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A New SML Observer Implementation for Speed Sensorless Based Robust IRFOC Induction Machine Drives

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Abstract: This study proposed a new Sliding Mode-Luenberger (SML) speed observer for robust Indirect Rotor Field Oriented Control (IRFOC) induction machine (IM) drive system, feed through an ameliorate voltage inverter. The effectiveness of the proposed SML in induction motor control has been effectively demonstrated by comparing the SML with the Luenberger observer using Fuzzy-PI controller under varying operating conditions.

Key words: Sliding mode-luenberger observer, fuzzy-PI controller, IM drive, IRFOC, robust sensorless control

INTRODUCTION

The IM vectorial control uses the FOC has attracted much attention in the past few decades (Mezouar *et al*., 2007) unfortunately, this control approach suffers from its sensitivity to the motor parameter variations. When the motor parameters change with temperature and magnetic saturation, the performance of the system will deteriorate, one of ways to solve this problem is the uses of a robust control algorithm.

The Sliding Mode has been widely studied and developed for the control and state estimation problems since the studies of Utkin (1977). This control technique allows a good steady state and good dynamic behavior in the presence of system parameters' variation and disturbances, however, in this technique, the estimated fluxes are basically dependent on the motor model and the variation in the parameters inevitably propagates to the flux estimated error.

Some researches have proposed various induction motor drives with rotor resistance or rotor time-constant identification (Toliyat *et al*., 2003; Hinkkanen, 2004) to produce better control performance, such as a model reference adaptive system, Luenberger observer and the extended Kalman filter.

The study proposed Luenberger observer to estimate the machine speed as well as the load torque, forward by sliding mode current observer, the convergence of SML observer structure is guaranteed by the convergence of the error between the actual and observed currents to zero.

Firstly, we describe the speed control strategies of an IRFOC for IM. Next, with help of the Matlab/Simulink, we propose the F-PI controller, an observer is used for predict the load torque and speed. Finally, we compare the SML proposed with the conventional Luenberger observer using Fuzzy-PI controller. The simulation results validate the robustness and reliable of the proposed SML Observer for high performance of induction motor drive.

FIELD ORIENTED CONTROL STRUCTURE

A block diagram for an IRFOC can be seen on Fig. 1. This design uses a more robust structure known as Indirect Rotor Field Oriented Control, meaning that the rotor angle isn't determined directly by measuring the air gap flux with hall-effect sensors. These sensors are not particularly suited for use in large industrial motors as they can be fragile and sensitive to temperature change (Abed *et al*., 2006a, b; Rajashekara *et al*., 1996).

In this drive system, the inner feedback loop performs the synchronous current regulation. The current command i^*_{qs} is produced by the outer speed control loop based on the estimated and observed speed. This speed regulation is conventionally done by using an F-PI controller.

The dynamic model of an induction motor can be represented according to usual d-q axes components in asynchronous rotating frame as follows:

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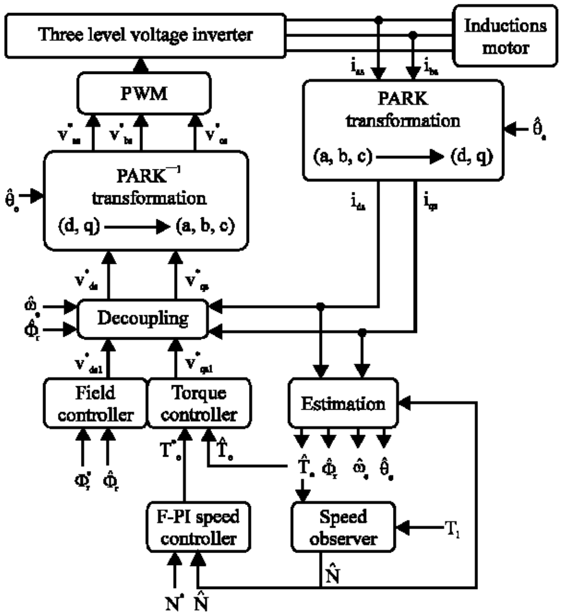

