Design of Sliding-mode Observer for Robust Speed Sensorless Induction Motor Drive

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Abstract: In this paper, the design of a speed sensorless vector control system for induction motor is performed by using a new sliding mode technique based on current model flux observer. A current and flux observer based on the current estimation error is constructed. The proposed current observer includes a sliding mode function, which is derivative of the flux. That is, sliding mode observer which allows the estimation of both the rotor speed and flux based on the measurement of motor terminal quantities, would be proposed. And, a synergetic speed controller using the estimated speed signal is designed to stabilize the speed loop. Simulation results are presented to confirm the theoretical analysis, and to show the system performance with different observer gains and the influence of the motor parameter.

Keywords: Sliding-mode observer, Speed sensorless vector control system, Synergetic controller

1. INTRODUCTION

This paper presents the design of a speed sensorless vector control system for induction motor having the robust sliding observers based on current estimation error against rotor parameter deviations. Conventional vector control methods require motor speed information as a feedback signal, and to acquire the speed information, digital encoders are used, which degrade the system's reliability and cause the cost problem. Owing to this, much research has been presented for eliminating the speed sensor. Nowadays, sensorless induction motor drive systems are widely being used in high performance applications. However, the fifth order dynamics and nonlinearity of the induction motor make it difficult to estimate the speed and rotor flux without the measurement of mechanical speed. To solve these difficulties, observer-based algorithms have been presented in many literatures. Observer-based methods offer good performance in a large speed range, and those make use of the analytical model of the machine and allow the estimation of both the rotor speed and flux from the motor currents and voltages. And their implementation is relatively simple by means of DSP controller, and the hardware of standard vector control system only is sufficient.

In general, two algorithms such as the voltage model and current model are used to obtain the information for rotor flux components. Estimation of flux using voltage model flux observer is sensitive to stator resistance and leakage inductance, and has some difficulties in low speed range because of integral operation. Current model flux observer is alternatives to get over these problems in low speed range. But, this approach doesn't have a good performance in high speed range because of high sensitivity to rotor resistance.

As a speed observation algorithm, the speed observer based on MRAS(Model Reference Adaptive System) theory is one of the most general methods for speed sensorless induction motor drive. In this approach, the error vectors are made by using the differences between the output of two dynamic models of induction motor, and just one of the two models includes the estimated speed value as a system parameter. And, the error vectors are driven to zero by using adaptive law, and then the estimated speed value converges to the real value. But, as this observer is very sensitive to stator resistance variations and integral drifts in low speed range, the accuracy of speed estimation is affected by the parameter variations of induction motor[3].

Meanwhile, the sliding mode control theory can offer many good properties, such as insensitivity to parameter variations, external disturbance rejection, system order reduction, simplicity of implementation and fast dynamic responses. Nowadays, the basic principles of sliding mode control of electrical drives which have been demonstrated in many literatures is being implemented by the power converter and single-chip microcontroller. Furthermore, sliding mode observers have been proposed for estimating the states of the control system. Sliding mode observers also have the same robust nature as the sliding mode controllers. In reference [1], the observer model to estimate the flux components is a copy of the original system, which has corrector gains with switching terms. But, since this method requires the measured speed information for flux estimation, it can not be applicable to sensorless control system of induction motor. In reference [2], an adaptive sliding mode observer for speed-sensorless induction motor drive is presented. The observer detects the rotor flux components in the two-phase stationary reference frame by the motor voltage equations, and the motor speed is estimated by a further relation obtained by a Lyapunov function.

In this paper, speed sensorless induction motor drive system with robust control characteristics is proposed. First, a speed observation system, which is insensitive to the variations of motor parameters, is derived on the concept of sliding mode. Next, a synergetic speed controller[4] using the estimated speed signal is designed to stabilize the speed loop. Then, to estimate the performance characteristics of this synergetic control scheme, the fuzzy sliding mode control[5] scheme which is designed with the object of reducing the torque chattering problem, is compared with the proposed control scheme. That is, design and implementation of indirect vector control system of induction motor is performed by using a new sliding mode technique based on current model flux observer. A current and flux observer based on the current estimation error is constructed. The proposed current observer includes a sliding mode function, which is derivative of the flux. That is, sliding mode observer which allows the estimation of both the rotor speed and flux based on the measurement of motor terminal quantities, is proposed. And, the asymptotic stability of the synergetic speed control system and the convergence of the sliding-mode flux/speed observer is proved also.

