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Investigation of vector controlled PV powered induction motor drive performance using hybrid fuzzy controller

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Abstract

Hybrid fuzzy PI controller based vector control of Induction Motor drive is proposed in this paper. Generally, Induction Motor drives are extensively used in many industries for adjustable speed applications. Induction motor drives are selected for its simple and easy control. Vector control of an induction motor is suitable to achieve good dynamic performance. The Hybrid controller is proposed in this paper to improve the dynamic performance of the drive. The fuzzy logic controller is proposed for less computation and easy to implement. Hybrid fuzzy PI based vector control of Induction Motor drive is proposed to develop static and dynamic performance of the system. In this paper, the performance of proposed controller is compared with fuzzy logic controller and PI controller based drive. The added feature in the proposed system is Photovoltaic power source. This paper proposes PV power-driven Hybrid fuzzy PI based vector controlled Induction Motor drive which produces a good dynamic response. This system is analyzed using Matlab / Simulink and compared with the conventional controls.

Keywords: Induction motor drive, Vector control, Proportional Integral controller, Fuzzy logic controller, Hybrid fuzzy PI controller, Photovoltaic power.

1. Introduction

Induction motors (IM) are generally used in many industries due to its good self-starting capability, simple and rugged structure, low cost and reliability. In general, the induction motors are connected with the Voltage Source Inverters (VSI) for variable speed control [12]. Adjustable speed control is the main application of Induction Motor drive for industries. The adjustable speed can be achieved using scalar control and vector control. Scalar control methods are variable frequency control and variable voltage and frequency (V/Hz) control.

Many researchers analyzed IM drive using scalar method. Scalar control of Induction Motor speed control leads to be able to adjust the motor speed by control the frequency and amplitude of the stator voltage, the ratio of stator voltage to frequency should be kept constant, which is called as V/F or scalar control of Induction Motor drive [18]. Constant torque characteristics is analyzed and experimented by Volts/Hertz control scheme using VSI PWM inverter fed induction machine [3].

Speed and electromechanical torque characteristics are analyzed using a modified closed loop V/F speed controlled drive [17]. A new V/F control method is used to control the motor and speed curve is discussed with low speeds [2]. Robust controller is provided by experimental realistic tests on scalar controlled IM drives [21]. Volt-per-Hertz (V/F) controlled IM drive using RT-Lab software and Matlab/Simulink are analyzed in the feature of speed [10].

An analytical approach based design of Proportional Integral (PI) controller with anti-windup controller is analyzed for IM control and validated the simulation performance using DS1104 hardware [1]. Scalar control (Volt-Hertz) method is designed with fuzzy speed controller for the motor and the speed-torque performances are analyzed [6]. The disadvantage of this method is the uncontrolled magnetic flux. This problem can be rectified by vector control method.

Vector control method improves the dynamic performance of motor [15] such as fast response. Performance of vector control drive mainly depends on the speed controller used in it. In conventional drives, PI controller [16] is used to control

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the speed. But, it produces poor performance in case of sudden change in load and transients. So, in this paper fuzzy logic controller is proposed to control the speed.

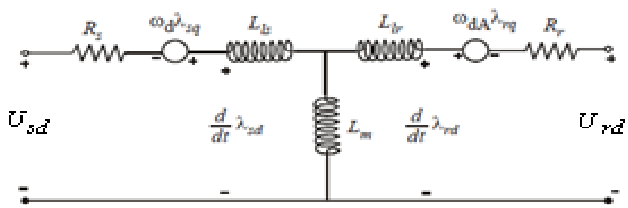
Fuzzy is proposed for its ability to handle with system nonlinearity and its control performance is less affected by system parameter variations [9]. Moreover, fuzzy techniques utilize a linguistic rule base which is designed by taking advantage of system qualitative characteristics and expert knowledge.

Utilization of non-conventional energy resources reduces usage of fossil fuel and pollution. It makes the researchers passion for renewable energy. Photovoltaic energy generation offers many advantages compared to other renewable energy sources, particularly in terms of reliability and less maintenance. Domestic lighting, street lighting, electric vehicles, water pumping, military and space applications [19] or grid-connected configurations [13] such as hybrid systems [14] and power plants are the applications of PV system. Therefore, this paper proposes PV source for IM drive.

