Vector control of induction motor using moving sliding mode fuzzy controller

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Abstract

A sliding motion can be divided into two phases: reaching phase and sliding phase. One of the features of sliding mode control is that it is robust to parameter uncertainties and external disturbances in the sliding phase. But in the reaching phase, SMC may be sensitive to parameter uncertainty and external disturbance. The moving sliding surface proposed by Choi et al can minimize or eliminate the reaching phase. In this article, the sliding mode fuzzy controller design method with a moving sliding surface is presented. The simulation results show the superiority of SMFC over classical SMC and PID controller in the presence of external disturbances.

Keywords: Vector control; Sliding-mode control; moving sliding surface; Fuzzy control; Induction motor

1. Introduction

Inaccuracy in modeling can have severe undesirable effects on nonlinear systems. Inaccuracies in modeling may be due to plan uncertainties or due to the purposeful choice of a simplified representation of system dynamics. Uncertainties can be divided into two categories: structural and non-structural. Controlling nonlinear systems that have both structural uncertainty and non-structural uncertainty is a difficult matter [1,2]. Variable structure control was proposed for the first time in the early 1950s by Emalyanov. Sliding mode control is a variable structure control method that has the ability to deal with uncertainties and external disturbances [1-5].

In sliding mode control, the sliding movement can be divided into two phases: reaching phase and sliding phase. One of the disadvantages of sliding mode control is that the system is robust against uncertainty and disturbances only in the sliding phase, while it is sensitive to these uncertainties in the reaching phase. One of the methods to minimize or eliminate the reaching phase was proposed by Choi et al in articles [3, 4] that used a moving sliding surface to minimize the reaching phase. In the past three decades, fuzzy systems have replaced conventional technologies in many applications, especially in control systems. One major feature of fuzzy logic is its ability to express the amount of ambiguity in human thinking. Thus, when the mathematical model of one process does not exist, or exists but with uncertainties, fuzzy logic is an alternative way to deal with the unknown process. Another interesting feature of fuzzy logic controller is that as an expert knowledge, it can be easily entered into the control rules and has the ability to deal with uncertainties [6,7]. According to the above statements, the combination of FLC and SMC to achieve stability and better performance can be an interesting topic for research [8-12]. In this article, a sliding mode fuzzy controller with a moving sliding surface is proposed, which has good features such as: stability, fast response, good tracking and robustness to parametric uncertainties and external disturbances. The simulation results show the superiority of SMFC over classical SMC and PID controller in the presence of external disturbances.

2. Problem Formulation

The induction motor model in the synchronous rotating frame of reference ($\omega = \omega_e$) if d and q components of stator current and rotor flux are assumed to be state variables, will be as follows [13-15]:

$$\begin{aligned}
\dot{\psi}_{dr} &= \omega_{sl}\,\psi_{qr} - \frac{R_r}{L_r}\,\psi_{dr} + L_m\frac{R_r}{L_r}i_{ds} \\
\dot{\psi}_{qr} &= -\omega_{sl}\,\psi_{dr} - \frac{R_r}{L_r}\,\psi_{qr} + L_m\frac{R_r}{L_r}i_{qs} \\
\dot{i}_{ds} &= \frac{1}{L_\sigma L_s}u_{ds} - \frac{1}{L_\sigma L_s}\left(R_s + \frac{R_r L_m^2}{L_r^2}\right)i_{ds} \\
&\quad + \frac{R_r L_m}{L_r^2 L_\sigma L_s}\psi_{dr} + \frac{L_m}{L_r\,L_\sigma L_s}\omega_r\psi_{qr} + \omega_e i_{qs} \\
\dot{i}_{qs} &= \frac{1}{L_\sigma L_s}u_{qs} - \frac{1}{L_\sigma L_s}\left(R_s + \frac{R_r L_m^2}{L_r^2}\right)i_{qs} \\
&\quad + \frac{R_r L_m}{L_r^2 L_\sigma L_s}\psi_{qr} - \frac{L_m}{L_r\,L_\sigma L_s}\omega_r\psi_{dr} - \omega_e i_{ds}
\end{aligned} \tag{1}$$

Where u_{ds} , u_{qs} are the applied voltages to phases d and q of the stator, respectively; i_{ds} , i_{qs} , are the corresponding stator currents. The rotor flux in the direct axis is given by ψ_{dr} whereas in the quadrature axis it is defined by ψ_{qr} . the rotor speed is given by ω_r and the angular speed of the rotor flux linkage vector by ω_e . R_s , R_r are the stator and rotor resistances; L_s , L_r are the stator and rotor selfinductances; L_m is the stator-rotor mutual inductance. $L_\sigma = 1 - \frac{L_m^2}{L_r\,L_s}$ is the leakage coefficient.

