

Sensorless Sliding Mode Vector Control of Induction Motor Drives

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ABSTRACT

In this paper we present the design of sliding mode controllers for sensorless field oriented control of induction motor. In order to improve the performance of controllers, the motor speed is controlled by sliding mode regulator with integral sliding surface. The estimated rotor speed used in speed feedback loop is calculated by an adaptive observer based on MRAS (model reference adaptive system) technique. The validity of the proposed scheme is demonstrated by experimental results.

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1. INTRODUCTION

With development of DSPs and power electronic technologies, many novel control strategies can be easily applied in electrical machines drives [8].

The variable structure control using sliding mode has attracted many researchers and made an important development for the control of electrical machinery, because it can offer good properties [8][10][12]: good performance against unmodeled dynamic, robustness to parameter variations and external disturbances, and fast dynamic response.

Generally, in some application of induction motor drive systems using SMC, “two-loop control” strategy is applied in speed drive system. An outer-loop speed controller that employs SMC strategy, with integral sliding surface, and an inner-loop vector controller based on SMC regulator too. The aim of vector control is to enable decoupling control of torque and flux as separated excite DC motor.

The vector control of induction motor require the knowledge of rotor speed and stator current measurement. However speed sensor cannot be mounted in some cases due to their high cost, exit difficulties in maintaining this speed sensors, and make the system easy be disturbed. Several field-oriented control methods without speed sensors have been proposed. Some of them can be applied only to the indirect field-oriented control and some to the direct field-oriented control, and stability has not been explained clearly. In addition, some methods are unstable in a low speed region.

This study presents a sensorless decoupling control scheme. A description of model and field oriented motor is presented in section II. A speed estimation algorithm is reported in section-III, which overcomes the necessity of the speed sensor. A sliding mode control is discussed in section-IV, to compensate the uncertainties that are present in the system. The experimental results in section-V show the validity of the proposed scheme, and we end with a conclusion and some remarks in section-VI.

2. MATHEMATICAL MODEL AND VECTOR CONTROLLED IM DRIVE

One particular approach for the control of induction motor is the field oriented control (FOC). This control strategy is based on the orientation of the flux on the d axis, which can be expressed by considering [14]

$$\phi_{rd} = \phi_r \text{ and } \phi_{rq} = 0 \quad (1)$$

With field orientation the dynamic equations of stator current components, rotor flux and electromagnetic torque are given by:

$$\frac{di_{sd}}{dt} = \frac{1}{\sigma L_s} \left(- \left(R_s + \left(\frac{L_m}{L_r} \right)^2 R_r \right) i_{sd} + \sigma L_s \omega_s i_{sq} + \frac{L_m R_r}{L_r^2} \Phi_r + V_{sd} \right) \quad (2)$$

$$\frac{di_{sq}}{dt} = \frac{1}{\sigma L_s} \left(-\sigma L_s \omega_s i_{sd} - \left(R_s + \left(\frac{L_m}{L_r} \right)^2 R_r \right) i_{sq} - \frac{L_m}{L_r} \Phi_r \omega_r + V_{sq} \right) \quad (3)$$

$$\frac{d\Phi_{rd}}{dt} = \frac{L_m R_r}{L_r} i_{sd} - \frac{R_r}{L_r} \Phi_r \quad (4)$$

$$Te = \frac{pL_m}{L_r} i_{sq} \Phi_r \quad (5)$$

where, L_r , L_s and L_m are the rotor, stator and mutual inductances, respectively, R_r and R_s are respectively rotor and stator resistances

ω_s is the synchronous speed (electrical) in rad/s

ω_r is rotor speed (mechanical) in rad/s

V_{ds} and V_{qs} are d- and q-axis components of stator voltage

$\sigma = 1 - \frac{L_m^2}{L_s L_r}$ is the leakage coefficient

For the flux oriented control, we have two approaches. The first is known as indirect flux oriented control. While, the second is named as direct flux oriented control. For the IRFOC, the rotor flux vector is aligned with d axis and setting the rotor flux to be constant and equal to the rated rotor flux. Based on these conditions, we establish the d and q axis voltage. While for the DRFOC, the d and q axis rotor flux must be known and they will be regulated so that the d axis rotor flux will be equal to the rated rotor flux and the q axis rotor flux will be equal to zero.

