

# A Novel Sensorless Fuzzy Sliding-Mode Control of Induction Motor

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## Abstract

A novel fuzzy sliding-mode structure has been proposed for the model reference adaptive system (MRAS) based sensorless control of an induction motor in this paper. The design includes a hybrid MRAS from measured stator terminal voltages and currents. The estimated speed is used as feedback in an indirect vector control system achieving the speed control without using shaft mounted transducers. Fuzzy sliding-mode structure includes two nonlinear controllers, one of which is sliding mode type and the other is PI-fuzzy logic based controller, the latter define a new control structure. Both controllers are combined by means of an expert system based on Takagi-Sugeno fuzzy reasoning. The sliding mode controller acts in the steady state. The new structure has two advantages: sliding-mode controller increasing system stability and PI-like fuzzy logic based controller reducing the chattering in permanent state. The scheme has been implemented and experimentally validated.

**Keywords:** Model Reference Adaptive System; Fuzzy Sliding Mode; Induction Motor

## 1. Introduction

Recently, many research has been carried on the design of speed sensorless control schemes [1,2]. In these schemes the speed is obtained based on the measurement of stator voltages and currents. However, the estimation is usually complex and heavily dependent on machine parameters. Therefore, although sensorless vector controlled drives are commercially available at this time, the parameter uncertainties impose a challenge in the control performance.

Fuzzy sliding-mode controller have been researched and applied to different systems, however there are not many applications to an induction motor. In [3], a fuzzy neural network (FNN) sliding-mode controller with an integral-operation switching surface was adopted to control the position of an induction servomotor drive. In [4], another fuzzy sliding-mode controller was proposed for position control. In this case, the fuzzy controller is added to the sliding-mode controller, but the stability of the system could not be guaranteed.

This paper presents a new sensorless vector control scheme consisting of two aspect, the one is a speed estimation algorithm which overcomes the necessity of the speed sensor, the other is a novel fuzzy sliding-mode structure controller which combines the best of sliding-mode control (SLMC) and fuzzy logic based control (FLBC), SLMC mostly acts in a transient state, providing a fast dynamic response and enlarging the stability of the system, while the PI-like FLBC acts mainly in steady state to reduce chattering.

If we compare this approach with a classical PI controller, steady state performance is enhanced. Using this structure, better performances are achieved than using the SLM controller alone and similar to PI-like FLBC alone; in this case,

global stability is also assured. The effectiveness of this control method is demonstrated through experimental verifications.

## 2. Hybrid Model Reference Adaptive System

The improved MRAS based back electromagnetic force(BEMF) offers excellent characteristics such as simple algorithm, high precision in the steady state and wide adjustable speed range, but lack of response rapidity. So in this paper Attempted to realize a system which not only has rapid in the transient state but also has high accurate in the steady state, a novel hybrid MRAS method is proposed to improve rapidity and precision of speed identification. This method is combined direct synthesis with improved model referencing adaptive system and realized closed loop control of speed sensorless with flux observer. Speed identification control system based hybrid MRAS is shown in Figure 1, speed adjust signal of model reference adaptive is  $\varepsilon$ , a novel speed estimate  $\hat{\omega}_{r2}$  is obtained by feeding the error term  $\varepsilon_1$  into a PI controller, where,  $\varepsilon_1 = \hat{\omega}_r - \hat{\omega}_{r2}$ ,  $\hat{\omega}_{r1}$  is obtained by direct synthesis method, speed estimate values of system is  $\hat{\omega}_r$ ,  $\hat{\omega}_r$  is gained by equation(1).

$$\hat{\omega}_r = k \cdot \hat{\omega}_{r1} + (1 - k) \cdot \hat{\omega}_{r2} \quad 0 \leq k \leq 1 \quad (1)$$

Where,  $k$  is hybrid weighting factor.

Following speed is connected with PI regulators at the condition of variable command speed, rapidly dynamic response is obtained after adaptive model is adjusted by  $\hat{\omega}_r$  and adding  $\varepsilon_1$  to input PI controller.

