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Hybrid Speed Control of Induction Motor using PI and Fuzzy Controller

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ABSTRACT

This paper presents a modified fuzzy control for speed control of induction motor (IM). At first, the PI controller is investigated for speed control of Induction Motor, and then fuzzy logic controller performance is simulated. Induction Motor performance is checked through the simulation studies in MATLAB/SIMULINK environment. Hybridization of fuzzy logic (FL) and PI controller for the speed control of given motor is also performed to remove the disadvantages of FL controller (steady-state error) and PI controller (overshoot and undershoot). According to the simulation results, hybrid controller creates better performance in terms of rice time, overshoot, undershoot and settling time.

Keywords

Induction Motor (IM), PI Controller, Fuzzy Logic Controller, Hybrid Controller, Indirect Vector Control

1. INTRODUCTION

Traditionally, dc motors were used for precise wide range speed control. Nowadays with progress in power electronic industry and development of inexpensive convertors and many advantages of ac motors than dc motors, use of ac motors are usual in electrical drives. Some of these advantages are: lack of commutator, the reduced maintenance costs, less volume and weight and consequently lower cost. In addition, induction motors are robust and have better performance in high speed and torque.

In recent years, the control and estimation of induction motor drives is an active research area, and the technology has further advances in this field. Induction motor drives, especially squirrel cage rotor-type, have been the workhorses in industry for variable-speed applications in a wide power range that covers from fractional horsepower to multi-megawatts.

Generally, the control and estimation of ac drives are significantly more complex than those of dc drives, and this complexity increases to a large extent if high performances are demanded. The need of variable-frequency, harmonically optimum converter power supplies, the complex dynamics of ac machines, machine parameter variations, and the difficulties of processing feedback signals in the presence of harmonics create this complexity.

Induction motor can be controlled like a separately excited dc motor, brought a great improvement in the high-performance control of ac drives especially with the invention of vector control in the beginning of 1970s. Because of dc machine-like performance, vector control is also known as decoupling, orthogonal, or transvector control. The vector control and the corresponding feedback signal processing, particularly for modern sensorless vector control, are complex and the use of powerful microcomputer or DSP is necessary. Because of major advantages of vector control, this method of control will oust scalar control, and will be accepted as the industry-standard control for ac drives.

PI controllers are widely used in different industries for control of different plants and have a reasonable performance. This performance, however, may not be desirable for some applications such as ac drive control. Therefore it is essential to use a more advance controller in these cases.

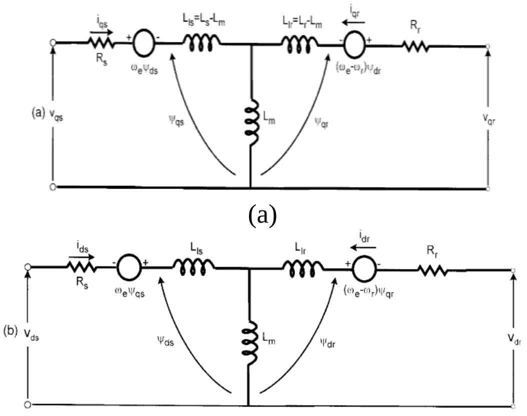
PI controller can never achieve perfect control, that is, keep the speed of induction motor continuously at the desired set point value in the presence of disturbance or set point changes. Therefore, we need an advance control technique such as fuzzy logic controller for this goal.

Nowadays, fuzzy systems are applied in wide range of academic and industrial fields such as modeling and control, signal possessing, medicine, and etc. An important Fuzzy Logic application is finding a new solution for control problems that will be discuses later. The present paper discusses a Fuzzy Logic Based Intelligent controller. A Fuzzy Logic Controller (FLC) does not need complex mathematical algorithms and is based on the IF_THEN linguistic rules (Rajesh Kumar et al, 2008).

In this article we first introduce electrical and mechanical modeling of an induction motor. Then we will explain the block diagram of the indirect vector control. In the section 4 we will discuss the PI, fuzzy logic and hybrid controller, respectively. Finally we will present the simulation results and a brief discussion.

2. INDUCTION MOTOR MODELING

The electrical part of an induction motor is represented with a fourth-order state-space model and the mechanical part with a second-order system. All electrical parameters and variables are referred to the stator. This is indicated by the prime symbols in the machine Equations 1 and 2 for electrical and mechanical systems. All rotor and stator quantities are in the arbitrary two-axis reference frame (d-q frame, see Fig 1).