2. Dynamic model of an induction motor

2.1 Circuit Description

The equations of an Induction Motor are developed in a rotating reference frame. The rotor of an IM is squirrel cage type. The equivalent circuit used for obtaining the mathematical model [4] [25] of the motor is shown in the Figure 1.



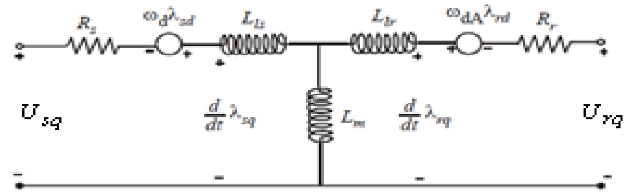


Figure 1. Equivalent circuit of induction motor in d -q frame.

The induction motor model is established using a rotating (*d*, *q*) field reference concept. The model is used to predict the voltage which is required to drive the flux and torque within a specified period of time.

$$U_{sd} = R_s i_{sd} + \frac{d}{dt}\lambda_{sd} - \omega_d \lambda_{sq} \quad (1)$$

$$U_{sq} = R_s i_{sq} + \frac{d}{dt}\lambda_{sq} - \omega_d \lambda_{sd} \quad (2)$$

$$U_{rd} = R_r i_{rd} + \frac{d}{dt}\lambda_{rd} - \omega_{dA} \lambda_{rq} \quad (3)$$

$$U_{rq} = R_r i_{rq} + \frac{d}{dt}\lambda_{rq} - \omega_{dA} \lambda_{rd} \quad (4)$$

U_{sd} and U_{sq}, U_{rd} and U_{rq} are the direct axes & quadrature axes stator and rotor voltages. The flux linkages to the currents are given by the equation (5)

$$\begin{bmatrix} \lambda_{sd} \\ \lambda_{sq} \\ \lambda_{rd} \\ \lambda_{rq} \end{bmatrix} = M \begin{bmatrix} i_{sd} \\ i_{sq} \\ i_{rd} \\ i_{rq} \end{bmatrix}; M = \begin{bmatrix} L_s & 0 & L_m & 0 \\ 0 & L_s & 0 & L_m \\ L_m & 0 & L_r & 0 \\ 0 & L_m & 0 & L_r \end{bmatrix} \quad (5)$$

The electrical part of an induction motor can thus be described by combining the above equations we get equation (6).

$$\begin{bmatrix} i_{sd} \\ i_{sq} \\ i_{rd} \\ i_{rq} \end{bmatrix} = \frac{1}{L_m^2 - L_r L_s} \times \left(A \begin{bmatrix} i_{sd} \\ i_{sq} \\ i_{rd} \\ i_{rq} \end{bmatrix} + \begin{bmatrix} L_s & 0 & L_m & 0 \\ 0 & L_s & 0 & L_m \\ L_m & 0 & L_r & 0 \\ 0 & L_m & 0 & L_r \end{bmatrix} \begin{bmatrix} U_{sd} \\ U_{sq} \\ U_{rd} \\ U_{rq} \end{bmatrix} \right) \quad (6)$$

$$A = \begin{bmatrix} L_r R_s & (\omega_{dA} L_m^2 - \omega_s L_r L_s) & -L_m R_r & -L_r L_m (\omega_s - \omega_{dA}) \\ -(\omega_{dA} L_m^2 - \omega_s L_r L_s) & L_r R_s & L_r L_m (\omega_s - \omega_{dA}) & -L_m R_r \\ -L_m R_s & L_s L_m (\omega_s - \omega_{dA}) & L_s R_r & (\omega_s L_m^2 - \omega_{dA} L_r L_s) \\ -L_s L_m (\omega_s - \omega_{dA}) & -L_m R_s & -(\omega_s L_m^2 - \omega_{dA} L_r L_s) & L_s R_r \end{bmatrix} \quad (7)$$