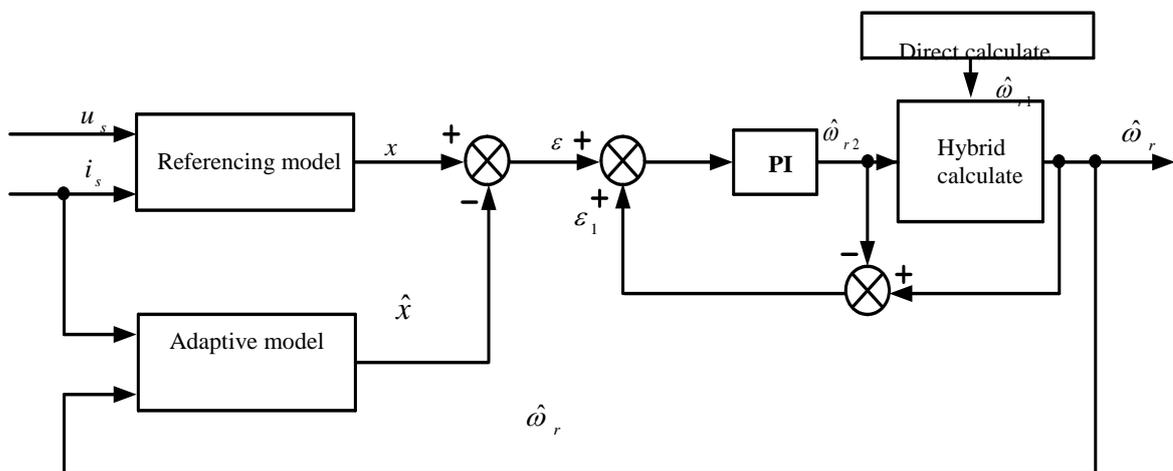
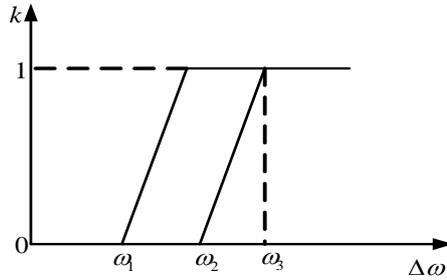


Figure 1. Controlled Diagram of Hybrid MARS Speed Identification Method

The speed Error Equation can be written as:

$$\Delta \omega = \left| \omega^* - \hat{\omega}_r \right| \quad (2)$$

$k$  value is determined by  $\Delta \omega$ , adopted simply hysteresis control in order to improve response rapidly, weighting model of hybrid control as Figure 2, MRAS controller acts as  $\Delta \omega$  is very small. The direct synthesis controller acts as  $\Delta \omega$  is very large, double controllers act as  $\Delta \omega$  is medium ( $0 \leq k \leq 1$ ). This method improved speed identification rapidity and precision by combining direct Integrate with Model Reference Adaptive system. Realized Closed loop control of sensorless with flux observer.



