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Simulation of non linear adaptive observer for sensorless induction motor control

Benheniche Abdelhak[1, 2], Bensaker Bachir[2]

[1]Electrotechnical Department, Mouloud Mammeri Tizi-Ouzou University
[2]Electronic Department, Badji Mokhtar Annaba University

Email address:
benheniche2006@yahoo.fr(B. Abdelhak), bensaker_bachir@yahoo.fr(B. Bachir)

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Abstract: This paper presents a model reference adaptive system based sensorless induction motor drive. In this scheme, an adaptive full order flux observer is used. The simulation result show that with the large PI gain for the adaptive scheme, the convergence for the speed estimation is fast and very well, however higher harmonics and noises are included in the estimated speed. Usually noises caused by inverter. Simulation results show that proposed scheme can estimate the motor speed under various adaptive PI gains and estimated speed can replace to measured speed in sensorless induction motor.

Keywords: Induction Motor, Sensorless Control, Pole Placement, MRAS Speed Estimation, Lyapunov Function

1. Introduction

Three phase induction motor is widely used in many industries, mainly due to its rigidness, maintenance free operation, and relatively low cost. In contrast to the commutation dc motor, it can be used in aggressive or volatile environments since there are no risks of corrosion or sparks. However, induction motor constitute a theoretically challenging control problem since the dynamical system is non linear, the electrical rotor variable are not measurable, and the physical parameters are most often imprecisely known[1-2-3-6].

Machine model based methods of speed estimation have found a great interest among different speed estimation methods for their simplicity. They include different methods such as Luenberger observer (LO)[10-13], Model Reference Adaptive System (MRAS)[1-2-4-10-15]; Adaptive Flux Observer (AFO)[2-12-14-16]; Sliding Mode Observer (SMO)[17-18] Artificial Intelligence Techniques (AI)[19-20-21]; and Kalman Filer (KF)[22-23].Machine model-based methods are characterized by their simplicity and good performance at high and medium speeds. However at low speeds, they are problematic. The main limitations arise from instability problems associated with most speed estimation schemes at low speeds due to the change of machine parameters.

Adaptive flux observer is one of the machine model based methods of speed estimation of sensorless induction motor drive. Parameters variations, low speed operation and the difficulty encountered in the design in the feedback gain and the adaptation mechanism are the most crucial aspects affecting the accuracy and stability of this method. This unstable region of AFO can be reduced by proper design of both the observer feedback gain and adaptive law using several techniques. . Instability problems of low speed regenerative mode of reduced-order observers and their remedies have been proposed in[24].

Many researches have been devoted to yielding better speed estimation of sensorless induction motor drives using AFO. However, there is a well known unstable region encountered at low speeds. One of the techniques to study the stability analysis of the speed estimation and simplify the structure of the sensorless control system by means of the using Routh–Hurwitz criterion[12].Or using Lyapunov theory[13]. Stability analysis of both rotor speed and stator resistance estimators for stable AFO[8] and in the regenerative mode at low speeds has been presented in[9-11].and parallel speed and stator resistance estimation algorithm based on a sliding mode current observer which combines variable structure control and Popov’s hyper stability theories[7].

It is well known from control theory that a state estimator, called also state observer, is a dynamic system that is driven by the input-output of the considered system, estimate asymptotically its un-measurable state variable. It uses an adaptive mechanism involving as input, the error between the measured and estimated output value of the system. It is a “software sensor» that plays an important role in the estimation of the un-measurable state variables that are essential not only in the sensorless control techniques.

As au result, the drive has a wider adjustable speed range and can be operated at very low speed. This paper presents the simulation results of the proposed scheme which has been implanted on a 0.75KW induction motor driver. The systematic of this paper consist of six sections. Section 1 describes the overview of the observation and control system structure of induction motor under studies. Section 2 discusses with the model of adaptive flux observer; the model reference adaptive system is presented in section 3 while section 4 describes the adaptive scheme for speed estimation. Section 5 depicts the simulation results of the designed induction motor control. Finally, section 6 gives the conclusion of this paper.

