INTERNATIONAL JOURNAL OF FUZZY SYSTEMS and ADVANCED APPLICATIONS
DOI: 10.46300/91017.2022.9.4 Volume 9, 2022

Sensorless sliding mode control of induction motor using fuzzy logic Luenberger observer

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Abstract—Many industrial applications require high performance speed sensorless operation and demand new control schemes in order to obtain fast dynamic response. In this paper, we present a speed sensorless sliding mode control (SMC) of induction motor (IM). The sliding mode control is a powerful tool to reject disturbances. However, the chattering phenomenon presents a major drawback for variable structure systems. To decrease this problem, a saturation function is used to limit chattering effects. A Luenberger observer based on fuzzy logic adaptation mechanism is designed for speed estimation. Numerical simulation results of the proposed scheme illustrate the good performance of sensorless induction motor and the robustness against load torque disturbances.

Keywords—Fuzzy logic control, induction motor, Luenberger observer, sliding mode control.

I. Introduction

THE induction motor is one of the most widely used machines in various industrial applications due to its high reliability, relatively low cost, and modest maintenance requirements [1]. Many industrial applications require high dynamic performances and robustness to different perturbations. Thus, the robust control algorithm is desirable in stabilization and tracking trajectories. The variable structure control can offer a good insensitivity to parameter variation, external disturbances rejection and fast dynamics [2]-[3].

The sliding mode control is a type of variable structure system characterized by high simplicity and robustness against insensitivity to parameters variation and disturbances. This approach utilizes discontinuous control laws to drive the system state trajectory onto a sliding or switching surface in the state space. The dynamic of the system while in sliding mode is insensitive to model uncertainties and disturbances [4]. However, the discontinuous control presents a major drawback presented in chattering phenomenon. In order to reduce this phenomenon, a saturation function is used.

In recent years, great efforts have been made to increase the mechanical robustness and reliability of the induction motor, and to reduce costs and hardware complexity. Thus, it is necessary to eliminate the speed sensor. Several methods of speed estimators have been proposed in the literature among them the Luenberger observer. It is able to provide both rotor speed and flux without problems of closed-loop integration. In this paper, the fuzzy logic controller (FLC) replaces the PI controller in the speed adaption mechanism of the Luenberger observer. The main advantages of the FLC introduced by Zadeh [5] that it does not require accurate mathematical model of the system studied. Fuzzy logic is based on the linguistic rules by means of IF-THEN rules with the human language.

II. Induction Motor Oriented Model

In field oriented control, the flux vector is forced to align with d-axis ($\Phi_{rd} = \Phi_r$ and $\Phi_{rq} = 0$). Thus, the dynamic model of the induction motor in (d, q) reference frame can be expressed in the form of the state equations as shown below:

$$\begin{cases} \dfrac{di_{sd}}{dt} = -\gamma i_{sd} + \omega_s i_{sq} + \dfrac{K}{T_r}\varphi_r + \dfrac{1}{\sigma L_s} v_{sd} \\ \dfrac{di_{sq}}{dt} = -\gamma i_{sq} - \omega_s i_{sd} - K\varphi_r\omega_r + \dfrac{1}{\sigma L_s} v_{sq} \\ \dfrac{d\varphi_{rd}}{dt} = \dfrac{L_m}{T_r} i_{sd} - \dfrac{1}{T_r}\varphi_r \\ \dfrac{d\varphi_{rq}}{dt} = \dfrac{L_m}{T_r} i_{sq} - \left(\omega_s - \omega_r\right)\varphi_r \\ \dfrac{d\Omega}{dt} = \dfrac{PL_m}{JL_r}\varphi_r i_{sd} - \dfrac{f}{J}\Omega - \dfrac{T_L}{J} \end{cases} \tag{1}$$

Where:

