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Modeling and Simulation of Interior Permanent Magnet Synchronous Motor Drive System Using Different Speed Controllers

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***Abstract* - This work presents modeling and simulation of interior permanent magnet synchronous motor (IPMSM) drive system using controllers. Vector control is the basic technique used for control of the IPMSM. The speed controllers used are Proportional Integral (PI), Fuzzy Logic Controller (FLC) and hybrid PI-FLC. The speed controllers are implemented at the outer loop, while the current controller, hysteresis band current controller is implemented in the inner loop. MATLAB/SIMULINK software version 2014a was used to design the model. The simulation was carried out under no-load and variable loads torque 1.0Nm, 2.0Nm, 3.0Nm, and 4.0Nm applied at 0.25s. The result shows PI controller with more ripples and high settling time. And the FLC shows less ripples and low settling time, while the hybrid PI-FLC shows the desired results with lesser ripples and settling time. Hybrid PI-FLC also shows smooth speed and a torque response. The results of PI, FLC and hybrid PI-FLC were compared by plotting their load with respect to settling time. The FLC with little effect from parameter changes, load variations and speed changes, whereas, the PI performed poorly under thesame conditions. The graph shows hybrid PI-FLC superiority under transient conditions and parameter changes. Load variations and speed changes have no effect on the hybrid PI-FLC. Therefore, the hybrid PI-FLC is more suitable for control of IPMSM drive system.**

***Keywords* – PI Controller, Fuzzy Logic Controller, Hybrid PI-FLC and Hysteresis current controller**

I. INTRODUCTION

Permanent Magnet Synchronous Motor (PMSM) has better dynamic performance, smaller size and higher efficiency. In recent years, with rapid development of electric power machines, rare earth permanent magnetic materials and the increasingly research in permanent magnet motor is widely used in national defense, agriculture and daily life activities [1].

In a PMSM, the dc field winding of the rotor is replaced by a permanent magnet to produce the air-gap magnetic field. Having the magnets on the rotor, some electrical losses due to field winding of the machine are reduced and the absence of the field losses improves the thermal characteristics of the PM machine hence its efficiency. Also lack of mechanical components such as brushes and slip rings makes the motor lighter, high power to weight ratio which assures a higher efficiency and reliability [2].

Permanent Magnet electric machines are classified as, Permanent Magnet Direct Current (PMDC) and Permanent Magnet Alternating Current (PMAC) machines. The PMDC machines are similar to the DC commutator machines; the only difference is that the field winding is replaced by the permanent magnets. While in PMAC the field is generated by the permanent magnets placed on the rotor with out slip rings, the brushes and the commutator. Consequently, the PMAC motor is simpler and more attractive in terms of application than PMDC motor. PMAC motor is further classified depending on the type of the back electromotive force (EMF), which includes trapezoidal type and sinusoidal type. Sinusoidal type PM machine can further be classified as Surface and Interior mounted PMSM.

II. LITERATURE REVIEW

Vector control is also known as decoupling or field oriented control. Vector control decouples three phase stator currents into two phase d-q axis currents, one producing flux and other producing torque. This allows direct control of flux and torque. Using vector control, the PMSM is equivalent to a separately excited dc machine. The model of PMSM is nonlinear and by using vector control; the model of PMSM is linear. This control method was developed specifically to meet the challenges of transient condition analysis and oscillating flux with torque responses in inverter fed induction and synchronous motor drives during transient as well as steady state condition mostly experienced in scalar control [3]. The scheme of vector control is based on coordinate transformation and motor torque equation by means of controlling stator current to improve the performance of the motor. In the control of a three-phase PMSM system, modulated current is supplied to the A-B-C stator windings to build rotating magnetic field to drive the rotor. The vector control strategy is formulated in the synchronously rotating reference frame. By Clarke-Park transformations and inverse

Park's transformations equivalent relations of currents are built in the a-b-c stator coordinates, stationary α-β coordinates and rotating d-q coordinates [4]. [5] presented a field oriented controlled PM motor drive system. A closed loop control system with PI controller in the speed loop was designed to operate in constant torque angle and flux weakening regions. A comparative study of hysteresis and PWM control schemes associated with current controllers was made. Simulation results for both hysteresis and PWM control schemes associated with current controllers were presented for two speeds of operation, one below and above rated speed with hysteresis band current showing superiority. A comparative analysis of speed control of PMSM using PI-controller and Fuzzy controller was carried out by [6].The results of traditional PI controller as speed control of PMSM were not satisfactory to the higher degree of accuracy. The study reported that, the fuzzy control not only has the prominent advantage in complex, time varying and nonlinear system control but also does not need the mathematical model of controlled object. Effectiveness of the model was established by performance prediction over a wide range of operating conditions. A performance comparison between the fuzzy controller and the conventional PI controller was carried out and simulation results confirmed the validity and superiority of the fuzzy logic controller for implementing the fuzzy logic controller over the traditional PI controllers. The performance of the PMSM drive with reference to PI controller and Fuzzy controller was compared in this paper and observed that Fuzzy logic speed controller improved the performance of PMSM drive better than the PI controller.

Fuzzy Adaptive Control (FAC) was used to tune the scaling factors of the direct fuzzy logic controller (FLC) and to have a control system that could achieve improvement in tracking set point change and rejection of load disturbance [7]. From the simulated results, FAC was able to track set point change and reject the uncertainties resulting from external disturbances. The responses were somehow sluggish in the face of external disturbances but give no oscillatory behaviors. For PI controller, the performance deteriorated for set point changes and under the influence of external disturbances. The simulation results had confirmed the efficiency of the proposed fuzzy adaptive scheme for changing load torque.

[8] combined merits of PI and FLC to form a hybrid PI-FLC such that, the output can be either of the two, i.e the PI or FLC units being switched during a particular period as per the predetermined speed errors. Hybrid PI-FLC was found to have quick dynamic response, and steady state error, with a good robust dynamic characteristics and stability. [9] proposed three types of controllers, PI, Fuzzy PI in speed loop and Tuned Fuzzy PI to control the speed and performance of PMSM. The performances of the three controllers were examined for torque and speed. The simulation results indicated that, PI controller has less over shoot throughout starting time and poor performance under load disturbances, while Fuzzy PI show less over shoot with less load disturbances. The proposed Tuned Fuzzy PI controller offers higher speed response with overshoot throughout starting conditions and the output torque ripples were greatly reduced. A fuzzy-logic based speed controller of an Interior Permanent Magnet Synchronous Motor drive based on vector control was explored by [10]. PI controller was mostly used in a speed control loop based field oriented control of an IPMSM. A complete comparison between the two tuning algorithms of the classical PI controller and the fuzzy PI controller was carried out and a simplified FLC for the IPMSM drive was found to maintain high performance standards with simpler and low implementation time. The simulated results confirmed that the FLC-PI has lower ripple than the conventional PI controller. [11] Improved the performance of a PMSM drive system by achieving more precise speed tracking by using conventional hysteresis band and adaptive hysteresis band current controllers as inner loop of the vector control. The PI, PID and FLC speed controllers were implemented at the outer loop. Steady state and transient conditions under variable loads were carried out in MATLAB/SIMULINK environment. The conventional hysteresis band current controller has proven that, it is most suitable for current regulated VSI fed AC drives due to its simplicity and fast speed tracking than the adaptive hysteresis band current controller.

III. MATERIALS AND METHOD

The modeling of IPMSM is done in three phase variable, the transformation of stator equations (stationary frame) to rotor equations (rotating frame) using Park's transformation equation. The inverse Park's transformation equation returned the phase equations back to their original form.