The instantaneous torque produced is given by

$$T_{em} = \frac{P}{2}\left(\lambda_{rq} i_{rd} - \lambda_{rd} i_{rq}\right) \tag{8}$$

The electromagnetic torque expressed in terms of inductances is given by

$$T_{em} = \frac{P}{2} L_m\left(i_{sq} i_{rd} - i_{sd} i_{rq}\right) \tag{9}$$

The mechanical part of the motor is modeled by the equation

$$\frac{d}{dt}\omega_{Mech} = \frac{T_{em} - T_L}{J_{EQ}} = \frac{\frac{P}{2} L_m\left(i_{sq} i_{rd} - i_{sd} i_{rq}\right) - T_L}{J_{eq}} \tag{10}$$

2.2 Vector control of an Induction motor drive

Vector control of an Induction motor drive mainly consists of two parts such as speed controller and hysteresis current controller. The block diagram of a drive is shown in Figure 2.

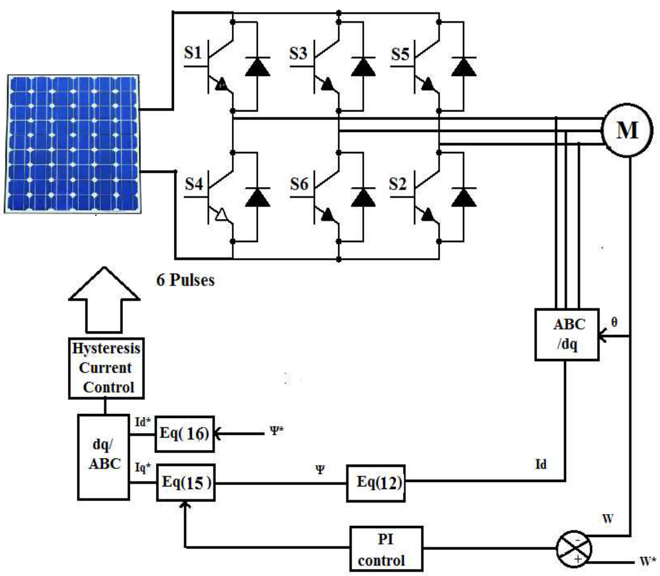


Figure 2. Block diagram of Vector controlled Induction motor drive [24]

Induction motor is energized from Voltage Source Inverter given by PV source. The speed of an induction motor and three phase current from inverter are sensed inputs for vector control. In a speed controller, the actual speed and reference speed are compared. The error speed is processed by PI/ FLC to produce reference torque T*. Meantime, the three phase inverter current Iabc is converted into dq frame using (11). In balanced three-phase circuits, the dqo transform minimizes the three AC quantities into two DC quantities and before doing the inverse transformation, calculations may be done on imaginary DC quantities. The dqo transform is referred to as Park's transformation.

$$I_{dqo} = T I_{abc} = \sqrt{\frac{2}{3}}\begin{bmatrix} \cos(\theta) & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ -\sin(\theta) & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} \end{bmatrix}\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \tag{11}$$

From the I_d the actual flux is calculated using (12)

$$\Psi = L_m * \frac{I_d}{1 + T_r} \tag{12}$$

Where, L_m is the mutual inductance, T_r is the torque. From the flux the Electrical angle Θ is calculated using (13)

$$\theta = \int (w_r + w_m) \tag{13}$$

$$w_r = L_m * \frac{I_q}{T_r * \Psi} \tag{14}$$

ω_r is the Rotor frequency (rad/s) and ω_m is the Rotor mechanical speed (rad/s).
The reference I_q* is calculated from flux and reference torque T* as shown in (15).

