Hybrid Fuzzy based Scalar Speed Control of Three Phase Induction Motor

Safdar Fasal T K, Unnikrishnan L

Abstract - This paper presents a hybrid fuzzy controller for scalar speed control of three phase squirrel cage induction motor. In this hybrid fuzzy controller, both proportional integral controller and fuzzy logic controller are operated alternately according to speed error to utilize the advantages of both controllers. Here the speed control is possible by varying supply frequency using a voltage source inverter while keeping voltage to frequency ratio as a constant. Speed error is given as input to the proportional integral controller, and speed error and speed error variation are given as input to the fuzzy logic controller. The controller output controls the reference of space vector pulse width modulation. Hence the fundamental frequency and fundamental voltage of inverter output can be varied to control the motor speed. The performance of hybrid fuzzy controller under reference speed and load torque variation is evaluated using simulation results in Simulink.

Index Terms - Fuzzy Logic Controller, Hybrid Fuzzy Controller, Proportional Integral Controller, Space Vector Pulse Width Modulation, Three Phase Induction Motor, Voltage source inverter.

1. Introduction

NOW-a-days Three phase induction motors have wide applications in industries due to robustness in construction, easiness in speed control, low cost of maintenance and adaptation to speed and load torque variations [1], [2]. Usually Induction motor (IM) drives are used in fan and pump applications for energy saving by speed control.

Two important methods of speed control of three phase induction motors are Scalar control and Vector control. Several studies are going on in the field of vector control due to better dynamic response [3], [4], [5]. However, Scalar control is widely used in industries because of its simple structure characterized by low steady-state error [6], [7], [8]. Therefore, constant voltage-frequency ratio (V/f) scalar control is considered in this paper for analysis.

Proportional integral (PI) controllers are commonly used in scalar speed control of induction motors due to its fast response [9], [10], [11]. However, in this case a mathematical model of the real plant is required for the controller design while using conventional methods. The difficulty of identifying the accurate parameters for a complex nonlinear and time-varying nature of real plants may render, in many cases, the fine tuning of parameters which is time consuming. Also, PI controllers are sensitive to parameter variations inherent in real plant operations [12].

Conversely, the scalar speed control using fuzzy logic controller (FLC) overcomes disadvantages of conventional PI controllers. FLCs have the ability to adapt with nonlinearity. Also, the control performance is less affected by plant parameter variations. FLCs are based on certain well defined linguistic rules, hence the requirement of precise mathematical model of real plant can be avoided [13], [14], [15]. Also overshoot of the system is very less in the case of FLCs. However, higher rise time is the major drawback of Fuzzy logic controller.

In order to overcome the drawbacks of both PI controllers and Fuzzy logic controllers, Hybrid controllers are proposed in Vector control of three phase induction motor [16], [17]. The proposed hybrid fuzzy controller in this paper utilizes the best attributes of both PI controller and Fuzzy logic controller to obtain a faster response without any overshoot in Scalar speed control of three phase induction motor. PI controllers are chosen when a fast response is needed while fuzzy logic controllers are preferred when the system behaviour is oscillatory or tend to overshoot.

This paper is organized as follows. In section 2, modelling of three phase IM in stationary reference frame in per unit system is explained. Section 3 gives a brief idea about Space vector pulse width modulation (SVPWM) technique. In section 4, Fuzzy logic controller design is described. In section 5, Induction motor with Hybrid fuzzy controller is presented. In section 6, Performance analysis of PI, Fuzzy and Hybrid fuzzy controllers under various conditions is discussed based on simulation results in MATLAB/Simulink [18]. Finally, Section 7 gives conclusion of this work.