A. Structure of the modelled IPMSM

The schematic diagram of a 4- pole interior permanent magnet synchronous motor with three phase windings fixed at 120^o to each other is shown in figure 1(a) and figure 1(b).

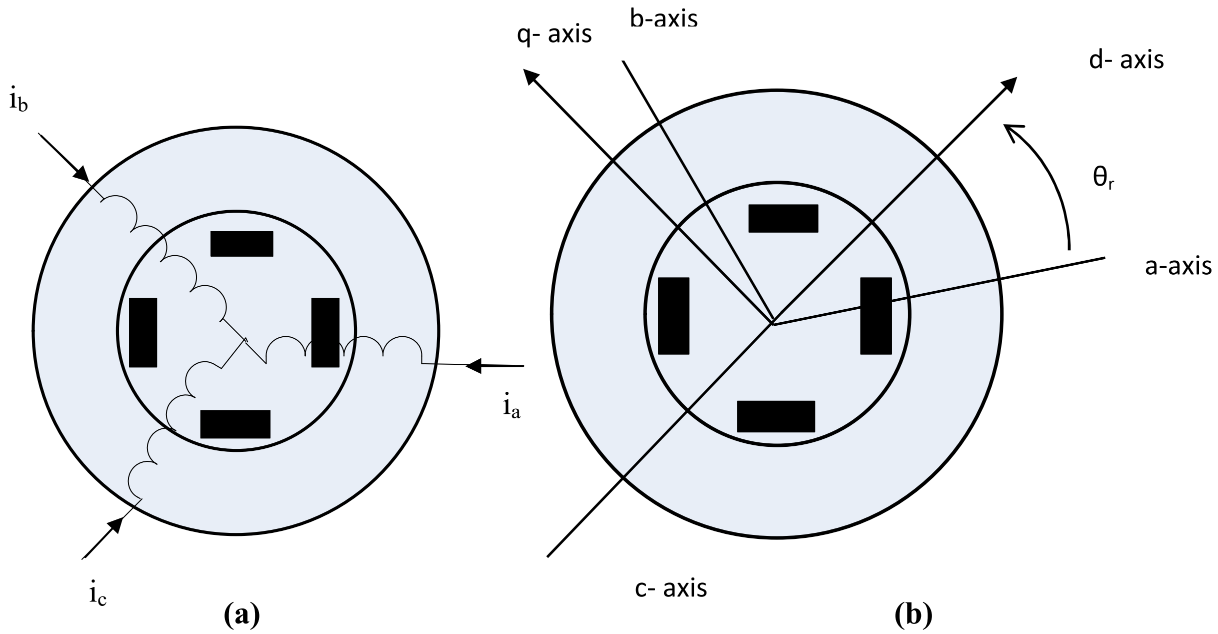


Figure 1: Schematic Diagram of a 4-pole IPM Synchronous Motor

i. *Voltage Equations*

The stator voltage equations in terms of phase variables can be expressed as:

$$V_{as} = r_s i_{as} + \rho\lambda_{as} \tag{1}$$

$$V_{bs} = r_s i_{bs} + \rho\lambda_{bs} \tag{2}$$

$$V_{cs} = r_s i_{cs} + \rho\lambda_{cs} \tag{3}$$

ii. *Flux Linkage Equations*

$$\lambda_{abcs} = L_{abcs} \,.\, I_{abcs} + \lambda_{abcm} \tag{4}$$

$$\lambda_a = L_{aa}.i_a + L_{ab}.i_b + L_{ac}i_c + \lambda_{ma} \tag{5}$$

$$\lambda_b = L_{ba}.i_a + L_{bb}i_b + L_{bc}i_c + \lambda_{mb} \tag{6}$$

$$\lambda_c = L_{ca}i_a + L_{cb}i_b + L_{cc}i_c + \lambda_{mc} \tag{7}$$

Park's transformation is defined by equation (8):

$$T(\theta) = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta - \frac{4\pi}{3}\right) \\ \sin\theta & \sin\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta - \frac{4\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \tag{8}$$

The inverse Park's transformation is defined by equation (9)

$$\left[T(\theta)\right]^{-1} = \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta - \frac{2\pi}{3}\right) & 1 \\ \cos\left(\theta + \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) & 1 \end{bmatrix} \tag{9}$$

The voltage equations and flux linkage equations are transformed in rotating frame and are written in expanded form as:

$$V_{qs} = r_s i_{qs} + \omega\lambda_{ds} + \rho\lambda_{qs} \tag{10}$$

$$V_{ds} = r_s i_{ds} - \omega\lambda_{qs} + \rho\lambda_{ds} \tag{11}$$

$$V_{0s} = r_s i_{0s} + \rho\lambda_{0s} \tag{12}$$

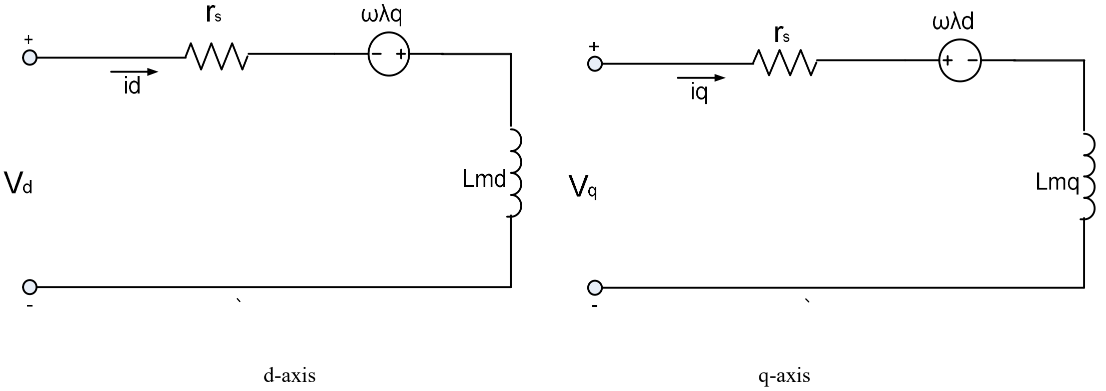
$$\lambda_{qs} = L_{ls} i_{qs} + L_{md}\,(i_{qs} + i_{qr}{}') \tag{13}$$

$$\lambda_{ds} = L_{ls} i_{ds} + L_{md}\,(i_{ds} + i_{dr}{}') \tag{14}$$

$$\lambda_{0s} = L_{ls} i_{0s} \tag{15}$$

B. Equivalent d-q Circuit of IPMSM

From the d-q equations of IPMSM given in equations (10), (11) and (13), (14), gives equivalent d-q circuits of IPMSM as shown in figure 2.



d-axis

q-axis

Figure 2: Equivalent d-q Circuits of IPMSM

Since the output power is a product of the motor mechanical speed and the developed/output torque, the output torque can be obtained as:

$$T_e = \frac{P_{out}}{\omega_m} = \frac{3}{2}\frac{p}{2}(\lambda_{pm} i_q + (L_d - L_q) i_d i_q) \quad (16)$$

The machine's dynamic equation is written as follows:

$$T_e - T_{load} - T_{friction} = J\frac{d\omega_m}{dt} \quad (17)$$

where, T_{load} is the load torque, $T_{friction}$ is the motor-load system friction torque, and J is the polar moment of inertia of the rotor and the connected load.

The schematic block diagram for the drive system showing how the various components are connected together is shown in figure 3.