Fig. 1: Field oriented controller block diagram (Abed *et al*., 2006)

$$\begin{bmatrix} \dfrac{di_{ds}}{dt} \\ \dfrac{di_{qs}}{dt} \\ \dfrac{d\phi_{dr}}{dt} \\ \dfrac{d\phi_{qr}}{dt} \end{bmatrix} = \begin{bmatrix} -\gamma & \omega_e & \dfrac{k}{\tau_r} & N_pNk \\ -\omega_e & -\gamma & -N_pNk & \dfrac{k}{\tau_r} \\ \dfrac{L_m}{\tau_r} & 0 & -\dfrac{1}{\tau_r} & \omega_e - N_pN \\ 0 & \dfrac{L_m}{\tau_r} & -\left(\omega_e - N_pN\right) & -\dfrac{1}{\tau_r} \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} i_{ds} \\ i_{qs} \\ \phi_{dr} \\ \phi_{qr} \end{bmatrix} + \begin{bmatrix} \dfrac{1}{\sigma L_s} & 0 \\ 0 & \dfrac{1}{\sigma L_s} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} v_{ds} \\ v_{qs} \end{bmatrix}$$

Where,

$$\sigma = 1 - \frac{M^2}{L_sL_r},\ k = \frac{M}{\sigma LsLr},\ \tau_r = \frac{L_r}{R_r}$$

The decoupling control between d and q axes can be achieved by aligning the rotor flux vector to the d-axis and setting the rotor flux linkage to be constant, which means:

$$\Phi_{qr} = 0; \frac{d\Phi_{qr}}{dt} = 0 \quad (2)$$

$\Phi_{dr} = \Phi_r$ rated flux

Substituting (2) in (1) yields:

$$\begin{cases} v_{ds} = \sigma L_s \dfrac{di_{sd}}{dt} + \left(R_s + R_r \dfrac{M^2}{L_r^2}\right) i_{ds} - \\ \qquad \omega_e \sigma L_s i_{qs} - \dfrac{M}{L_r^2} R_r \Phi_r \\ v_{qs} = \sigma L_s \dfrac{di_{sq}}{dt} + \omega_e \sigma L_s i_{sq} + \left(R_s + R_r \dfrac{M^2}{L_r^2}\right) i_{ds} - \\ \qquad \dfrac{M}{L_r^2} N_p N \Phi_r \\ \tau_r \dfrac{d\Phi_r}{dt} + \Phi_r = Mi_{ds} \\ \omega_e = N_p N + \dfrac{M}{\tau_r} \dfrac{i_{qs}}{\Phi_r} \end{cases} \quad (3)$$

The electromagnetic torque equation and the mechanical speed motor are related by:

$$J\frac{dN}{dt} + fN = T_e - T_l \quad (4)$$

Where, the electromagnetic torque expression is:

$$T_e = N_p \frac{M}{L_r} \Phi_r i_{qs} \quad (5)$$

The decoupling control system is given by:

$$\begin{cases} v^*_{ds} = v_{ds1} - e_{ds} \\ v^*_{qs} = v_{qs1} - e_{qs} \end{cases} \quad (6)$$

Where,

$$\begin{cases} e_{ds} = \hat{\omega}_e \sigma L_s i_{qs} + \dfrac{M}{L_r^2} R_r \Phi_r \\ e_{qs} = -\hat{\omega}_e \sigma L_s i_{ds} - \dfrac{M}{L_r} \hat{\omega}_e \Phi_r + \dfrac{M^2}{L_r \tau_r} i_{qs} \end{cases} \quad (7)$$

DESIGN OF F-PI CONTROLLER

The fuzzy logic controller is attractive approach, which can accommodate the motor parametric variations and difficulty in obtaining an accurate mathematical model of induction motor due to rotor parameter and load time constant variations. In order to have fast transient

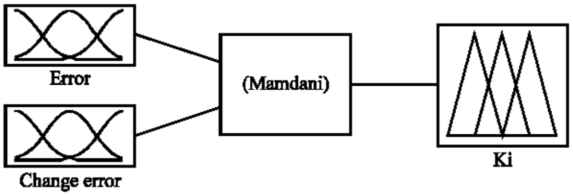

Fig. 2: Fuzzy controller architecture

Table 1: Control rule base

ECE	NL	NM	NS	ZE	PS	PM	PL
N	ZE	S	M	L	M	S	ZE
ZE	ZE	S	M	L	M	S	ZE
P	ZE	M	L	L	L	M	ZE

response, the controller must have the robustness against speed variations and external perturbations. The Fuzzy logic is applied to optimize the PI controller gains which designed to optimize the step response of the system.

