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Fuzzy Control of Induction Motor with Reduced Rule Base

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Abstract: Several methods have been proposed and published for control of induction motors. The objective of this work is to develop a fuzzy controller with reduced rule base. Using concepts of direct torque control, a fuzzy controller has been designed with a cascaded final state selector, which reduced rule base and gave birth to a new control technique of induction motor. Details and performance of the fuzzy controller has been discussed in the paper.

Keywords: Induction motor, Fuzzy logic, Direct torque control.

1 Introduction

For last two decades researchers are working on development of AC. drives to control speed and torque of induction motors. Their efforts in this field are justified, as induction motor is one of the cheapest and robust motors available to the industry today. Suitable design of AC. drives for induction motor can transform the nonlinear torque-speed characteristics of induction motor to constant torque-speed characteristics similar to that of a DC. motor. Development of AC. drives for induction motors started with variable frequency control followed by vector control and recently leading to direct torque control using space vector modulation [1]. Here Application Specific Fuzzy Switching (ASFS) has been designed for direct torque control of squirrel cage induction motor, so space vector modulation for direct torque control shall be dealt subsequently.

Variable frequency control is simple to design and implement and even offers the advantage of operating without an encoder. Control is generated by maintaining constant volts per hertz output; used to drive a pulse width modulated (PWM) circuit. Since torque and flux are neither directly nor indirectly controlled, it results in limited speed accuracy and poor torque control.

To overcome this limitation, vector control used the concept of vectorizing voltage and current into two orthogonal axes (*d*-axis and *q*-axis) so as to control flux and torque independently similar to that of a DC. motor control. This results

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in good torque response and inclusion of an encoder increases accuracy of speed and torque, disadvantage being mandatory inclusion of an encoder. Moreover, the PWM modulator processes voltage and frequency reference outputs of the vector control stage thereby creating a signal delay between the input references and resulting stator voltage vector produced. This limits achievement of very rapid flux and torque control.

2 Direct Torque Control with Space Vector Modulation

Concepts of direct torque control have been explained in [1, 3]. Direct torque control (DTC) combines field-oriented control, digital signal processing and application specific integrated circuit. The control blocks associated are mathematical model of induction motor observer, hysteresis controller and ASIC for optimal switching. The mathematical model of induction motor observer estimates actual torque and flux of the motor from current and voltage feedback. Reference/desired values of torque and flux are fed to the hysteresis controller. Torque and flux comparators in hysteresis controller compare actual torque and actual flux with their respective desired values. If actual torque is below its differential hysteresis limit, the torque status goes high and if it is above its differential limit the torque status goes low. Similarly flux status goes high or low depending on actual flux value is below or above it's differential limit. Torque and flux status are fed to ASIC, which decides the switching state to be selected and accordingly switches it.

