High Performances Induction Motor Drive Based on Fuzzy Logic Control

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Abstract

This paper deals with high performance speed control approach using direct flux and torque control for the induction motor (IM). The closed loop scheme of the drive utilizes the fuzzy logic controllers both in speed and electromagnetic torque control loops. Due to the drawbacks of the sensors, an algorithm is evolved to reconstruct the IM fluxes and electromagnetic torque. In fact, based on the model of the IM, the observed stator currents and IM fluxes are simultaneously obtained based on full order Luenberger observer. The observed stator currents and IM fluxes are adversely affected by rotor speed feedback signal and stator resistance variations due to temperature and frequency changes. To improve the performance of the overall system, the rotor speed and stator resistance are both estimated in such away to assume the overall stability of the state observer based on Lyaponov criterion. Digital simulation results are presented to show the improvement in performance of the proposed method.

Keywords: *Adaptive Luenberger Observer, Fuzzy controllers, Induction Motor, Lyaponov Criterion, Parameter Variation, Sensorless*

1. Introduction

Since many years, thanks to the development of fast calculators, IMs are widely used in industry due to their reliability, ruggedness and relatively low cost. Compared to DC motors, they can be used in aggressive environments since there is no problem with spark and corrosion. In fact, IM constitute a class of the highly coupled system. Therefore, it is very difficult to obtain good performance for an entire speed range and transient states using classical methods (conventional PI controller). High-performance servo systems have good dynamic speed command tracking and load regulating responses. However, the control algorithms applicable to these systems have become increasingly more complicated, requiring extensive computations for real-time implementation. Vector-controlled IM with a conventional PI speed controller is used extensively in industry [1, 2].

The conventional PI controller is easily implemented and is highly effective if the load changes are small and operating conditions do not force the system too far away from the linearization equilibrium point [3].

Here, the proposed system combines the stator vector control technique and the advantages of fuzzy logic control [4]. So, a speed and torque fuzzy logic controllers (FLC) for IM via direct vector control is presented in order to achieve better tracking performances. Simulation results show the importance of the fuzzy logic inclusion in designing stator vector control laws. Similarly, it validates the robustness and effectiveness of the proposed control scheme[5, 6]. In fact, accurate speed information is necessary to realize high performance and high precision IM speed control. The speed feedback signal is achieved through mechanical sensors such as resolvers or pulse encoders. However, these sensors are usually expensive and bulky. Therefore, the cost and size of the drive systems are increasing. Sensorless control has been introduced in the drives literature to provide an alternative, yet lower cost solution [7, 8]. Here, the vector control principle is used with sensorless control based on an adaptive Luenberger observer: The rotor speed and the stator resistance are estimated in such away to assume the overall stability of the state observer[9, 10].

2. Basic Induction Motor Model

Assuming linear magnetic circuits, equal mutual inductances and neglecting iron losses, the IM dynamic model can be represented according to the usual d-axis and q-axis components in a synchronous frame as:

$$\vec{V}_s = R_s\vec{i}_s + \dot{\vec{\varphi}}_s + j\omega_s\vec{\varphi}_s. \tag{1}$$

$$\vec{0} = R_r\vec{i}_r + \dot{\vec{\varphi}}_r + j(\omega_s - \omega_r)\vec{\varphi}_r. \tag{2}$$

$$\vec{\varphi}_s = L_s\vec{i}_s + M\vec{i}_r. \tag{3}$$

$$\vec{\varphi}_r = L_r\vec{i}_r + M\vec{i}_s. \tag{4}$$

Where $\vec{V}_s$ is a stator voltage vector, $\vec{i}_s, \vec{i}_r$ are the stator and the rotor current vectors, $\vec{\varphi}_s, \vec{\varphi}_r$ are the stator and the rotor flux vectors, ω_s, ω_r are the synchronous and the rotor speed, Ls, Lr are the stator and the rotor self inductances and M is the mutual inductance.