The purpose of this design is to synthesize a controller without the exact knowledge of a model, numerically simple and simulated on Matlab/Simulink allowing good performance in terms of overshoot, fast and accuracy under the speed and load variations.

The Fuzzy Logic Toolbox based controller architecture is shown in Fig. 2.

The fuzzy logic controller employs speed error and its rate of change as inputs, the Ki of PI controller is output.

$$e(k) = \overset{*}{N} - \hat{N} \qquad (8)$$

$$\Delta e(k) = e(k) - e(k-1) \qquad (9)$$

And it uses following linguistic labels: {NL (Negative Large), NM (Negative Medium), NS (Negative Short), ZE (Zero), PS (Positive Short), PM (Positive Medium), PL (Positive Large)}. Each fuzzy label has an associated membership function.

The control rules are represented as a set if then rules. The fuzzy rules of proposed controller for speed control of induction motor are presented in Table1. And formulated as follows:

If e (k) is NL and Äe (k) is N then Te*(k) is ZE

SENSORLESS SPEED CONTROL ALGORITHM

Synchronous angular speed estimation (Pinard, 2004; Abed *et al.*, 2007; Abed *et al.*, 2008): From the row 4 of (3) we obtain

$$\omega_e = N_p N + \frac{M}{\tau_r}\frac{i_{qs}}{\hat{\Phi}_r + \varepsilon} \qquad (10)$$

Because $\hat{\Phi}_r = 0$ in t = 0 s
Where, $\hat{\Phi}_r$ is the estimate flux, $\varepsilon = 0.01$.

From the row (3):

$$\hat{\Phi}_r = \frac{M}{1+\tau_r p} ids \qquad (11)$$

Once we obtain the synchronous angular speed, θ_e is simply equal to:

$$\theta_e = \int \omega_e \qquad (12)$$

Knowledge of the synchronous angular speed and θ_e is essential for applying the Clarke and Park transforms.

Speed control: Sensorless control is another extension to the IRFOC algorithm that allows IMs to operate without the need for mechanical speed sensors. These sensors are notoriously prone to breakage, so removing them not only reduces the cost and size of the motor but improves the drive's long term accuracy and reliability (Shoudao *et al.*, 2004; Shi *et al.*, 2000; Lysherski, 2000; Chavez *et al.*, 2004). This is particularly important if the motor is being used in a harsh, inaccessible environment such as an oil well.

From expression (4), we establish the following transfer function

$$N = \frac{1}{Jp+f}(T_e - T_l) \qquad (13)$$

Instead of physically measuring certain values control engineers can calculate them from a system's state variables. This is known as the state space modeling approach and is a powerful method for analyzing and controlling complex non-linear systems with multiple inputs and outputs.

Closed loop observer implantation: The objective here is to use a load torque and speed observer in order to delete all mechanical sensors.
From (4) and (5)

$$\frac{dN}{dt} = -\frac{f}{J}N + \frac{N_p M \Phi_r}{J L_r} i_{qs} - \frac{1}{J}T_l \qquad (14)$$

The system of the 2nd order Luenberger observer is given by Ghosn (2001).

$$\begin{cases} \hat{\dot{X}}=A\hat{X}+BU+L(Y-\hat{Y}) \\ \hat{Y}=C\hat{X} \end{cases} \tag{15}$$

With:

$$\hat{X}=\begin{bmatrix} N_{obs} \\ T_{l-obs} \end{bmatrix};L=\begin{bmatrix} l1 \\ l2 \end{bmatrix} \tag{16}$$