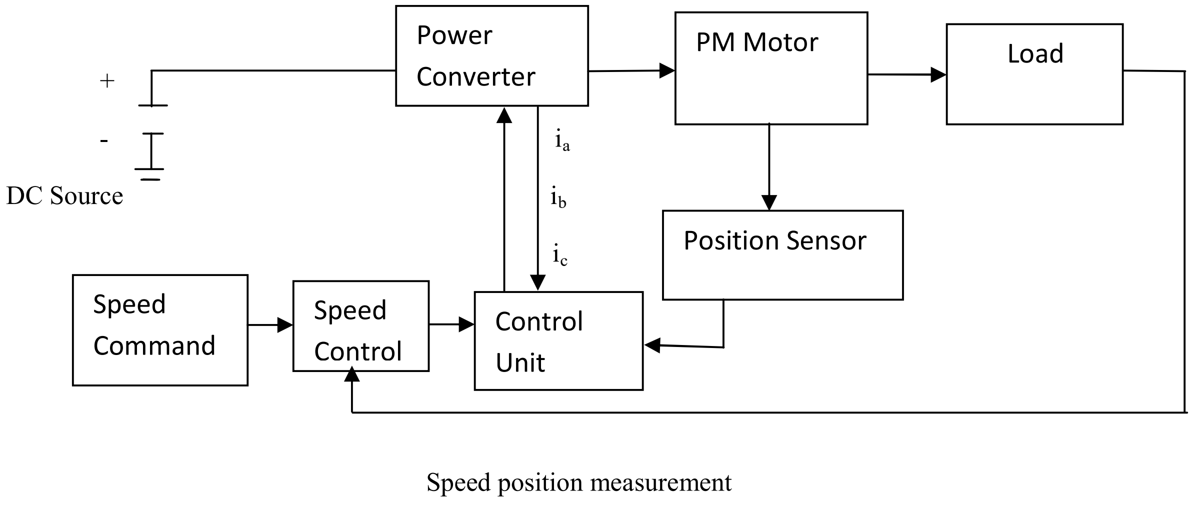


Figure 3: Schematic Block Diagram for Drive System

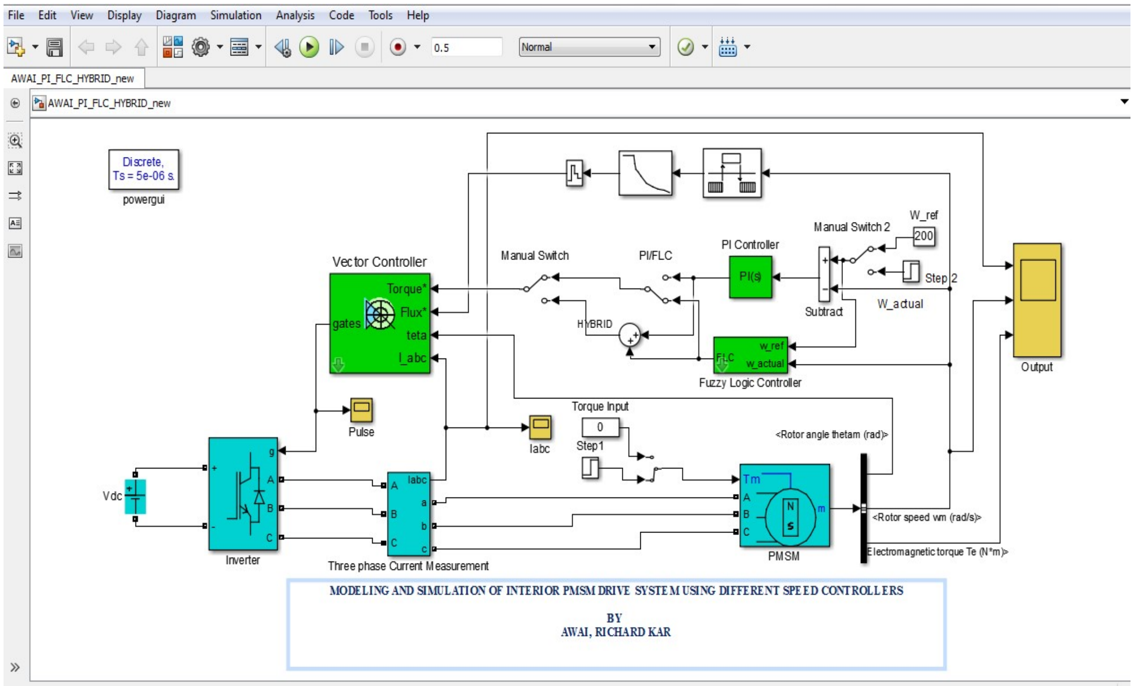


Figure 4: Simulink Model of IPMSM using PI, FLC, Hybrid PI-FLC and Hysteresis Current Band Controller.

IV. RESULTS

The motor was simulated using PI, FLC and hybrid PI-FLC as speed controllers and hysteresis band as current controller. It was simulated under variable loads of 1.0Nm, 2.0Nm, 3.0Nm, and 4.0Nm applied at 0.25s under reference speed of 200rad/sec. Below are the scope output showing the current, speed and the torque of respective loads.

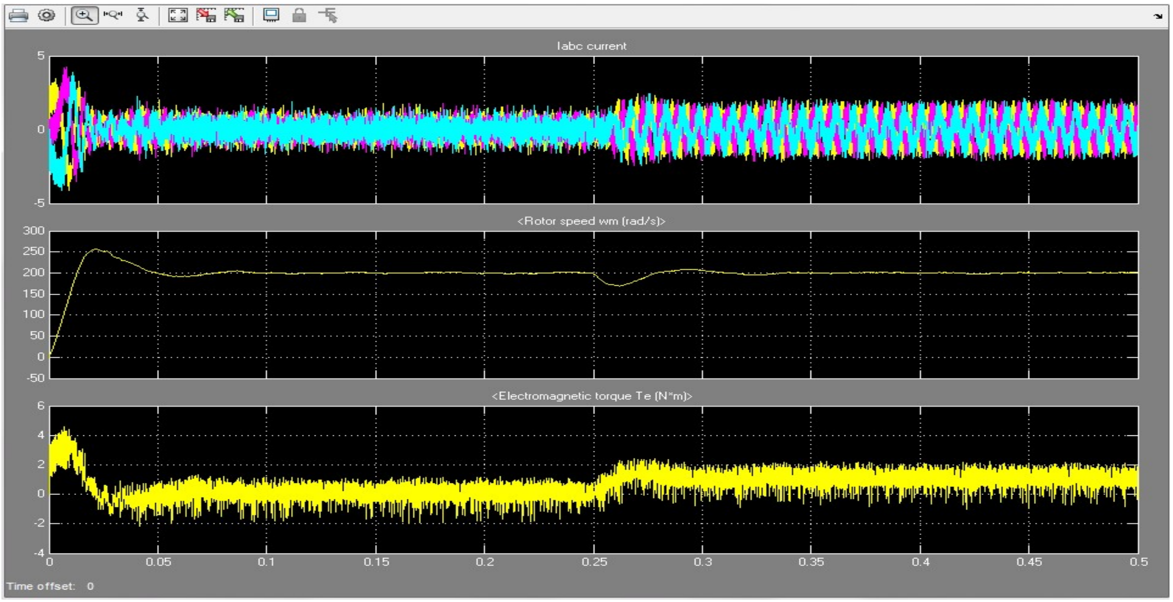


Figure 5: Stator Currents I_{abc}, Rotor Speed and Electromagnetic Torque verses Time Plot under Step Load Condition of 1.0Nm using PI-controller