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2. Induction Motor Per unit Model

In this section, per unit modeling of three phase squirrel cage induction motor in stator reference frame is discussed. The modeling equations for per unit currents are as follows:

$$I_{qsn} = \frac{w_b}{X_{sn}} \int (V_{qsn} - R_{sn} I_{qsn} - \frac{X_{mn}}{w_b} P I_{qrn})\, dt \tag{1}$$

$$I_{dsn} = \frac{w_b}{X_{sn}} \int (V_{dsn} - R_{sn} I_{dsn} - \frac{X_{mn}}{w_b} P I_{drn})\, dt \tag{2}$$

$$I_{qrn} = \frac{w_b}{X_{rn}} \int [w_{rn}(X_{mn} I_{dsn} + X_{rn} I_{drn}) - R_{rn} I_{qrn} - \frac{X_{mn}}{w_b} P I_{qsn}]\, dt \tag{3}$$

$$I_{drn} = \frac{w_b}{X_{rn}} \int [w_{rn}(X_{mn} I_{qsn} + X_{rn} I_{qrn}) - R_{rn} I_{drn} - \frac{X_{mn}}{w_b} P I_{dsn}]\, dt \tag{4}$$

Where, I_{qsn} and I_{dsn} are per unit stator currents in q-axis and d-axis respectively. V_{qsn} and V_{dsn} are per unit stator voltages in q-axis and d-axis respectively. I_{qrn} and I_{drn} are per unit rotor currents in q-axis and d-axis respectively. w_b is base frequency. R_{sn} and R_{rn} are per unit stator and rotor resistance respectively. X_{sn} and X_{rn} are per unit stator and rotor reactance respectively. X_{mn} is per unit mutual reactance.

The modeling equations for per unit flux linkages are as follows:

$$F_{qsn} = X_{sn} I_{qsn} + X_{mn} I_{qrn} \tag{5}$$

$$F_{dsn} = X_{sn} I_{dsn} + X_{mn} I_{drn} \tag{6}$$

$$F_{qrn} = X_{rn} I_{qrn} + X_{mn} I_{qsn} \tag{7}$$

$$F_{drn} = X_{rn} I_{drn} + X_{mn} I_{dsn} \tag{8}$$

Where, F_{qsn} and F_{dsn} are per unit stator flux linkages in q-axis and d-axis respectively. F_{qrn} and F_{drn} are per unit rotor flux linkages in q-axis and d-axis respectively. Torque and speed equations are given as follows:

$$T_{en} = (I_{qsn} F_{dsn} - I_{dsn} F_{qsn}) \tag{9}$$

$$w_{rn} = \frac{1}{J_n} \int (T_{en} - T_{ln})\, dt \tag{10}$$

Where, T_{en} is per-unit electromagnetic torque produced by induction motor. T_{ln} is load torque in per unit. w_{rn} is rotor speed in per unit and J_n is Inertia constant in per-unit.

Fig. 1 shows Simulink model of three phase IM using (1) to (10). Here V_{asn}, V_{bsn} and V_{csn} are the input voltages to the IM. Using this model, simulations are done in section 6 to analyze the performance of PI, Fuzzy and Hybrid fuzzy controllers.