Simulation results from a sliding-mode observer based sensorless drive system are presented to confirm the theoretical analysis, and to show the system performance with different observer gains and the influence of the motor parameter.

2. SPEED ESTIMATION OF INDUCTION MOTOR

2.1 Induction Motor Model

The dynamic model of induction motor on the rotor flux stationary reference frame is defined by the stator currents and rotor flux components as follows.

$$\begin{bmatrix} \dot{i}_{ds} \\ \dot{i}_{qs} \\ \dot{\lambda}_{dr} \\ \dot{\lambda}_{qr} \end{bmatrix} = \begin{bmatrix} -\left(\frac{R_s}{\sigma L_s}+\frac{1-\sigma}{\sigma T_r}\right) & 0 & \frac{L_m}{\sigma L_s L_r T_r} & \frac{L_m}{\sigma L_s L_r}\omega_r \\ 0 & -\left(\frac{R_s}{\sigma L_s}+\frac{1-\sigma}{\sigma T_r}\right) & -\frac{L_m}{\sigma L_s L_r}\omega_r & \frac{L_m}{\sigma L_s L_r T_r} \\ \frac{L_m}{T_r} & 0 & -\frac{1}{T_r} & -\omega_r \\ 0 & \frac{L_m}{T_r} & \omega_r & -\frac{1}{T_r} \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \\ \lambda_{dr} \\ \lambda_{qr} \end{bmatrix} + \begin{bmatrix} \frac{1}{\sigma L_s} & 0 \\ 0 & \frac{1}{\sigma L_s} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} V_{ds} \\ V_{qs} \end{bmatrix} \quad (1)$$

where, $\sigma = 1-(L_m{}^2/L_s L_r)$: leakage coefficient, $T_r = L_r/R_r$: rotor time constant, ω_r : rotor speed, i_{ds} and i_{qs} represent two axis current component, λ_{dr} and λ_{qr} the rotor flux component in stationary reference frame respectively.

2.2 Design of Current Observer

The proposed speed observation system is based on sliding mode current observer which its convergence is guaranteed by the introduction of equivalent control. And, the rotor flux estimation is performed by using the observed current components. Finally, motor speed as the output of speed observation system is obtained by using the estimated rotor flux. To show its procedure, equation (1) can be divided into two other parts, that is, the current and flux part each, as follows.

$$\begin{bmatrix} \dot{i}_{ds} \\ \dot{i}_{qs} \end{bmatrix} = \frac{L_m}{\sigma L_s L_r}\left(\begin{bmatrix} \frac{1}{T_r} & \omega_r \\ -\omega_r & \frac{1}{T_r} \end{bmatrix} \begin{bmatrix} \lambda_{dr} \\ \lambda_{qr} \end{bmatrix} \right. + \begin{bmatrix} -\left(\frac{R_s}{\sigma L_s}+\frac{1-\sigma}{\sigma T_r}\right) & 0 \\ 0 & -\left(\frac{R_s}{\sigma L_s}+\frac{1-\sigma}{\sigma T_r}\right) \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} + \frac{1}{\sigma L_s}\begin{bmatrix} V_{ds} \\ V_{qs} \end{bmatrix} \quad (2)$$

$$\begin{bmatrix} \dot{\lambda}_{dr} \\ \dot{\lambda}_{qr} \end{bmatrix} = \begin{bmatrix} -\frac{1}{T_r} & -\omega_r \\ \omega_r & -\frac{1}{T_r} \end{bmatrix} \begin{bmatrix} \lambda_{dr} \\ \lambda_{qr} \end{bmatrix} + \begin{bmatrix} \frac{L_m}{T_r} & 0 \\ 0 & \frac{L_m}{T_r} \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} \quad (3)$$

Equation (2) and (3) can be rearranged into following equation.

$$\begin{bmatrix} \dot{i}_{ds} \\ \dot{i}_{qs} \end{bmatrix} = \frac{L_m}{\sigma L_s L_r}\left(\begin{bmatrix} \frac{1}{T_r} & \omega_r \\ -\omega_r & \frac{1}{T_r} \end{bmatrix} \begin{bmatrix} \lambda_{dr} \\ \lambda_{qr} \end{bmatrix} - \frac{L_m}{T_r}\begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix}\right) - \frac{R_s}{\sigma L_s}\begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} + \frac{1}{\sigma L_s}\begin{bmatrix} V_{ds} \\ V_{qs} \end{bmatrix} \quad (4)$$

$$\begin{bmatrix} \dot{\lambda}_{dr} \\ \dot{\lambda}_{qr} \end{bmatrix} = -\begin{bmatrix} \frac{1}{T_r} & \omega_r \\ -\omega_r & \frac{1}{T_r} \end{bmatrix} \begin{bmatrix} \lambda_{dr} \\ \lambda_{qr} \end{bmatrix} + \frac{L_m}{T_r}\begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} \quad (5)$$