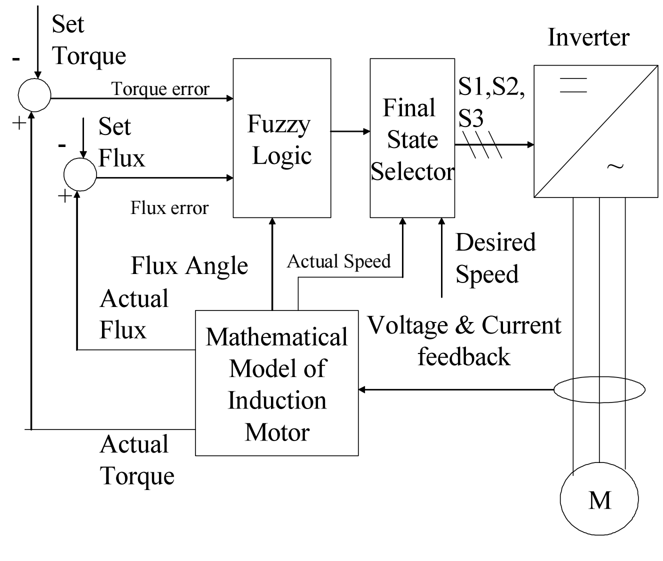

Fig. 1 – *Block diagram of proposed IM controller.*

The biggest drawback of direct torque control is that ASIC switching is not optimal switching. This would be clear if we consider a particular case. Suppose torque and flux levels are below their differential hysteresis limits. So say, switching state 2, as shown in Fig. 2 is optimal selection so that both torque and flux increases simultaneously. At an instant of time torque reaches it's lower differential limit (which is supposed to be desired torque) but flux level is still below. Since torque level has not reached upper hysteresis limit, torque status has not yet changed and so switching state 2 continues to be selected. This results in unwanted increase in torque and partial increase in flux till actual torque reaches upper hysteresis limit. Instead, say, switching state 1 would have been optimal selection of switching under such condition. There can be several such instances where optimal switching may fail with hysteresis controller and ASIC switching [2]. In such cases fuzzy logic with its linguistic capability decides optimal switching states for better control.

Several works have been reported on design of fuzzy controllers for induction motor control. In some works [10] DTC rules have been replaced with fuzzy rules. Chiraz et al [11] discussed design of fuzzy controller to address undesirable torque and current distortion caused by basic DTC. Efforts are evident to determine K_p and K_I for PI regulator using fuzzy logic [12]. Deflection angle of stator flux is derived from torque and flux errors using fuzzy inference method [13]. Fuzzy logic controller based on space vector modulation has been designed to address problem of drop of stator flux while stator flux vector changes position from one sector to another sector [14].

Moreover, for direct torque control, two different sets of switching states are selected for clockwise and counterclockwise rotation of induction motor. With the new designed technique, both have been combined in one set of switching states by design of the fuzzy controller cascaded with the final state selector. This helped in reducing total number of fuzzy rules thereby improving processing time for real time control application. The new induction motor controlller has been designed as shown in block diagram in Fig. 1.

3 New Control Technique of Induction Motor with Fuzzy Logic

Three inputs have been considered for the fuzzy controller i.e. torque error, flux error and flux angle. Inverter vector state is considered as output. A fuzzy rule base comprising of 36 rules has been developed based on **Table 1** and vector states as shown in Fig. 2.

In **Table1**, 1 denotes that the actual parameter is less than desired value and –1 denotes that the actual parameter is more than desired value and zero indicates that the difference between actual and desired values is within acceptable range. Defuzzification technique used here is mean of median and output denotes a switching state.

Table 1
Selection of inverter states.

Flux Status	1			0		
Torque Status	1	0	–1	1	0	–1
Sector 1	2	7	6	3	0	5
Sector 2	3	0	1	4	7	6
Sector 3	4	7	2	5	0	1
Sector 4	5	0	3	6	7	2
Sector 5	6	7	4	1	0	3
Sector 6	1	0	5	2	7	4

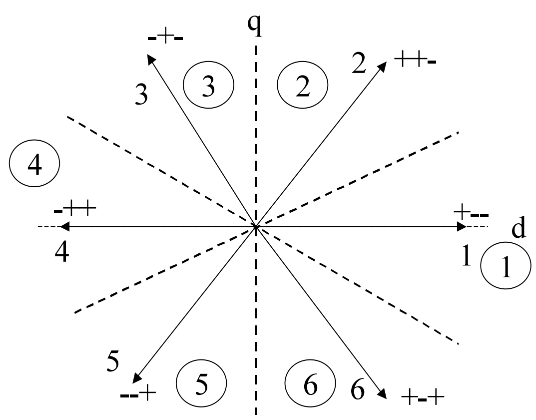

Fig. 2 – *Stator voltage vectors.*

Actual torque, flux and flux angle are determined from current and voltage feedbacks [3]. Desired speed is an input from user in the control model. Actual speed of rotating flux is determined as

$$\omega_e = \frac{\mathrm{d}\,\theta_e}{\mathrm{d}t}\,, \tag{1}$$

where ω_e is the actual speed of rotor flux and θ_e is the angle of rotor flux

The actual rotor speed [3] is

$$\omega_a = k\,P_n\,(\omega_e - (R_r\,T_e)/\phi_r^2), \tag{2}$$

where

P_n - number of pole pairs;

R_r - rotor resistance;

T_e - electromagnetic torque;

ϕ_r - rotor power factor and

k - 0.25 (empirically determined).