(a)

(b)

Fig 1: Stator and rotor in two-axis reference frame (a) q-axis, and (b) d-axis

2.1 Electrical system

$$V_{qs} = R_s i_{qs} + \frac{d}{dt}\phi_{qs} + \omega\phi_{ds}$$

$$V_{ds} = R_s i_{ds} + \frac{d}{dt}\phi_{ds} - \omega\phi_{qs}$$

$$V'_{qr} = R'_r i'_{qr} + \frac{d}{dt}\phi'_{qr} + (\omega - \omega_r)\phi'_{dr}$$

$$V'_{dr} = R'_r i'_{dr} + \frac{d}{dt}\phi'_{dr} - (\omega - \omega_r)\phi'_{qr}$$

$$T_e = 1.5P(\phi_{ds} i_{qs} - \phi_{qs} i_{ds})$$

$$\phi_{qs} = L_s i_{qs} + L_m i'_{qr}$$

$$\phi_{ds} = L_s i_{ds} + L_m i'_{dr}$$

$$\phi'_{qr} = L'_r i'_{qr} + L_m i_{qs} \qquad (1)$$

$$\phi'_{dr} = L'_r i'_{dr} + L_m i_{ds}$$

$$L_s = L_{ls} + L_m$$

$$L'_r = L'_{lr} + L_m$$

2.2 Mechanical system

$$\frac{d}{dt}\omega_m = \frac{1}{2H}(T_e - F\omega_m - T_m) \qquad (2)$$

$$\frac{d}{dt}\theta_m = \omega_m$$

The induction motor parameters have been defined in Table 1 (all quantities are referred to the stator). Induction motor parameters have been shown in Table 2.

Table 1. The induction motor parameters defined in equations

Parameter	***Description***
R_s, L_{ls}	Stator resistance and leakage inductance
R'_r, L'_{lr}	Rotor resistance and leakage inductance
L_m	Magnetizing inductance
L_s, L'_r	Total inductances of stator and rotor
v_{qs}, i_{qs}	Stator voltage and current of q axis
v'_{qr}, i'_{qr}	Rotor voltage and current of d axis
v_{ds}, i_{ds}	Stator voltage and current of d axis
v'_{dr}, i'_{dr}	Rotor voltage and current of d axis
ϕ_{qs}, ϕ_{ds}	Stator q and d axis fluxes
ϕ'_{qr}, ϕ'_{dr}	Rotor q and d axis fluxes
ω_m	Rotor angular velocity
θ_m	Angular position of the rotor
P	Pole pairs number
ω_r	Electrical angular velocity (ω_m .p)
θ_r	Electrical rotor angular position (θ_m .p)
T_e	Electromagnetic torque
T_m	Mechanical torque of shaft
J	Joined rotor and load inertia coefficient
H	Joined rotor and load inertia constant
F	Joined rotor and load viscous friction coefficient

The motor used in this case study is a 50 HP, 460 V, four-pole, 60 Hz motor having the following parameters:

Table 2. Induction motor parameters

R_s	L_{ls}	L_m	R_r	L_{lr}
0.087 Ω	0.8 mH	34.7 mH	0.228 Ω	0.8 mH

3. INDIRECT VECTOR CONTROL

The squirrel cage IM using direct and quadrature axes (d-q) theory in the stationary reference frame, which needs less variables and thus analysis becomes easy [14]. Fig 2 shows the block diagram of the indirect vector control technique. The drive is controlled with two control loops, i.e. internal pulse width modulation (PWM) current control loop and external speed control loop.

The induction motor is fed by a current-controlled PWM inverter. This inverter operates as a three-phase sinusoidal current source. The error between speed ω and the reference speed ω* (ω - ω*) is processed by the speed controller to produce a command torque T_e^*.

As shown in the Fig 3, the rotor flux and torque can be independently controlled by the stator direct-axis current i_{ds} and quadrature-axis current i_{qs}, respectively.

We will write the basic equations. The stator quadrature-axis current reference is i_{qs}^* calculated from command torque T_e^* as shown in Equation 3.

$$i_{qs}^* = \frac{2}{3}\frac{2}{P}\frac{L_r}{L_m}\frac{T_e}{\left|\psi_r\right|_{est}} \tag{3}$$

where L_r is the rotor inductance, L_m is the mutual inductance, and $\left|\psi_r\right|_{est}$ is the estimated rotor flux linkage given by Equation 4.

$$\left|\psi_r\right|_{est} = \frac{L_m i_{ds}}{1+\tau_r s} \tag{4}$$

where $\tau_r = L_r / R_r$ is the rotor time constant.