If the two axis coupling terms exist in the equation (4) and (5) are substituted by sliding functions, current and flux observer which is independent of rotor time constant and speed can be designed. Accordingly, the current observer designed by using equation (4) is as follows.

$$\begin{bmatrix} \dot{\widehat{i_{ds}}} \\ \dot{\widehat{i_{qs}}} \end{bmatrix} = \frac{L_m}{\sigma L_s L_r}\begin{bmatrix} F_d \\ F_q \end{bmatrix} - \frac{R_s}{\sigma L_s}\begin{bmatrix} \widehat{i_{ds}} \\ \widehat{i_{qs}} \end{bmatrix} + \frac{1}{\sigma L_s}\begin{bmatrix} V_{ds} \\ V_{qs} \end{bmatrix} \quad (6)$$

where, $\widehat{i_{ds}}$ and $\widehat{i_{qs}}$ represent the ovserved value of i_{ds} and i_{qs} respectively, and designed switching functions are $F_d = -k\,\mathrm{sgn}(S_d)$, $F_q = -k\,\mathrm{sgn}(S_q)$, $S_d = \widehat{i_{ds}} - i_{ds}$, $S_q = \widehat{i_{qs}} - i_{qs}$.

And, the switching plane is defined as follows.

$$S(t) = \begin{bmatrix} S_d & S_q \end{bmatrix}^T \quad (7)$$

Also, the designed current observer can be stable if the gain of switching function satisfying following inequality is applied.

$$k \rangle \frac{-\frac{L_r}{L_m}R_s(S_d{}^2 + S_q{}^2) + \left|S_d A_1 + S_q A_2\right|}{\left|S_d\right| + \left|S_q\right|} \quad (8)$$

where, $A_1 = \frac{L_m}{T_r}i_{ds} - \frac{1}{T_r}\lambda_{dr} - \omega_r\lambda_{qr}$, $A_2 = \frac{L_m}{T_r}i_{qs} + \omega_r\lambda_{dr} - \frac{1}{T_r}\lambda_{qr}$.

Thus, if we properly select k value in the range of satisfying the inequality (8), the sliding mode will exist on switching plane defined by equation (7) and the system will be stable. Accordingly, the current observer will be independent of system parameters or disturbances.

2.3 Design of Flux Observer

The flux observer directly designed from equation (5) is as follows.

$$\begin{bmatrix} \dot{\widehat{\lambda_{dr}}} \\ \dot{\widehat{\lambda_{qr}}} \end{bmatrix} = -\begin{bmatrix} \frac{1}{T_r} & \widehat{\omega_r} \\ -\widehat{\omega_r} & \frac{1}{T_r} \end{bmatrix} \begin{bmatrix} \widehat{\lambda_{dr}} \\ \widehat{\lambda_{qr}} \end{bmatrix} + \frac{L_m}{T_r} \begin{bmatrix} \widehat{i_{ds}} \\ \widehat{i_{qs}} \end{bmatrix} \tag{9}$$

In case that the estimated and real currents are equal, the switching plane $S=0$, and $\dot{S}=0$, hence, this corresponds that the equivalent control inputs to the system. Accordingly, the following equation is obtained from equation (4) and (6).

$$\begin{bmatrix} F_d \\ F_q \end{bmatrix} = \begin{bmatrix} \frac{1}{T_r} & \widehat{\omega_r} \\ -\widehat{\omega_r} & \frac{1}{T_r} \end{bmatrix} \begin{bmatrix} \widehat{\lambda_{dr}} \\ \widehat{\lambda_{qr}} \end{bmatrix} - \frac{L_m}{T_r} \begin{bmatrix} \widehat{i_{ds}} \\ \widehat{i_{qs}} \end{bmatrix} \tag{10}$$

Therefore, from equation (9) and (10), the following equation is obtained.

$$\begin{bmatrix} \dot{\widehat{\lambda_{dr}}} \\ \dot{\widehat{\lambda_{qr}}} \end{bmatrix} = -\begin{bmatrix} F_d \\ F_q \end{bmatrix} = \begin{bmatrix} k\,\mathrm{sgn}(S_d) \\ k\,\mathrm{sgn}(S_q) \end{bmatrix} \tag{11}$$

That is, as the flux can be estimated by designed switching function only without the information of right term in equation (9) if we use equation (11), the proposed flux observer can be totally insensitive to rotor time constant and motor speed.