Let ω_d be the desired speed fed by user and T_{ed} the desired torque to achieve desired speed and T_{ea} the actual electromagnetic torque. Therefore from equation (2) follows

$$(\omega_d - \omega_a) = (T_{ea} - T_{ed})(kP_nR_r / \phi_r^2).$$

Therefore torque error,

$$T_{err} = (T_{ea} - T_{ed}) = (\omega_d - \omega_a) / (kP_nR_r / \phi_r^2). \tag{3}$$

It is known that torque is proportional to flux till saturation.

So let Ψ_{rd} be desired flux for desired speed which is determined as

$$\Psi_{rd} = Td(\Psi_r / T_e). \tag{4}$$

Therefore flux error,

$$\Psi_{err} = \Psi_{rd} - \Psi_r. \tag{5}$$

So torque error from equation (3), flux error from equation (5) and flux angle are fed as inputs to the fuzzy controller. The fuzzy controller decides the switching state, which is encoded.

4 Encoding Fuzzy Controller Output

After the fuzzy controller selects optimal switching state, it is necessary to encode it properly for subsequent processing [4]. A matrix as shown in Fig. 3 is generated for encoding.

The fuzzy controller is defuzzified to generate a crisp value, which is rounded off to the nearest integer value. The rounded off integer value corresponds to the row number of the encoding matrix and corresponding encoded values are thus obtained. With reference to the matrix in Fig. 3, Sw1, Sw2 and Sw3 denotes the encoded fuzzy output for red, yellow and blue phases respectively.

$$\begin{array}{c} \\ 0 \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \end{array} \begin{array}{c} \begin{array}{ccc} \text{Sw1} & \text{Sw2} & \text{Sw3} \end{array} \\ \begin{pmatrix} 0 & 0 & 0 \\ 0.5 & 0 & 0 \\ 0.5 & 0.5 & 0 \\ 0 & 0.5 & 0 \\ 0 & 0.5 & 0.5 \\ 0 & 0 & 0.5 \\ 0.5 & 0 & 0.5 \\ 0.5 & 0.5 & 0.5 \end{pmatrix} \end{array}$$

Fig. 3 – *Encoding Matrix.*

5 Final State Selector

In order to reduce rule base of fuzzy controller, with unidirectional set of rules of direct torque control, both for maintaining desired speed under varying load conditions as well as change of direction of rotation even with mechanical load on motor shaft, the final state selector (FSS) has been designed. The inputs of the FSS are fuzzy outputs Sw1, Sw2, Sw3, the actual speed as derived from the observer and desired speed as fed by the user.

The sign of the desired speed is calculated in the FSS along with speed error. The speed error is calculated as

$$S_{er} = S_a - S_d, \tag{6}$$

where S_a is actual speed in r.p.m and S_d is desired speed in r.p.m.

The sign of desired speed is designated as $\operatorname{sgn}(S_d)$ and output is 1 if desired speed is positive and –1 if desired speed is negative, depending on direction of rotation.

Depending on speed error S_{err}, an output x is calculated as

$$x = \operatorname{sgn}(S_d) \cdot (-1) \quad \text{if } S_{err} \geq 0, \tag{7}$$

$$x = \operatorname{sgn}(S_d) \cdot 1 \qquad \text{if } S_{err} < 0. \tag{8}$$

With respect to the desired speed the synchronous frequency, f_s is calculated as

$$f_s = (S_d P) / 120 \tag{9}$$

where S_d in equation (9) is expressed in r.p.m.