3. Control Strategy

The IM can produce good performances using field-oriented vector control strategy [11]. The main idea of the vector control is to monitor the torque and the flux separately. This technique is based on the orientation of the flux vector along the d axis, which can be expressed by considering: $\varphi_{sd} = \varphi_s$ and $\varphi_{sq} = 0$.

The stator flux vector orientation and the state space equation lead to the following V_{sd}, V_{sq} and the electromagnetic torque expressions:

$$V_{sd} = R_s i_{sd} + \frac{d\varphi_s}{dt}. \tag{5}$$

$$V_{sq} = R_s i_{sq} + \omega_s\varphi_s. \tag{6}$$

$$T_e = n_p\,\varphi_{sd}\,i_{sq}. \tag{7}$$

Where T_e is the electromagnetic torque and np is the number of pole pairs.

Combining equations (6) and (7), the *d* and *q* components of stator voltage in the stationary reference frame are:

$$V_{sd} = R_s i_{sd} + \frac{d\varphi_s}{dt} \approx \frac{d\varphi_s}{dt}. \tag{8}$$

$$V_{sq} = \frac{R_s}{n_p\varphi_s} T_e + \omega_s\varphi_s. \tag{9}$$

The above equations show, for a constant magnitude stator flux vector, that the stator voltage *d* component affects only the stator flux and can be used to control it directly. The *q* component of stator voltage affects the torque variable, and if the term $\omega_s\varphi_s$ is decoupled, it can be used to control the produced torque.

4. Fuzzy Logic Control

In fact, many researchers have used classical PI controllers for the speed and the torque control. It receives as inputs the speed and torque errors and generates the inverter's command signal. In this paper, the PI controllers are replaced by two fuzzy ones. The FLC is used here in order to exploit the advantages of this technique: intuitiveness, simplicity, easy implementation and minimal knowledge of system dynamics [5]. FLC is simpler than other control schemes since it doesn't need complicated mathematical manipulation. A speed FLC used in the proposed control scheme has two inputs: the speed error e(k) and its variation Δe(k). These inputs are given as :

$$e(k) = \omega_r(k) - \hat{\omega}_r(k). \tag{10}$$

$$\Delta e(k) = e(k) - e(k-1). \tag{11}$$

These inputs will be treated using the fuzzy logic rules in order to produce the estimated speed $\hat{\omega}_r$. A conventional FLC consists of three stages: fuzzyfication, inference and defuzzyfication as shown in Figure 1. The input variables are first converted to fuzzy representation using linguistic values (or fuzzy sets). These linguistic values are then executed by inference engine using rule base to produce a fuzzy set for output. This fuzzy set is finally re-converted to crisp value for the controlled system. A linguistic variable is attributed to 3, 5 or 7 levels (sets). The structure of the speed and torque FLC are described in Figure 1 and 2. For these controllers, the universe discourse can be partitioned into five (for the speed FLC) and seven (for the torque FLC) linguistic variables: NB, NM, NS, EZ, PS, PM and PB. Triangular membership functions are chosen to represent the linguistic variables. Figure 1 shows the input and output membership functions, the fuzzy rules are summarized in Table 1.