3. SPEED ESTIMATION USING ROTOR FLUX OBSERVER

Many schemes have been developed to estimate motor speed from measured terminal quantities. Most of these estimation techniques are based on adaptive system. In order to obtain a better estimation of the motor speed, it is necessary to have dynamic representation based on the stationary ($\alpha \beta$) reference frame [7]. Since motor voltages and currents are measured in a stationary frame, it is also convenient to express these equations in stationary ($\alpha \beta$) reference frame.

3.1. Full Order Observer of Induction Motor:

The state observer, which estimates the stator current and the rotor flux together, is written as the following equation [17]:

$$\frac{d}{dt} \begin{bmatrix} \hat{i}_s \\ \hat{\phi}_r \end{bmatrix} = \hat{A} \begin{bmatrix} \hat{i}_s \\ \hat{\phi}_r \end{bmatrix} + \begin{bmatrix} (1/\sigma L_s)I \\ 0 \end{bmatrix} v_s + G(i_s - \hat{i}_s) \quad (6)$$

where:

$$\hat{A} = \begin{bmatrix} -\gamma I & \delta(I/T_r - \hat{\omega}_r J_1) \\ (L_m/T_r)I & -(I/T_r - \hat{\omega}_r J_1) \end{bmatrix}$$

$$i_s = [i_{\alpha s} \ i_{\beta s}]^T \text{ stator current}, \phi_r = [\phi_{\alpha r} \ \phi_{\beta r}]^T \text{ rotor flux}$$

$$v_s = [v_{ds} \ v_{qs}] \text{ stator voltage}, I = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, J_1 = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$$

$$T_r = \frac{L_m}{R_r}, \sigma = 1 - \frac{L_m^2}{L_s L_r}, \delta = \frac{L_m}{\sigma L_s L_r}, \gamma = \frac{R_s}{\sigma L_s} + \frac{R_r L_m^2}{\sigma L_s L_r^2}$$

Where $\hat{}$ means the estimated values and G is the observer gain matrix which is decided so that (6) can be stable. It is important to note that the estimated speed is considered as a parameter in

3.2. Adaptive Scheme for Speed Estimation

The scheme consists of two models; reference and adjustable ones and an adaptation mechanism. The "reference model" represents the Real system. The "adjustable model" represents the observer with adjustable parameters. The "adaptation mechanism" consists of a PI-type of controller which estimates the unknown parameter using the error between the reference and the adjustable models and updates the adjustable model with the estimated parameter until satisfactory performance is achieved. The configuration is given in Figure 1 [2].

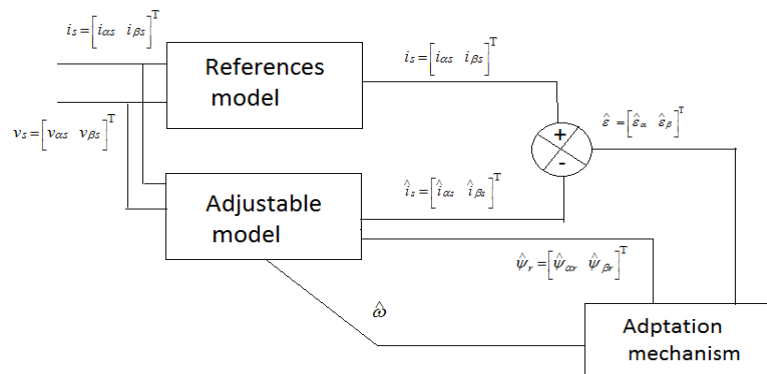


Figure 1. Adaptive scheme for speed estimation

The induction motor speed observer equation is given by [1]:

$$\hat{\omega}_r = K_p (\epsilon_{i\alpha} \hat{\Phi}_{r\beta} - \epsilon_{i\beta} \hat{\Phi}_{r\alpha}) + K_i \int (\epsilon_{i\alpha} \hat{\Phi}_{r\beta} - \epsilon_{i\beta} \hat{\Phi}_{r\alpha}) dt \tag{7}$$

Where: $\epsilon_{i\alpha} = i_{\alpha s} - \hat{i}_{\alpha s}$, $\epsilon_{i\beta} = i_{\beta s} - \hat{i}_{\beta s}$

K_p and K_i is the arbitrary positive gain [15]-[17].