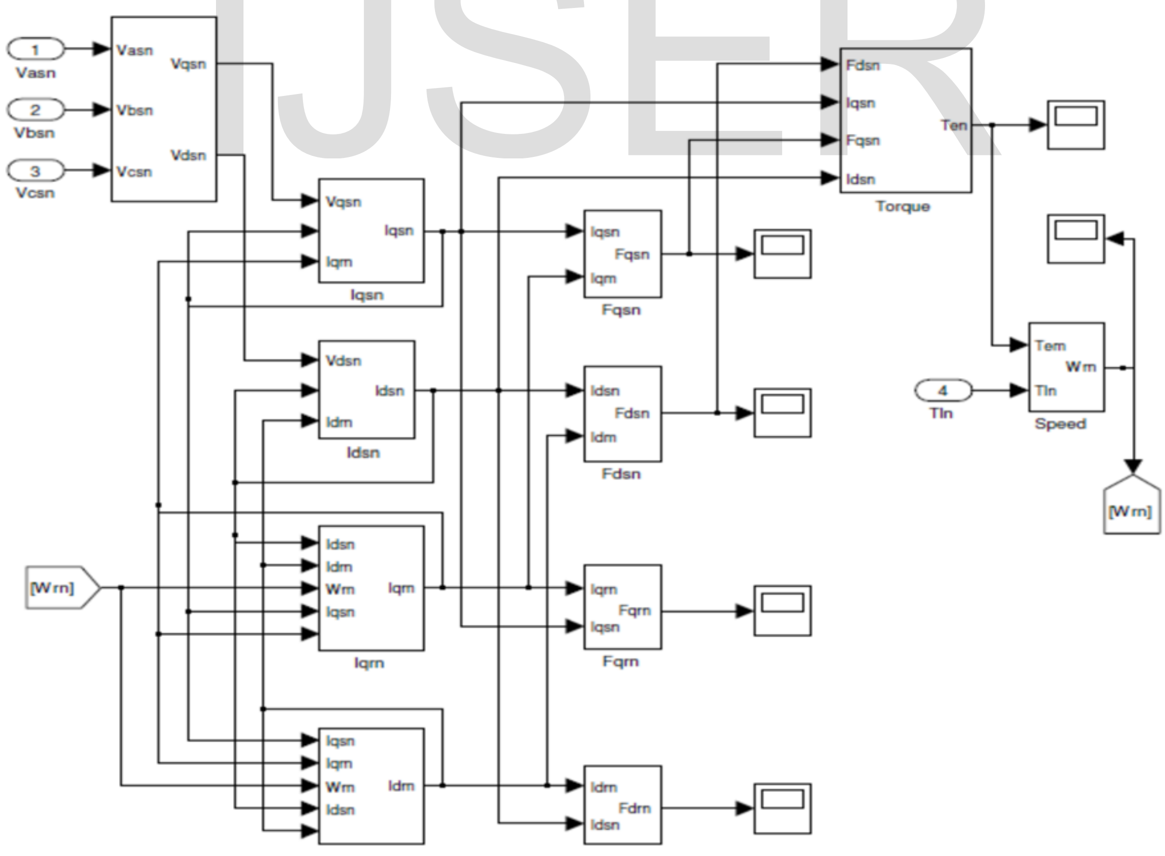

Fig 1. Simulink model of Induction motor

3. Space Vector Pulse Width Modulation

Space vector modulation is one of the advanced pulse width modulation (PWM) technique used for inverter switching. Usually there are eight possible switching states in an inverter. In these, six are active vectors viz. V_1,V_2, V_3, V_4, V_5, V_6 and two are null vectors viz. V_0, V_7 as shown in Fig. 2. We utilize only six active vectors in sinusoidal pulse width modulation but SVPWM uses six active vectors and two null vectors to generate the required space voltage vector.

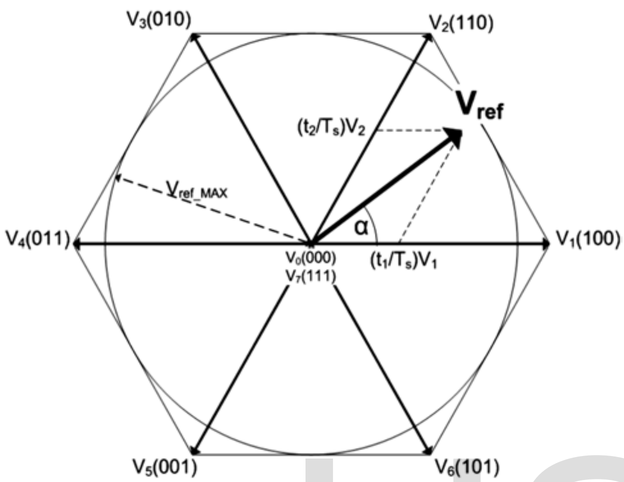

Fig 2. Basic active vectors and null vectors

The required space vector V_{ref} can be generated using two neighbouring active vectors, V_1 and V_2 for a time period of t_1 and t_2 respectively, along with null vectors for a time period of $(T_s-(t_1+t_2))$, where T_s is the switching period.

4. Fuzzy Logic Controller Design

In the case of three phase IM drive, speed error (e) and speed error variation (Δe) are input variables to the FLC. Frequency variation (Δf) is the output obtained from the FLC based on certain linguistic rules defined in fuzzy logic controller to achieve the reference speed.