$$I_q^* = (2/3) * (2/p) * (L_r/L_m) * (T_e^*/\Psi) \tag{15}$$

Where, p is the number of poles and L_r is the rotor inductance. The reference I_d* is calculated from reference flux Ψ* shown in (16)

$$I_d^* = \frac{P_{hir}^*}{L_m} \tag{16}$$

The reference I_d* and I_q* are converted into an I_{abc}* using inverse park transform us (17)

$$I_{abc} = T^{-1} I_{dqo} = \sqrt{\frac{2}{3}}\begin{bmatrix} \cos(\theta) & -\sin(\theta) & \frac{\sqrt{2}}{2} \\ \cos\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta - \frac{2\pi}{3}\right) & \frac{\sqrt{2}}{2} \\ \cos\left(\theta + \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) & \frac{\sqrt{2}}{2} \end{bmatrix}\begin{bmatrix} I_d \\ I_q \\ I_o \end{bmatrix} \tag{17}$$

The reference three phase current I_{abc}* is compared with actual current I_{abc} in Hysteresis current controller. It produces pulses to three phase hex bridge inverter to feed the motor. Hence, the motor is controlled to set the speed with controlled magnetic flux. In this paper, the performance is compared using PI and Fuzzy logic controllers.

2.3 Speed Control Using PI Controller

Easy design and implementation makes wide use of

Proportional plus Integral Controller. It increases the speed of response of the system [5]. It produces very low steady state error. PI controller is proposed in this paper for T*. In this paper speed Error (e) is given as input to both PI controllers. General equation of the PI controller is [15]

$$U(s) = K_p E(s) + \frac{k_i}{s} E(s) \quad (18)$$

Where K_p is proportional gain, K_i is the integral gain, E(s) is the controller input and U(s) is the controller output. Figure 3 shows the block diagram of PI controller.

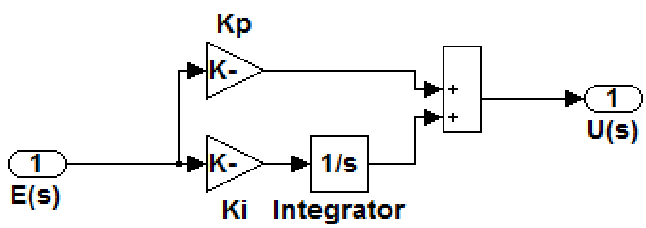


Figure 3. Block diagram of PI controller

In this paper Ziegler Nichols' method of tuning is implemented to find the optimum value of K_p & K_i values. But the drawback of this controller is it produces the high overshoot and long settling time.

2.4 Speed Control Using Fuzzy Logic Controller

Fuzzy logic is the mathematical technique deals inaccurate data which are having numerous solutions rather than one. Linguistic, non-numerical, variables are used which is similar to the way of humans think. Fuzzy control methodology is an effective method to deal with disturbances and uncertainties in terms of ambiguity. In this paper, Fuzzy Logic Controller (FLC) is implemented to reduce overshoot and settling time. Figure 4 shows the basic block diagram of FLC [8].

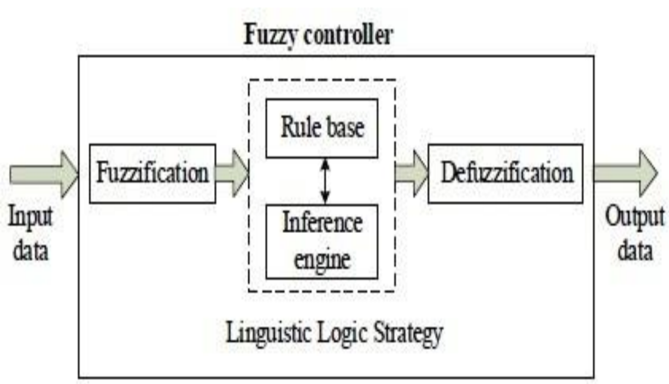


Figure 4. Block diagram of Fuzzy Logic controller

Fuzzy inference system contains fuzzification, fuzzy rule and defuzzification. There are lot of methods to define the result of a rule; this paper implies max-min method of inference. Here, fuzzy controller of Mamdani type is implemented. It has the inputs such as speed error (e) and change in error (ec). FLC produces T* as output [26].

$$E = w^* - w \quad (19)$$

Both inputs and output have five membership functions such as NB-Negative Big, NS-Negative Small, Z-Zero, PS-Positive Small, and PB-Positive Big. Defuzzification is the mathematical procedure to convert fuzzy values into crisp values. In this study, we have selected centroid method of defuzzification. Table 1 shows the fuzzy rules. Figure 5 and Figure 6 shows the input membership functions & Output membership functions respectively [23].

