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Fuzzy Sliding Mode Speed Controller for a Vector Controlled Induction Motor

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Abstract**—**This paper presents a speed fuzzy sliding mode controller for a vector controlled induction machine (IM) fed by a voltage source inverter (PWM).

The sliding mode based fuzzy control method is developed to achieve fast response, a best disturbance rejection and to maintain a good decoupling.

The problem with sliding mode control is that there is high frequency switching around the sliding mode surface. The FSMC is the combination of the robustness of Sliding Mode Control (SMC) and the smoothness of Fuzzy Logic (FL). To reduce the torque fluctuations (chattering), the sign function used in the conventional SMC is substituted with a fuzzy logic algorithm.

The proposed algorithm was simulated by Matlab/Simulink software and simulation results show that the performance of the control scheme is robust and the chattering problem is solved.

Keywords**—**IM, FOC, FLC, SMC, and FSMC.

I. Introduction

THE field-oriented control technique has been widely used in industry for high-performance induction machine (IM) drive, where the knowledge of synchronous angular velocity is often necessary in the phase transformation for achieving the favorable decoupling control. However, the control performance of the IM is still influenced by the variations of motor parameters, especially the rotor time-constant, which vanes with the temperature and the saturation of the magnetizing inductance, the uncertainties, such as mechanical parameter variation, external disturbance, unstructured uncertainty due to non ideal field orientation in transient state, and unmodelled dynamics [l, 2, 3]. The control method presented is indirect rotor field oriented control (IFOC) with stator currents regulation [5, 6, 7, 8, 9]. The motivation of this study is to design a suitable control scheme to confront the uncertainties existed in practical applications of an indirect field-oriented IM drive. One of the possible approaches to the robust control of the uncertain systems has been found in variable structure systems and sliding mode control [3, 4, 10]. The sliding mode controller has been suggested to achieve robust performance against parameter variations and load disturbances. It also offers a fast dynamic response, stable control system and easy hardware-software implementation. On the other hand, this control method offers some drawbacks associated with the large torque chattering that appears in steady state. Chattering involves high-frequency control switching and may lead to excitation of unmodelled high frequency system dynamics. Chattering also causes high heat losses in electronic systems and undue wear in mechanical systems [3]. In order to reduce the system chattering, a SMC with fuzzy sliding surface were proposed [3, 10]. The sliding mode control and fuzzy control are combined to improve the dynamic performance of the fast response and robust of the sliding mode control and the softening and intellect of fuzzy control. The fuzzy logic controller (FLC) is not dependent on the accurate mathematical model of the system. It is based on 'IF…THEN' rules and experiences of human beings [3, 4, 10]. In this paper, by means of the advantage of SMC and FLC, a synthetic control scheme is presented. The fuzzy sliding mode controller (FSMC) is designed for the speed regulation of an indirect vector controlled DSIM fed by a two voltage source inverters. To evaluate the usefulness of the proposed method, we compare it to SMC. The simulation results show that our method can achieve very robust and satisfactory performance. The proposed control for the IM is simulated on MATLAB/SIMULINK.

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II. IM Mathematic Model

The study presented in this paper is based on the following assumptions: The air gap is uniform and the windings are sinusoidally distributed around the air gap. The magnetic saturation and core losses are neglected.

A. Electrical Equations

$$\begin{cases} V_{ds} = R_s\, I_{ds} + \dfrac{d\phi_{ds}}{dt} - \dfrac{d\theta_s}{dt}\,\phi_{qs} \\ V_{qs} = R_s\, I_{qs} + \dfrac{d\phi_{qs}}{dt} + \dfrac{d\theta_s}{dt}\,\phi_{ds} \end{cases}$$
$$\begin{cases} V_{dr} = 0 = R_r\, I_{dr} + \dfrac{d\phi_{dr}}{dt} - \dfrac{d\theta_{sr}}{dt}\,\phi_{qs} \\ V_{qr} = 0 = R_r\, I_{qr} + \dfrac{d\phi_{qr}}{dt} + \dfrac{d\theta_{sr}}{dt}\,\phi_{ds} \end{cases} \tag{1}$$

with

$$\begin{cases}\phi_{ds} = L_s\, I_{ds} + M\, I_{dr}\\ \phi_{qs} = L_s\, I_{qs} + M\, I_{qr}\end{cases}$$
$$\begin{cases}\phi_{dr} = L_r\, I_{dr} + M\, I_{ds}\\ \phi_{qr} = L_r\, I_{qr} + M\, I_{qs}\end{cases} \tag{2}$$