On the assumption that the effects of magnetic saturation, core loss and skin effect are neglected. The electrical model is augmented by the mechanical subsystem given as:

$$\dot{\omega}_r = -\frac{B}{J}\,\omega_r + \frac{P}{J}(T_e - T_l) \tag{2}$$

$$T_e = \frac{3}{4}P\frac{L_m}{L_r}\left(\psi_{dr}i_{qs} - \psi_{qr}i_{ds}\right) \tag{3}$$

Where J and B denote the motor-load moment of inertia and the viscous friction coefficient; P is the number of pole pairs and T_l is the load torque.

The desired values of rotor flux under the rotor flux linkages oriented in the d-axis are given by:

$$\psi_{dr}^* = L_m i_{ds}^* \tag{4}$$

$$\psi_{qr}^* = 0 \tag{5}$$

Under the complete field-oriented control, the mechanical equation (2) can be equivalently described as [17]:

$$\dot{\omega}_r + a\,\omega_r + f = b\psi_{dr}^* i_{qs}^* \tag{6}$$

Where:

$$a = \frac{B}{J}\quad,\quad b = \frac{3P^2 L_m}{4L_r J}\quad,\quad f = P\frac{T_l}{J} \tag{7}$$

Let $\omega_r = \dot{\theta}_r$, the mechanical equation of IM system can be represented as:

$$\ddot{\theta}_r + a\,\dot{\theta}_r + f = b\psi_{dr}^* i_{qs}^* \tag{8}$$

Furthermore, consider (8) with uncertainties:

$$\ddot{\theta}_r + (\hat{a} + \Delta a)\dot{\theta}_r + \left(\hat{f} + \Delta f\right) = (\hat{b} + \Delta b)\psi_{dr}^* i_{qs}^* \tag{9}$$

Where the term Δa , Δb and Δf represents the uncertainties of the terms a , b and f respectively $\hat{a}$, $\hat{b}$ and $\hat{f}$ are the nominal values of the terms a, b and f respectively. It shoud be noted that these uncertainties are unknow, and that the precise calculation of its upper bound are, in general, rather difficult to achieve.

Let us define the tracking position error as follows:

$$e = \theta_r - \theta_r^* \tag{10}$$

Now the issue of tracking control is to design a moving sliding mode fuzzy control law for i_{qs}^* in such a way that θ_r can track the desired path in the presence of uncertainty and disturbance.

3. classical Sliding-Mode Control

In order to design a sliding mode controller, two essential steps should be carefully investigated, namely, the selection of sliding mode surface and the design of control law.

The selection of sliding mode surface is based on desired motion of the system. considering the simplicity of design, we define a sliding surface as:

$$s = \dot{e} + \lambda e \tag{11}$$

The derivative of s is: (12)

$$\dot{s} = \ddot{e} + \lambda \dot{e}$$

Substituting Eq. (8) and (10) into Eq. (12) then

$$\dot{s} = -a\,\dot{\theta}_r - f + b\psi_{dr}^* i_{qs}^* - \ddot{\theta}_r^* + \lambda \dot{e} \tag{13}$$

When the sliding mode occurs, $s = \dot{s} = 0$ and the equivalent control value is obtained from zero-setting equation (13), as follows:

$$i_{qseq}^* = -\left(\hat{b}\psi_{dr}^*\right)^{-1}\left[-\hat{a}\,\dot{\theta}_r - \ddot{\theta}_r^* + \lambda\dot{e} + \hat{f}\,\right] \tag{14}$$

