INTELLIGENT CONTROL DESIGN OF PMSM SERVO DRIVE

[1]Radhika. S.,[2]Marsalin Beno.M., [3]Jaikumar. R.A.

[1]Research Scholar, St.Peter's University, Avadi, Chennai-54,
[2]Professor & Head, Dept. of EEE, St.Xavier's Catholic College of Engineering, Kanyakumari, Tamilnadu.
[3]Professor, Annai Vailankanni College of Engineering, Kanyakumari, Tamilnadu.

Abstract

The permanent-magnet synchronous motor (PMSM) is a simple Synchronous motor. It has gained a wide acceptance in motion control applications due to its high performance such as compact structure, high air-gap flux density, high power density, high torque to inertia ratio, and high efficiency. Due to the existence of nonlinearities, uncertainties, and disturbances, conventional linear control methods, including the proportional-integral (PI) control method, cannot guarantee a sufficiently high performance for the PMSM servo system. To enhance the control performance an intelligent controller is proposed. The servo specifications and design variables are to be analyzed to formulate a controller optimization problem. According to the objective functions and design specifications, the servo control parameter has to be properly tuned toward their optimal values by using the proposed optimization techniques. Because of the nonlinear property of the digital servo drives, the tuned servo control parameters may be only optimal for a particular operating point, therefore, once the optimum design is achieved, the proposed intelligent controller can perform as an intelligent tuner for on-line gain adaptation under different loading conditions.

Keywords: PMSM, Fuzzy PID, Lab VIEW program , Accelerated fuzzy PI, Intelligent Hybrid Fuzzy, neuro fuzzy controller, PWM, PID controller, neural controller, fuzzy controller, extrusion system, synthetic optimizing.

I. INTRODUCTION

A permanent magnet synchronous motor (PMSM) is a motor that uses permanent magnets to produce the air gap magnetic field rather than using electromagnets. These motors have significant advantages, attracting the interest of researchers and industry for use in many applications. Permanent magnet synchronous motors (PMSM) are widely used in low and mid power applications such as computer peripheral equipments, robotics, adjustable speed drives and electric vehicles. The different views of permanent Magnet synchronous motors shown in Fig.1. The growth in the market of PMSM drives has demanded the need of simulation tools capable of handling motor drive simulations. Simulations have helped the process of developing new systems including motor drives, by reducing cost and time. Simulation tools have the capabilities of performing dynamic simulations of motor drives in a visual environment so as to facilitate the development of new systems. In this work, the simulation of a field oriented controlled PMSM motor drive system is developed using Simulink. The simulation circuit will include all realistic components of the drive system. This enables the calculation of currents and voltages in different parts of the inverter and motor under transient and steady conditions. The losses in different parts can be

Fig. 1 Permanent Magnet Synchronous Motors different views

calculated facilitating the design of the inverter. A closed loop control system with a PI controller in the speed loop has been designed to operate in constant torque and flux weakening regions. Implementation has been done in Simulink. A comparative study of hysteresis and PWM control schemes associated with current controllers has been made in terms of harmonic spectrum and total harmonic distortion. Simulation results are given for two speeds of operation, one below rated and another above rated speed.

Now-a-days, the research community is well known Fuzzy Logic Controller (FLC) based speed control with its superior performance in worldwide. It has proven by many simulations and experimental verifications by numerous publications with diversity of industrial drive applications such as high performance drives using vector controlled Induction motor, Permanent Magnet Synchronous Motor and brushless DC motor. The vector controlled PMSM drives provides better dynamic response and lesser torque ripples. The outer speed loop in vector control greatly affects the system performance. Proportional plus Integral (PI) controllers are usually preferred but due to its fixed proportional gain (Kp) and integral time constant (Ti), the performance of the PI controllers are affected by parameter variations, load disturbances and speed variations. These problems can be overcome by the fuzzy logic controllers, which do not require any mathematical model and are based on the experience of the system operator. But the performance of the fuzzy controller as compared to the PI controller is superior under transient conditions. The establishment of the simulation model of PMSM and its control system is of great significance to the verification of a variety of control algorithms and the optimization of entire control system. The entire PMSM control system as a whole will be divided into several independent functional modules: PMSM module, inverter module, co-ordinate transformation module and so on. The speed controller used in PMSM drive system plays an important role to meet the requirements of the drive system as shown in Fig.2.