B. Mechanical Equation

$$C_e = \frac{3}{2} P \frac{M}{L_r}\left(\phi_{dr}\, I_{qs} - \phi_{qr}\, I_{ds}\right) \tag{3}$$

III. Inverter Modelling

PWM is used in power electronics to "digitalize" the power so that a sequence of voltage pulses can be generated by the on and off for the power converter. Then, the PWM-VSI is expressed by the imposed sequencings at semiconductors which realize modulation of voltages applied to stator windings. Voltages at load neutral point, for one SVI, can be given by the following expression:

$$\begin{bmatrix} v_a\\ v_b\\ v_c\end{bmatrix} \frac{V_d}{6}\begin{bmatrix}2 & -1 & -1\\ -1 & 2 & -1\\ -1 & -1 & 2\end{bmatrix}\begin{bmatrix}S_1\\ S_2\\ S_3\end{bmatrix} \tag{4}$$

$S_i \quad (i = 1,2,3)$: Logic signal $\quad V_d$: direct voltage.

IV. IM Field Oriented Control

The application of the field oriented control consists on the orientation of the rotor flux vector along the'*d*' axis [6,7] which can be expressed by considering $\emptyset_{dr} = \emptyset_r^*$ and $\emptyset_{qr} = 0$. Consequently, the dynamic equations (3) after arrangement yield to:

- The relationship between torque and flux:

$$T_e^* = p\,\frac{l_m}{l_m + l_r}(I_{qs})\emptyset_r^* \tag{5}$$

- The relation between slip speed and stator currents

$$\omega_{sl}^* = \frac{R_r}{l_m + l_r}(I_{qs}) \tag{6}$$

- The relations between voltages and currents components are:

$$V_{ds}^* = R_s I_{ds} + s l_s I_{ds} - \omega_s^*\left(l_s I_{qs} + T_r \emptyset_r^* \omega_{sl}^*\right) \tag{7}$$

$$V_{qs}^* = R_s I_{qs} + s l_s I_{qs} + \omega_s^*(l_s I_{ds} + \emptyset_r^*) \tag{8}$$

where, $T_r = \frac{l_r}{R_r}$ is time rotor constant.

The voltage expressions show that the axes 'd q' are not independents, so, for a decoupling system, it is necessary to introduce new variables.

$$V_{ds} = \omega_s^*(l_s I_{qs} + T_r \emptyset_r^* \omega_s^*)$$
$$V_{qs} = \omega_s^*(l_s I_{ds} + \emptyset_r^*)$$

And

$$V_{ds1} = R_s I_{ds} + s l_{s1} I_{ds}$$
$$V_{qs1} = R_s I_{qs} + s l_{s1} I_{qs}$$

The equation system (7) and (8) shows that stator voltages are directly related to stator currents. To compensate the error introduced at decoupling time, the voltage references at constant flux are given by:

$$V_{ds}^* = V_{ds1} - V_{ds}$$
$$V_{qs}^* = V_{qs1} - V_{qs}$$

For a perfect decoupling, we add stator currents regulation loops I_{ds}, I_{qs}, and we obtain at their output stator voltages V_{ds}, V_{qs} . The regulation goal is to assure a good performance for internal current loops. In this work, indirect field oriented control (IFOC) with PWM source voltage inverter which fed the IM is studied. So, the SMCs and FSMCs have been tested for the IFOC decoupling block and the speed controller. The flux is generally maintained constant at its nominal value through the field weakening block described by a nonlinear function. According to the above analysis, the IM block diagram with speed controller and IFOC strategy is shown in Fig. 1.