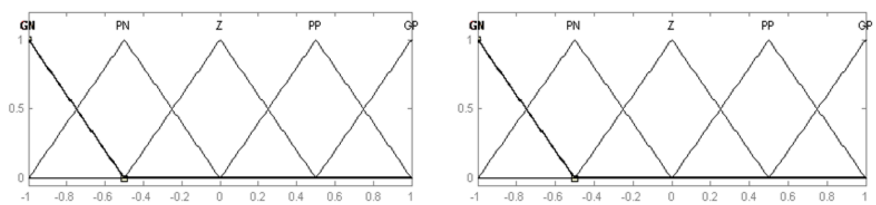

Figure 1. Input and Output Membership Functions for the Speed FLC

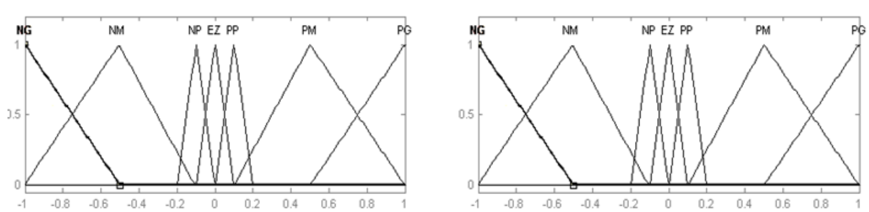

Figure 2. Input and Output Membership Functions for the Torque FLC

Table 1. Fuzzy Controller Rule Base for the Torque FLC

Δe \ e	NG	NM	NP	EZ	PP	PM	PG
NG	NG	NG	NG	NG	NM	NP	EZ
NM	NG	NG	NG	NM	NP	EZ	PP
NP	NG	NG	NM	NP	EZ	PP	PM
EZ	NG	NM	NP	EZ	PP	PM	PG
PP	NM	NP	EZ	PP	PM	PG	PG
PM	NP	EZ	PP	PM	PG	PG	PG
PG	EZ	PP	PM	PG	PG	PG	PG

Figure 3 shows the overall bloc diagram of the sensorless IM drives based on adaptive Luenberger observer and fuzzy controllers. The speed FLC is desired to track the dynamic response of the reference speed ω_r^*. The error signal e(k) between the estimated speed and the reference one constitute with its variation the inputs of the fuzzy controller so as to make the tracking error zero [5] and [13].

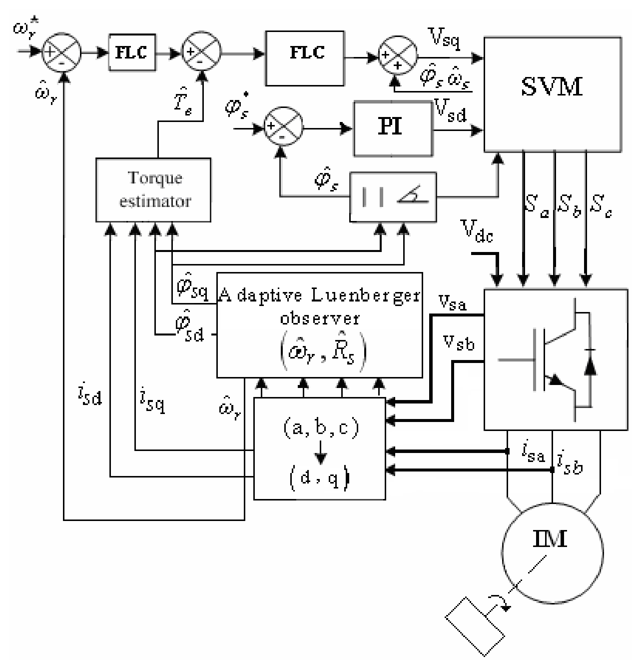

Figure 3. Block Diagram of the Sensorless Control Strategy with Stator Flux and Stator Resistance Estimators and Fuzzy Controllers

5. Luenberger Observer for Fluxes and Stator Currents

The Luenberger Observer used in this work is a deterministic one, which is well adapted to a linear time-variant deterministic system. It uses the errors of the estimated variables compared with the actual ones to correct the errors of the estimated state variables. The general equations of Luenberger Observer for the IM have the following form [12, 13]:

$$\begin{cases} \dot{\hat{x}}(t) = A(t)x(t) + B(t)u(t) + L(t)\left[y(t) - \hat{y}(t)\right] \\ \hat{y}(t) = C\hat{x}(t) \end{cases} \tag{12}$$