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

The angular frequency ω_s of the rotor flux is obtained as the sum of the slip frequency ω_{sl} and rotor electrical speed:

$$\omega_s = \omega_r + \omega_{sl} \tag{2}$$

The space angle of the rotor flux is given by:

$$\theta_s = \theta_r + \int \frac{1}{T_r} \frac{i_{sq}}{i_{sd}} \tag{3}$$

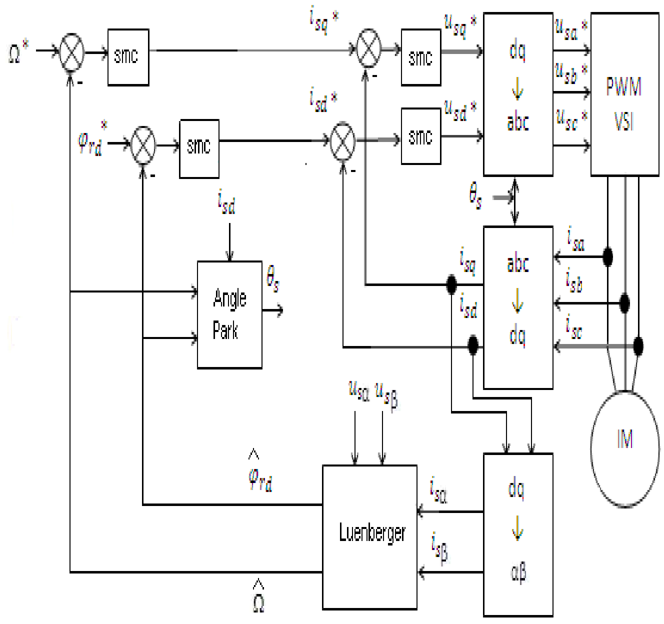

Fig. 1 Block diagram of proposed scheme

III. SLIDING MODE CONTROL

Sliding mode technique is a type of variable structure system (VSS) applied to the non-linear systems. The sliding mode control design is to force the system state trajectories to the sliding surface S(x) and to stay on it by means a control defined by the following equation [6]:

$$u = u_{eq} + u_n \tag{4}$$

Where u_{eq} and u_n represent the equivalent control and the discontinue control respectively.

$$u_n = k.sat\left(\frac{s}{\xi}\right) \tag{5}$$

Here ξ defines the thickness of the boundary layer and $sat\left(\frac{s}{\xi}\right)$ is a saturation function.

$$sat\left(\frac{s}{\xi}\right) = \begin{cases} \mathbf{sgn}\left(\frac{s}{\xi}\right) si \left|\frac{s}{\xi}\right| > 0 \\ \frac{s}{\xi} si \left|\frac{s}{\xi}\right| < 0 \end{cases} \tag{6}$$

To attract the trajectory of the system towards the sliding surface in a finite time, $u_n(x)$ should be chosen such that Lyapunov function, satisfies the Lyapunov stability:

$$\dot{S}(x)S(x) < 0 \tag{7}$$

The general equation to determine the sliding surface proposed is as follow [7]:

$$S(x) = \left(\frac{d}{dt} + \lambda\right)^{n-1} e \tag{8}$$

Here, e is the tracking error vector, λ is a positive coefficient and n is the system order.

A. Sliding Mode Speed Controller

Considering the equation (8) and taken $n = 1$, the sliding surface of speed can be defined as:

$$S(\Omega) = \Omega^* - \Omega \tag{9}$$

By derivation of equation (9) and taken the fifth equation of the system (1), we obtain:

$$\dot{S}(\Omega) = \dot{\Omega}^* - \frac{PL_m}{JL_r}\varphi_{rd} i_{sq} - \frac{T_L}{J} - \frac{f}{J}\Omega \tag{10}$$

We take:

$$i_{sq} = i_{sq}^{eq} + i_{sq}^{n} \tag{11}$$

During the sliding mode and in permanent regime, $S(\Omega) = \dot{S}(\Omega) = 0$, $i_{sq}^n = 0$. The equivalent control action can be defined as follow:

$$i_{sq}^{eq} = \frac{JL_r}{PL_m\varphi_{rd}}\left(\Omega^* + \frac{T_L}{J} + \frac{f}{J}\Omega\right) \tag{12}$$

During the convergence mode, the condition $\dot{S}(\Omega)S(\Omega) < 0$ must be verified. Therefore, the discontinue control action can be given as:

$$i_{sq}^{n} = k_{isq}.sat\left(\frac{S(\Omega)}{\xi_{isq}}\right) \tag{13}$$

To verify the system stability, coefficient k_{isq} must be strictly positive.