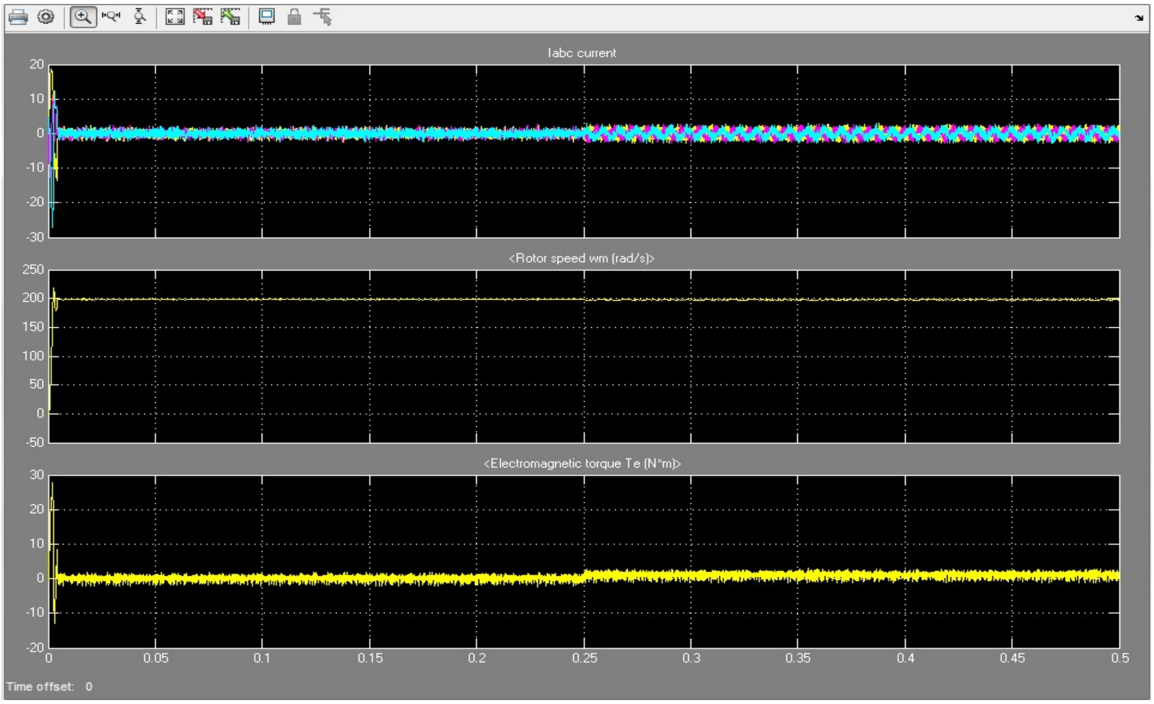


Figure 6: Stator Currents I_{abc}, Rotor Speed and Electromagnetic Torque verses Time Plot under Step Load Condition of 1.0Nm using FLC

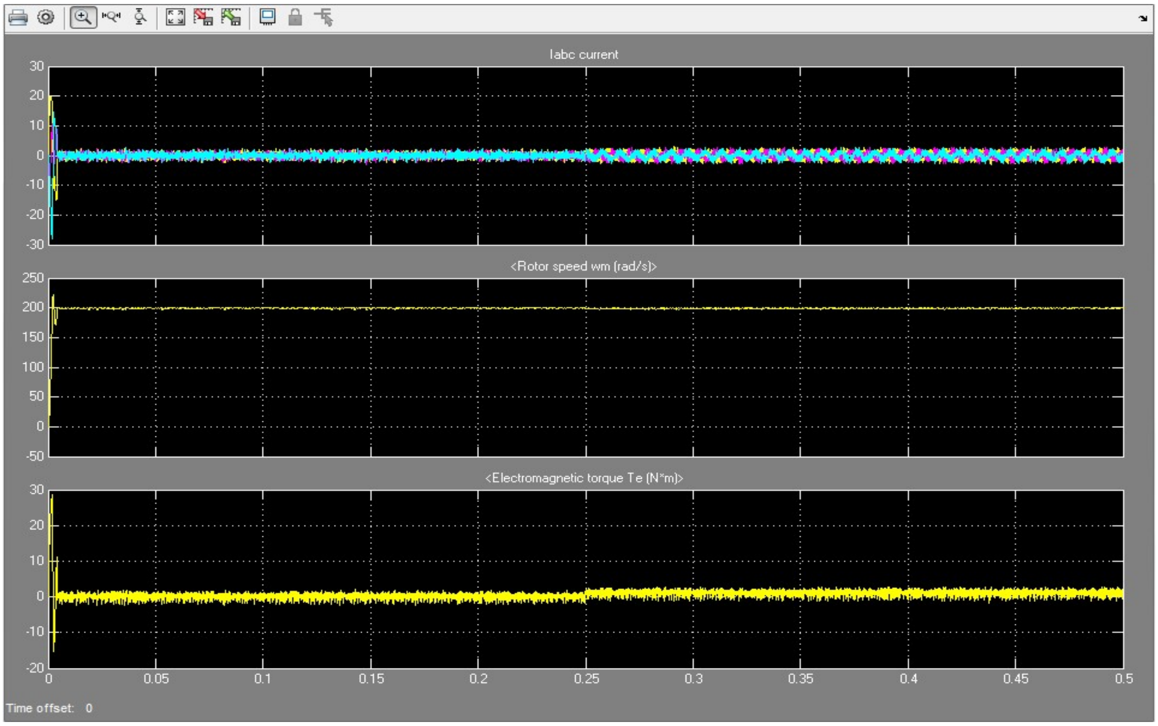


Figure 7: Stator Currents I_{abc}, Rotor Speed and Electromagnetic Torque verses Time Plot under Step Load Condition of 1.0Nm using Hybrid PI-FLC

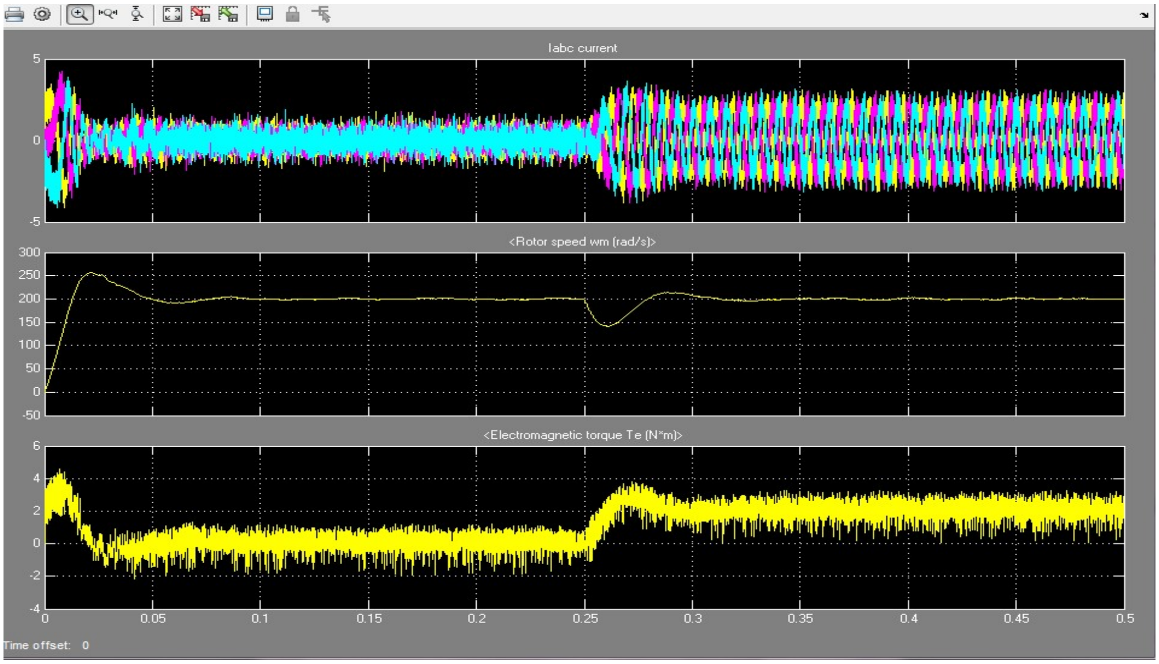


Figure 8: Stator Currents I_{abc}, Rotor Speed and Electromagnetic Torque verses Time Plot under Step Load Condition of 2.0Nm using PI