2. Mathematical Models for Induction Motor and Adaptive Flux Observer

2.1. Dynamic Model of Induction Motor

For an induction motor, if the stator current $\boldsymbol{i_s}$ and rotor flux $\boldsymbol{\emptyset_r}$ are selected as the state variables equations can be expressed as (1) in the stationary reference frame[2]

$$\frac{d}{dt}\begin{bmatrix} i_s \\ \emptyset_r \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix}\begin{bmatrix} i_s \\ \emptyset_r \end{bmatrix} + \begin{bmatrix} B_1 \\ 0 \end{bmatrix} v_s \quad (1)$$

$$i_s = Cx \quad (2)$$

Where

$i_s = [i_{ds} \quad i_{qs}]^T$ is stator current

$\emptyset_r = [\emptyset_{dr} \quad \emptyset_{qr}]^T$ is rotor flux

$v_s = [v_{ds} \quad v_{qs}]^T$ is stator voltage

$$x = [i_s \quad \emptyset_r]^T$$

$$A_{11} = -\left\{\frac{R_s}{\sigma L_s} + \frac{1-\sigma}{\sigma \tau_r}\right\} I = a_{r11} I$$

$$A_{12} = \frac{L_m}{\sigma L_s L_r}\left\{\frac{1}{\tau_r} I - \omega_r J\right\} = a_{r12} I + a_{i12} J$$

$$A_{21} = \left(\frac{L_m}{\tau_r}\right) I = a_{r21} I$$

$$A_{22} = \left(\frac{1}{\tau_r}\right) I + \omega_r J$$

$$B_1 = \frac{1}{\sigma L_s} I \ , \qquad C = [I \quad 0]$$

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

$$I = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \ and \ J = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$$

Where R_s , R_r and L_s , $L_r$are stator and rotor resistances and self inductances ,respectively, L_m is mutual inductance, τ_r is the rotor time constant $\frac{L_r}{R_r}$ and ω_r is electrical motor angular speed.

The electromechanical equation of induction motor is given by

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}\left(\emptyset_{dr} i_{qs} - \emptyset_{qr} i_{ds}\right) \quad (3)$$

3. Model Reference Adaptive System

The model reference adaptive system (MRAS) is one of the major approaches for adaptive control[4][6]. The model reference adaptive system (MRAS) is one of many promising techniques employed in adaptive control. Among various types of adaptive system configuration, MRAS is important since it leads to relatively easy-to-implement systems with high speed of adaptation for a wide range of applications. Theoretically MRAS computes a desired state (called as the functional candidate) using two different models (i.e. reference and adjustable models). The error between the two models is used to estimate an unknown parameter (here speed is the unknown parameter). A condition to form the MRAS is that the adjustable model should only depend on the unknown parameter. Here, the reference model is independent of rotor speed, whereas the adjustable model is dependent on the same. The error signal is fed to the adaptation mechanism. The output of the adaptation mechanism is the estimated quantity ($\widehat{\omega}_{rest}$), which is used for the tuning in adjustable model and also for feedback. The stability of such closed loop estimator is achieved through Popov’s Hyper stability criterion[1-2].

Several other approaches such as variable structure-based technique, passivity based technique, etc. are also reported to estimate the speed of a PMSM drive. The more recent approach based on Artificial Intelligence (AI) are the Artificial Neural Networks (ANN)[21] and Fuzzy Logic[22] for speed estimation. But, the AI-based methods require huge memory and involve computational complexity.

Out of all the techniques discussed so far, MRAS is widely accepted for speed estimation due to its simplicity and good stability. Also the method does not require any extra hardwire or signal injection or huge memory like EKF or ELO.

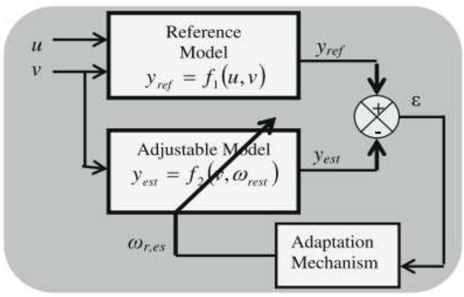

Figure 1. *Basic configuration of a parallel adaptive system.*

2.2. Adaptive Flux Observer

The APFO flux observer can be written as fellows[1]:

$$\frac{d}{dt}\hat{\imath}_s = \hat{A}_{11}\hat{\imath}_s + \hat{A}_{12}\hat{\emptyset}_r + Bv_s + G(\hat{\imath}_s - i_s) \quad (4)$$

$$\frac{d}{dt}\hat{\emptyset}_r = \hat{A}_{21}\hat{\imath}_s + A_{22}\hat{\emptyset}_r \quad (5)$$