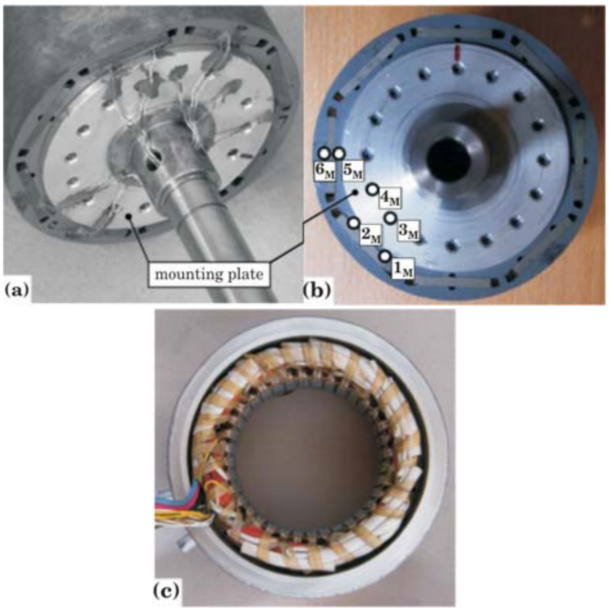

Fig. 2. (a) Interior permanent magnet rotor with type-K thermocouples and wiring through the hollow shaft at the non drive end. (b) Temperature measurement locations of the interior permanent magnet In the axial direction, the sensors are placed in the center of the rotor. (c) Single-layer fractional slot-distributed stator winding with 36 stator slots and eight poles.

In this Research work, a nonlinear fuzzy PI controller is proposed to improve the transient response of the PMSM system based on fuzzy control law . Most of the popular fuzzy controllers developed so far with two inputs, such as error and rate of change of error about a set point. However, the nonlinear fuzzy PID controller proposed in this paper has an additional input named accelerated rate of change of error to improve the transient response of the PMSM system. The PMSM drive system with three types of controllers named as fuzzy PI, Accelerated fuzzy PI and Intelligent Hybrid fuzzy controller are implemented to improve the transient response, load disturbances and speed variations.

II. PMSM-MATHEMATICAL MODEL

The PMSM equations are developed in rotating reference frames. The stator of the PMSM and the wound rotor synchronous motor are similar. The permanent magnets used in the PMSM are of a modern rare-earth variety with high resistivity, so induced currents in the rotor are negligible. In addition, there is no difference between the back EMF produced by permanent magnet and that produced by an excited coil. Hence the mathematical model of PMSM is similar to that of the wound rotor Synchronous Motor and it is shown in the Fig. 3.

Fig. 3. Permanent Magnet Synchronous Motors
The model of the PMSM is developed using the following assumptions

(a) Saturation is neglected

(b) The induced EMF is sinusoidal

(c) Eddy current and hysteresis losses are negligible

(d) There are no field current dynamics.

With these assumptions, the stator d, q equations of the PMSM in the rotor reference frame are,

$$V_q = Rsiq + Lqpiq + \omega\, rLdid + \omega\, r\varphi f \qquad ...(1)$$

$$V_d = Rsid + Ldpid - \omega\, rLqiq \qquad ...(2)$$

Also flux linkage equation can be written as,

$$\varphi\, d = Ldid + \varphi\, f \qquad ...(3)$$

$$\varphi\, q = Lqiq \qquad ...(4)$$

Where V_d and V_q are the *d*, *q* axis voltages, *id*, *iq* are the *d*, *q* axis stator currents, *Ld*, and *Lq* are the *d*, *q* axis inductances, $\varphi\, d$ and $\varphi\, q$ are the *d*, *q* axis stator flux linkages, Rs is the stator winding resistance per phase and $\omega\, r$ is rotor electrical speed.