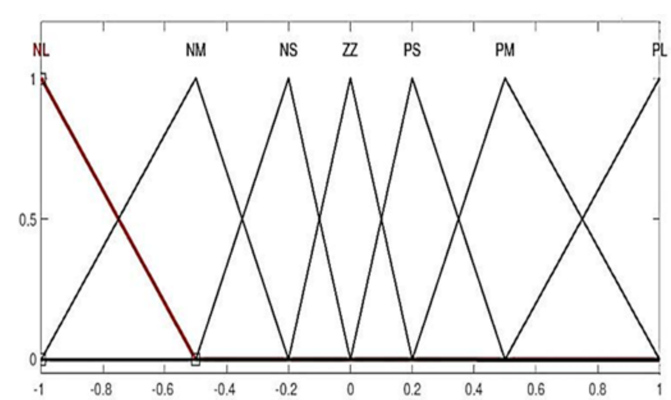

Fig 3. Input variables of fuzzy system (e) and (Δe)

Input variables, both speed error (e) and speed error variation (Δe) have seven membership functions. These membership functions are triangular in shape and vary between the interval [-1, 1].

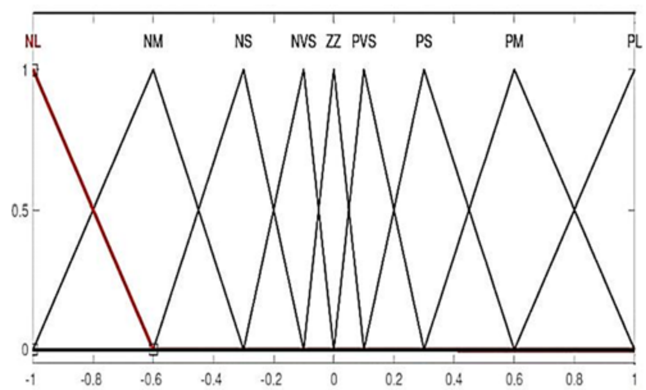

Fig 4. Output variable of fuzzy system (*Δf*)

Frequency variation (*Δf*) has nine membership functions which vary between the interval [-1,1] . The membership functions are described as follows: "NL" is "Negative and Large"; "NM" is "Negative and Medium"; "NS" is "Negative and Small"; "NVS" is "Negative and Very Small"; "ZZ" is "Zero"; "PVS" is "Positive and Very Small"; "PS" is "Positive and Small"; "PM" is "Positive and Medium"; "PL" is "Positive and Large." The linguistic rules used in fuzzy logic controller are shown by TABLE 1.

TABLE 1

Fuzzy Rules

Δe/e	**NL**	**NM**	**NS**	**ZZ**	**PS**	**PM**	**PL**
NL	NL	NL	NL	NM	NS	NVS	ZZ
NM	NL	NL	NM	NS	NVS	ZZ	PVS
NS	NL	NM	NS	NVS	ZZ	PVS	PS
ZZ	NM	NS	NVS	ZZ	PVS	PS	PM
PS	NS	NVS	ZZ	PVS	PS	PM	PL
PM	NVS	ZZ	PVS	PS	PM	PL	PL
PL	ZZ	PVS	PS	PM	PL	PL	PL

The linguistic rules of fuzzy system can be explained using examples:

- **If** (speed error is **NL**) **and** (speed error variation is **NL**) , **Then** (frequency variation is **NL**)

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- **If** (speed error is **ZZ**) **and** (speed error variation is **NS**) , **Then** (frequency variation is **NVS**)
- **If** (speed error is **PM**) **and** (speed error variation is **PL**), **Then** (frequency variation is **PL**) and so on.

5. IM WITH HYBRID FUZZY CONTROLLER

Fig. 5 shows the internal configuration of a hybrid fuzzy controller. The input to the hybrid fuzzy controller is speed error and output is frequency variation.

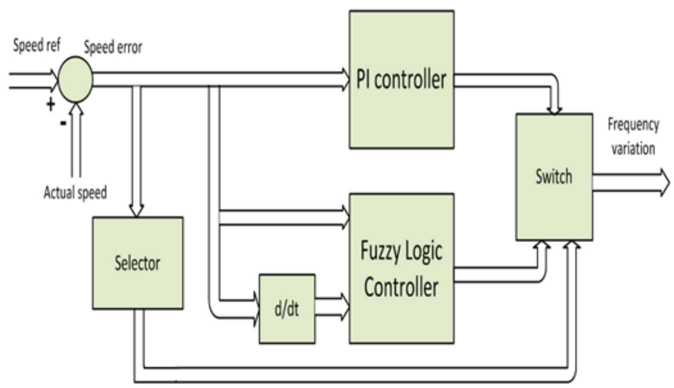


Fig 5. Internal configuration of hybrid fuzzy controller

Here both PI controller and FLC are operated alternately based on speed error using a selector switch arrangement. If the speed error is high, PI controller is chosen to get faster response. When response reaches near the reference value, FLC is chosen to avoid the tendency overshoot by operating selector switch at suitable instant.