**Figure 2. Hybrid Control Weighting Model**

### 3. Speed Sensorless Induction Motor Model

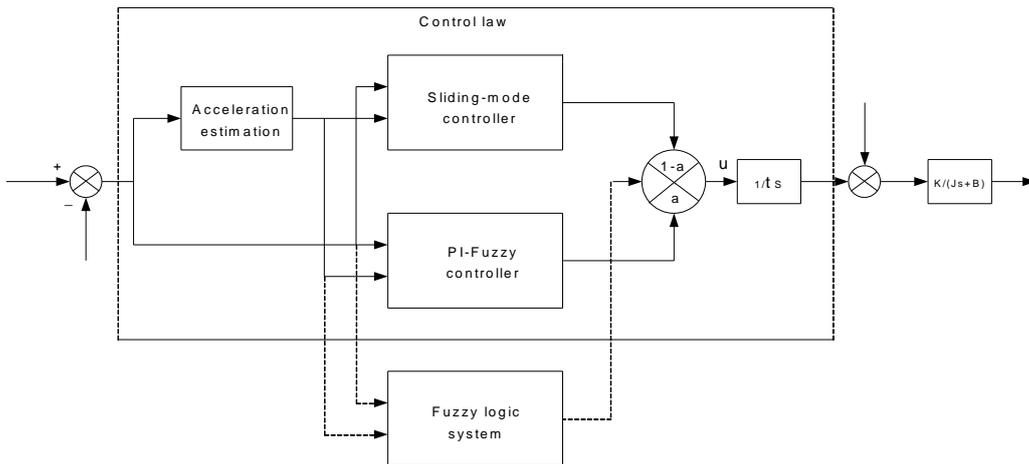
The structure of the control system is shown in Figure 3. The indirect vector control method is used and the flux component of the stator current,  $i_{ds}^{ref}$ , is maintained constant, although this is not a restriction. The output of the proposed controller is the desired torque component of the stator current,  $i_{qs}^{ref}$ . The electromagnetic torque  $T_e$  is proportional to this current component.

$$T_e = k \cdot i_{qs}^{ref} \quad (3)$$

where  $k$  is the proportional constant. The vector controlled induction motor model can be expressed by (4)

$$\frac{d\omega_m}{dt} = \frac{1}{J} (k \cdot i_{qs}^{ref} - T_l - B \cdot \omega_m) \quad (4)$$

where  $J$  represents the inertial constant,  $k$  is the torque constant,  $B$  is the friction constant,  $T_l$  is the load torque, and  $\omega_m$  is the measured speed. The model is a first-order model and is shown by Laplace transformation in Figure 3.



**Figure 3. Structure of the Control System Proposed**

To obtain the control law, the SLMC and the PI-FLBC are separately designed to obtain especially good characteristics in the state where each one provides the prevailing control action. Afterwards, they are adjusted to achieve satisfactory features when they are combined. The error between the desired speed  $\omega_{ref}$ , and the estimated speed  $\omega_m$ , and the change in that error are the inputs to both controllers. The control actions are combined by means of a weighting factor,  $\alpha$ , which is the output of a fuzzy logic system

that operates at a higher hierarchical control level. It divides the control region depending on the speed error and change in error. The final action  $i_{qs}^{ref}$  is built as follows:

$$\begin{aligned} u_{sl} &= \Delta i_{qs}^{ref-sl} \\ u_{fc} &= \Delta i_{qs}^{ref-fc} \\ u &= \Delta i_{qs}^{ref} = (1 - \alpha) \cdot u_{sl} + \alpha \cdot u_{fc} \\ i_{qs}^{ref} &= \frac{1}{\tau} \int_0^t \Delta i_{qs}^{ref} dt \quad (5) \end{aligned}$$

where  $\Delta i_{qs}^{ref-sl}$  is the output of the SLMC and  $\Delta i_{qs}^{ref-fc}$  is the output of the FLBC.

$u$  represents the global control action before the integrator and it is equal to  $\Delta i_{qs}^{ref}$  and  $\tau$  is the control action integration constant.

### 3.1. SLMC

One of the drawbacks related to the high gain inherent in sliding-mode methods is the large torque chattering due to the sliding mode switching control law. One cause for this phenomenon is the presence of finite time delays in control computations. Another one is the limitations of the physical actuators which are unable to switch current at an infinitely fast rate. Although it is specially noticeable in the steady state it also exists when the system is approaching this state.

Thus, an integral compensation can be inserted in order to decrease chattering and enable smooth torque control [4-6].