Where the estimated state variables for the IM are chosen as follow:

$$\hat{x}(t) = \begin{bmatrix} \hat{i}_{\alpha s} & i_{\beta s} & \hat{\varphi}_{\alpha r} & \varphi_{\beta r} & \hat{\varphi}_{\alpha s} & \varphi_{\beta s} \end{bmatrix}^T$$

$$A = \begin{bmatrix} -\frac{1}{\sigma L_s}\left(R_s + \frac{R_r M^2}{L_r^2}\right) & 0 & \frac{R_r M}{\sigma L_s L_r^2} & \frac{M\omega_r}{\sigma L_s L_r} & 0 & 0 \\ 0 & -\frac{1}{\sigma L_s}\left(R_s + \frac{R_r M^2}{L_r^2}\right) & -\frac{M\omega_r}{\sigma L_s L_r} & \frac{R_r M}{\sigma L_s L_r^2} & 0 & 0 \\ \frac{R_r M}{L_r} & 0 & -\frac{R_r}{L_r} & -\omega_r & 0 & 0 \\ 0 & \frac{R_r M}{L_r} & \omega_r & -\frac{R_r}{L_r} & 0 & 0 \\ -R_s & 0 & 0 & 0 & 0 & 0 \\ 0 & R_s & 0 & 0 & 0 & 0 \end{bmatrix}$$

The input and output variables are:

$$u(t) = \begin{bmatrix} u_1 & u_2 \end{bmatrix}^T = \begin{bmatrix} u_{sd} & u_{sq} \end{bmatrix}^T \quad \hat{y}(t) = \begin{bmatrix} y_1 & \hat{y}_2 \end{bmatrix}^T = \begin{bmatrix} \hat{i}_{sd} & i_{sq} \end{bmatrix}^T$$

$$y(t) = \begin{bmatrix} y_1 & y_2 \end{bmatrix}^T = \begin{bmatrix} i_{sd} & i_{sq} \end{bmatrix}^T$$

Since L is the observer gain matrix, it must be chosen so that all eigen values of the matrix $A_0 = A - LC$ have negative real parts. Because the matrix A elements depend on the motor speed, L has to be adapted at each sampling time. The feedback matrix gain is determined by using the (LQR) principle which is defined by the equation as follow:

$$J = \frac{1}{2}\int_0^{\infty}\left(x^T Q x + u^T R u\right)dt. \tag{13}$$

Where Q is positive semi definite and R is positive definite.
The optimal linear state feedback gain k is defined by the following equation:

$$k = -R^{-1}B^T P. \tag{14}$$

If we choose $k = -R^{-1}B^T P$ as feedback gain of Luenberger observer, we ensure that the matrix $A_0 = A - LC$ is stable.

6. Adaptive Scheme for Stator Resistance and Speed Estimation

The first step is to drive an equation governing the state estimation error. Subtracting the induction motor model from the observer model, we get the model governing the state observation error e.

$$\dot{e} = e^{T}\left(A - LC\right)e - \Delta A\left(\omega\right)\hat{x} - \Delta A\left(r_s\right)x. \tag{15}$$

Where $\Delta A(\omega)$ and $\Delta A(r_s)$ are the model mismatch errors.

$$\Delta A(\omega) = \begin{bmatrix} O_2 & -\frac{\Delta\omega}{g}J & O_2 \\ O_2 & \Delta\omega J & O_2 \\ O_2 & O_2 & O_2 \end{bmatrix}, \Delta A(r_s) = \begin{bmatrix} -\frac{\Delta R_s}{\sigma L_s}I & O_2 & O_2 \\ O_2 & O_2 & O_2 \\ \Delta R_s F & O_2 & O_2 \end{bmatrix}$$

$$J = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}, I = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, F = \begin{bmatrix} -1 & 0 \\ 0 & 1 \end{bmatrix}.$$

$\Delta\omega_r = \omega_r - \hat{\omega}_r$, $\Delta R_s = R_s - \hat{R}_s$ and $g = \dfrac{M}{\sigma L_s L_r}$.

