum. Sci. Techn. – Electrotechn. et Energ., 2004, 406–416.

Received January 3, 2008, accepted April 17, 2009

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