V. Sliding Mode Control Design

The basic principle of the sliding mode control consists in moving the state trajectory of the system toward a surface $S(X) = 0$ and maintaining it around this surface with the switching logic function U_n. The basic sliding mode control law is expressed as.

$$U_c = U_{eq} + U_n \tag{9}$$

This expression uses two terms, U_{eq} and U_n. U_{eq}: is determined off line with a model that represents the plant as accurately as possible. It is used when the system state is in the sliding mode. The term U_n : is a sign function defined as $U_n = k\,\mathrm{sgn}(S(X))$, where:

$$sgn(S(X)) = \begin{cases} 1 & if \quad S(X) < 0\\ -1 & if \quad S(X) > 0\end{cases} \tag{10}$$

This will guarantee that the state is attracted to the switching surface by satisfying the Lyapunov stability criteria shown in (15):

$$S(X)\dot{S}(X) < 0 \tag{11}$$

This strategy enforces the system trajectory to move toward and to stay on the sliding surface from any initial condition. Using a sign function often causes chattering in practice. One solution to reduce chattering is to introduce a boundary layer around the sliding surface [5], [6]. This is expressed by:

$$U_n = \begin{cases} \frac{k}{\varepsilon} S(X) & if \quad \left|S(X)\right| < \varepsilon \\ k\, sgn(S(X)) & if \quad \left|S(X)\right| > \varepsilon \end{cases} \tag{12}$$

with k, a positive coefficient and ε, the thickness of the boundary layer. However, a small value of ε might produce a boundary layer so thin that it can excite high frequency dynamics [7].

VI. IM Sliding Mode Control

The 'd' axis, has the stator current component (Ids) loop and the 'q' axis allows the control stator current component (Iqs), whereas the external loop provide the regulation of the speed.

A. Speed SMC

Under field oriented assumptions, the electromagnetic torque can be expressed as:

$$T_e = \frac{Pl_m}{l_m + l_r}\left(I_{qs}\right)\emptyset_r^* = k_T I_{qs} \tag{13}$$

where, k_T is the torque constant and $\emptyset_r^*$ is the flux reference.

To design a sliding mode speed controller for the double star induction motor FOC drive, consider the mechanical equation:

$$\frac{J}{p}\dot{\Omega}_r + \frac{K_f}{p}\Omega_r + T_L = T_e \tag{14}$$

where Ω_r is the rotor speed in electrical rad/s, rearranging to get:

$$\dot{\Omega}_r = \frac{p}{J}T_e - \frac{K_f}{J}\Omega_r - \frac{p}{J}T_L \tag{15}$$

Considering Δa and Δb as bounded uncertainties introduced by system parameters J and K_f, (15) can be rewritten as:

$$\dot{\Omega}_r = (a + \Delta a)\Omega_r + (b + \Delta b)T_e + cT_L \tag{16}$$

where $a = -\frac{K_f}{J}$, $b = \frac{p}{J}$, $c = -\frac{p}{J}$

Defining the state variable of the speed error as:

$$e(t) = \Omega_r(t) - \Omega_r^*(t) \tag{17}$$

Combining (16) with (17) and taking the derivative of (17) yields:

$$\dot{e}(t) = ae(t) + b\{\overline{T}_e + d(t)\} \tag{18}$$

where d(t) is the lumped uncertainty defined as:

$$d(t) = \frac{\Delta a}{b}\Omega_r(t) + \frac{\Delta b}{b}T_e + \frac{c}{b}T_L \tag{19}$$

And :

$$\overline{T}_e(t) = T_e(t) + \frac{a}{b}\Omega^* \tag{20}$$

Defining a switching surface $s(t)$ from the nominal values of system parameters a and b [7-9]:

$$s(t) = e(t) - \int_0^t (a + bk)e(\tau)d\tau \tag{21}$$

Such that the error dynamics at the sliding surface s(t) = ṡ(t) = 0 will be forced to exponentially decay to zero, then the error dynamics can be described by:

$$\dot{e}(t) = (a + bk)e(t) \tag{22}$$

where k is a linear negative feedback gain [9]. The variable structure speed controller law can be defined as:

$$\overline{T}_e = ke(t) - \beta sign(s(t)) \tag{23}$$

where β is known as hitting control gain used to make the sliding mode condition possible and the sign function can be defined as [9]:

$$sign(s) = \begin{cases} 1 & if \quad s > 0 \\ 0 & if \quad s = 0 \\ -1 & if \quad s < 0 \end{cases} \tag{24}$$