The stability analysis of the dynamical system observation error will be analyzed using the Lyaponov method. Now, let us suppose that the suitable Lyaponov function will be :

$$\vartheta = e^{T}e + \frac{\left(\hat{\omega}_r - \omega_r\right)^2}{\lambda} + \frac{\left(R_s - R_s\right)^2}{\beta\sigma L_s}. \tag{16}$$

The system will be stable if

$$\dot{\vartheta} < 0. \tag{17}$$

For any combination of variable values. After a long calculation, $\dot{\vartheta}$ can be written as:

$$\dot{\vartheta} = e^{T}\left[(A - LC)^{T} + (A - LC)\right]e - 2\frac{\Delta\omega_r}{g}\left(e_{i\alpha s}\hat{\Phi}_{\beta r} - e_{i\beta s}\Phi_{\alpha r}\right) + \frac{2}{\lambda}\Delta\omega_r\frac{d\Delta\omega_r}{dt} + 2\left(1 + \frac{1}{\sigma L_s}\right)\Delta R_s\left(e_{i\alpha s}\hat{i}_{\beta r} + e_{i\beta s}i_{\alpha r}\right) + \frac{2}{\beta\sigma L_s}\Delta R_s\frac{d\Delta R_s}{dt}. \tag{18}$$

It is necessary to fulfill the following conditions to achieve the validity of (17)

$$(A - LC)^{T} + (A - LC) < 0. \tag{19}$$

$$\frac{\Delta\omega_r}{g}\left(e_{i\alpha s}\hat{\Phi}_{\beta r} - e_{i\beta s}\Phi_{\alpha r}\right) + \frac{2}{\lambda}\Delta\omega_r\frac{d\Delta\omega_r}{dt} = 0. \tag{20}$$

$$2\left(1 + \frac{1}{\sigma L_s}\right)\Delta R_s\left(e_{i\alpha s}\hat{i}_{\beta r} + e_{i\beta s}i_{\alpha r}\right) + \frac{2}{\beta\sigma L_s}\Delta R_s\frac{d\Delta R_s}{dt} = 0. \tag{21}$$

The condition (19) can be easily fulfilled as it is freely selected in such away to assume the stability of the stator and rotor flux Luenberger observer. The conditions (20) and (21) can be fulfilled by stating:

$$\frac{d\Delta\omega_r}{dt} = \frac{\lambda}{g}\left(e_{i\alpha s}\hat{\Phi}_{\beta r} - e_{i\beta s}\Phi_{\alpha r}\right), \tag{22}$$

$$\frac{d\Delta R_s}{dt} = -\frac{\beta}{\sigma L_s + 1}\left(e_{i\alpha s}\hat{i}_{\beta r} + e_{i\beta s}i_{\alpha r}\right), \tag{23}$$

Equations (22) and (23) can be used to construct adaptation rules for stator resistance and speed estimation. The changes of IM parameters including angular speed are very slow compared with stator voltages and currents. Thus one can consider them to be constant.

$$\frac{d\Delta\omega_r}{dt} = \frac{d\hat{\omega}_r}{dt} - \frac{d\omega_r}{dt} \cong \frac{d\omega_r}{dt}, \tag{24}$$

$$\frac{d\Delta R_s}{dt} = \frac{d\hat{R}_s}{dt} - \frac{dR_s}{dt} \cong \frac{dR_s}{dt}, \tag{25}$$

The adaptation rules are then,

$$\frac{d\hat{\omega}_r}{dt} = \frac{\lambda}{g}\left(e_{i\alpha s}\hat{\Phi}_{\beta r} - e_{i\beta s}\Phi_{\alpha r}\right), \tag{26}$$

$$\frac{d\hat{R}_s}{dt} = -\frac{\beta}{\sigma L_s + 1}\left(e_{i\alpha s}\hat{i}_{\beta r} + e_{i\beta s}i_{\alpha r}\right), \tag{27}$$

The real value of stator resistance and rotor speed may change quickly. Thus, to improve the response of the observers, an adaptive law based on PI controller can be used. Finally, the adaptive schemes for stator resistance and rotor speed can be written as:

$$\frac{d\hat{\omega}_r}{dt} = K_{p1}\left(e_{i\alpha s}\hat{\Phi}_{\beta r} - e_{i\beta s}\Phi_{\alpha r}\right) + K_{I1}\int\left(e_{i\alpha s}\hat{\Phi}_{\beta r} - e_{i\beta s}\Phi_{\alpha r}\right)dt, \tag{28}$$

$$\frac{d\hat{R}_s}{dt} = K_{p2}\left(e_{i\alpha s}\hat{i}_{\beta r} + e_{i\beta s}i_{\alpha r}\right) + K_{I2}\int\left(e_{i\alpha s}\hat{i}_{\beta r} + e_{i\beta s}i_{\alpha r}\right)dt \tag{29}$$

Where K_{I1}, K_{I2}, K_{p1} and K_{p2} are adjustable gains.