2.4 Speed Observer

If we multiply the first row of equation (9) by $\widehat{\lambda_{qr}}$, the second row by $\widehat{\lambda_{dr}}$ and obtain the difference between the results, the following equation for speed estimation is obtained.

$$\widehat{\omega_r} = \frac{F_d \widehat{\lambda_{qr}} - F_q \widehat{\lambda_{dr}} - \frac{L_m}{T_r} (\widehat{i_{qs}} \widehat{\lambda_{dr}} - \widehat{i_{ds}} \widehat{\lambda_{qr}})}{\widehat{\lambda_{dr}}^2 + \widehat{\lambda_{qr}}^2} \tag{12}$$

2.5 Synergetic Speed Controller Design

Synergetic control theory has several advantages: it's well suited to digital control, it operates at constant switching frequency which lessens the burden of filtering design, and it exhibits low chattering as well as the intrinsic robustness features of sliding mode control.

In synergetic controller design for induction motor speed control, the speed error and its derivatives are selected as state variables. That is, $x_1 = \omega_r^* - \omega_r$, $x_2 = dx_2/dt = -\alpha_r$ (acceleration). Then, the state space representation of the mechanical equations of induction motor can be written as follows:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & -\frac{B}{J} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ -\frac{K}{J} \end{bmatrix} u \tag{13}$$

where, $u = i_{qs}^*$ and $K = K_T/\tau$ (K_T and τ represent torque constant and integral time constant, respectively).

Suppose the system to be controlled is described by a set of nonlinear differential equations of the form

$$\dot{x} = f(x, u, t) \tag{14}$$

where, x is the state vector, u is the control input vector and t is time.

Start by defining a macro-variable as a function of the state variables:

$$\psi = \psi(x) \tag{15}$$

The control will force the system to operate on the manifold $\psi = 0$. The designer can select the characteristics of this macro-variable according to the control specifications(e.g. limitation in the speed, acceleration or current). In the trivial case, the macro-variable can be a simple linear combination of the state variables.

The desired dynamic evolution of the macro-variable is

$$T\dot{\psi} + \psi = 0; \quad T>0 \tag{16}$$

where, T is a design parameter specifying the convergence speed to the manifolds specified by the macro-variables. The chain rule of differentiation gives

$$\dot{\psi} = \frac{d\psi}{dx}\dot{x} \tag{17}$$

Combining (14) and (17), we obtain

$$T\frac{d\psi}{dx} f(x, u, t) + \psi = 0 \tag{18}$$

Equation (18) is finally used to synthesize the control law u. Therefore, each manifold introduces a new constraint on the state space domain and reduces the order of the system, working in the direction of global stability.

If we limit our investigation to a macro-variable that is a linear function of mechanical state variables related with induction motor, in general it has the following form.

$$\psi = c x_1 + x_2 \tag{19}$$

Substitution of ψ from (19) into the equation (16) yields

$$T(c\dot{x}_1 + \dot{x}_2) + c x_1 + x_2 = 0 \tag{20}$$

Now substituting the derivatives $\dot{x}_1$ and $\dot{x}_2$ from (13) and solving for u, the following control law is obtained:

$$u = H(A_1 x_1 + A_2 x_2) \tag{21}$$

where, $H = 1/K$, $A_1 = cJ/T$, $A_2 = cJ - B + J/T$.

3. SYSTEM CONFIGURATION AND SIMULATION

In order to test and verify the control performance of the proposed sensorless control strategy and synergetic speed controller discussed above, the simulation study of control system was performed using the C language. Fig. 1 shows the speed control system of induction motor which performance characteristics of the proposed synergetic controller and the sliding mode observer are evaluated. Table 1 gives the electrical parameters of induction motor and the controller parameters used for comparison. These controllers are applied in rotor flux oriented indirect vector control system of induction motor having an inner loop current controller composed of a PI compensator and a space vector PWM modulator.

The synchronous frame PI controller used as current error compensator in fig. 1 is

$$(k) = (k-1) + (K_P + K_I)\,E(k) - K_P\,E(k-1) \tag{22}$$

where, E and indicate the synchronous frame current error and voltage reference.

The electrical parameters of applied induction motor to this control system are as follows:

R_s =8.5 Ω , R_r =9.119 Ω , L_s =0.3638 H,
L_r =0.37295 H, L_m =0.3455 H, Output = 1Hp.