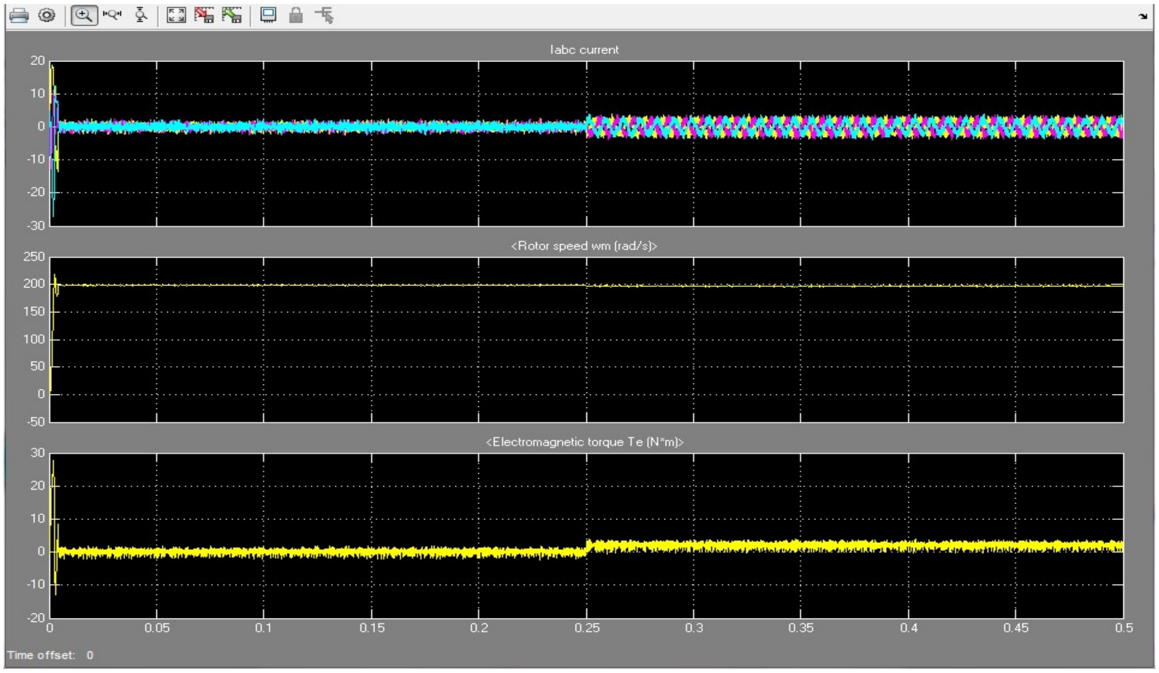


Figure 9: Stator Currents I_{abc}, Rotor Speed and Electromagnetic Torque verses Time Plot under Step Load Condition of 2.0Nm using FLC

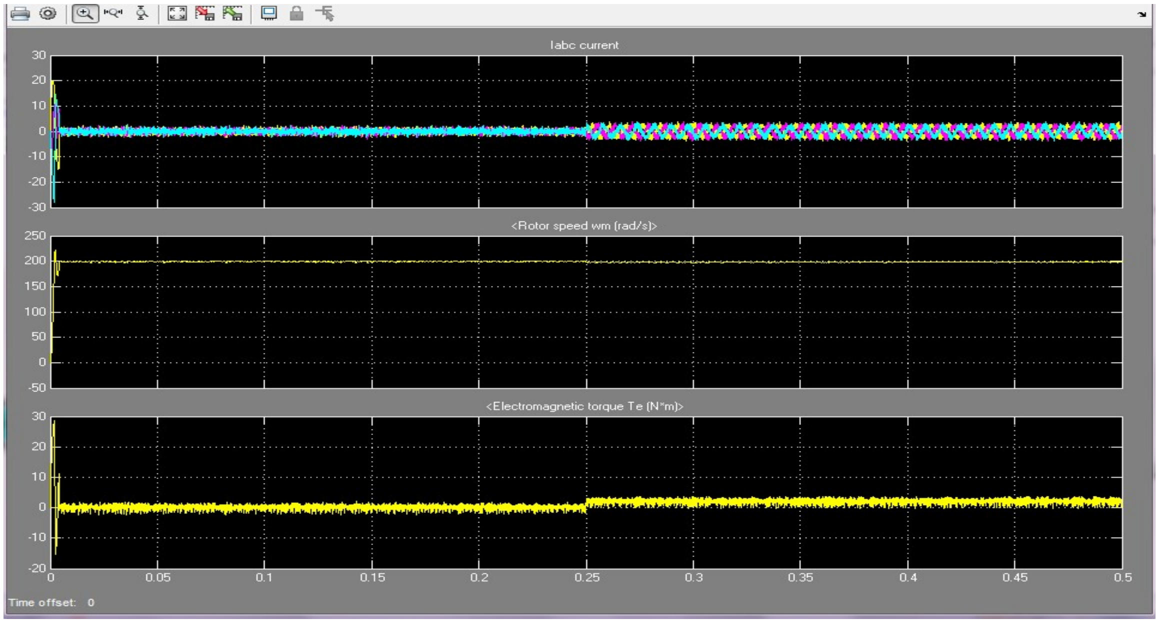


Figure 10: Stator Currents I_{abc}, Rotor Speed and Electromagnetic Torque verses Time Plot under Step Load Condition of 2.0Nm using Hybrid PI-FLC