B. Sliding Mode Flux Controller

Considering the equation (8) and taken $n = 1$, the sliding surface of flux can be defined as:

$$S(\varphi_{rd}) = \varphi_{rd}^* - \varphi_{rd} \tag{14}$$

By derivation of equation (14) and taken the third equation of the system (1), we obtain:

$$\dot{S}(\varphi_{rd}) = \dot{\varphi}_{dr}^{*} + \frac{1}{T_r}\varphi_{rd} i_{sq} - \frac{L_m}{T_r} i_{sd} \quad (15)$$

We take:

$$i_{sd} = i_{sd}^{eq} + i_{sd}^{n} \quad (16)$$

During the sliding mode and in permanent regime, $S(\varphi_{rd}) = \dot{S}(\varphi_{rd}) = 0$, $i_{sd}^{n} = 0$. The equivalent control action can be defined as follow:

$$i_{sd}^{eq} = \frac{L_r}{L_m}\left(\dot{\varphi}_{dr}^{*} + \frac{1}{T_r}\varphi_{rd}\right) \quad (17)$$

During the convergence mode, the condition $\dot{S}(\varphi_{rd}) S(\varphi_{rd}) < 0$ must be verified. Therefore, the discontinue control action can be given as:

$$i_{sd}^{n} = k_{isd} . sat\left(\frac{S(\varphi_{rd})}{\xi_{isd}}\right) \quad (18)$$

To verify the system stability, coefficient k_{isd} must be strictly positive.

C. Sliding Mode Current Controller

Considering the equation (8) and taken $n = 1$, the sliding surface of stator currents can be defined as:

$$S(i_{sd}) = i_{sd}^{*} - i_{sd} \quad (19)$$

$$S(i_{sq}) = i_{sq}^{*} - i_{sq} \quad (20)$$

By derivation of equation (19) and (20) and taken the first and second equation of the system (1) respectively, we obtain:

$$\dot{S}(i_{sd}) = \dot{i}_{sd}^{*} + \gamma i_{sd} - \omega_s i_{sq} - \frac{K}{T_r}\varphi_r - \frac{1}{\sigma L_s} v_{sd} \quad (21)$$

$$\dot{S}(i_{sq}) = \dot{i}_{sq}^{*} + \gamma i_{sq} + \omega_s i_{sd} + K\varphi_r \omega_r - \frac{1}{\sigma L_s} v_{sq} \quad (22)$$

During the sliding mode, $S(i_{sd}) = \dot{S}(i_{sd}) = 0$, $v_{sd}^{n} = 0$ and $S(i_{sq}) = \dot{S}(i_{sq}) = 0$, $v_{sq}^{n} = 0$. The equivalent control actions can be defined as follow:

$$v_{sd}^{eq} = \sigma L_s\left(\dot{i}_{sd}^{*} + \gamma i_{sd} - \omega_s i_{sq} - \frac{K}{T_r}\varphi_{rd}\right) \quad (23)$$

$$v_{sq}^{eq} = \sigma L_s\left(\dot{i}_{sq}^{*} + \gamma i_{sq} + \omega_s i_{sd} + K\omega_r \varphi_{rd}\right) \quad (24)$$

During the convergence mode, the conditions $\dot{S}(i_{sd}) S(i_{sd}) < 0$ and $\dot{S}(i_{sq}) S(i_{sq}) < 0$ must be verified. Therefore, the discontinue control action can be given as:

$$v_{sd}^{n} = k_{vsd} . sat\left(\frac{S(i_{sd})}{\xi_{vsd}}\right) \quad (25)$$

$$v_{sq}^{n} = k_{vsq} . sat\left(\frac{S(i_{sq})}{\xi_{vsq}}\right) \quad (26)$$

To verify the system stability, coefficients k_{vsd} and k_{vsq} must be strictly positive.