The stator direct-axis current reference i_{ds}^* is obtained by Equation 5 from rotor flux reference input $\left|\psi_r\right|^*$.

$$i_{ds}^* = \frac{\left|\psi_r\right|^*}{L_m} \tag{5}$$

The rotor flux position θ_e required for coordinates transformation is generated from the rotor speed ω_m and slip frequency ω_{sl} (Equation 6).

$$\theta_e = \int\left(\omega_m + \omega_{sl}\right)dt \tag{6}$$

The slip frequency is calculated by Equation 7 from the stator reference current i_{qs}^* and the motor parameters.

$$\omega_{sl} = \frac{L_m}{\left|\psi_r\right|_{est}}\frac{R_r}{L_r}i_{qs}^* \tag{7}$$

The i_{qs}^* and i_{ds}^* current references are converted into phase current references i_a^*, i_b^*, i_c^* for the current regulators. The regulators use the measured and reference currents to form the inverter gating signals.

The speed controller keeps the motor speed equal to the reference speed input in steady state and provides a good dynamic during transient periods.

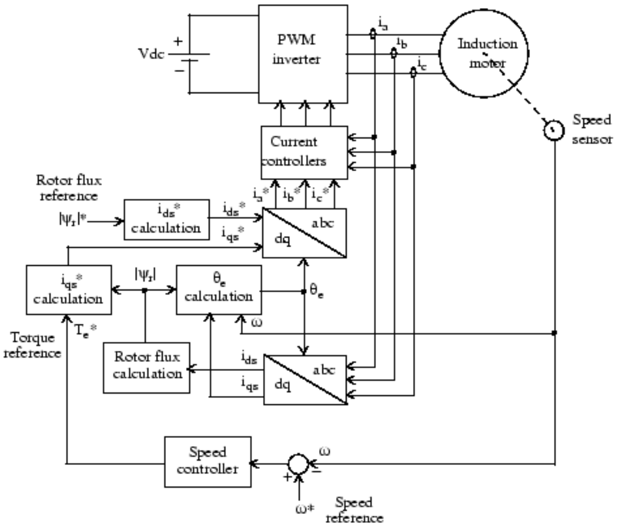


Fig 2: Block diagram of the indirect vector control technique

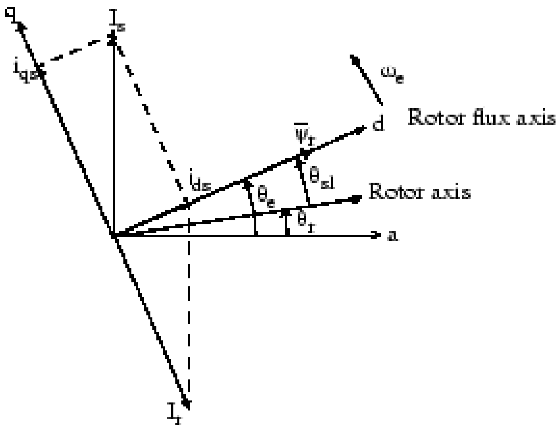


Fig 3: Phase diagram of indirect vector control principle

4. SPEED CONTROL OF IM

The proportional integral (PI) controller can be used for speed control of IM. The PI and differential (PID) controller is not normally used because differentiation could be causing the problem when input reference is a step. Usually, the difference of reference speed (ω^*) and actual speed (ω), which is called the speed error, is given as input to the controller. The speed controller processes the speed error and gives torque value as an input. Then the torque value is fed to the limiter, which gives the final value of command torque. The speed error and change in speed error at n-th instant of time are as below

$$\begin{aligned} e_{(n)} &= \omega^*{}_{(n)} - \omega_{(n)} \\ \Delta e_{(n)} &= e_{(n)} - e_{(n-1)} \end{aligned} \tag{8}$$

This article presents the performance of three types of speed control methods for simulation study: PI controller, fuzzy speed controller and hybrid controller (hybridization of fuzzy logic (FL) and PI controller).

4.1 PI Controller

The general block diagram of the PI speed controller is shown in Fig 4. The output of the speed controller (command torque) at n-th instant of time is expressed as follows:

$$T_{e(n)} = T_{e(n-1)} + K_p \Delta e_{(n)} + K_i e_{(n)} \tag{9}$$

where $T_{e(n)}$ is the output torque of the controller at the n-th instant, and K_p and K_i are the proportional and integral gain constants, respectively.