4. SLIDING-MODE CONTROL

According to the above analysis, the speed control of the field oriented induction motor with current-regulated PWM drive system can be reasonably represented by the block diagram shown in Figure 2

$$\text{sat}(S) = \begin{cases} +1 & \text{if } S > \varepsilon \\ \frac{S}{\varepsilon} & \text{if } -\varepsilon < S < \varepsilon \\ -1 & \text{if } S < -\varepsilon \end{cases} \quad (14)$$

4.2. Current Control

We define the error of direct and quadratic current respectively as:

$$\begin{cases} e_d = i_d^* - i_d \\ e_q = i_q^* - i_q \end{cases} \quad (15)$$

The switching surfaces of two currents (direct and quadratic) are designed as:

$$\begin{cases} S_d = i_d^* - i_d \\ S_q = i_q^* - i_q \end{cases} \quad (16)$$

The outputs of SMC currents controllers, reference voltage V_{sd}^* and V_{sq}^* respectively are given by:

$$\begin{cases} V_{sd}^* = K_d \text{sat}\left(\frac{S_d}{\varepsilon_d}\right) + \sigma L_s \dot{i}_{sd}^* + R_{sm} i_{sd}^* - \sigma L_s \omega_s i_{sq}^* - \frac{L_m}{T_r L_r} \Phi_r \\ V_{sq}^* = K_q \text{sat}\left(\frac{S_q}{\varepsilon_q}\right) + \sigma L_s \dot{i}_{sq}^* + R_{sm} i_{sq}^* + \sigma L_s \omega_s i_{sd}^* + \frac{L_m}{L_r} \Phi_r \end{cases} \quad (17)$$

where K_d and K_q are positive gain which respect condition of convergence .

5. EXPERIMENTAL RESULTS

In this section the proposed overall closed-loop control system including the speed observer has been tested experimentally on a suitable test setup (Fig. 3). The test setup consists of the following:

- Three-phase induction motor with rated values shown in appendix;
- Synchronous machine for loading the induction motor;
- Electronic power converter: three-phase diode rectifier and VSI composed of three IGBT modules without any control system;
- Electronic card with voltage sensors (model LEM LV 25-P) and current sensors (model LEM LA 55-P) for monitoring the instantaneous values of the stator phase voltages and currents;
- Voltage sensor (model LEM CV3-1000) for monitoring the instantaneous value of the dc-link voltage;
- Incremental encoder (model RS 256-499, 2500 pulses per round), only for comparison measurements;
- DSpace card (model DS1104) with a PowerPC 604e at 400 MHz and a fixed-point digital signal processor (DSP) TMS320F240

Figure 4 shows the behavior of the induction motor at different values of speeds with load torque $T_L = 0$. It can be seen that the proposed SMC control scheme has a fast response time, a good tracking performance.

We note that the real and the estimated speed have a same behavior. This means that even during the speed transients the adaptive observer can track the speed command accurately. It also important to mention that the estimated speed coincides exactly with real speed at low speed region (Figure 5)

Figure 6 is speed error between estimated and reference values. From Fig. 6 we can see that the estimated rotor speed approaches the actual values. That means the observer system has good estimation accuracy even in low speed region and satisfies our requests completely.

The Figure 7 and Figure 8 depict the trajectories of the quadratic and direct current (I_q s and I_d s) respectively. We note that the I_q s and I_d s references follow the real I_q s and I_d s even in transient state.

The Figure 9 and Figure 10 show the corresponding speed and I_q s response. When the load torque changed from 0Nm to 1.5Nm, the control scheme has a good robustness to external load torque variation.