Therefore, control law can be described as follow:

$$i_{qs}^* = i_{qseq}^* + i_{qsdis}^* = i_{qseq}^* - \left(\hat{b}\psi_{dr}^*\right)^{-1} K\, sign(s) \tag{15}$$

that K is positive definite and is defined in such a way as to guarantee the condition of stability. $sign(s)$ also represents the sign function. The permissible range of K is equal to [1]:

$$K \geq \hat{b}b^{-1}\left[\left|a\,\dot{\theta}_r\right| + |f| + \left|b\hat{b}^{-1}\hat{a}\,\dot{\theta}_r\right| + \left|b\hat{b}^{-1} - 1\right|\left|\ddot{\theta}_r^* - \lambda\dot{e}\right| + \eta\right] \tag{16}$$

The existence of the discontinuous part i_{qsdis}^* causes the chattering phenomenon around the sliding surface. In order to reduce it, we define a boundary layer with thickness φ around the sliding surface. To create this layer, it is enough to replace $sign$ with the saturation function sat, which is defined as follows, in relation (15).

$$sat\left(\frac{s}{\varphi}\right) = \begin{cases} sgn\left(\frac{s}{\varphi}\right) & |s| \geq |\varphi| \\ \frac{s}{\varphi} & |s| < |\varphi| \end{cases} \tag{17}$$

Remark: The decoupling control method with compensation is to choose inverter output voltages such that:

$$u_{qs} = \left(K_{pq} + \frac{K_{iq}}{s}\right)\left(i_{qs}^* - i_{qs}\right) \tag{17}$$

$$u_{ds} = \left(K_{pd} + \frac{K_{id}}{s}\right)\left(i_{ds}^* - i_{ds}\right) \tag{18}$$

$$u_{ds} = \left(K_{pd} + \frac{K_{id}}{s}\right)\left(i_{ds}^* - i_{ds}\right) \tag{19}$$

4. Moving Sliding ModeFuzzy Control

One of the problems of the classic sliding mode controller is that it is robust only in the sliding phase of the uncertainty and the disturbance, and it is not robust in the reaching phase. One of the proposed solutions is to minimize the reaching phase by rotating or shifting the sliding surface, which is called the moving sliding surface (MSS) [3-5]. For the nonlinear system with dynamic equation (1), the moving sliding surface is considered as follows:

$$s(e,e,t)=e+\lambda e-\gamma \quad (20)$$

The rotation of the surface is done by changing λ, which is the slope of the surface, and the displacement is done by changing the value of γ. In second-order systems, if the initial condition is in quadrant one or three, we will shift the sliding surface, and if it is in quadrant two or four, we will rotate it. Based on the above statements, the control law of the sliding mode with a boundary layer and a moving sliding surface is as follows:

$$i_{qs}^{*}=i_{qseq}^{*}-K\hat{b}^{-1}\ sat(\frac{\dot{e}+\lambda e-\gamma}{\varphi}) \quad (21)$$

Where i_{qseq}^{*} is the equivalent control and can be calculated from equation (14).

We will use fuzzy logic to adjust the values of λ and γ and adjust them based on the error and error changes. With two inputs and one output, the fuzzy rules in the simple Sugeno method are as follows:

IF e is A_i and $\dot{e}$ is B_i **THEN**

$$i_{qs}^{*}=i_{qseq}^{*}-K\hat{b}^{-1}\,sat(\frac{\dot{e}+\lambda_i e-\gamma_i}{\varphi}) \quad (22)$$

First, for each of the inputs e and $\dot{e}$, we define six membership functions $\{NL,NS,NZ,PZ,PS,PL\}$ according to Figure 1, then the Sugeno fuzzy rule base to obtain λ_i and γ_i as Tables 1 and 2 is considered.