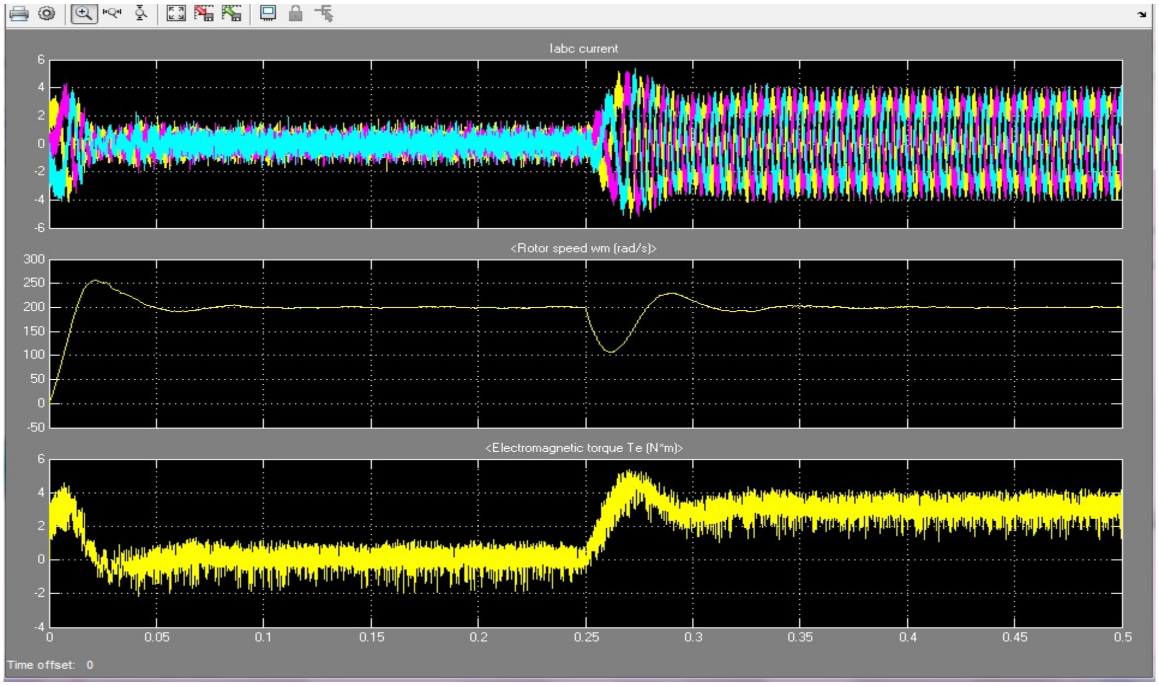


Figure 11: Stator currents I_{abc}, Rotor Speed and Electromagnetic Torque verses Time Plot under Step Load Condition of 3.0Nm using PI

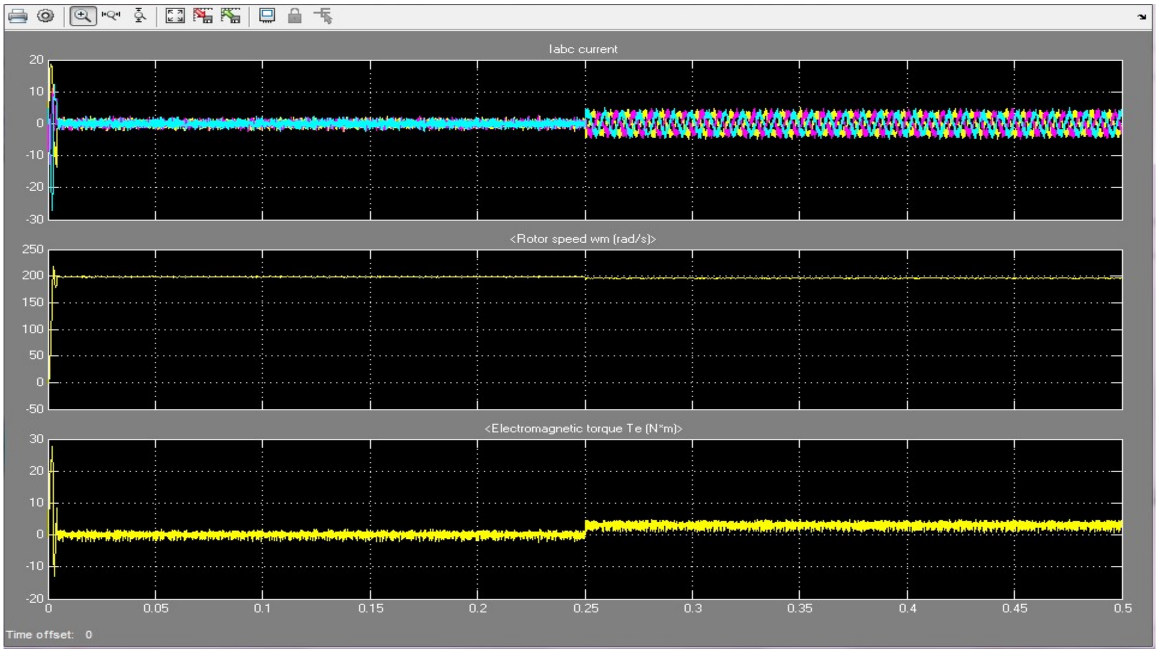


Figure 12: Stator currents I_{abc}, Rotor Speed and Electromagnetic Torque verses Time Plot under Step Load Condition of 3.0Nm using FLC

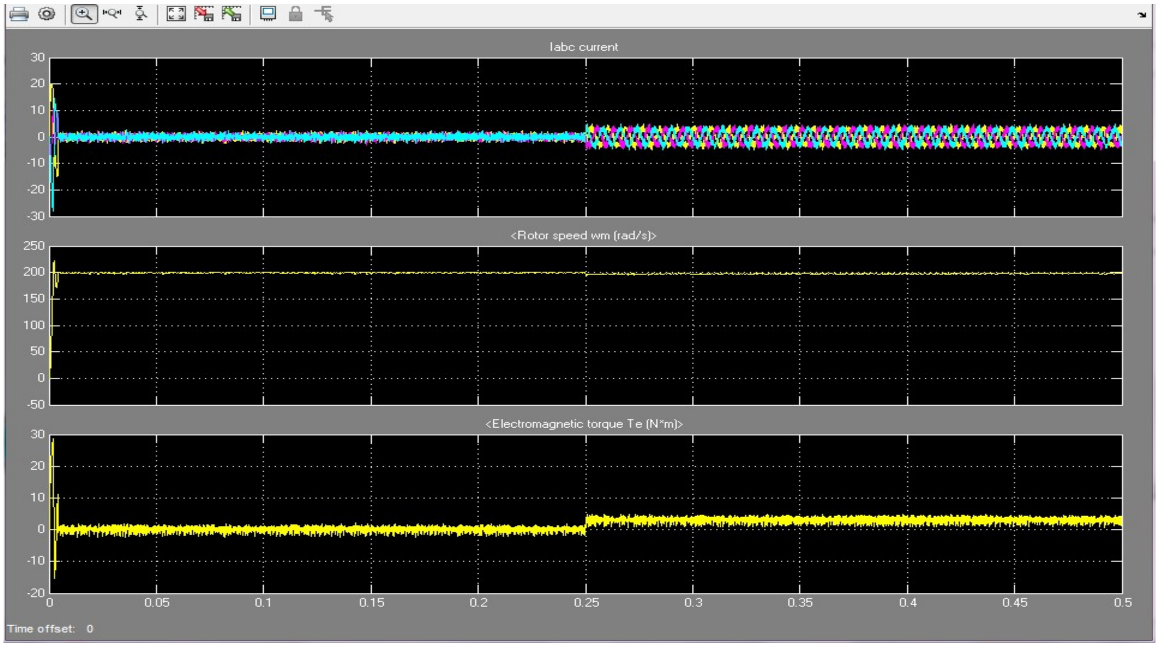


Figure 13: Stator currents I_{abc}, Rotor Speed and Electromagnetic Torque verses Time Plot under Step Load Condition of 3.0Nm using Hybrid PI-FLC.