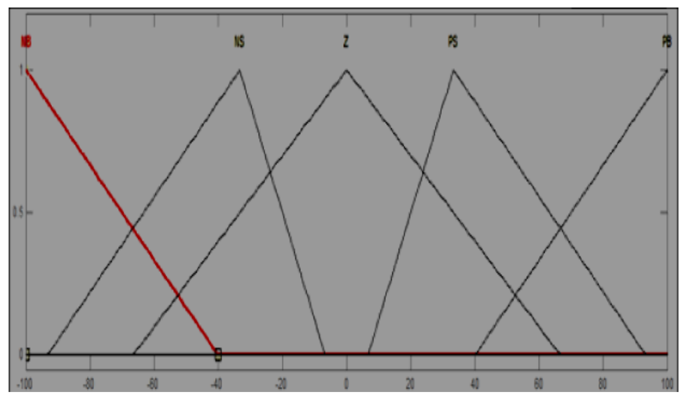


Figure 5. Membership functions of input e & ec

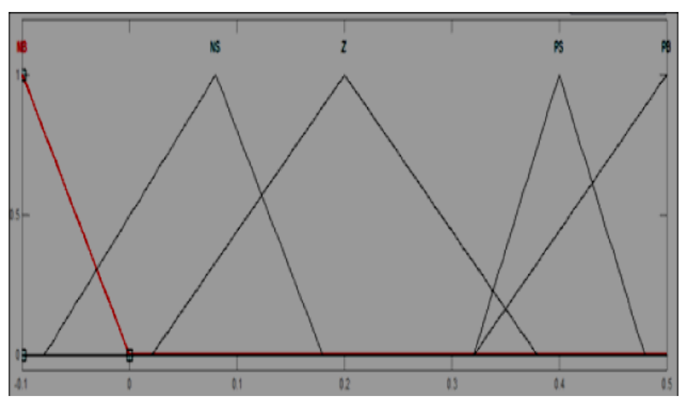


Figure 6. Output membership functions

Table 1. Fuzzy Rules

Error/Change in Error	NB	NS	Z	PS	PB
NB	NB	NS	NS	Z	PS
NS	Nb	NS	NS	PS	PB
Z	NB	NS	Z	PS	PB
PS	NB	NS	PS	PS	PB
PB	NS	Z	PS	PS	PB

3. Hybrid Fuzzy PI Controller

In Hybrid Fuzzy PI Controller, the classical PI and fuzzy controller are combined by a merger mechanism. The difference between the actual speed and the reference speed is the actuating error. A switching scheme creates a decision on the priority of the two controller parts. The hybrid fuzzy PI controller has the advantage of PI control and fuzzy control. The hybrid fuzzy PI controller offers better speed responses for large speed errors [7] [20]. The block diagram of IM control system with Hybrid fuzzy PI controller is shown in Figure 7.

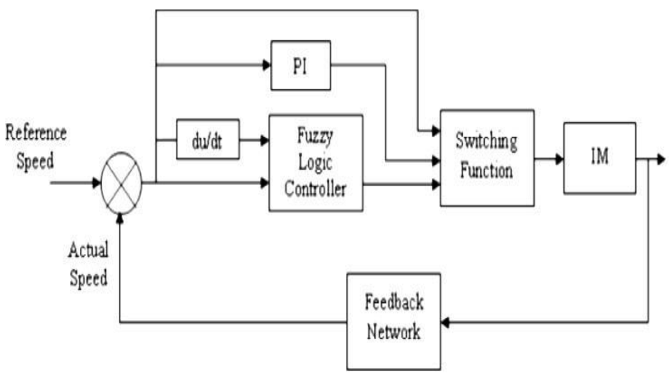


Figure 7. Block diagram of IM control system with hybrid fuzzy PI controller

4. PV Panel

The solar modules (photovoltaic PV Cell) generate DC electricity whenever sunlight falls in solar cells. Solar radiation sustains all forms of life on earth. According to estimates, the sun radiates 1.74 x 10^{17} W of power per hour to earth the daily solar energy radiation varies from 4-7 kWh per m^2 and there are 270-300 sunny days in a year. The single PV cell produces a rather small voltage that has a less practical use. The real PV panel always uses many cells to generate a large voltage [22]. The following parameters were used in the calculation of the net current of a PV cell.