The electromechanical equation that governs the evolution of the system was represented by (4). If (4) is derived with respect to time, (6) is obtained

$$\frac{d^2 \omega_m}{d^2 t} = \frac{k}{J_T} u - \frac{B}{J} \dot{\omega}_m \quad (6)$$

Since  $T_l$  is considered to be constant, it does not appear in (6). The variable state representation can be simplified as follows:

$$\begin{aligned} X_1 &= \omega_m - \omega_{ref} \\ X_2 &= \dot{X}_1 \end{aligned} \quad (7)$$

$$\begin{bmatrix} \dot{X}_1 \\ \dot{X}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & -a \end{bmatrix} \cdot \begin{bmatrix} X_1 \\ X_2 \end{bmatrix} + \begin{bmatrix} 0 \\ b \end{bmatrix} \cdot u \quad (8)$$

where  $a = B / J, b = k / J_T$ .

The trajectory, which the SLMC forces the system to slide along, is a straight line described in (9)

$$\sigma = cX_1 + \dot{X}_1 = 0 \quad (9)$$

The dynamics described in (9) is a first-order response with a defined speed response time constant  $C$ . Various control laws can be used to force the system response.

We used the same sliding-mode speed controller, as in [6], which is a variation of that presented in [7] that is a position controller.

$$u_{sl} = \psi_1 X_1 + \psi_2 X_2 + k_\sigma \sigma \quad (10)$$

where  $\psi_1$  and  $\psi_2$  are nonlinear functions defined in this form.

Although it is specially noticeable in the steady state,

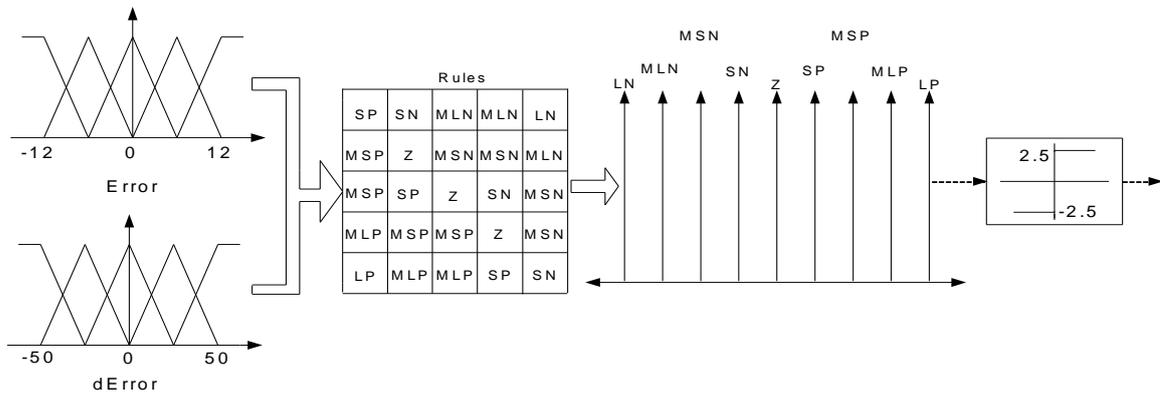
$$\psi_1 = \begin{cases} \alpha_1, & \text{if } \sigma X_1 > 0 \\ \beta_1, & \text{if } \sigma X_2 < 0 \end{cases}$$

$$\psi_2 = \begin{cases} \alpha_2, & \text{if } \sigma \dot{X}_1 > 0 \\ \beta_2, & \text{if } \sigma \dot{X}_2 < 0 \end{cases}$$

$$k_\sigma \in R^- \quad (11)$$

$\alpha_1, \beta_1, \alpha_2, \beta_2$  and  $k_\sigma$  are constants.

The control signal is generated by a combination of linear and nonlinear terms. The term  $k_\sigma \sigma$  has been added to provide system robustness without producing torque ripples principally when the control action is large[7-9].



**Figure 4. PI-fuzzy Logic-based Controller: Rules and Membership Functions**

### 3.2. PI-Like Fuzzy Controller(PI-FLBC)

The principal drawback associated with fuzzy logic controlled systems is the difficulty in stating system stability. However, this kind of control has experimentally shown excellent results, especially when faced with nonlinear control systems. This controller provides a smooth performance when reaching a steady state.