Figure 4 compares the back EMF estimated by: 1. the conventional SMO; 2. the proposed SMO (Sliding Mode Observer) with the sigmoid function as a switching function; and 3. the ISMO(Iterative Sliding Mode Observer) for 2000 rpm speed control without any experimental load. The conventional SMO suffers from the large ripples in the back EMF in the high speed control. As a result, the sensor less control of the PMSM becomes unstable in the case of the conventional SMO. The SMO with the sigmoid function exhibits good performance for stable sensor less control. However, there still exists a relatively large ripple in the back EMF, which can be reduced by the ISMO. Therefore, it is concluded that the ISMO is a good control algorithm for the sensor less control of PMSMs with small ripples in the estimated back EMF.

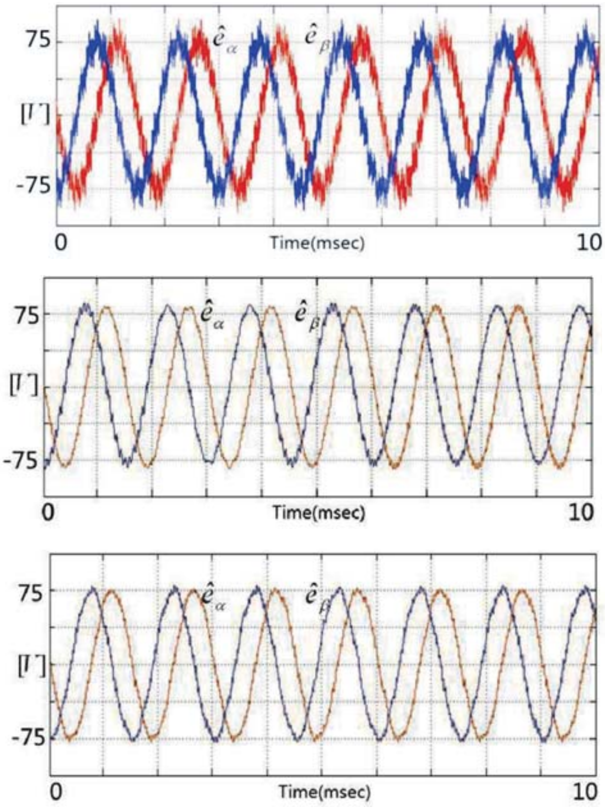

Fig..4 Performance comparison of conventional SMO and ISMO for 2000-rpm motor control. (a) $\hat{e}\alpha$ and $\hat{e}\beta$ of SMO with signum function. (b) $\hat{e}\alpha$ and $\hat{e}\beta$ of SMO with sigmoid function. (c) $\hat{e}\alpha$ and $\hat{e}\beta$ of ISMO

The electro mechanical torque is given by

$$Te = (3/2)\,(P/2)\,[\varphi\, fiq - (Ld - Lq)\, id\, iq] \qquad ...(5)$$

and the equation of motor dynamics is,

$$Te = TL + {}'B\,\omega\, m + J_p\, \omega m \qquad ...(6)$$

Where *P* is the number of poles, *TL* is the load torque, *B* is the damping co-efficient, $\omega\, m$ is the rotor