Figure.3. Experimental prototypes for Laboratory

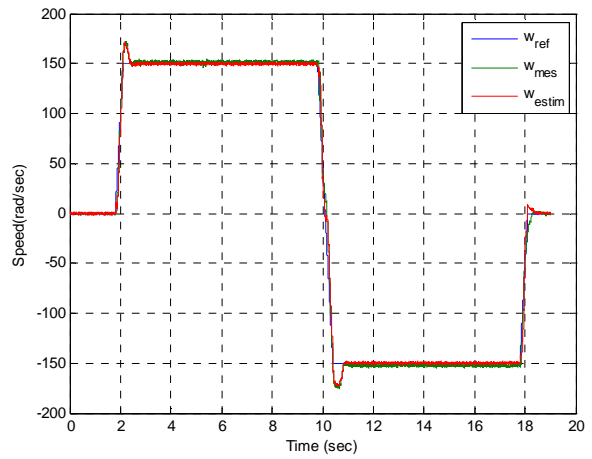


Figure 4. Real and estimate speed

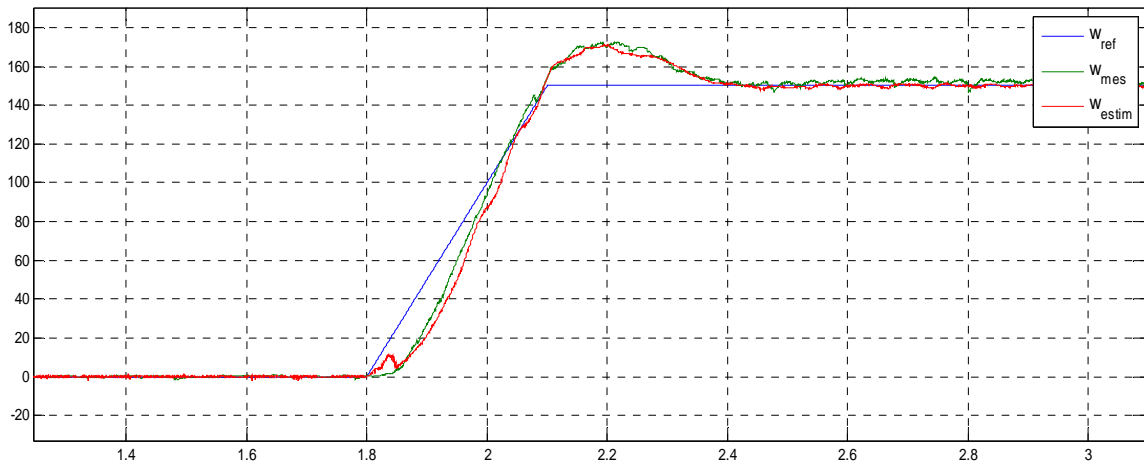


Figure 5. Zoom Speed

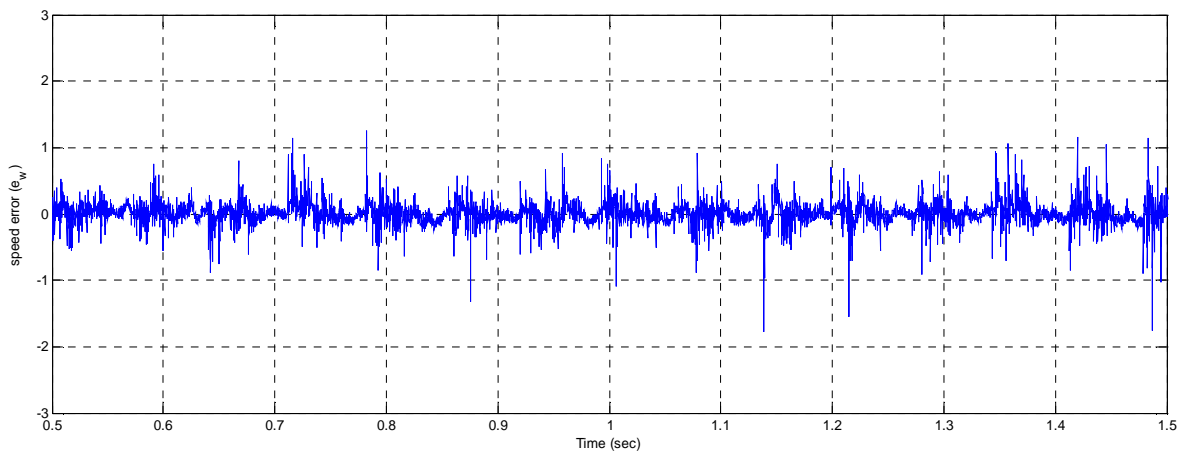


Figure 6. Speed estimation error

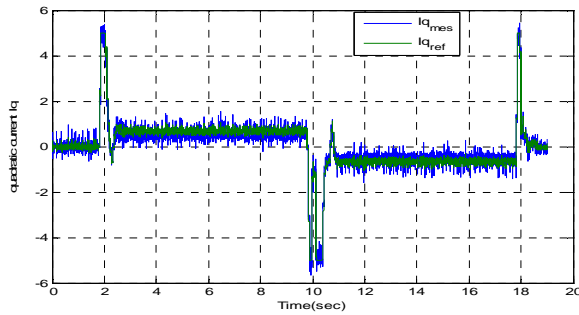


Figure 7. Quadratic current response.

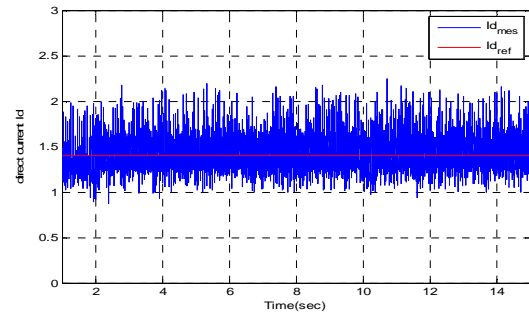


Figure 8. Direct current response

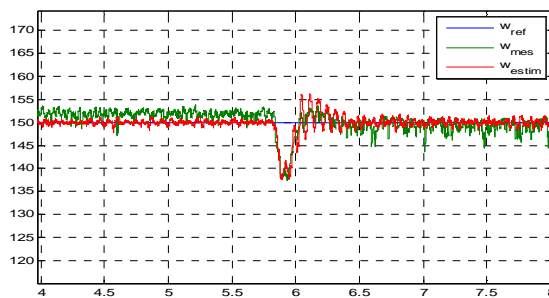


Figure 9. Real and estimate speed

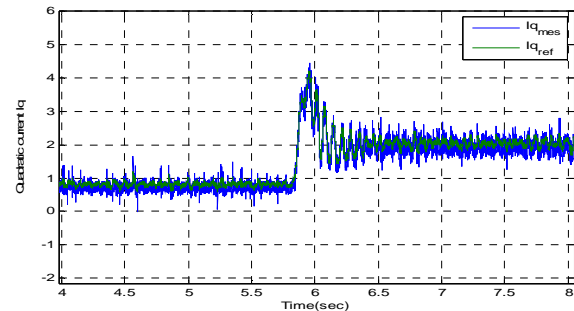


Figure 10. Quadratic current response

From these Figures, we can find that the adaptive observer follows the actual speed even in transient states. That means the observer system has good estimation accuracy and satisfies our requests completely.

6. CONCLUSION

In this paper, a field oriented controller by using sliding mode technique has been designed for IM drive without mechanical sensors. The major contributions of this study are summarized as follows:

- An adaptive interconnected observer based on MRAS technique has been presented to estimate speed and fluxes, where its performance has been tested.
- An FOC combined with a robust sliding mode controller has been proposed to achieve a good speed tracking for IM without mechanical sensor under different operating conditions, and particularly at low speed.

The successful application of the observer-controller scheme on an experimental set-up with a significant sensorless control benchmark dealing with the low frequencies case.

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