Saturation current of the diode, I_o, Net current from the PV panel I, Light-generated current inside the cell I_L, Series resistance R_s, which is the internal resistance of the PV panel, Shunt resistance R_{sh}, in parallel with the diode, R_{sh}, is very large unless many PV modules are connected in a large system, Diode quality factor, n.

In an ideal cell R_s is 0 and R_{sh} is infinite. The net current of the PV cells is the difference between the output current from the PV cells and the diode current is given by [7].

$$I = I_L - I_O \left[e^{\left(q\frac{(V+IRs)}{nKT} \right)} - 1 \right] \quad (20)$$

Where V is the voltage across the PV cell, k is the Boltzmann's constant (1.381 x 10^{-23} J/K), T is the junction temperature in Kelvin, q is the electron charge (1.602 x 10^{-19} C), n is the diode ideality factor (1.62). In this paper, PV panel supplies Voltage Source Inverter.

5. Simulation results and analysis

To analyze the performance of Vector controlled Induction Motor, 5 HP squirrel cage type motor is taken. It is analyzed using various controllers like PI and Fuzzy logic controller under various speeds and loads. Parameters of induction motors are shown in Table 2.

Table 2. Motor Parameters

Line Voltage	415
Frequency	50HZ
Stator Resistance (R_s)	1.15 Ω
Rotor Resistance (R_r)	1.083Ω
Stator inductance (L_s)	5.974 mH
Rotor inductance (L_r)	5.974 mH
Mutual inductance (L_m)	0.2037H
Moment of Inertia (J)	0.02 Kg.m^2
Number of poles (P)	4

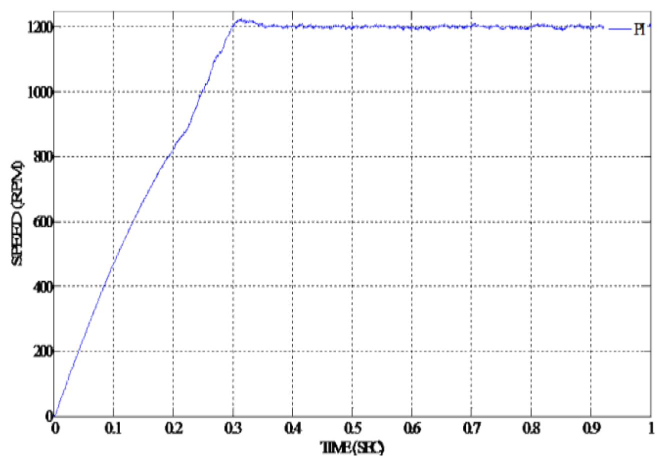


Figure 8. Speed performance of PI based vector control

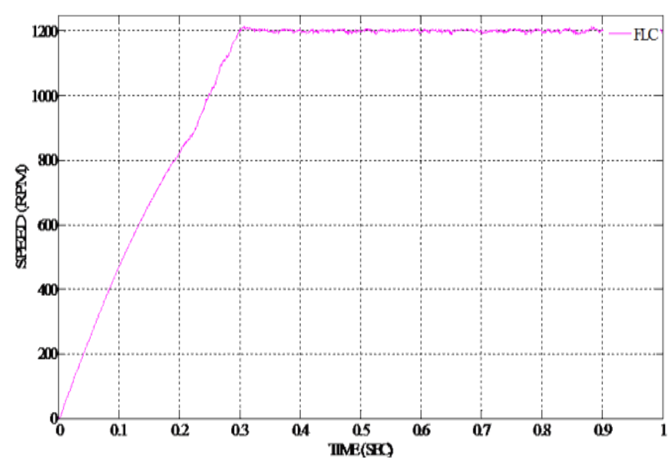


Figure 9. Speed performance of FLC based vector control

The performance of the motor using PI based vector control is shown in Figure 8. The performance is analyzed under no load while the machine is running. The reference speed of the machine is set at 1200 RPM.