IV. LUENBERGER OBSERVER

The Luenberger observer is a deterministic type of observer based on a deterministic model of the system [8]. In this work, the LO state observer is used to estimate the flux components and rotor speed of induction motor by including an adaptive mechanism based on the Lyapunov theory. In general, the equations of the LO can be expressed as follow:

$$\begin{cases} \dot{\hat{x}} = A\hat{x} + Bu + L(y - \hat{y}) \\ \hat{y} = C\hat{x} \end{cases} \quad (27)$$

The symbol ^ denotes estimated value and L is the observer gain matrix. The mechanism of adaptation speed is deduced by Lyapunov theory. The estimation error of the stator current and rotor flux, which is the difference between the observer and the model of the motor, is given by [9]:

$$\dot{e} = (A - LC)e + \Delta A\hat{x} \quad (28)$$

Where:

$$e = x - \hat{x} \quad (29)$$

$$\Delta A = A - \hat{A} = \begin{bmatrix} 0 & 0 & 0 & \mu\Delta\omega_r \\ 0 & 0 & -\mu\Delta\omega_r & 0 \\ 0 & 0 & 0 & -\Delta\omega_r \\ 0 & 0 & \Delta\omega_r & 0 \end{bmatrix} \quad (30)$$

$$\Delta\omega_r = \omega_r - \hat{\omega}_r \quad (31)$$

We consider the following Lyapunov function:

$$V = e^T e + \frac{(\Delta\omega_r)^2}{\lambda} \quad (32)$$

Where λ is a positive coefficient. By derivation equation (32), the adaptation law for the estimation of the rotor speed $\hat{\omega}_r$ can be deduced as:

$$\hat{\omega}_r = \int \lambda K \left(e_{is\alpha}\hat{\varphi}_{r\beta} - e_{is\beta}\hat{\varphi}_{r\alpha} \right) dt \tag{33}$$

The speed is estimated by a PI controller described as:

$$\hat{\omega}_r = K_p\left(e_{is\alpha}\hat{\varphi}_{r\beta} - e_{is\beta}\hat{\varphi}_{r\alpha}\right) + \frac{K_i}{s}\int\left(e_{is\alpha}\hat{\varphi}_{r\beta} - e_{is\beta}\hat{\varphi}_{r\alpha}\right)dt \tag{34}$$

With K_p and K_i are positive constants. The feedback gain matrix L is chosen to ensure the fast and robust dynamic performance of the closed loop observer [10]-[11].

$$L = \begin{bmatrix} l_1 & -l_2 \\ l_2 & l_1 \\ l_3 & -l_4 \\ l_4 & l_3 \end{bmatrix} \tag{35}$$

With l_1, l_2, l_3 and l_4 are given by:

$$\begin{aligned} l_1 &= (k_1 - 1)\left(\gamma + \frac{1}{T_r}\right) \\ l_2 &= -(k_1 - 1)\hat{\omega}_r \\ l_3 &= \frac{(k_1^2 - 1)}{K}\left(\gamma - K\frac{L_m}{T_r}\right) + \frac{(k-1)}{K}\left(\gamma + \frac{1}{T_r}\right) \\ l_4 &= -\frac{(k-1)}{K}\hat{\omega}_r \end{aligned}$$

Where k_1 is a positive coefficient obtained by pole placement approach [12].