7. Simulation Results

To verify the effectiveness of the proposed sensorless control scheme as illustrated in figure below, a digital simulation based on Matlab/Simulink has been carried out. Motor parameters used in simulation are given in Table 2. The used sampling period for simulation is T = 10-4s. Figures 4 to 8 show the simulation results of the speed sensorless vector control using adaptive Luenberger observer and fuzzy controllers for a variable speed command. The first test in Figure 4 concerns a speed starting with a reference of ω_{ref} = 157 rad/sec then 78.5 rad/sec; a load torque (T_l = 4 Nm) is then applied at t = 1.1 sec. The dynamics of the flux magnitude are presented in Figure 6. We can highlight the decoupling role of the flux controller where the flux tracks its nominal value of 1.1 Wb for all speed ranges. Note that the speed and the flux reach the desired reference values, and there is no effect of the load torque variation on the flux which means that the speed and the flux are decoupled. Figure 8 shows that a 50% variation of the stator resistance from its actual value is applied at t = 0.8sec, and as shown in Figure 6 that this variation has a very small influence on the flux at the application moment of the resistance variation and then the flux component conserve its nominal values.

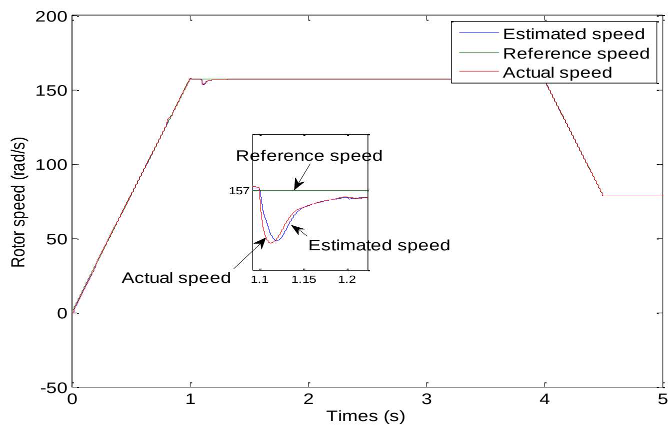

Figure 4. Actual and Estimated Speed Responses

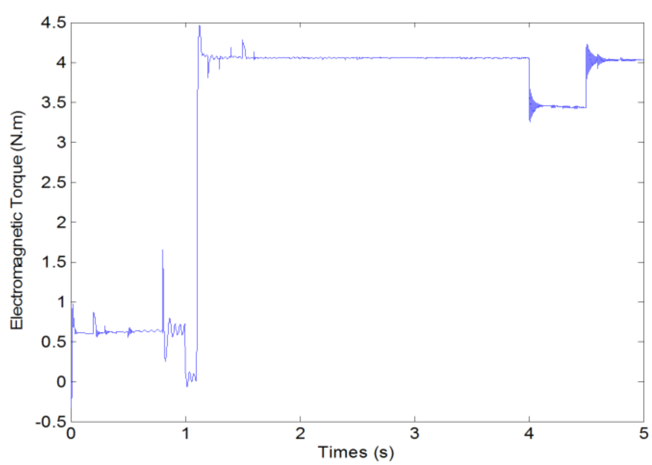

Figure 5. Electromagnetic Torque

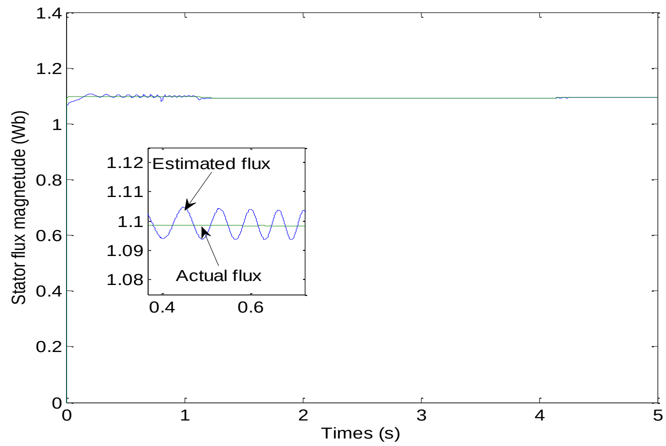

Figure 6. Actual and Estimated Stator Flux

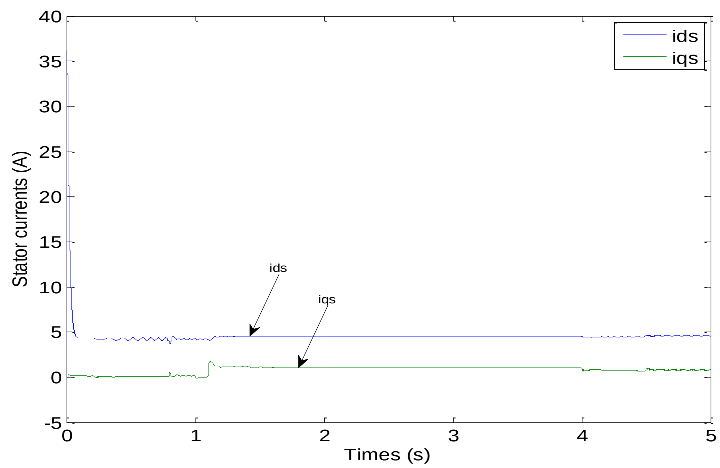

Figure 7. Stator Currents i_{ds} and i_{qs}

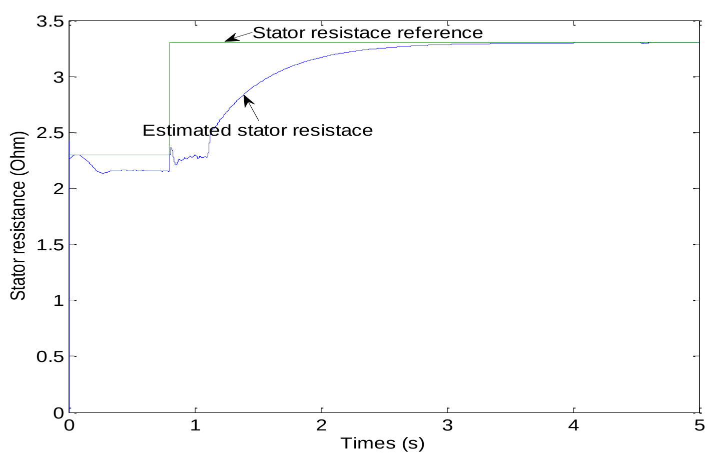

Figure 8. Actual and Estimated Stator Resistance

Table 2. Induction Motor Parameters

Frequency	fn = 50 Hz
Power	Pn = 3000 W
Rated voltage	Un = 220/380 V
Stator resistance	Rs = 2.3 Ω
Rotor resistance	Rr = 1.55 Ω
Stator inductance	Ls = 261 mH
Rotor inductance	Lr = 261 mH
Mutual inductance	M = 249mH
Pair pole number	np = 2
Inertia moment	J = 0.0076 kgm^2
Friction factor	f = 0.0007 kgm^2/s

8. Conclusion

This paper present a fuzzy logic speed sensorless control based on the vector control of IM. Theoretical analysis and simulation results demonstrate that the proposed speed control scheme has a good speed response and so confirm the feasibility of the proposed algorithm. In fact, this control scheme allows one to estimate the rotor speed and to achieve robustness against the load torque dynamics and parameter variations. Practical implementation of the proposed method is a subject of future follow up research work.

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