Where $\boldsymbol{i_s}$ and $\boldsymbol{v_s}$ are measured values of stator current vector and stator voltage vector, respectively, G is the full order observer gain matrix which is also determined to make (3) stable and "^ "denote the estimated values. The observer is the closed loop system, which is obtained by driving estimated model of the induction motor by the residual of the current measurement, $\boldsymbol{e_{is}}$.

$$e_{is} = i_s - \hat{\imath}_s \quad (6)$$

The estimation of stator currents is conducted by a closed loop observer with[4X2] feedback gain matrix G as in (3), whereas the estimation of the rotor fluxes is carried out by an open loop observer of (4) without the flux error. Therefore, the real and estimated rotor fluxes are assumed the same.

$$\emptyset_r = \hat{\emptyset}_r \quad (7)$$

The observer gain matrix is chosen as:

$$G = \begin{bmatrix} g_1 & g_2 & g_3 & g_4 \\ -g_2 & g_1 & -g_4 & g_3 \end{bmatrix}^T \quad (8)$$

Where the observer gain matrix G is calculated based on the pole placement technique. The selection of the observer poles is a compromise between the rapidity of error responses and the sensitivity to disturbances and measurement noises. In practice, the eigen-values of the observer are selected to be negative, so that the state of the observer will converge to the state of the observed system, and they are chosen to be somewhat more negative than the eigen-values of the observed system so that convergence is faster than other system effects. Based on the above mentioned criteria the author chose[1],

$$g_1 = (k-1)(a_{r11} + a_{r22}) \quad (9)$$

$$g_2 = (k-1)a_{i11} \quad (10)$$

$$g_3 = (k^2-1)(ca_{r11} + a_{r21}) - c(k-1)(a_{r11} + a_{r22}) \quad (11)$$

$$g_4 = c(k-1)a_{i22} \quad (12)$$

$$c = \sigma L_s L_r / L_m \quad (13)$$

4. Adaptive Scheme for Speed Estimation

Consider the Lyapunov function candidate[9]:

$$V = V_1 + V_2 \quad (14)$$

$$V_1 = e^T e \qquad V_2 = \frac{e_\omega{}^2}{\lambda} \quad (15)$$

With $(\lambda > 0)$, is the positive constant ensuring the positive definiteness of V_2 and which will be tuned in (19) to improve observer dynamics. $e_\omega = \omega_r - \hat{\omega}_r$ and $e^T = [i_{sd} - \hat{\imath}_{sd} \; i_{sq} - \hat{\imath}_{sq} \;\; 0 \;\; 0]$ Because we supposed that $\emptyset_r = \hat{\emptyset}_r$

The derivatives of this lyapunov candidate function in thus:

$$\frac{dV}{dt} = e^T[(A-GC)^T + (A-GC)]e$$
$$-2(\omega_r - \hat{\omega}_r)\left[K\left(e_{isd}\hat{\emptyset}_{rq} - e_{isq}\hat{\emptyset}_{rd}\right) - \frac{1}{\lambda}\frac{d}{dt}\hat{\omega}_r\right] \quad (16)$$

$$e^T[(A-GC)^T + (A-GC)]e < -Q \quad (17)$$

With $Q = \varepsilon I_n$ and $\varepsilon > 0$

The stability of adaptive observer has proved if we respect two conditions as follows:

The eigen-value of the observer are selected to have negative real parts so that the states of the observer will converge to the desired states of the observed system. The term in factor of $(\omega_r - \hat{\omega}_r)$in the equation (16) must be zero. The expression of the derivative of estimated speed becomes then:

$$K\left(e_{isd}\hat{\emptyset}_{rq} - e_{isq}\hat{\emptyset}_{rd}\right) - \frac{1}{\lambda}\frac{d}{dt}\hat{\omega}_r = 0 \quad (18)$$

$$\frac{d}{dt}\hat{\omega}_r = \lambda K\left(e_{isd}\hat{\emptyset}_{rq} - e_{isq}\hat{\emptyset}_{rd}\right) \quad (19)$$