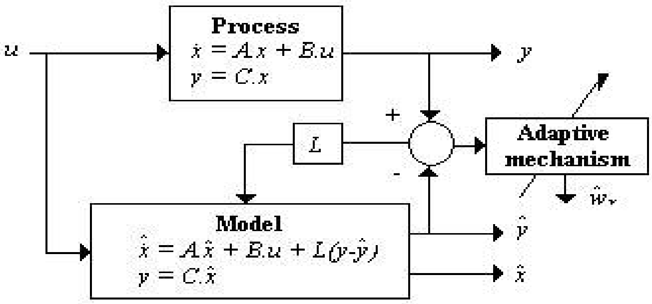

Fig. 2. Block diagram of Luenberger observer

In this paper, we will replace the PI controller in Luenberger observer adaptation mechanism by a fuzzy logic controller.

V. Fuzzy Logic Control

Fig. 3 shows the block diagram of fuzzy logic controller system where the variables K_p, K_i and B are used to tune the controller.

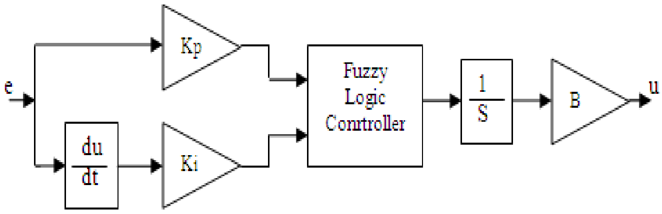

Fig. 3. Block diagram of a fuzzy logic controller

There are two inputs, the error and the change of error. The FLC consists of four major blocks, Fuzzification, knowledge base, inference engine and defuzzification.

A. *Fuzzification*

The crisp input variables are e and ce are transformed into fuzzy variables referred to as linguistic labels. The membership functions associated to each label have been chosen with triangular shapes. The following fuzzy sets are used, NL (Negative Large), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (positive Medium), and PL (Positive Large). The universe of discourse is set between –1 and 1. The membership functions of these variables are shown in Fig. 4.

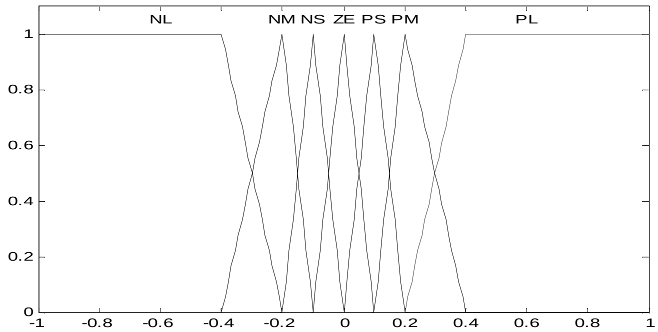

Fig 4. Membership functions

B. *Knowledge Base and Inference Engine*

The knowledge base consists of the data base and the rule base. The data base provides the information which is used to define the linguistic control rules and the fuzzy data in the fuzzy logic controller. The rule base specifies the control goal actions by means of a set of linguistic control rules [16]. The inference engine evaluates the set of IF-THEN and executes 7*7 rules as shown in Table I.

ce/e	NL	NM	NS	ZE	PS	PM	PL
NL	NL	NL	NL	NL	NM	NS	ZE
NM	NL	NL	NL	NM	NS	ZE	PS
NS	NL	NL	NM	NS	ZE	PS	PM
ZE	NL	NM	NS	ZE	PS	PM	PL
PS	NM	NS	ZE	PS	PM	PL	PL
PM	NS	ZE	PS	PM	PL	PL	PL
PL	ZE	PS	PM	PL	PL	PL	PL

Table I. Fuzzy rule base

The linguistic rules take the form as in the following example:

IF e is NL AND ce is NL THEN u is NL

C. *Deffuzzification*

In this stage, the fuzzy variables are converted into crisp variables. There are many defuzzification techniques to produce the fuzzy set value for the output fuzzy variable. In this paper, the centre of gravity defuzzification method is adopted here and the inference strategy used in this system is the Mamdani algorithm.