A system, analogous to the one described in [10], has been used. The fuzzy controller, whose rules are depicted in Fig.4, is adapted by changing the scaling factors of the input variables to obtain the desired closed loop system performance when the system is near to steady state behavior.

In this paper, fuzzy implication uses the product operation rule. The connective and is implemented by means of the minimum operation. Fuzzy rules are combined by means of the connective also which is implemented by means of the algebraic addition.

Defuzzification is carried out through the centroid method, which generates the center of gravity of the membership function of the output set. As the membership functions that define the linguistic terms of the output variable are Singletons, the center of gravity of the inferred fuzzy set can be obtained by means of the following:

$$u_{fc} = \frac{\sum_1^m \phi_i \omega_i}{\sum_1^m \Phi_i} \quad (12)$$

where  $u_{fc}$  is the value of the output of the fuzzy controller,  $m$  is the number of rules,  $\phi_i$  the value of the membership functions corresponding to rule  $R_i$ , and  $\omega_i$  is the value of the  $i$  the output Singleton.

### 3.3. Fuzzy Supervisory System

A fuzzy supervisory system is used to calculate the  $\alpha$  value. Figure 5 shows the structure of the proposed hierarchical control law. When an error and its derivative with respect to time in absolute value are small, the fuzzy controller must be dominant ( $\alpha = 1$ ). In the opposite case, sliding-mode controller is dominant. As shown in Fig.5, the membership functions are triangular ones and output functions are Singletons. Definitions of symbols are: very large(VL), large(L), medium(M), small(S) and zero(Z), Rules in this figure are defined by a table, for example, a rule in the table can be stated as follows: “If absolute value of error is medium and absolute value of the derivative error is large, then  $\alpha$  is zero.” Once the  $\alpha$  value is obtained the final control action,  $u$ , is determined by (12).

### 4. Experiment Conclusion

The proposed controller has been applied to 3-phase induction motor whose nominal parameters are shown in Table I, fuzzy sliding-mode controller parameters are shown in Table II. Fig 6 and fig7 shows the speed responses for the PI controller and for the fuzzy sliding mode controller, The fuzzy slidingmode controller result is better. In Fig. 8 (a) and (b), The current torque component for PI controller and fuzzy sliding mode controller are shown respectively. It can be observed that when steady state is reached, the torque chattering is reduced when the fuzzy sliding mode controller is used.

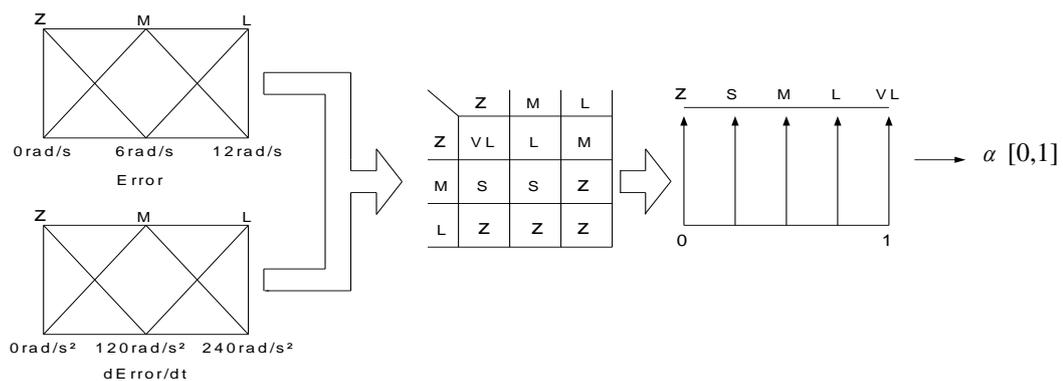


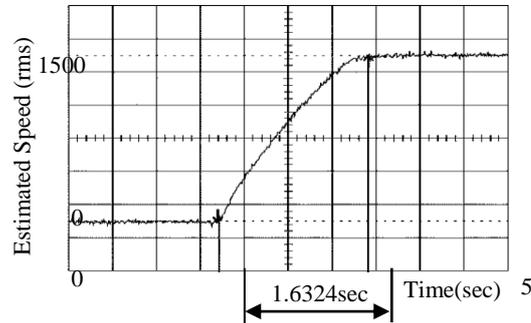
Figure 5. Structure of the Proposed Hierarchical Control Law