The final electromagnetic torque command T_e^* of the output of the sliding mode speed controller can be obtained by directly substituting (27) into (24). Basically, the control law for T_e^* is divided into two parts: equivalent control U_{eq} which defines the control action when the system is on the sliding mode and switching part U_s which ensures the existence condition of the sliding mode. If the friction k_f is neglected expressions for U_{eq} and U_s can be written as:

$$\begin{cases} U_{eq} = ke(t) \\ U_s = -\beta sign(s(t)) \end{cases} \tag{25}$$

To guarantee the existence of the switching surface consider a Lyapunov function [6, 9]:

$$V(t) = \frac{1}{2}s^2(t) \tag{26}$$

Based on Lyapunov theory, if the function $\dot{V}(t)$ is negative definite, this will ensure that the system trajectory will be driven and attracted toward the sliding surface *s(t)* and once reached, it will remain sliding on it until the origin is reached asymptotically [6]. Taking the derivative of (30) and substituting from the derivative of (25):

$$\dot{V}(t) = s(t)\dot{s}(t) = s(t)\{\dot{e}(t) - (a + bk)e(t)\} \leq 0 \quad (27)$$

Substitute from (19) into (28):

$$s(t)\dot{s}(t) = s(t)\{b\overline{T}_e(t) + bd(t) - bke(t)\} \quad (28)$$

Using (27) gives:

$$s(t)\dot{s} = s(t)\{-\beta sign(s(t)) - d(t)\} \leq 0 \quad (29)$$

To ensure that (28) will be always negative definite, the value of the hitting control gain β should be designed as the upper bound of the lumped uncertainties d(t), i.e.

$$\beta \geq |d(t)| \quad (30)$$

However, it is difficult practically to estimate the bound of uncertainties in (). Therefore the hitting control gain β has to be chosen large enough to overcome the effect of any external disturbance [5], [6]. Therefore the speed control law defined previously will guarantee the existence of the switching surface s(t) and when the error function e(t) reaches the sliding surface, the system dynamics will be governed by (22) which is always stable [10]. Moreover, the control system will be insensitive to the uncertainties Δa, Δb and the load disturbance T_L. The use of the sign function in the sliding mode control will cause high frequency chattering due to the discontinuous control action which represents a severe problem when the system state is close to the sliding surface [6]. To overcome this problem an approach which combines FL with SM is used. The saturation function is replaced by a fuzzy inference system to smooth the control action. The membership functions for the input and output of the FL controller are obtained by trial error to ensure optimal performance.

B. Current SMCs

$$S(I_{qs}) = (I_{qs}^* - I_{qs})$$
$$S(I_{ds}) = (I_{ds}^* - I_{ds})$$

The control law development for each variable in sliding mode theory is deduced from the reaching condition () and is indicated below

The current regulators laws in the 'd' axis and '*q*' axis can be written as

- ***Current Sliding Mode Control Law of*** I_{qs}

$$S(I_{qs}).\dot{S}(I_{qs}) < 0 \Rightarrow V_{qs}^s = V_{qs\_eq} + V_{qs\_n} \quad (31)$$

$$V_{qs\_eq} = R_s I_{qs} + l_s I_{qs} + \omega_s^*(l_s I_{ds} + \emptyset_r^*) \quad (32)$$

$$V_{qs\_n} = \begin{cases} \frac{k_q}{\varepsilon_q} S(I_{qs}) & if \ |S(I_{qs})| < \varepsilon_q \\ k_q sgn\left(S(I_{qs})\right) & if \ \ |S(I_{qs})| > \varepsilon_q \end{cases} \quad (33)$$

- ***Current Sliding Mode Control Law of*** I_{ds}

$$S(I_{ds}).\dot{S}(I_{ds}) < 0 \Rightarrow V_{ds}^s = V_{ds\_eq} + V_{ds\_n} \quad (34)$$
$$V_{ds\_eq} = R_s I_{ds} + l_s I_{ds} + \omega_s^*(l_s I_{qs} + T_r \emptyset_r^* \omega_{sl}^*) \quad (35)$$
$$V_{ds\_n} = \begin{cases} \frac{k_d}{\varepsilon_d} S(I_{ds}) & if \ |S(I_{ds})| < \varepsilon_d \\ k_q sgn(S(I_{ds})) & if \ \ |S(I_{ds})| > \varepsilon_d \end{cases} \quad (36)$$

To verify the system stability condition, the gains k_d, k_q, and ε_d, ε_q should be taken positive by selecting the appropriate values.

This sliding mode functions introduce some undesirable chattering. Hence, we will substitute it by the fuzzy logic function. In order to reduce the chattering, two current FSMCs are added to FSMC of the speed outer loop. These controllers are used under the same rules IF…THEN, max-min inference mechanism and center of gravity defuzzyfier [8]. The FSMCs are chosen as follows

$$\begin{cases} V_{ds}^f = V_{ds\_eq} + V_{ds\_f} \\ V_{qs}^f = V_{qs\_eq} + V_{qs\_f} \end{cases} \quad (37)$$

V_{ds_f}, V_{qs_f} are calculated with the fuzzy sliding rules described up.