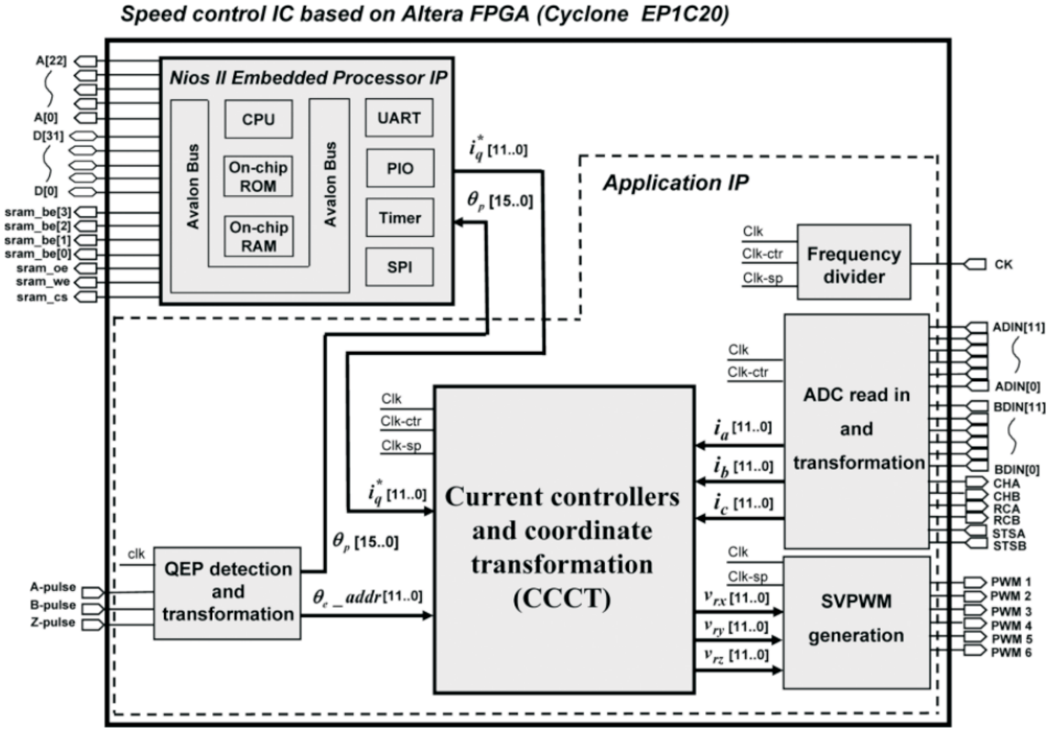

Fig. 5. Block diagram of internal circuit of an FPGA-based speed control IC.