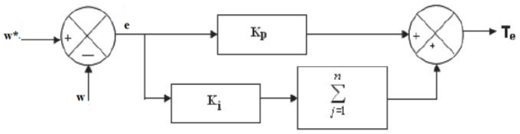


Fig 4: Block diagram of a PI controller

A restriction of the torque command is as follows

$$T_{e(n+1)} = \begin{cases} T_{e\max} \rightarrow T_{e(n+1)} \geq T_{e\max} \\ -T_{e\max} \rightarrow T_{e(n+1)} \leq -T_{e\max} \end{cases} \tag{10}$$

The PI controller gain parameters shown in (9) can be selected by many methods such as trial and error method, evolutionary techniques-based searching and Ziegler-Nichols method and so on. The numerical values of this controller gains depend on the ratings of the motor [14].

4.2 Fuzzy logic (FL) Speed Controller

The PI speed controller, which has been discussed in the previous section, is simple in operation and has zero steady-state error when operating on load. But the drawbacks of this PI controller are the occurrence of overshoot while starting, undershoot while load application and overshoot again while load removal [14]. Furthermore, it requires motor model to determine its gains and is more sensitive to parameter variations, load disturbances and suffer from poor performance when applied directly to systems with significant non-linearities [11, 18]. These drawbacks of PI controller can be removed with the help of a FL controller, which need not require model of the drive and can handle non-linearity of arbitrary complexity.

The fuzzy logic controller (FLC) has three functional blocks as shown in Fig 5.

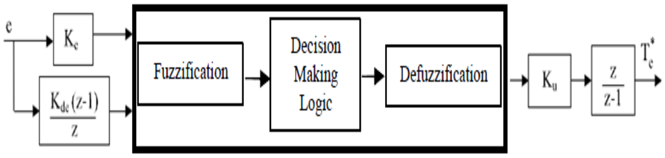
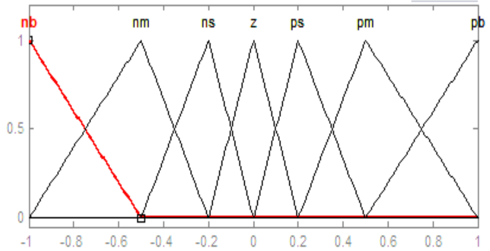
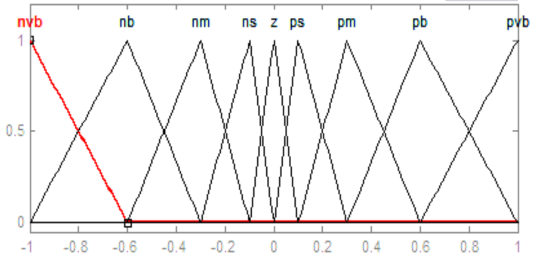


Fig 5: Structure of fuzzy logic controller

In the fuzzification block, the inputs and outputs crisp variables are converted into fuzzy variables 'e', 'de' and 'du' using the triangular membership function shown in Fig 6.



(a) Input variables 'e' and 'de'



(b) Output variable 'du'

Fig 6: (a) Input membership functions, (b) Output membership function

The fuzzification block produces the fuzzy variables 'e' and 'de' using their crisp counterpart. These fuzzy variables are then processed by an inference mechanism based on a set of control rules contained in (7*7) table as shown in Table 3. {NVB (negative very big), NB (negative big), NM (negative medium), NS (negative small), Z (zero), PS (positive small), PM (positive medium), PB (positive big), PVB (positive very big)} (Y.Miloud et al, 2000).

The fuzzy rules are expressed using the IF-THEN form. The crisp output of the FLC is obtained by using MAX-MIN inference algorithm and the center of gravity defuzzification approach.

The performance of the fuzzy controller depends on the membership functions, their distribution and the fuzzy rules that describe the control algorithm. There is no formal method to determine the parameters of the controller accurately. Tuning the FLC is an iterative process requiring modifications in membership functions and control rules. The adaptation can be done by considering the response of the system regulator and modifying the fuzzy sets of the input variables (e and de/dt) and output variable (du/dt) until desired response is obtained [4].