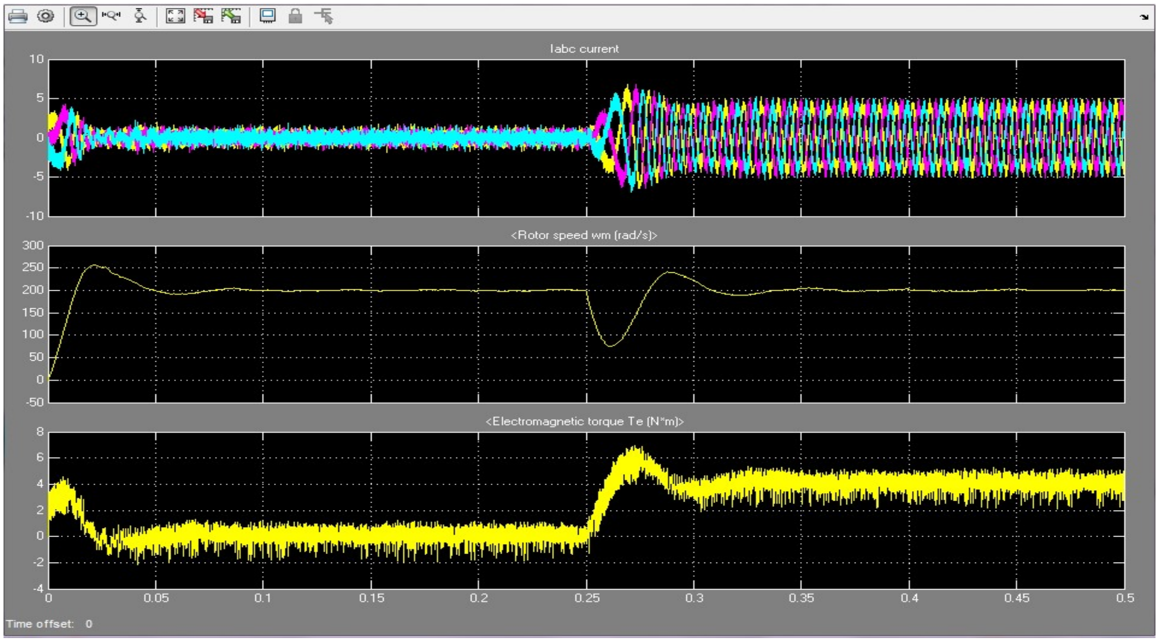


Figure 14: Stator Currents I_{abc}, Rotor Speed and Electromagnetic Torque verses Time Plot under Step Load Condition of 4.0Nm using PI

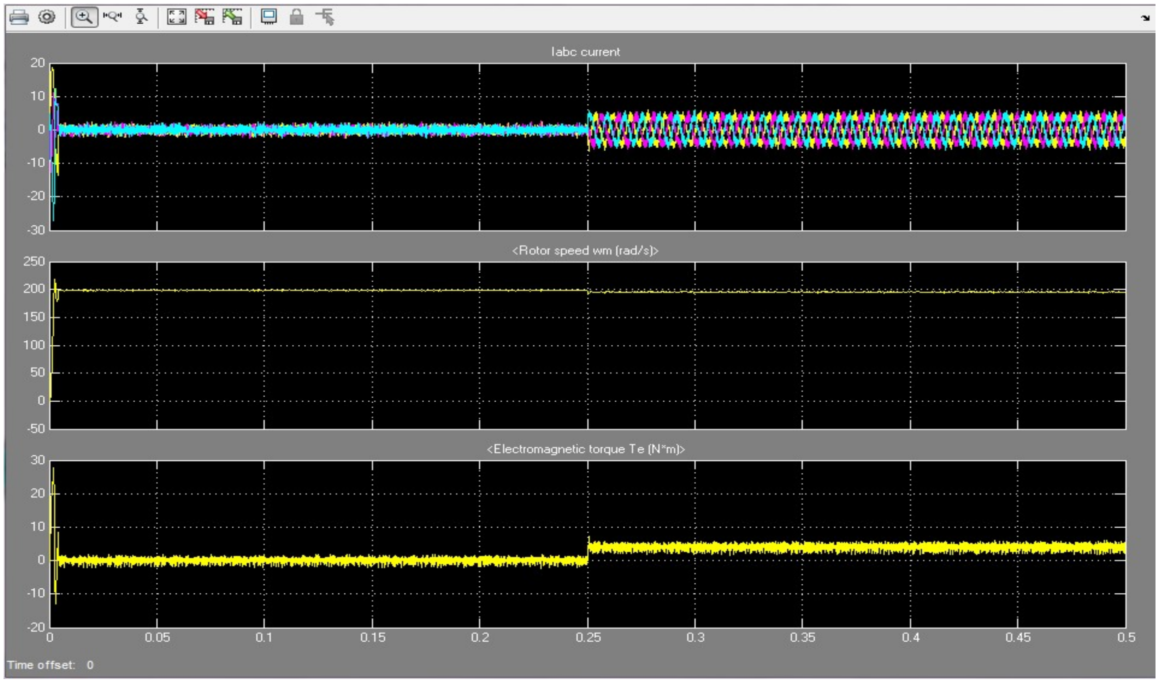


Figure 15: Stator Currents I_{abc}, Rotor Speed and Electromagnetic Torque verses Time Plot under Step Load Condition of 4.0Nm using FLC.

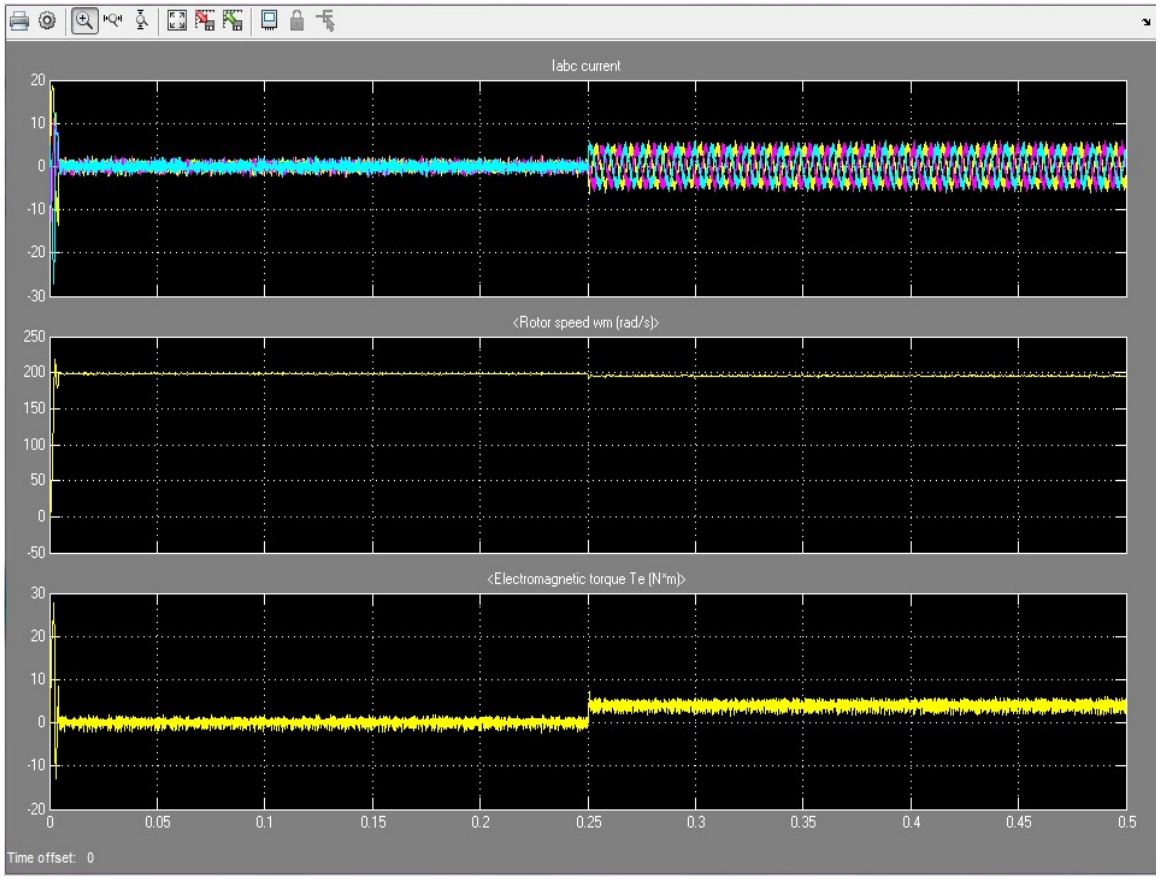


Figure 16: Stator Currents I_{abc}, Rotor Speed and Electromagnetic Torque verses Time Plot under Step Load Condition of 4.0Nm using Hybrid PI-FLC