However this adaptive law of the speed

$$\hat{\omega}_r = K_i\int_0^t\left(e_{isd}\hat{\emptyset}_{rq} - e_{isq}\hat{\emptyset}_{rd}\right)dt \quad (20)$$

Has obtained for the satatorique frame his dynamic has adjusted by K_i (finite positive constant). For augmented the dynamic of this observer during the transitory phase of rotor speed, we estim the speed by large PI regulator; we added a supplementary term proportional of error. Then

$$\hat{\omega}_r = K_p\left(e_{isd}\hat{\emptyset}_{rq} - e_{isq}\hat{\emptyset}_{rd}\right)$$
$$+ K_i\int_0^t\left(e_{isd}\hat{\emptyset}_{rq} - e_{isq}\hat{\emptyset}_{rd}\right)dt \quad (21)$$

Where K_p and K_i are adaptive gains for speed estimator. An identification system for speed is shown in Fig.2, which is constructed from a linear time-invariant forward block and a nonlinear time-varying feedback block.

5. Simulation Results

The basic configuration of speed estimation of sensorless induction motor drive is shown in figure (2).this configuration will be used for both simulations. All reference or command preset values are subscripted with a " * " in the diagram.IM speed will be estimated by (21) and will be compared with the reference speed in order to create the error speed. The proposed full order flux observer for induction motor states estimations has been developed and applied in the direct field oriented control of induction motor.

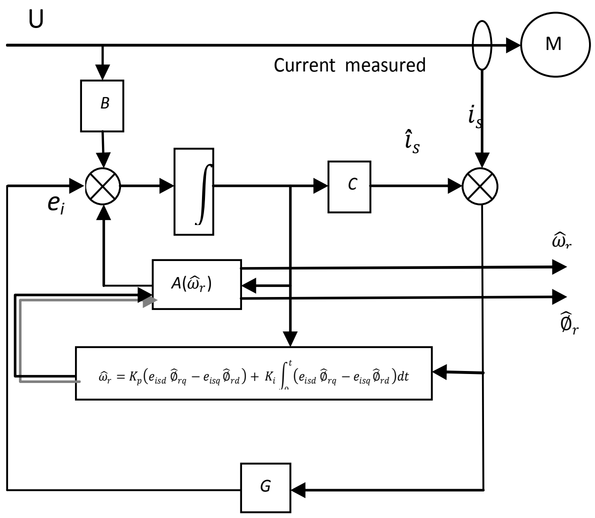

Figure 2. *Speed adaptive observer*

Table 1. *Induction motor parameters*

Symbol	Quantity	N. Values
P_a	Power	O.75KW
F	Supply frequency	50HZ
P	Number of pair poles	2
V	Supply voltage	220V
R_s	Stator resistance	10Ω
R_r	Rotor resistance	6.3Ω
L_s	Stator inductance	0.4642H
L_r	Rotor inductance	0.4612H
L_m	Mutual inductance	0.4212H
ω_r	Rotor angular velocity	157rd/s
J	Inertia coefficient	$0.02Kg^2/s$
f	Friction coefficient	0N.s/rd

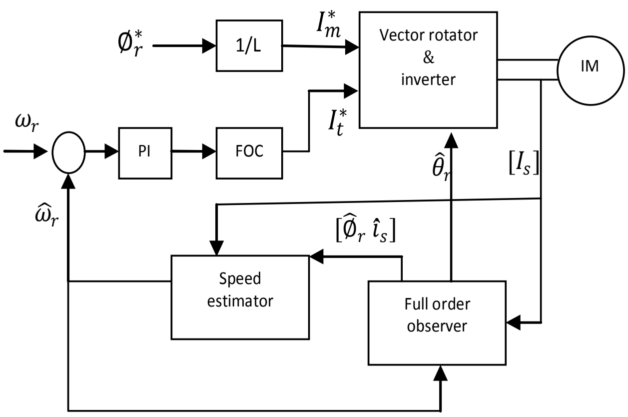

Figure 3. *Block diagram of sensorless IM drive*

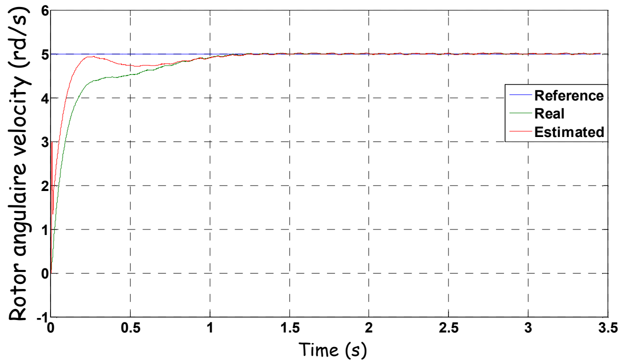

Figure 4. *Reference, measured and observed rotor angular velocity (very low speed)*