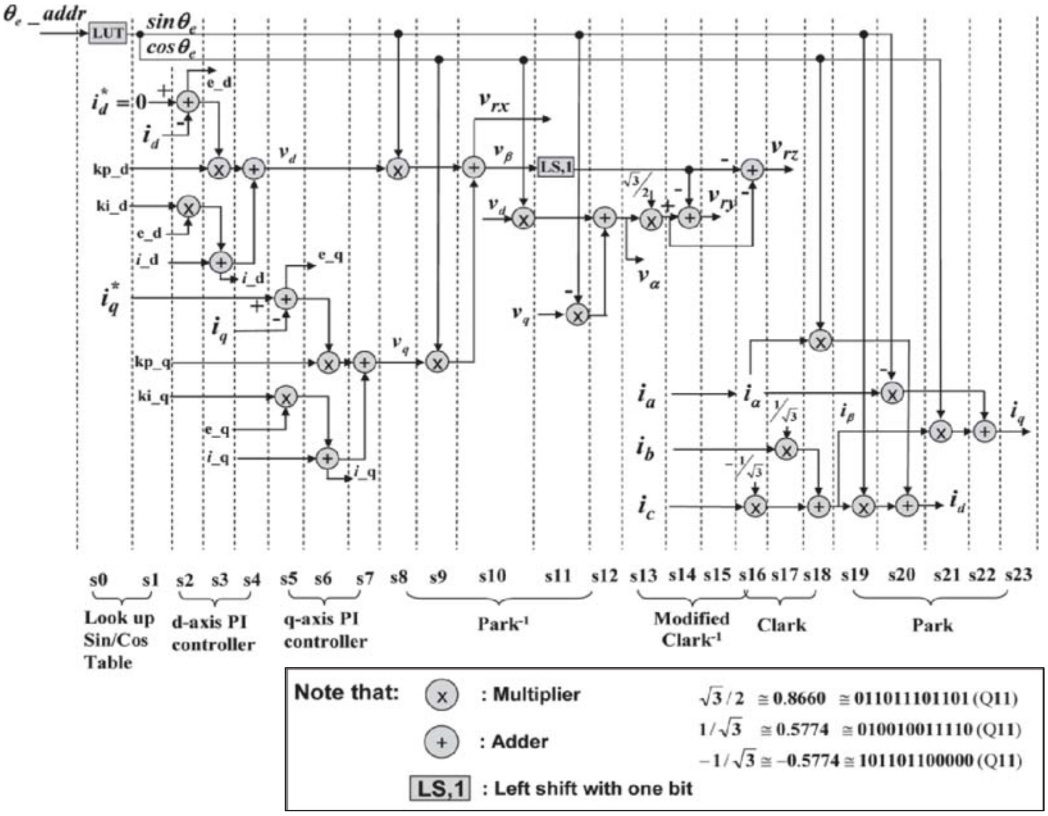

Fig. 6 Designed CCCT circuit in Figure. 5 by using FSM method.

mechanical speed, J is the moment of inertia and p is the differential operator.

$$\omega r = (P/2)\ \omega m \qquad \text{...(7)}$$

The model equations of PMSM can be rearranged in the form of following first order differential equations as,

$$pid = (Vd - Rsid + \omega\ rLqiq)/Ld \qquad \text{...(8)}$$

$$piq = (Vq - Rsiq - \omega\ rLdid - \omega\ r\ \varphi\ f)/Lq \qquad \text{...(9)}$$

$$p\ \omega m = (Te - TL - B\ \omega\ m)/J \qquad \text{...(10)}$$

$$p\ \theta\ m = \omega\ m \qquad \text{...(11)}$$

$$\theta\ m = \int \omega\ m \qquad \text{...(12)}$$

$\theta\ m$ is the position angle of rotor.

In order to achieve maximum torque per ampere and maximum efficiency with linear characteristics, direct axis current component id forced to zero and the reluctance torque is zero.

$$Te = (3/2)\ (P/2)\ \varphi\ fiq \qquad (13)$$

The d, q variables are obtained from a, b, c variables through the park transform as,

$$Vq = 2/3\ [Va \cos\theta + Vb \cos(\theta - 2\,\Pi/3) + Vc \cos(\theta + 2\,\Pi/3)]\text{.(14)}$$

$$Vd = 2/3\ [Va \sin\theta + Vb \sin(\theta - 2\,\Pi/3) + Vc \sin(\theta + 2\,\Pi/3)]\ \text{...(15)}$$

The a, b, c variables are obtained from the d, q variables through the inverse of the park transform as,

$$Va = Vq \cos\theta + Vd \sin\theta \qquad \text{...(16)}$$

$$Vb = Vq \cos(\theta - 2\,\Pi/3 + Vd \sin(\theta - 2\,\Pi/3) \qquad \text{...(17)}$$

$$Vc = Vq \cos(\theta + 2\,\Pi/3) + Vd \sin(\theta + 2\,\Pi/3) \qquad \text{...(18)}$$

The torque equation is similar to that of separately excited DC motor, and this completes the transformation of a PMSM to an equivalent separately excited dc motor.