Square waves with synchronous frequencies are generated for all three phases (red, yellow, blue) with 120° phase shifts. Amplitude of the square waves varies from 0.5 to –0.5. Instantaneous value of square wave is denoted as O_{syn}.

The encoded fuzzy output of the fuzzy controller is denoted as O_{fuzz}, where Sw1, Sw2 and Sw3 are corresponding outputs of the three phases. The synchronous frequency outputs are denoted as O_{syn}. So final output of the controller, O_{final} is given by

$$\text{if } x \geq 0 \quad \text{then} \quad O_{\text{final}} = O_{\text{syn}} + O_{\text{fuzz}} , \tag{10}$$

$$\text{if } x < 0 \quad \text{then} \quad O_{\text{final}} = O_{\text{fuzz}} . \tag{11}$$

The final state selector has been designed with respect to Lemma 1 as stated below.

Lemma 1: If actual speed is greater than desired speed in either direction, the final output is the fuzzy controller output else the final output is the summation of fuzzy controller output and synchronous controller output.

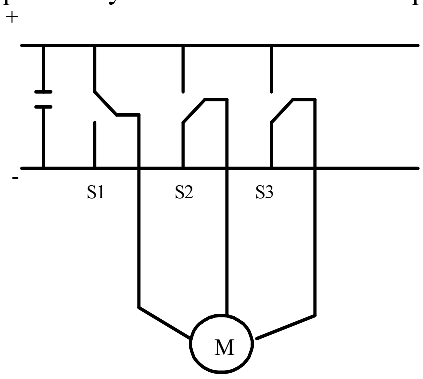

Fig. 4 – *Switching scheme motor control.*

Outputs from equations (10) and (11) are valid for the three phases.

With respect to Fig. 4, S1, S2 and S3 denote three-phase supply to induction motor. If output of final state selector for any phase is greater or equal to 0.5 the corresponding phase (S1 or S2 or S3) is switched to positive bus, otherwise it is switched to negative bus. The DC bus voltage to be maintained at 380 Volts.

6 Results

The proposed fuzzy controller along-with the final state selector has been used to control an induction motor with following specifications.

Voltage : 415V;	Amps : 7.7A
Kw : 3.7kW/5hp	R.P.M. : 1430
Frequency : 50 Hz	Poles : 4

Simulation model has been used to operate the motor at desired speed of 1500 r.p.m; 1000 rpm and even tested for speed changeovers from 1500 r.p.m to –1500 r.p.m and 1000 r.p.m to –1000 r.p.m. under loaded conditions.

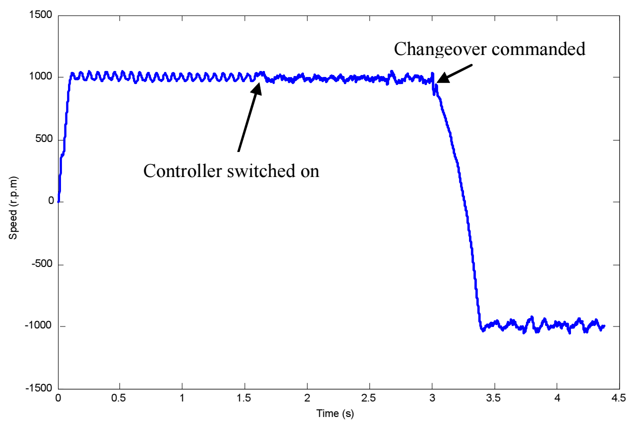

Fig. 5 – *Speed Control from* 1000 r.p.m. *to* –1000 r.p.m.

Fig. 5 shows simulation result of the induction motor with the newly designed fuzzy controller. Here the desired speed initially was 1000 r.p.m. After 0.6 s the motor shaft has been loaded. From beginning, the motor is running with normal synchronous frequency. At 1.6 s the fuzzy controller is switched on and it takes over the control mechanism. At 3 s a command is given to change the speed of the motor from 1000 r.p.m to –1000 r.p.m. Fig. 5 depicts how well the fuzzy controller changes over the speed even in the loaded condition. Fig. 6 depicts similar speed changeovers from 1500 r.p.m to –1500 r.p.m. Simulation has been carried out with 1 kHz sampling frequency.