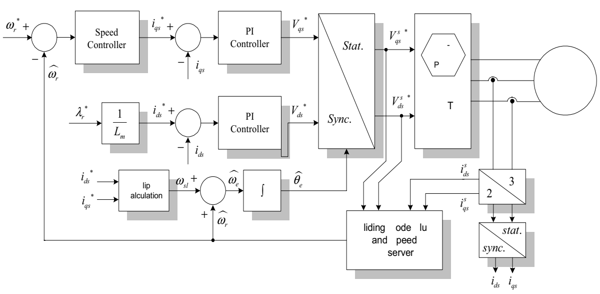


Fig. 1. Block diagram of the proposed sensorless vector control system

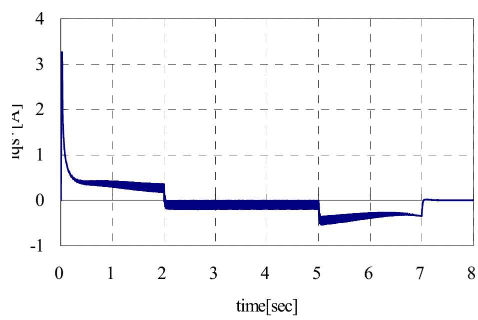
Fig. 2 shows the torque current reference characteristics of each controller when a trapezoidal speed command is given at time zero. During the time of 2sec, speed reference increases linearly with the time in slope of 50 until 100[rad/s].
At time 2sec, the speed reference keeps the 100 [rad/s] until time 5sec. Finally, during the time of 5-7sec, the speed reference decelerates linearly to zero speed.

As shown in fig. 2(a), the torque current characteristic of fuzzy sliding mode controller shows a reasonably good performance on the dynamic and steady state torque chattering. This is due to fine tuning of scaling factors and empirical selection of fuzzy rules, and adjustments of membership functions, except the basic gain tuning of standard vector controller.

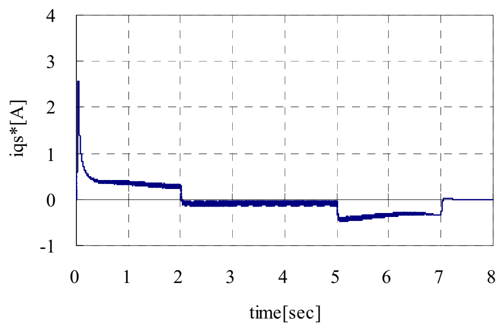
Table 1 Controller parameters of induction motor

Controller / Control Loop& Const.		Controller parameters: Fuzzy Sliding	Controller parameters: Synergetic
Speed Loop		GE=5000 GCE=3000 GU=1	$T=10\times T_S$
Current Loop	D	K_P =0.8 K_I = 10 T_S	K_P =0.8 K_I =10 T_S
	Q	K_P =0.8 K_I =10 T_S	K_P =0.8 K_I = 10 T_S
τ		1	$1\times T_S$
T_S		300 μ s	300 μ s
c		70 s^{-1}	70 s^{-1}

The performance characteristic of the proposed synergetic controller shown in fig. 2(b) represents the better performance compared to fuzzy sliding mode control method from the aspect of simulation results. That is, it has a pretty good dynamic and steady state torque current response, and comparatively low level of starting current.



(a) Fuzzy SLM control



(b) Synergetic control

Fig. 2. Torque current reference characteristics in trapezoidal speed reference

4. CONCLUSIONS

In this paper, we have designed the sliding-mode observer for speed-sensorless control, and the synergetic speed controller for the precise speed control of an induction motor for an industrial drive system. Also, the operating characteristics of synergetic controller are compared with the fuzzy sliding mode controller. As the detailed simulation results about proposed sliding observer are not shown in this paper yet, the observing characteristics is very simple and robust.
Meanwhile, synergetic controller exhibits a good performance in load torque rejection and steady state speed error, and reduction of torque chattering. On the other hand, it has the disadvantage of having higher sensitivity to motor mechanical parameter variations as compared to the fuzzy sliding mode controller. That is, mechanical parameter variations of induction motor have a direct effect on the control input of synergetic controller. And, since some trade-off relationship between the sliding mode existence and the dynamic evolution of controller exists, these problem should be examined closely in controller design.
Consequently, by applying the synergetic speed controller to the proposed sensorless vector control system, we have confirmed the effectiveness of this current model speed observer and synergetic control algorithm for robust AC servo drive system.

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