Figure 8 shows the speed response of PI controller it produces high overshoot. The performance of the motor using Fuzzy and Hybrid fuzzy PI based vector control are shown in Figure 8 and 9. Conditions for analyses are same as a PI controller test.

Figure 9 shows the speed response of FLC it produces less overshoot compare to the PI controller.

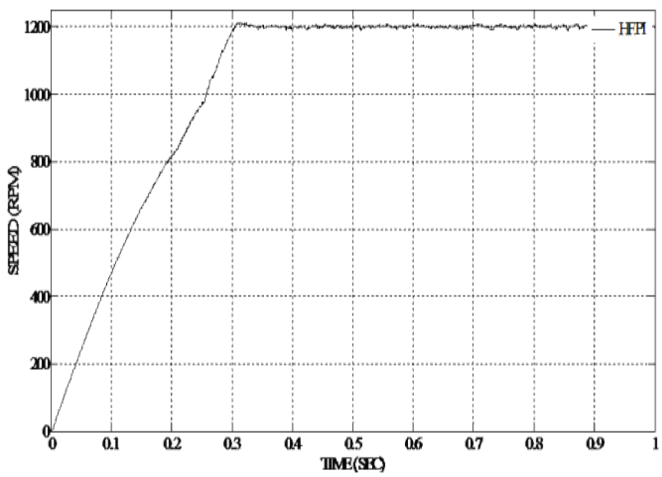


Figure 10. Speed performance of HFPI based vector control

Figure 10 shows the speed response of HFPI it produces less steady state error compare to the Fuzzy controller.

The performance of the motor using PI based vector control is shown in Figure 11.

The performance is analyzed under a load while the machine is running. Load is applied at 1 sec. The reference speed of the machine is set at 1200 RPM.

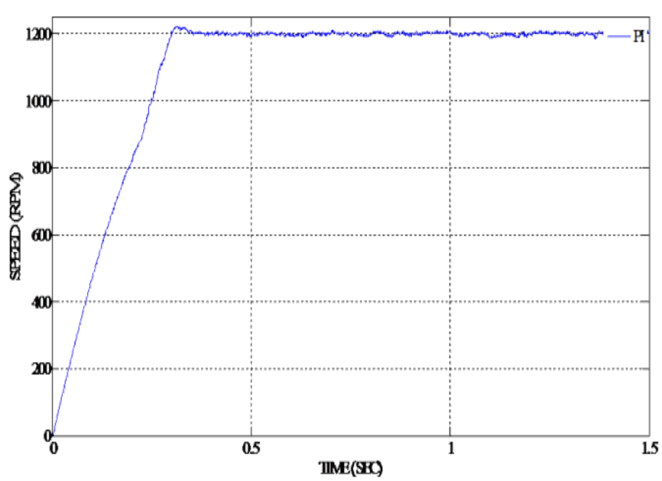


Figure 11. Speed performance of PI based vector control with change in load

The Figure 11 shows the speed response of the PI controller during changes in load it produces a large drop in speed.

The performance of the motor using Fuzzy based vector control is shown in Figure 12. Conditions for analyses are same as a PI controller test.

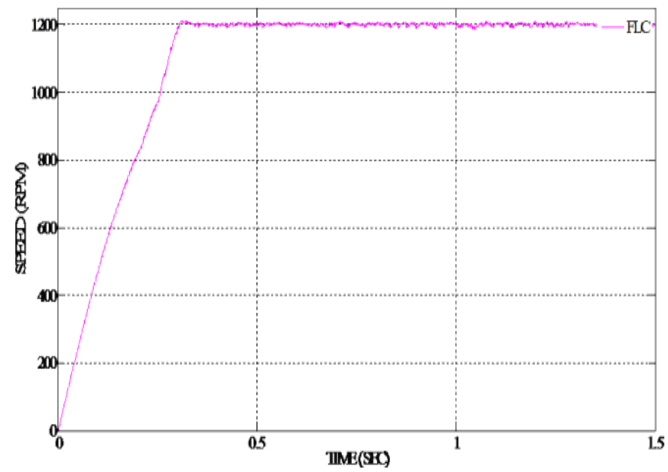


Figure 12. Speed performance of FLC based vector control with change in load

The Figure 12 shows the speed response of Fuzzy controller during changes in load it produces less drop in speed.