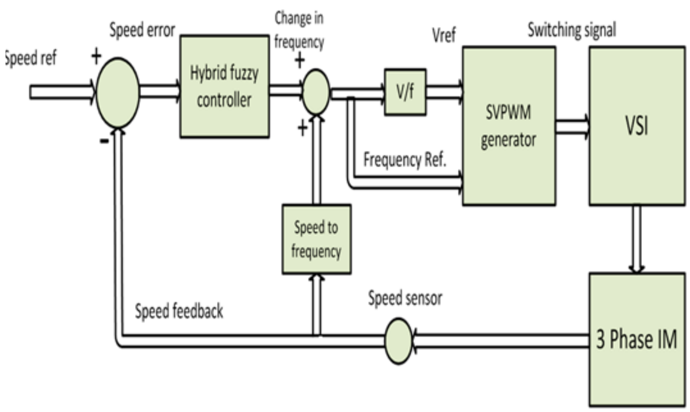


Fig 6. Basic block diagram of IM drive with hybrid fuzzy controller

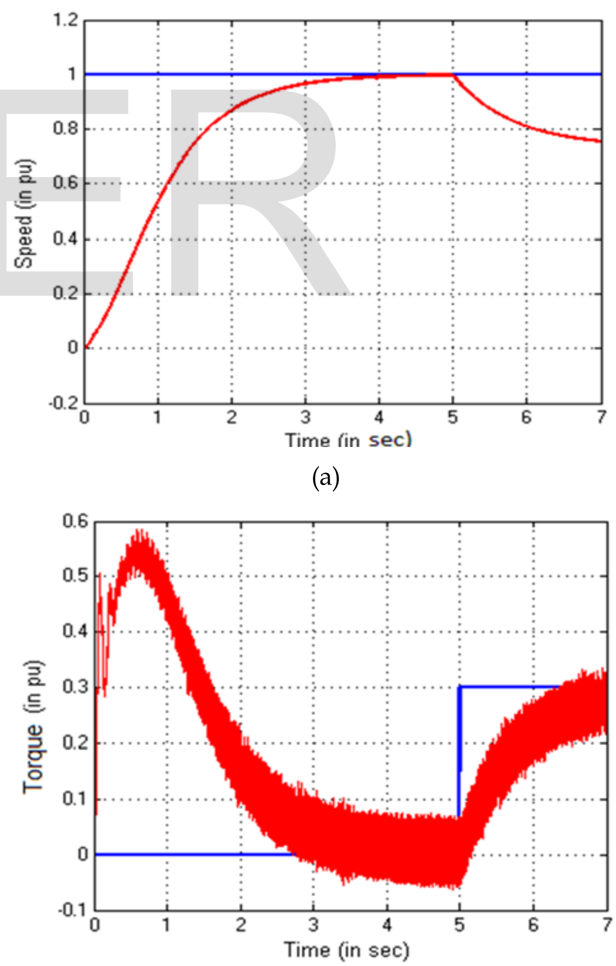
Fig. 6 shows basic block diagram of three phase IM with hybrid fuzzy controller. IM motor is supplied from a variable voltage variable frequency (VVVF) Voltage source inverter (VSI). The switching signal for VSI is obtained by space vector pulse width modulation (SVPWM). Speed is measured using speed sensor and is compared with reference speed. Speed error is input to the hybrid fuzzy controller, which gives the frequency variation as output, to achieve the reference speed. This frequency variation is added to the actual frequency obtained from the actual speed to get the reference frequency. Reference frequency is multiplied with constant voltage to frequency ratio (*V/f*) to obtain the amplitude of reference signal for SVPWM.