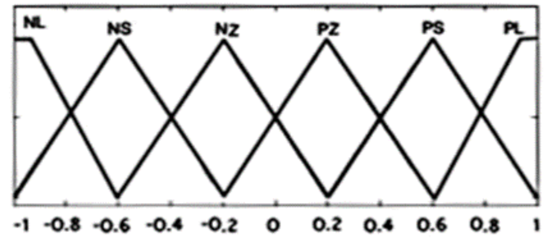

Fig. 1. Membership functions for inputs e and $\dot{e}$

$\dot{e}$	e					
	PL	PS	PZ	NZ	NS	NL
PL	0.6	0.7	0.6	0.7	0.8	0.6
PS	0.7	0.8	0.8	5	5	5
PZ	0.7	0.8	5	8	8	8
NZ	8	8	8	5	0.6	0.8
NS	5	5	5	0.7	0.7	0.6
NL	0.8	0.8	0.6	0.6	0.8	0.8

Table 1. Rule base for λ_i

$\dot{e}$	e					
	PL	PS	PZ	NZ	NS	NL
PL	-15	-7	-5	0	0	0
PS	-7	-3	-1	0	0	0
PZ	-3	-2	0	0	0	0
NZ	0	0	0	0	2	3
NS	0	0	0	1	3	7
NL	0	0	0	4	7	15

Table 2. Rule base for γ_i

In addition, the overall structure of moving sliding mode fuzzy control technique in the induction motor can be shown in Figure 2.

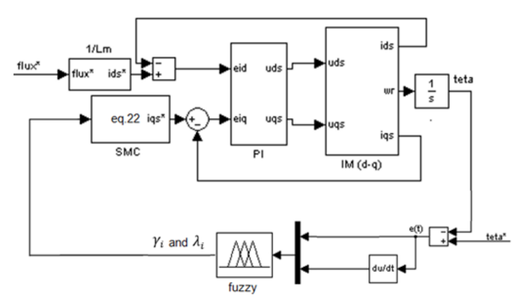

Fig. 2. Overall moving sliding mode fuzzy control scheme

5. Simulation Results

An induction motor with the following parameters is assumed:

$P_n = 1.5$ Kw , $V_n = 220$ V , $I_n = 6.31$ A , $f_n = 50$H,
$\omega_n = 1428$, $R_s = 4.85 \pm 50\%\ \Omega$,
$R_r = 3.805 \pm 50\%\ \Omega$, $L_s = 0.274 \pm 50\%$ H
$L_r = 0.274 \pm 50\%$ H , $L_m = 0.258 \pm 50\%$ H
$P = 2$, $J_n = 0.031 \pm 50\%$, $B_n = 0.008$

The ψ_{dr}^* is set to 1Wb and ψ_{qr}^* is set to 0Wb. Also, the parameters of PI controllers in relations (18) and (19) are equal to: $K_{pq} = 6$, $K_{iq} = 5$, $K_{pd} = 70$, $K_{id} = 5$.

In the simulations, the design parameters of all the controllers under consideration are as follows:

$$SMC:\ \lambda = 30\ , K = 1000\ , \varphi = 0.45 \quad (23)$$
$$SMFC:\ K = 1000\ , \varphi = 0.45$$
$$PID:\ K_p = 20\ , K_d = 1.8\ , K_i = 0.03$$

To check the performance of the above controllers, we consider two modes:

Case 1: without uncertainty and disturbance

$$R = \hat{R}\ , L = \hat{L}\ , T_l = 0 \quad (24)$$

Case 2: with uncertainty and disturbance

$$R = 1.5\hat{R}\ , L = 1.5\hat{L}\ , T_l = 4\, sin(3t) \quad (25)$$

In the first case, for the desired position input $\theta_r^* = 10\, u(t)$, Figure 3 shows the tracking of SMC, SMFC and PID controllers. As can be seen, the moving sliding mode fuzzy control has less rise time than other controllers. Figures 4 and 5 show the control effort and the $\dot{e} - e$ diagram of the controllers, respectively.

For the second case, Figure 6 shows the tracking of SMC, SMFC and PID controllers. The simulation results clearly show that the PID controller is sensitive to parametric uncertainty and external disturbances. On the other hand, as can be seen, the classical sliding mode control is robust in the sliding phase but sensitive to disturbance in the reaching phase, while the proposed moving sliding mode fuzzy control is completely robust to uncertainty and disturbance in both phases.

In order to better check the performance of the controllers, Figure 7 shows the tracking of the controllers in the presence of uncertainty and disturbance for the desired input $\theta_r^* = sin(t)$.