VI. Simulation Results and Discussion

A series of simulation tests were carried out on sliding mode control of induction motor based on the Luenberger observer using fuzzy logic controller in adaptation mechanism. Simulations have been realized under the Matlab/Simulink. The parameters of induction motor used are indicated in Table II.

A. *Operating at Load Torque*

Figures 5, 6 and 7 represent the simulation results obtained from a no load operating. We impose a speed of reference of 100 rad/s and we applied a load torque with 10 N.m between t = 1 s and t = 1.5 s.

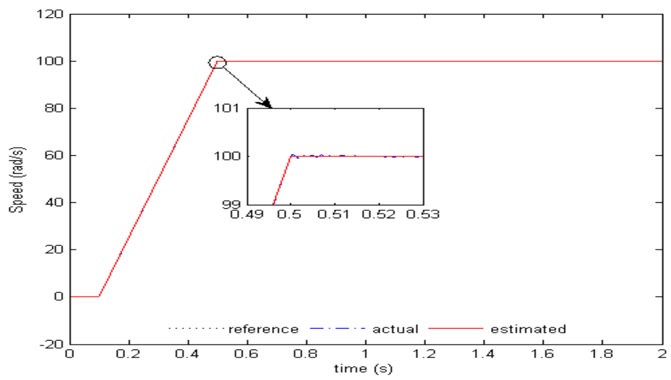

Fig 5. Rotor speed

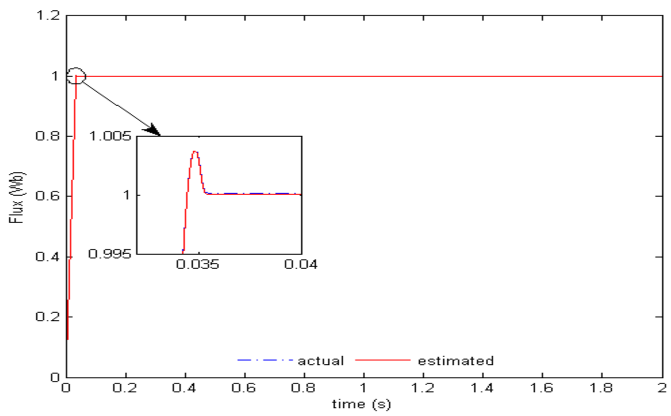

Fig 6. Rotor flux

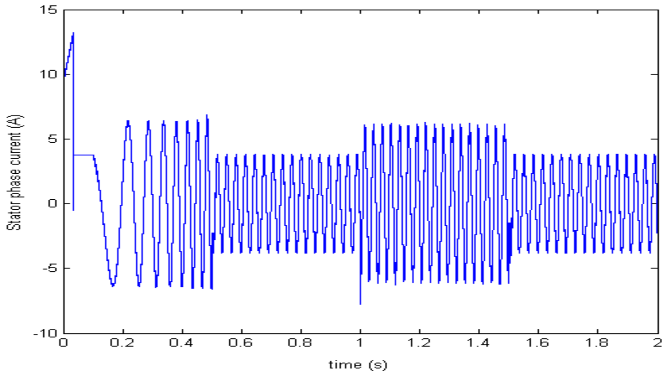

Fig 7. Stator phase current

B. *Operating at Inversion of Speed*

In this case, we applied a speed reference varying between 100 rad/s to -100 rad/s.