6. SIMULATION RESULTS

Performance study of PI, Fuzzy and Hybrid fuzzy controllers are carried out using simulation results in Simulink. Per unit IM model in section II is used for simulation of a 1hp, 380V, 50Hz, 6 pole three phase squirrel cage induction motor. All simulation values are in per unit.

6.1 Performance of PI controller under reference speed and load torque variation

Fig. 7 shows performance of PI controller under reference speed and load torque variation. Here, reference speed is 1pu. Step load of 0.3pu is given to IM at 5sec.



(a)

(b)

Fig 7. Performance of PI controller (a) Rotor speed (pu) (b) Torque (pu)

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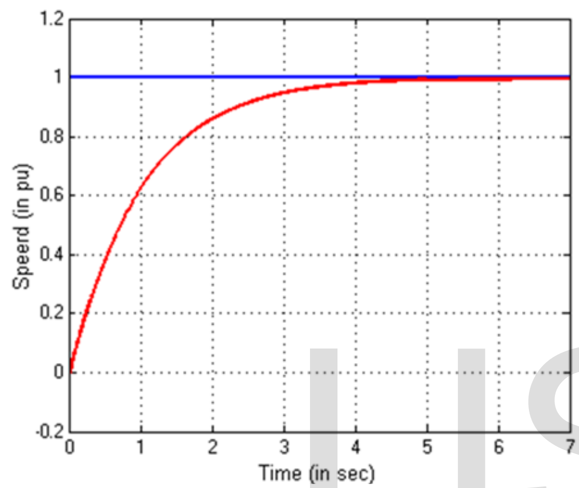
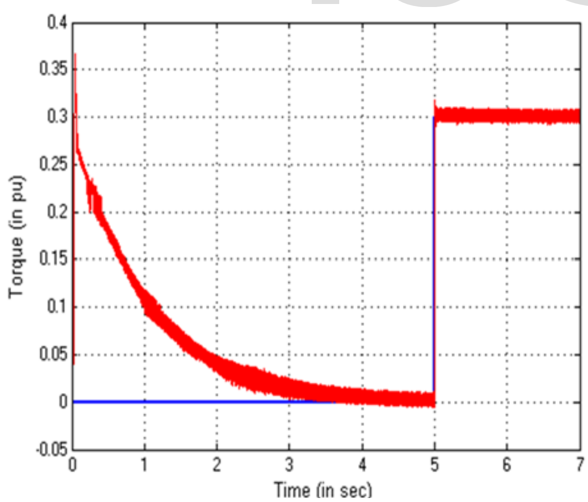
In Fig. 7, Rotor speed is increased gradually and settled to reference value at 4.5sec. Due to application of load torque of 0.3 pu at 5sec, speed is suddenly reduced to a lower value compared to reference speed. Also, torque is increased gradually and settled to 0.3 pu at 7sec.

6.2 Performance of Fuzzy logic controller under reference speed and load torque variation

Fig. 8 shows the performance of Fuzzy logic controller under reference speed and load torque variation. Here also, the reference speed is 1pu. Step load of 0.3pu is given at 5sec. Here Rotor speed is increased gradually from zero and settled to reference value at 4.5sec.



(a)



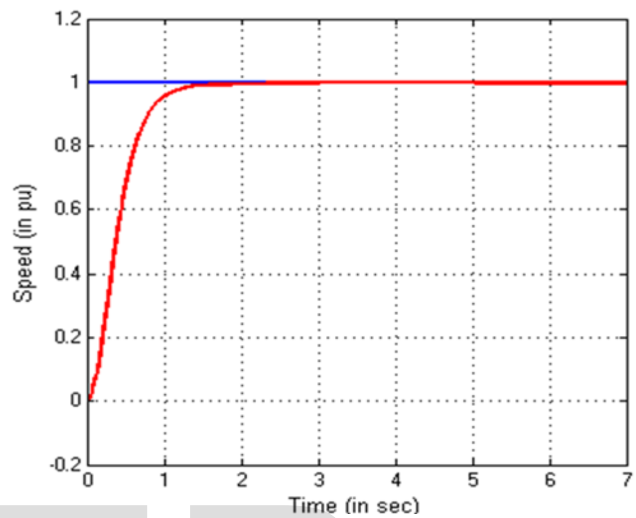
(b)