Table 3. Set of fuzzy control rules

DE/E	NB	NM	NS	ZE	PS	PM	PB
NB	NVB	NVB	NVB	NB	NM	NS	ZE
NM	NVB	NVB	NB	NM	NS	ZE	PS
NS	NVB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PVB
PM	NS	ZE	PS	PM	PB	PVB	PVB
PB	ZE	PS	PM	PB	PVB	PVB	PVB

4.3 Hybrid Speed Controller

To take over the advantages present in both FL (negligible overshoot and undershoot) and PI (zero steady-state error) controllers, a hybridization of FL and PI controllers, called fuzzy pre-compensated PI (FPPI) controller, is done and is used as a single controller. In this controller, FL is used for pre-compensation [12, 13, 15, 16, 17] of reference speed, which means that the reference speed signal (ω^*) is changed in advance in accordance with the rotor speed (ω), so that a new reference speed signal (ω_1^*) is obtained and the main control action is performed by PI controller. Some particular features such as overshoot and undershoot happening in the speed response, which are obtained with PI controller can be removed [15] and this controller is much useful to loads where the torque/speed of the motor varies every moment.

As is customary, the speed error ($e(n)^*$) and the change in speed error ($\Delta e(n)$) are the inputs to the FL, the output of the FL controller is added to the reference speed to generate a pre-compensated reference speed (δ), which is to be used as a reference speed signal by the PI controller shown in Fig 7.

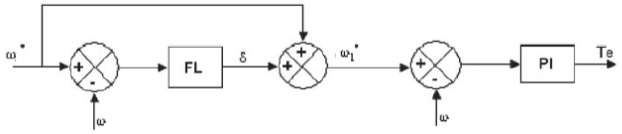


Fig 7: Block diagram of hybrid (FPPI) speed controller

The fuzzy pre-compensator can be mathematically modeled as follows [12]:
Referring (8) for the speed error and the change in speed error, pre compensated speed reference (δ) and update new reference speed (ω_1^*) can be calculated as

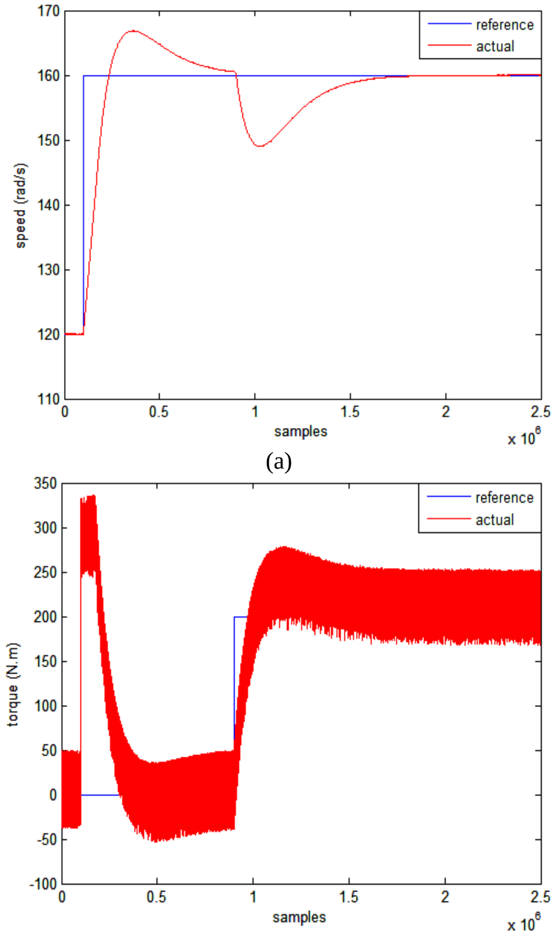
$$\delta_{(n)} = F\left[e_{(n)}, \Delta e_{(n)}\right] \tag{11}$$

$$\omega_1^* = \delta_{(n)} + \omega^*{(n)} \tag{12}$$

where F is FL mapping.

5. RESULT AND DISCUSSIONS

The simulation results are done in two mode, the starting mode and dynamic mode. But we only will show the dynamic mode. In the dynamic mode, the reference speed goes up from 120 (rad/s) to 160 (rad/s) at t=0.2 (s) and the motor torque changes from 0 (N.m) to 200 (N.m) at t=1.8 (s). The PI speed controller gains in (9) are selected by trial and error basis by observing their effects on the response of the drive. The values of k_p and K_i are 13 and 26, respectively. The dynamic performance of the motor with PI controller is shown in Fig 8.