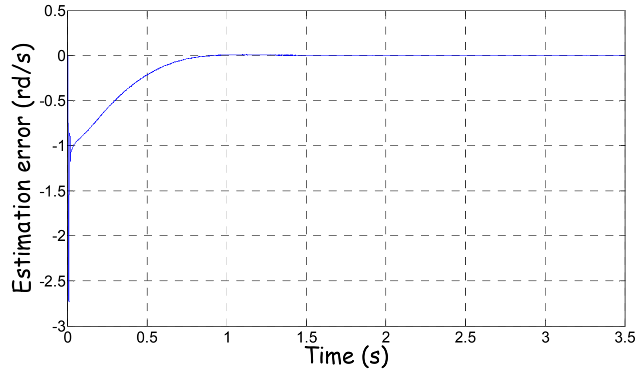

Figure 5. *Speed estimation error*

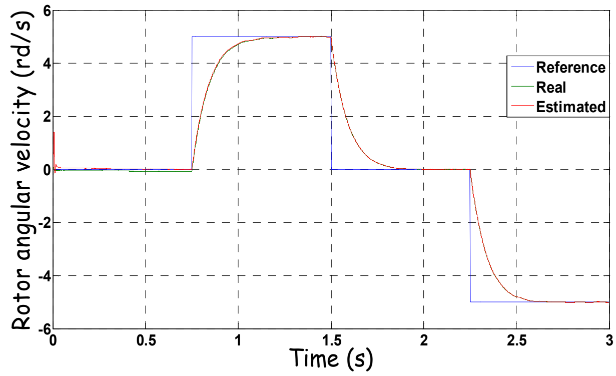

Figure 6. *Reference measured and observed rotor angular velocity during step change of speed reference from[0:5:0:-5] (very low and zero speed)*

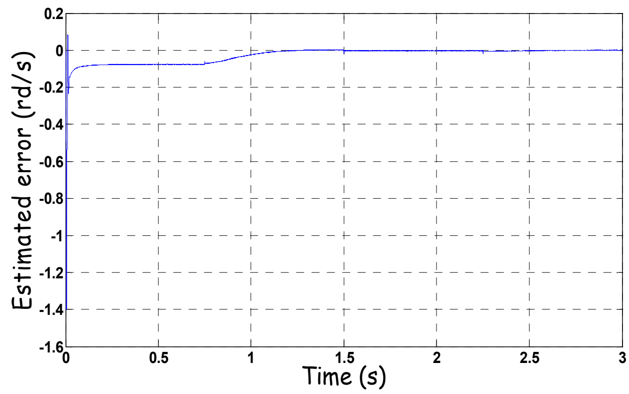

Figure 7. *Speed estimation error*

In fig.4-5 show the behavior of IM speed estimation and estimation error where the induction motor rotates at a constant very low speed (5 rd/s), the observed speed also converge to real speed at the time (0.8s for 5 rd/s) .these figures show that with large PI gain for adaptive scheme, the convergence for speed estimation is fast.

In fig.6-7 show the behavior of IM speed estimation and estimation error under various command speed , where the command speed is first set at a zero speed (0 rd/s), at (0.75s) the reference speed is changed to (5 rd/s) (very low speed),.at (1s) the reference speed is changed to (0rd/s) (zero speed),finally at (2.25s) the command speed is changed to (-5rd/s) .the proposed observer confront no problem in the low speed region. Furthermore the algorithm of speed identification scheme is characterized by their simplicity and small computation time.

6. Conclusion

This paper presents a MRAS-based adaptive full-order observer (AFFO) sensorless induction motor drive. This method has been applied to a direct field-oriented induction motor control without speed sensor. The simulation results demonstrated that with PI gains for the adaptive regulators, the convergence for the speed estimation is fast and well. The proposed observer can work accurately at very low speed region.

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