The results of the speed controllers with their respective loads were obtained base on their settling time. Table 1 showed the various settling time of respective speed controllers and figure17 present the graph that compared the three speed controllers used.

Table 1: Settling Time for Various Controllers (PI, FLC and Hybrid PI-FLC) with Respective Load Torque.

Load Torque (Nm)	**PI Settling Time (s)**	**FLC Settling Time(s)**	**Hybrid(PI-FLC) Settling time (s)**
0.0	0.01	0.005	0.003
1.0	0.09	0.003	0.002
2.0	0.11	0.015	0.010
3.0	0.06	0.014	0.01
4.0	0.15	0.015	0.01

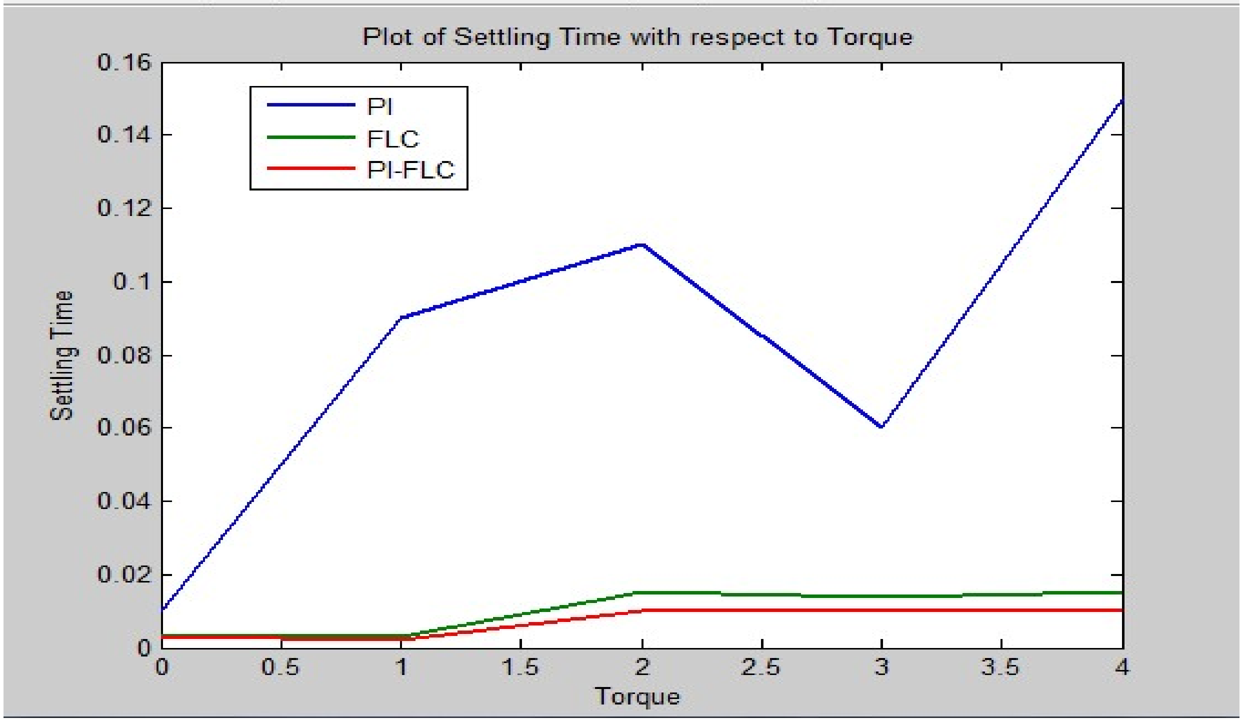


Figure 17: Graph of Settling Time againstTorque of PI, FLC and Hybrid PI-FLC Controllers

V. CONCLUSION

The hybrid PI-FLC show no changes to parameter fluctuations and has the least settling time as compare to conventional PI and FLC under steady state and transient conditions as shown in figure 17. Also, the torque ripples are minimal under hybrid PI-FLC as compare to PI and FLC controller. Therefore, the superiority of the hybrid PI-FLC displayed makes it suitable for the control of IPMSM.

REFERENCE

[1]. Jash K, Saha P.K and Panda G.K (2013). Vector Control of Permanent Magnet Synchronous Motor Based on Sinusoidal Pulse Width Modulated Inverter with Proportional Integral Controller. ***International Journal of Engineering Research and Application***. 3(5): 913-917

[2]. Panda, A. (2014). Direct Torque Control of Permanent Magnet Synchronous Motor (PMSM).***National Institute of Technology***, Rourkela: 1-46

[3]. Mamta P, Tejaswi P and Priyanka Y (2016). Hybrid PI-Fuzzy Logic Based Speed Control of an IPMSM Drive.***International Journal of Electrical Engineering and Technology (IJEET).*** 7(6): 117-121

[4]. Pavan Kumar and Sanyuktha P. (2013). Vector Control Drive of Permanent Magnet Synchronous Motor using Resolver Sensors.***International Journal of Computer Science Engineering (IJCSE)***. 2(4):81-95

[5]. Shahat. A and Shewy.H (2010). Permanent Magnet Synchronous Motor Drive System for Mechatronics Applications. ***International Journal of Research and Applied Studies (IJRRAS)***: 323 – 338

[6]. Chakraborty M. (2013). Comparative Analysis of speed control of PMSM using PI-controller and Fuzzy controller. ***International Journal of Scientific and Engineering*** *Research*.4(7): 103-108

[7]. Patil N.J, Chile R.H and Waghmare L.M (2010). Fuzzy Adaptive Controllers for Speed Control of PMSM Drive.***International Journal of Computer Applications***.1: 84-91

[8]. Mamta P, Tejaswi P and Priyanka Y (2016). Hybrid PI-Fuzzy Logic Based Speed Control of an IPMSM Drive.***International Journal of Electrical Engineering and Technology (IJEET).*** 7(6): 117-121

[9]. Maheswari.N and Ananthamoorthy N.P, (2014). Fuzzy Logic Based Ripple Minimization for PMSM Drive. ***International Journal of Emerging Trends in Engineering and Development***. 2(4):799-811

[10]. Abbood, A. A (2013). A Fuzzy Logic Controller Based Vector Control of IPMSM Drives.***Journal of Engineering.***19 (10):1287-1299.

[11]. Murmu R and Singh A.K (2016). Study to Improve the Performance of a PMSM Drive System by Achieving More Precise Speed Tracking and Smooth Torque Response.***International Journal of Science and Research (IJSR).*** 5(11): 955-958