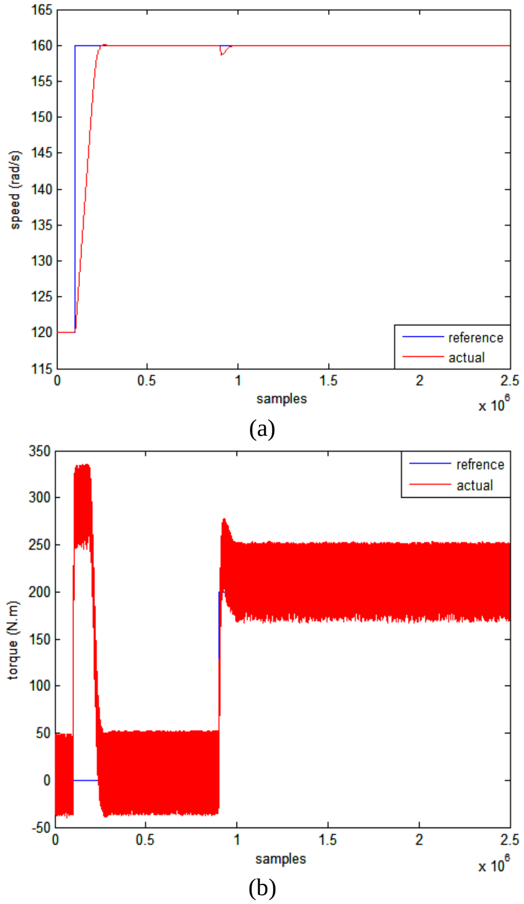
(a)

(b)

Fig 8: Performance of PI controller (a) Speed, and (b) Torque

The simulation results of speed and torque responses of the motor, which operate with FL speed controller, are shown in Fig 9. For all time instants, there is no speed overshoot and ripples are negligible (main advantageous of FL controller), but it offers more settling time and steady-state speed error (drawbacks of this controller), shown in Fig 9(a).

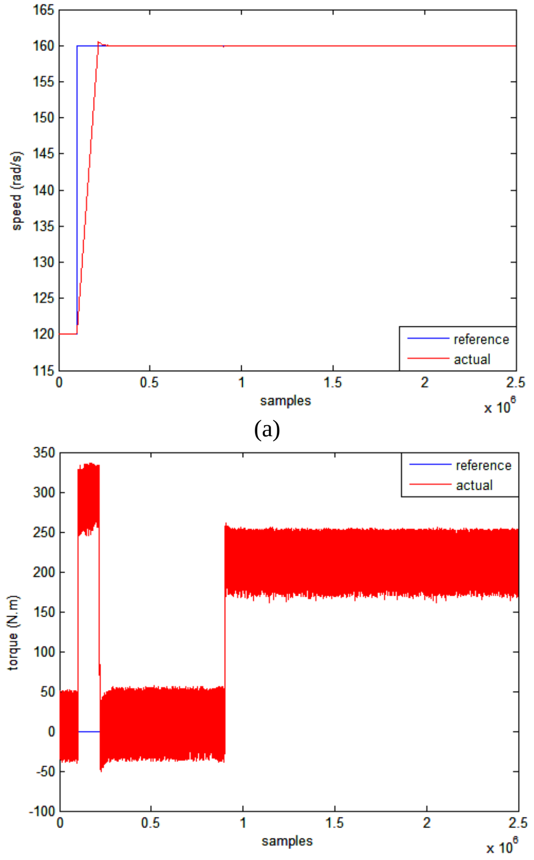
The results of hybrid speed controller are shown in Fig 10. The speed response with this controller has no overshoot and settles faster in comparison with FL controller. It is also noted that there is no steady-state error in the speed response during the operation when hybrid controller is activated. In addition, no oscillation occurred in the torque response before it finally settles (shown in Fig 10(a)), but oscillation occurred at PI controller. Good torque response is obtained with hybrid controller at all time instants and speed response is better than FL and PI controllers. There is a negligible ripple in speed response at hybrid controller in comparison with PI and FL controllers.



(a)

(b)

Fig 9: Performance of FL controller (a) Speed, and (b) Torque



(a)

(b)

Fig 10: Performance of hybrid controller (a) Speed, and (b) Torque

6. CONCLUSSIONS

This article presented performance of IM drive with three controllers. IM performance is checked through the simulation studies in MATLAB/SIMULINK environment. The performance of PI and fuzzy controllers in speed control of IM drive are simulated. Hybridization of FL and PI controllers is done and used as a single controller by extracting the advantages present in FL (negligible overshoot and undershoot) and PI (zero steady-state error) controllers.

According to the simulation results, hybrid controller produced better performances in terms of rise time, overshoot, undershoot and settling time.

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