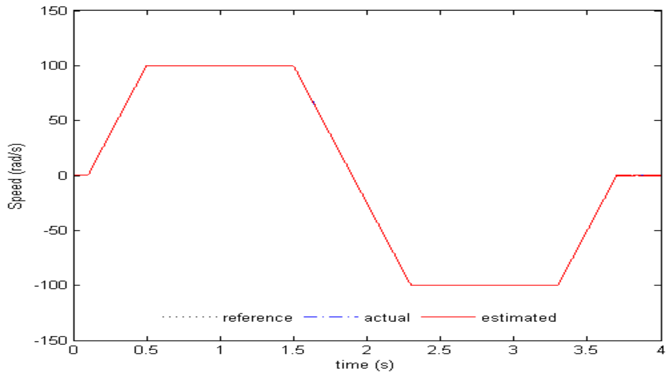

Fig 8. Rotor speed

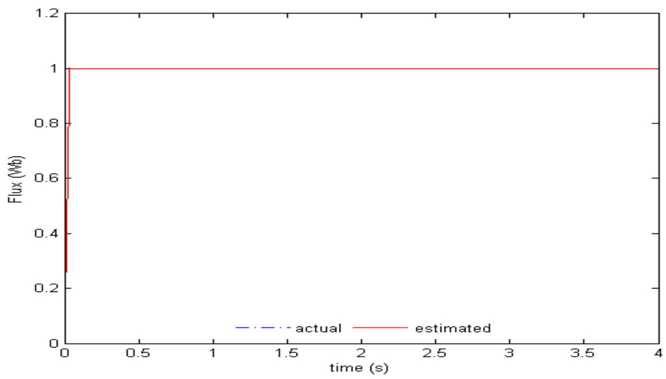

Fig 9. Rotor flux

C. *Operating at Load Speed*

Figures 10 and 11 illustrate simulation results with a speed carried out for low speed ±10 rad/s.

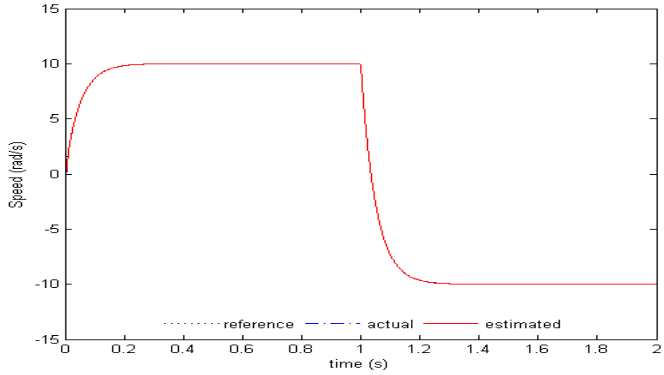

Fig 10. Rotor speed

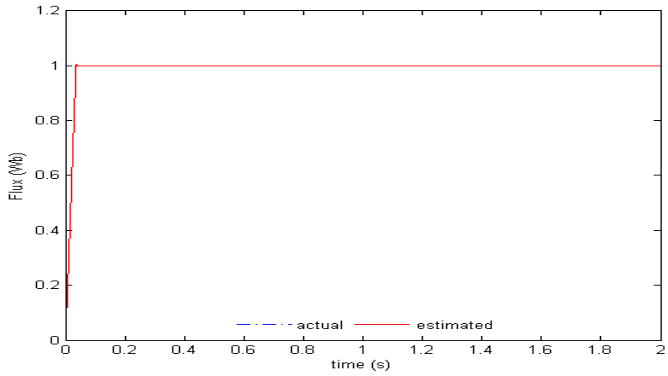

Fig 11. Rotor flux

With the results above, we can see the good estimated speed tracking performance test in different working in inverse and low speed in terms of overshoot, static error and fast response. The flux is very similar to the nominal case. The stator phase current remains sinusoidal and takes appropriate value. It is evident from these simulation results that the proposed sliding mode control presents an excellent performance.

VII. CONCLUSION

In this paper we have presented the sensorless sliding mode control using the Luenberger observer with fuzzy logic adaptation mechanism. The simulation results have demonstrated the performances of the proposed scheme for steady state responses of flux and speed even at inverse and low speed and with application of the load torque disturbances.

APPENDIX

Rated power	3 KW
Voltage	380V Y
Frequency	50 Hz
Pair pole	2
Rated speed	1440 rpm
Stator resistance	2.2 Ω
Rotor resistance	2.68 Ω
Inductance stator	0.229 H
Inductance rotor	0.229 H
Mutual inductance	0.217 H
Moment of Inertia	0.047 kg.m^2

Table II. Induction motor parameters

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