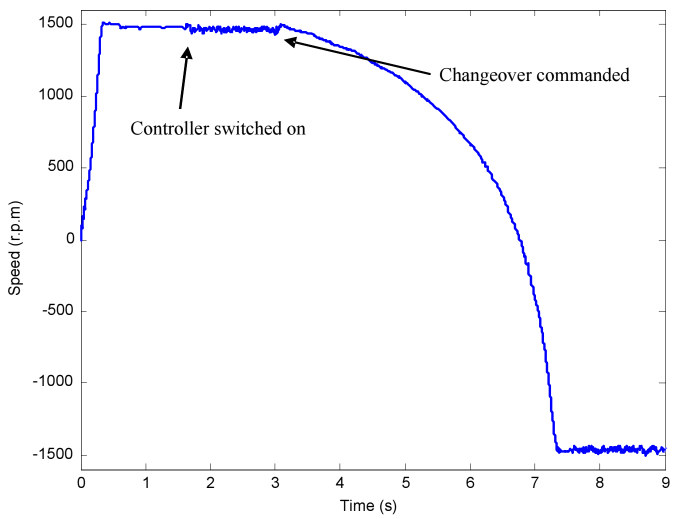

Fig. 6 – *Speed Control from* 1500 r.p.m. *to* –1500 r.p.m.

In order to eliminate continuous maintained speed error, an integrator has been introduced after speed error is calculated. Accordingly, torque error and flux error are calculated and fed to fuzzy controller. Performances deteriorate drastically if derivative component of speed error signal is fed to the controller to take care of transients. It has been observed, during change in direction of rotation, proportional error signal is suitable. Figs. 7 - 13 demonstrates such performances under varying load conditions and different commanded speeds. Here K_p, K_i and K_d are constants of proportional, integral and derivative (PID) components, which in some cases have been considered 1 without optimizing or tuning the constants. The loading time and fuzzy controller coming in action remains same as mentioned in the previous cases.

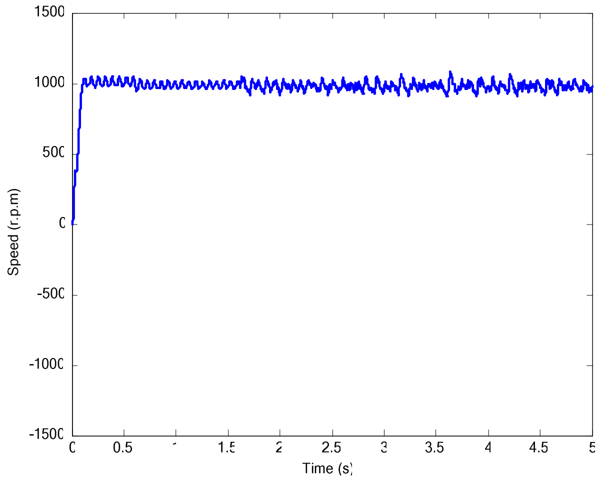

Fig. 7 – *Speed:* 1000 r.p.m. *Load:* 23 Nm; K_i =1 ; K_d = 0; K_p = 0.