VII. Simulation Results

The proposed scheme has been implemented with Matlab/Simulink in order to evaluate its performance.

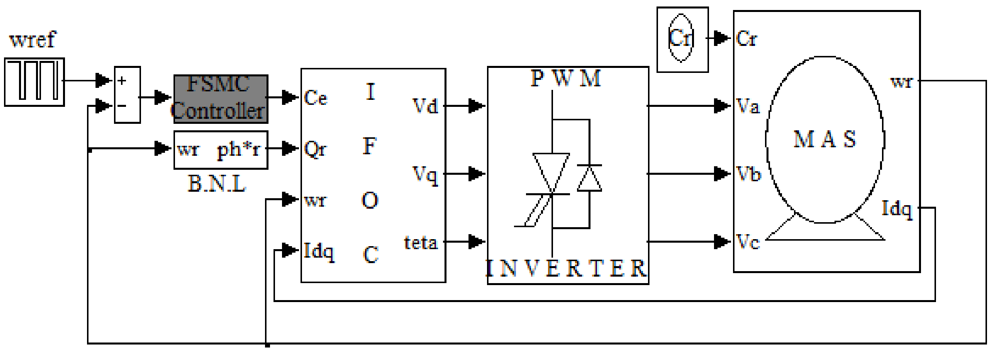

Fig. 1 Block diagram of simulated speed controller FSMC-IM scheme

First we present the simulated results of the IFOC system for IM where command input is step reference for speed with load torque variation. The speed regulator and the IFOC decoupling block are firstly controlled by FC and secondly by FSMCs.

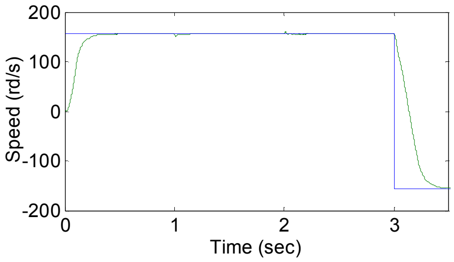

Fig. 2 Rotor speed

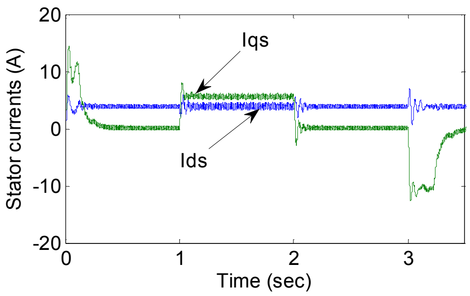

Fig. 3 Statoric currents

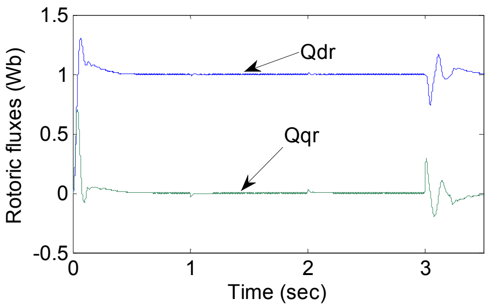

Fig. 4 Rotoric fluxes

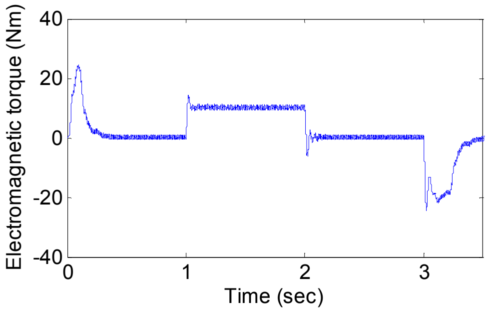

Fig. 5 Electromagnetic torque

VIII. Conclusion

From simulation results it was shown that the proposed Fuzzy Sliding Mode Controller is robust to external variations (application of the load torque) and has given satisfactory performances in speed response with no overshoot, rapid time response error and a good tracking reference speed.

The decoupling between the stator flux and the torque (speed) is maintained with regard to the application of external load disturbance. The FSMC performs a good reduction of the chattering effect (less fluctuation).

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