Fig 8. Performance of Fuzzy logic controller (a) Rotor speed (pu) (b) Torque (pu)

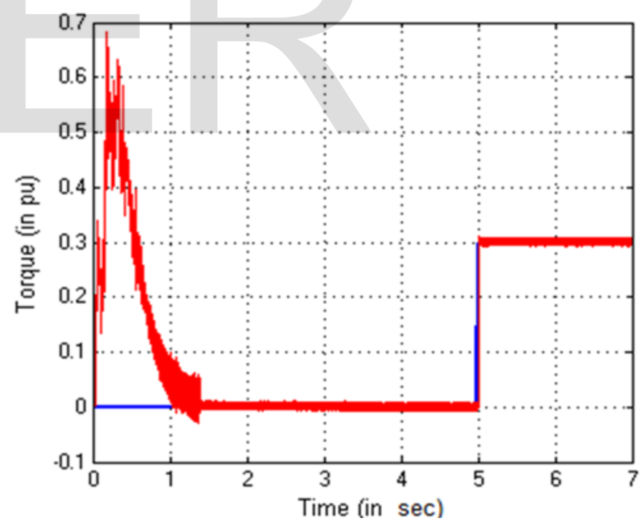
Application of load torque of 0.3 pu at 5sec causes a very small dip in rotor speed. However, Rotor speed follows the reference speed. Also, motor torque is increased suddenly and settled to 0.5 pu within milliseconds.

6.3 Performance of Hybrid fuzzy controller under reference speed and load torque variation

Fig. 9 shows the performance of Hybrid fuzzy controller under reference speed and load torque variation. The reference speed is 1pu. Step load of 0.3pu is given at 5sec.Rotor speed is increased gradually from zero and settled to reference value at 2.5sec. Time taken to settle at reference speed from zero speed is much lesser compared to PI and Fuzzy controllers.



(a)



(b)

Fig 9. Performance of Hybrid fuzzy controller (a) Rotor speed (pu) (b) Torque (pu)

6.4 Performance analysis of PI, Fuzzy and Hybrid fuzzy controllers

The comparison between PI, Fuzzy and Hybrid fuzzy controllers can be done using simulation results shown in Fig. 7, Fig. 8 and Fig. 9. Important observations are:

- Rise time is less in the case of PI controller while it is high in the case of Fuzzy controller. Settling time is lesser in the case of Fuzzy controller compared to PI

controller. So by utilizing the less rise time of PI controller and less settling time of Fuzzy controller, Hybrid fuzzy controller reduces total response time which is nearly 2.5 sec.
- When speed error is high, PI controller is operated to get fast response. When the response tends to overshoot then Fuzzy controller is utilized. So better response curve is obtained in the case of Hybrid fuzzy controller compared to the other controllers.
- High initial torque is available in the case of PI controller compared to Fuzzy controller. Therefore PI controller is initially operated in the case of Hybrid fuzzy controller to get high initial torque.
- Torque ripple is high in the case of PI controller but it is very small in the case of Fuzzy controller. In the case of Hybrid fuzzy controller under steady state condition, torque ripple can be minimized by utilizing Fuzzy controller.
- In the case of PI controller, speed is settled to a lower value of reference speed under load torque variations. In the case of Fuzzy controller, the rotor speed follows reference speed even if there is a small dip. In the case of Hybrid fuzzy controller, no such dip in rotor speed occurs due to the sudden application of load torque.
- Under load torque variations, the desired torque can be obtained gradually in the case of PI controller. While using Fuzzy controller desired torque can be obtained in a fraction of a second. During load torque variation, fuzzy controller is operated in the case of Hybrid fuzzy controller to attain the desired load torque within a fraction of second

7. Conclusion

The performance of Hybrid fuzzy controller for scalar speed control of three phase induction motor has been simulated and compared with PI controller and Fuzzy controller performance. This proposed Hybrid fuzzy controller utilizes the advantages of both PI and Fuzzy controllers. The simulation results proved that the Hybrid fuzzy controller performance is superior due to fast response under reference speed and load torque variations.

In future, a self-tuned Neuro-fuzzy controller can be developed to achieve much better performance under various operating conditions where the dynamics of the real plant is unpredictable.

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