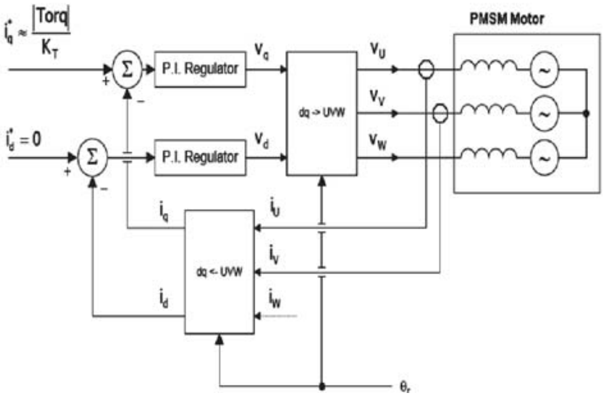

Fig. 7. Block diagram of current vector control

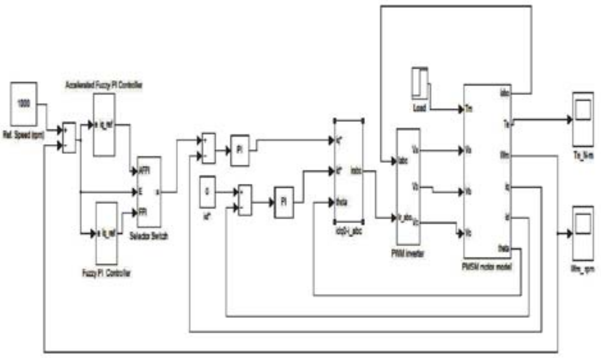

Fig. 8. Simulation Model of PMSM Drive System with Intelligent Hybrid Fuzzy Controller

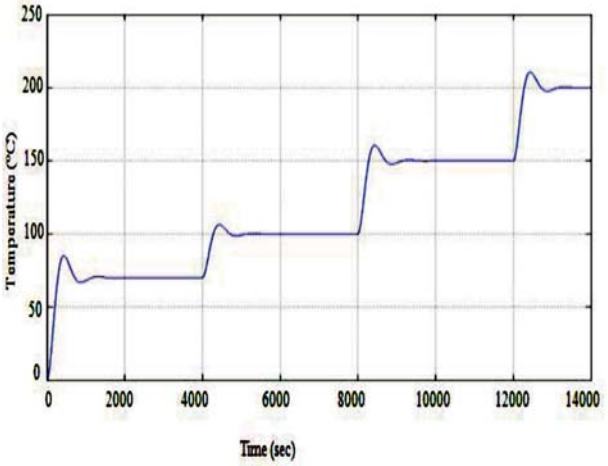

Fig. 9. PID control simulated output at different temperature set points

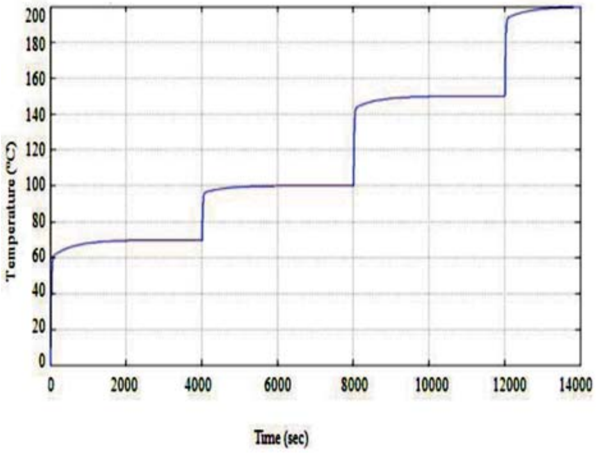

Fig. 10. Neuro fuzzy controller simulated output at different temperature set points