We have finally:

$$\begin{bmatrix} \frac{d}{dt}N_{obs} \\ \frac{d}{dt}T_{l-obs} \end{bmatrix} = \begin{bmatrix} \frac{-f}{J}-l1 & \frac{-1}{J} \\ -l2 & 0 \end{bmatrix} \begin{bmatrix} N_{obs} \\ T_{l-obs} \end{bmatrix} + \begin{bmatrix} \frac{N_p M\Phi_r}{JL_r} \\ 0 \end{bmatrix}(iqs)+\begin{bmatrix} l1 \\ l2 \end{bmatrix}.N \tag{17}$$

The factors l1 and l2 are selected to fix the observer dynamics, we put: l1 = 250, l2= -600

SLIDING MODE CURRENT AND FLUX OBSERVER DESIGN

The proposed speed and rotor time constant estimation structure is based on sliding mode current and flux observers. Ensuring the convergence of the current observer, the equivalent control is produced. Then, it is used in the flux observation to produce fluxes along the d and q axes. Once the flux values are found, then the rotor speed and rotor time constant are estimated by using observed fluxes.

From (1) we can write: (Inanc, 2007)

$$\begin{bmatrix} \frac{\partial}{\partial t}\hat{i}_{ds} \\ \frac{\partial}{\partial t}\hat{i}_{qs} \end{bmatrix} = -\gamma \begin{bmatrix} \hat{i}_{ds} \\ \hat{i}_{qs} \end{bmatrix} + k \begin{bmatrix} \Psi_{dr} \\ \Psi_{qr} \end{bmatrix} + \frac{1}{\sigma Ls} \begin{bmatrix} v_{ds} \\ v_{qs} \end{bmatrix} \tag{18}$$

$$\begin{bmatrix} \frac{\partial}{\partial t}\hat{\Phi}_{dr} \\ \frac{\partial}{\partial t}\hat{\Phi}_{qr} \end{bmatrix} = \frac{M}{\tau_r}\begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} - \begin{bmatrix} \Psi_{dr} \\ \Psi_{qr} \end{bmatrix} \tag{19}$$

Where,

$$\begin{aligned} \Psi_{dr} &= -u_{ds}\text{sign}(s_{ds}) \\ \Psi_{qr} &= -u_{qs}\text{sign}(s_{qs}) \end{aligned} \tag{20}$$

$$\begin{aligned} u_{ds} &= \left| -\gamma \bar{i}_{ds} - k\left(\frac{\phi_{dr}}{Tr} + N_p N\phi_{qr} \right) \right| \\ u_{ds} &= \left| -\gamma \bar{i}_{qs} - k\left(\frac{\phi_{qr}}{Tr} + N_p N\phi_{dr} \right) \right| \end{aligned} \tag{21}$$

Where,

$$\bar{i}_{ds} = \hat{i}_{ds} - i_{ds},\ \bar{i}_{qs} = \hat{i}_{qs} - i_{qs}$$

$$\begin{bmatrix} \Psi_{dr} \\ \Psi_{qr} \end{bmatrix} = \begin{bmatrix} \frac{1}{\hat{\tau}_r} & N_p\hat{N}k \\ -N_p\hat{N}k & \frac{1}{\hat{\tau}_r} \end{bmatrix} \begin{bmatrix} \hat{\Phi}_{dr} \\ \hat{\Phi}_{qr} \end{bmatrix} \tag{22}$$

And

$$\begin{aligned} s_{ds} &= \hat{i}_{ds} - i_{ds} \\ s_{qs} &= \hat{i}_{qs} - i_{qs} \end{aligned}$$

Using (22) speed and actual value of the rotor time constant can be found:

$$\begin{bmatrix} \frac{1}{\hat{\tau}_r} \\ N_p\hat{N}k \end{bmatrix} = \frac{1}{|\hat{\Phi}_r|} \begin{bmatrix} -\hat{\Phi}_{dr} & -\hat{\Phi}_{qr} \\ -\hat{\Phi}_{qr} & \hat{\Phi}_{dr} \end{bmatrix} \begin{bmatrix} \Psi_{dr} \\ \Psi_{qr} \end{bmatrix} \tag{23}$$

Where,

$$|\hat{\Phi}_r| = (-\hat{\Phi}_{dr}^2 - \hat{\Phi}_{qr}^2) \tag{24}$$

SIMULATION RESULTS

The SIMULINK model used in this paper, models the induction motor as a continuous system for its dynamic equivalent circuit. The IGBT 3 level (NPC) inverter is controlled by a PWM with a switching frequency of 18 kHz.