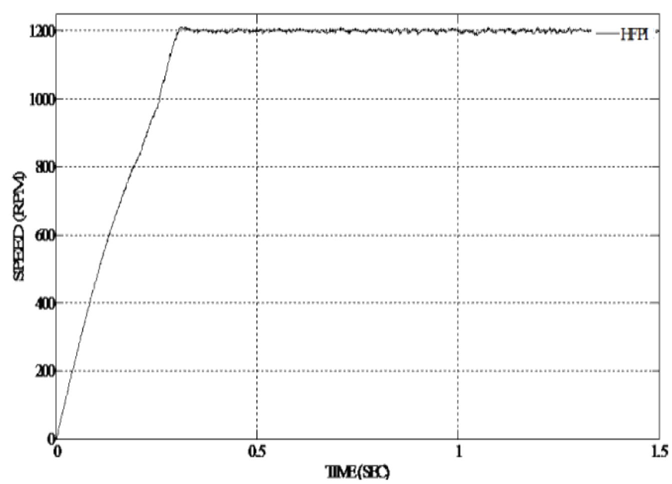


Figure 13. Speed performance of HFPI based vector control with change in load

The Figure 13 shows the speed response of HFPI controller during changes in load it produces less drop in speed and peak overshoot is also less.

Combined performance of drive using various controllers is shown in Figure 14.

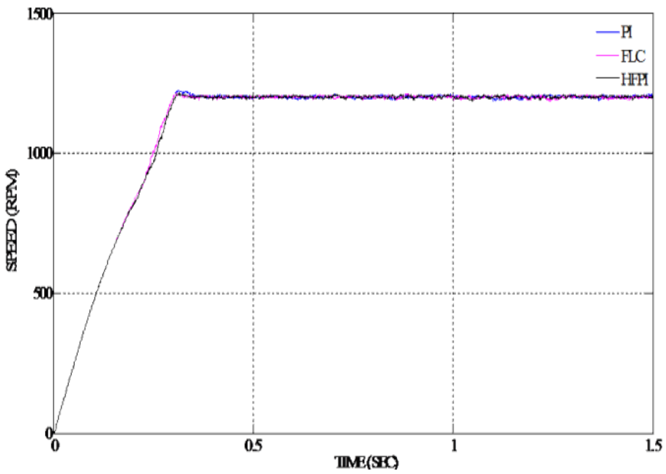


Figure 14. Speed performance of vector controlled IM drive using various controllers with change in load

Table 3 shows the comparative performance of the various controllers based vector control under a step change in load at 1.1 seconds and reference speed at 1200 RPM.

Table 3. Performance comparison of various controllers

Controllers	Vector drive (PI)	Open loop (SVM)
Overshoot (%)	1.67	6
Steady state error (%)	2	2.1
Settling time (Sec)	0.42	0.18
Drop in speed during the change in Load (%)	1.17	1.27

6. Conclusion

Generally, induction motors are used in many industries and for pumping in domestic applications. The use of PV power reduces more power consumption from the grid. Adjustable speed drive is the most used application of an induction motor. The vector control method produces good dynamic response because of its magnetic flux control. In this paper, performance of the drive is analyzed using Fuzzy logic controller and Hybrid fuzzy PI controller. From the results, it is confirmed that the fuzzy logic controller reduces peak overshoot, steady state error and speed drop during a change in load. The steady state error is yet to be improved. The hybrid fuzzy PI controller reduces all parameters, especially steady state error compare to FLC. Hence it states that HFPI based vector controlled drive is optimized for startup, steady state and dynamic state.

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