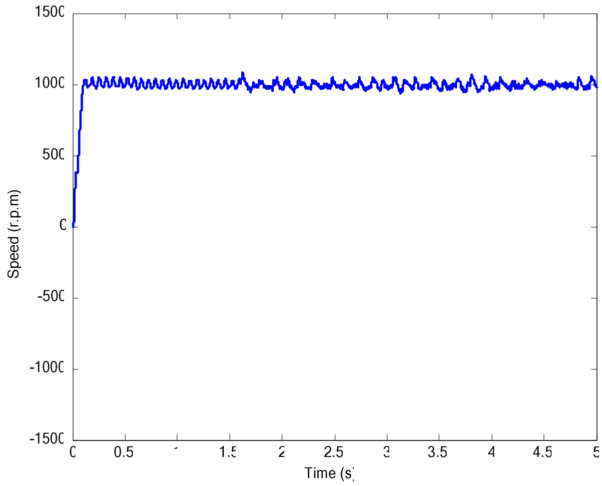

Fig. 8 – *Speed:* 1000 r.p.m. *Load:* 11 Nm; K_i =1 ; K_d = 0; K_p = 0.

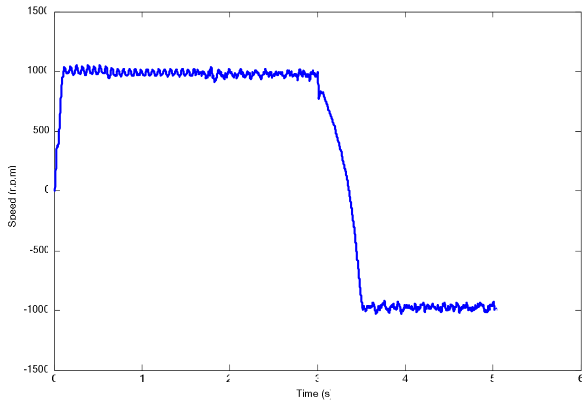

Fig. 9 – *Speed:* 1000 *to* –1000 r.p.m. *Load:* 23 Nm; K_i =0 ; K_d = 0; K_p = 1.

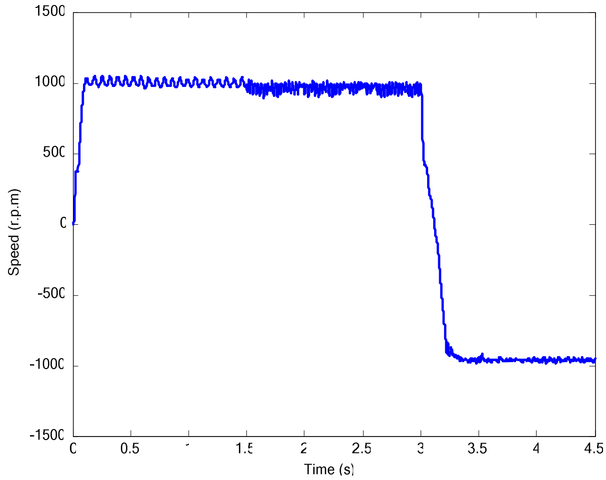

Fig. 10 – *Speed:* 1000 *to* –1000 r.p.m. *Load:* 11 Nm; K_i =0 ; K_d = 0; K_p = 1 *with motor model speed estimator.*

If Figs. 5 and 10 are compared as well as Figs. 6 and 13 are compared, it is observed there is change in commutation time though the commanded speed changeovers are from 1000 r.p.m to –1000 r.p.m and 1500 r.p.m. to –1500 r.p.m respectively. This difference is due to differences adopted in estimation of speed. Figs. 5 and 6 are with reference to estimation of speed derived by differentiating flux angle. The discontinuous points at Π and –Π result in generation of spikes, which result in improper selection of final state selection from equations (10) and (11). In Figs. 10 and 13, speed estimation is given by the simulation motor model in MATLAB, which resulted in elimination of such unwanted spikes. This resulted in faster commutation from one direction of rotation to another by proper selection of final states from equations (10) and (11). So performance of the fuzzy controller with the final state selector is dependent on proper estimation of speed, which can further improve performance of the drive. The performance will further improve with increase in sampling frequency. But there are some limitations. It has been observed that the controller is suited up to speeds of ±700 r.p.m. Better design of the fuzzy controller with different membership functions and tuning of PID parameters will improve performance of the motor control even for lower speeds. However, presently the new control method has been discussed and further improvement has been kept for future work. The present work highlights capability of the new method for bi-directional control of induction motor with reduced rule base. Introduction of the final state selector helped to reduce the rule base to 36 rules as compared to 72 rules for direct torque control. Thus the advantage of the proposed technique is to improve real time processing. Moreover, it presents a new control technique of induction motor.