We have tested the robust controller for sensorless speed controlled induction motor drive

The comparison between the observed load torque and the real one in Fig. 3a reveals that the observation is satisfactory even if there is a difference between these two torques at the time of the transitory modes such as speed or load change.

Figure 3b shows that the Closed Loop Observered speed follows the estimated speed given in §4.2,

The simulation results confirm the efficiency of the SML observer compared with the F-PI; these results show that the sliding mode control with the proposed

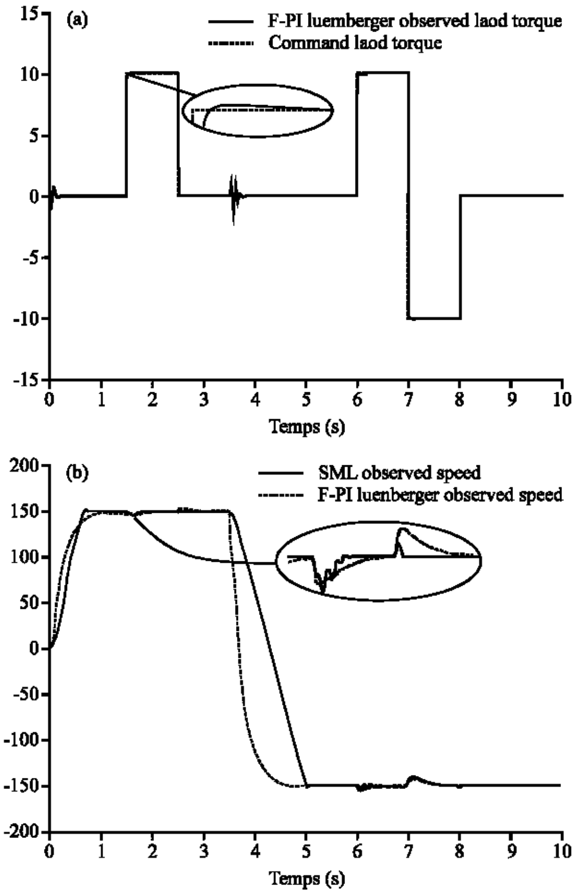

Fig. 3: Simulation results of the IRFOC closed loop observer implementation: (a): Observed and real load torque, (b): Comparison between SML and F-PI Observed speed

observer can track the reference command accurately and quickly. Therefore, it able to reacted positively with an ameliorate three level inverter to control the IM.

CONCLUSION

Using conventional PI controller, it is very difficult and complex to design a high performance induction motor drive system and the Fuzzy-PI Controller is very complex with respect to the software and requires extensive calculation that put extra load on the processor.

In this study, we presented the states variations in an objective of ameliorate the IM sensorless speed control by a SML Observer. A comparison between the SML and F-PI controller reveals the effectiveness of the first one and argues that the SML observer has a good performance and is the least involved in terms of design.

The SML observer can be used for parameter estimation as well as state estimation is less sensitive to the system parameters variation and this proves its robustness.

Future research is oriented at experimental validation.

NOMENCLATURES

v_{ds}, v_{qs} : d-q axis stator applied voltages.
i_{ds}, i_{qs} : d-q axis stator currents.
Φ_{dr}, Φ_{qr} : d-q rotor flux linkage.
R_s, R_r : Stator and rotor winding resistances.
L_s, Lr : Stator and rotor.
M : Mutual magnetizing inductances.
N_p : Number of pole pairs.
p : Laplace operator.
ω_e, ω_r : Synchronous and electrical angular speed.
T_e, Tl : Eelectromagnetic and load torque.
J : Total inertia.
f : Friction coefficient.
τ_r : Rotor time constant.
σ : Leakage coefficient.
^ : Denotes the estimated value.
* : Denotes the reference value.
N, N_{obs} : Estimated and observed speed.
T_{l_obs} : Observed load torque.

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