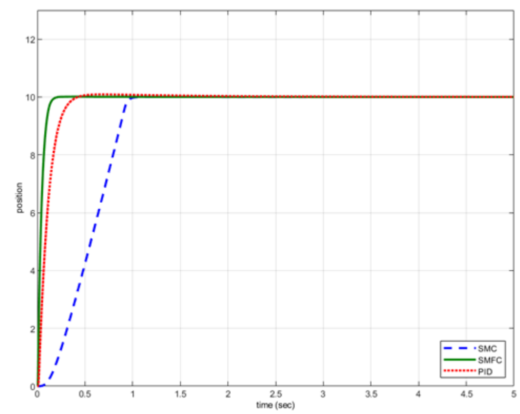

Fig. 3. Tracking of SMC, SMFC and PID controllers for with desired step input for the first case.

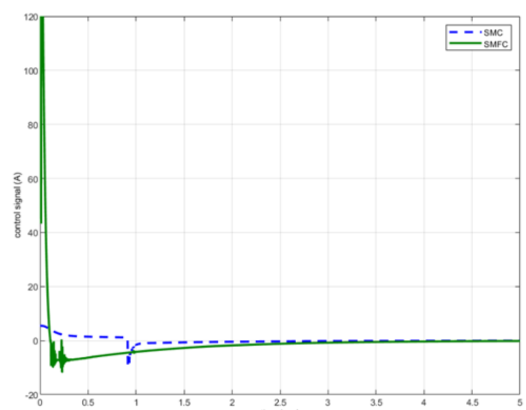

Fig. 4. Control effort of SMC and SMFC.

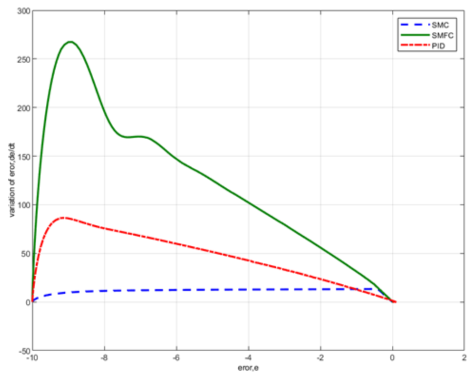

Fig. 5. Diagram of $\dot{e} - e$.

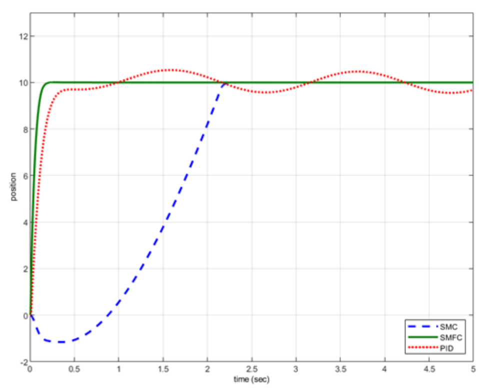

Fig. 6. Tracking of SMC, SMFC and PID controllers for with desired step input for the second case.

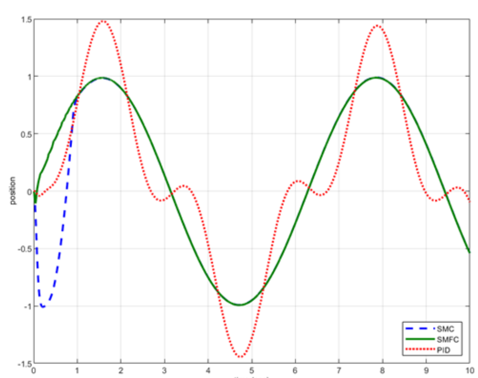

Fig. 7. Tracking of SMC, SMFC and PID controllers for with desired input θ_r^*=sin(t) for the second case.

Conclusions

Classical sliding mode control methods are not robust to uncertainty and disturbance in the sliding phase. In this paper, a sliding mode fuzzy controller with moving sliding surface was proposed for nonlinear systems to reduce or eliminate the sliding phase. The simulation results showed the superiority of the proposed method over classical sliding mode control and PID controller.

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