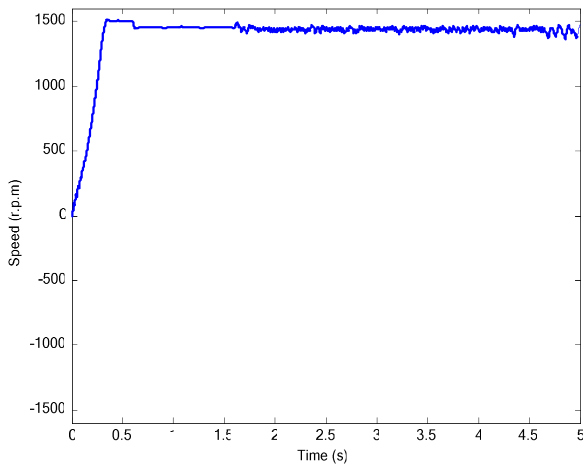

Fig. 11 – *Speed:* 1500 r.p.m. *Load:* 23 Nm; K_i =1; K_d = 0; K_p = 0

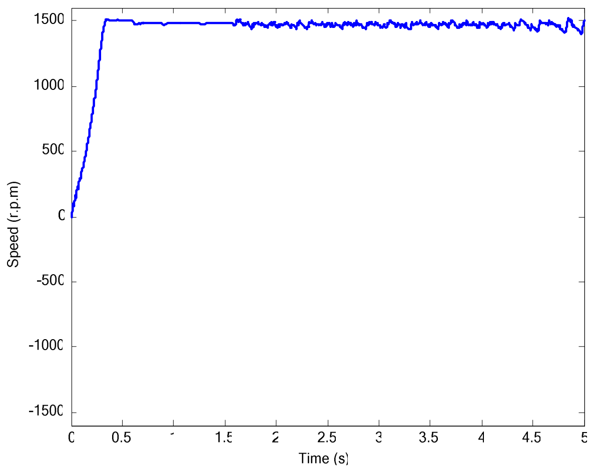

Fig. 12 – *Speed:* 1500 r.p.m. *Load:* 11 Nm; K_i =1; K_d = 0; K_p = 0.

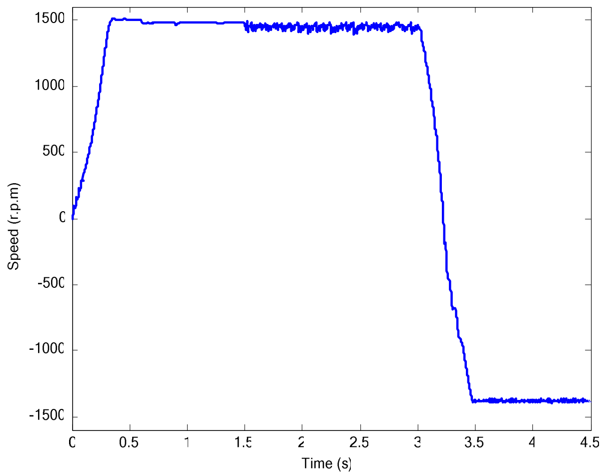

Fig. 13 – *Speed:* 1500 to –1500 r.p.m. *Load:* 11 Nm; K_i =0; K_d = 0; K_p = 1 *with motor model speed estimator.*

7 Conclusion

Though several methods of control of induction motor exist, here an intelligent controller has been developed. The new method of control of induction motor depicts good speed control under varying load conditions and transition from clockwise to counterclockwise direction or vice-versa. The reduced rule base with bi-directional control capability helped to improve processing time of the controller, which can be utilized for other control actions in real time processing environments.

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