Table 1. Inductor Motor Nominal Parameters

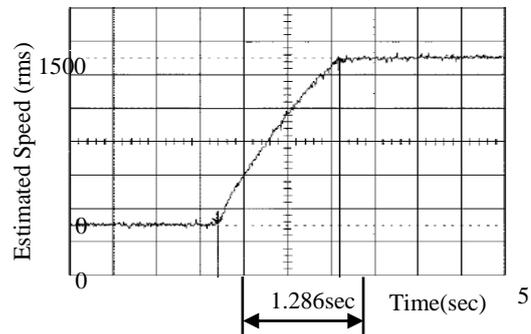
Lm(H)	2.0642	Rs(Ω)	24.45
Ls(H)	2.0888	Rr(Ω)	41.774
Lr(H)	2.0887	P	2
$\alpha = B/J$	0.15	$b_T = K_t/J$	$\in [196,981]$

**Table 2. Fuzzy Sliding Mode Controller Parameters**

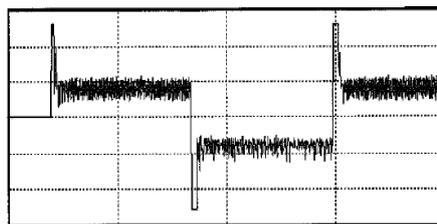
C	20	$\alpha_1$	-0.667	$\beta_1$	0.424
$k_\sigma$	-0.021	$\alpha_2$	-0.167	$\beta_2$	0.167



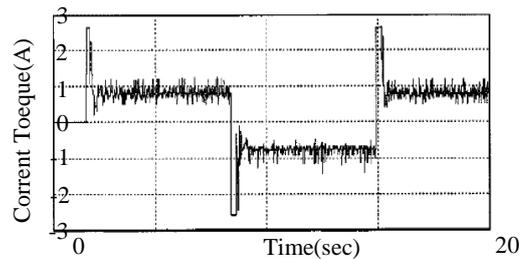
**Figure 6. Estimated Speed for PI Controller**



**Figure 7. Estimated Speed for Fuzzy Sliding Mode**



**Figure 8. (a) Current Torque for PI Controller**



**Figure 8. (b) Current Torque for Fuzzy Sliding Mode Controller**

The torque chattering is reduced when the fuzzy sliding mode controller is used.

**Table 3. Summarizes System Response Using Different Controllers**

$P_L$	Classical PI	SLMC	PI-FLBC	Proposed Controller
0W	1.796s	1.564s	1.432s	1.432s
10W	1.924s	1.54s	1.668s	1.54s
50W	2.465s	1.886s	1.786s	1.786s

Where  $P_L$  denote power load, SLMC denote sliding mode controller, PI-FLBC denote PI and fuzzy logic based control

In a practical implementation, the system response obtained with the Fuzzy sliding mode method are better than with a PI controller in steady and transient states (see Table III). Meanwhile using the fuzzy sliding mode controller provides robustness and assures global stability of the overall system.

This paper have proposed a hybrid MRAS of an induction motor indirectly follows the model speed. Meanwhile, A new type of fuzzy sliding mode controller is presented. The proposed control structure combines a sliding-mode and a PI-fuzzy logic based controller. The control action is weighted between two basic nonlinear controllers by a fuzzy inference machine that provides a fuzzy division of the control region. The control dynamics of the proposed hierarchical structure has been experimentally investigated. The experiments show that the dynamic response of the system using the proposed controller is better when compared against a classical PI controller. Also, in steady state, torque chattering is decreased when compared with a PI controller. Finally, the proposed method provides drive robustness improvement and assures global stability in relation with PI controller

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