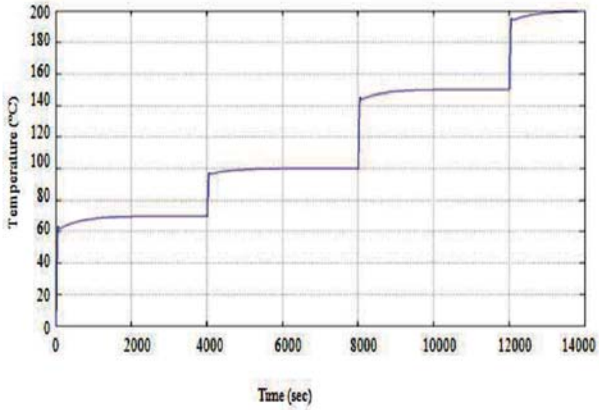

Fig. 11. Fuzzy control simulated output at different temperature set points

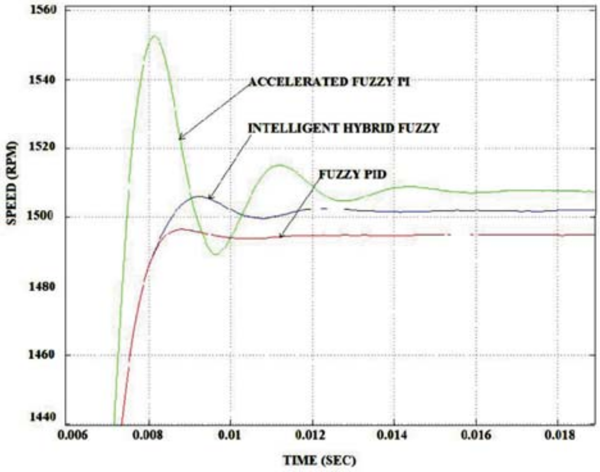

Fig. 12. Comparison of overshoot of Speed for Fuzzy PID, Accelerated Fuzzy PI and Intelligent Hybrid Fuzzy Controllers

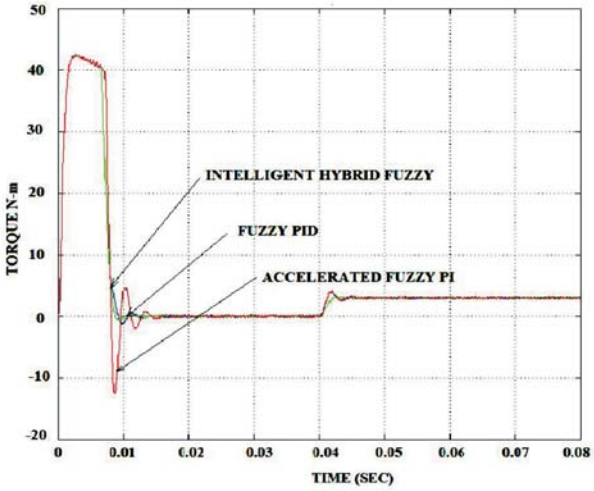

Fig. 13. Comparison of Torque Response for Fuzzy PID, Accelerated Fuzzy PI and Intelligent Hybrid Fuzzy Controllers

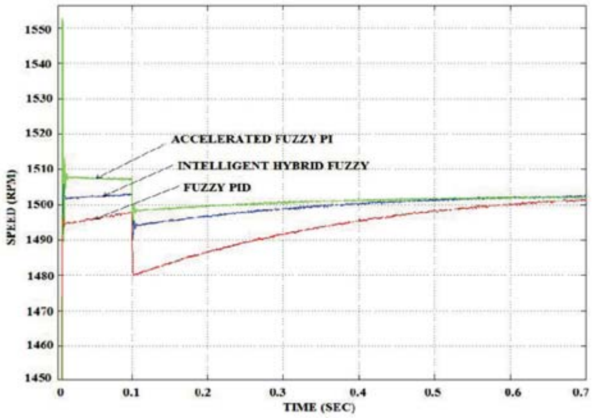

Fig. 14. Comparison of Speed under load

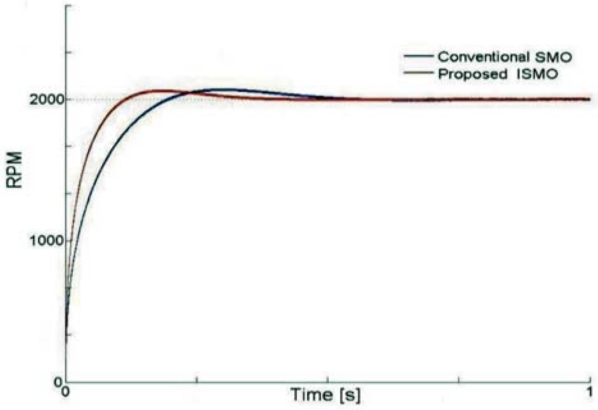

Fig. 15. Response times of conventional SMO and ISMO.

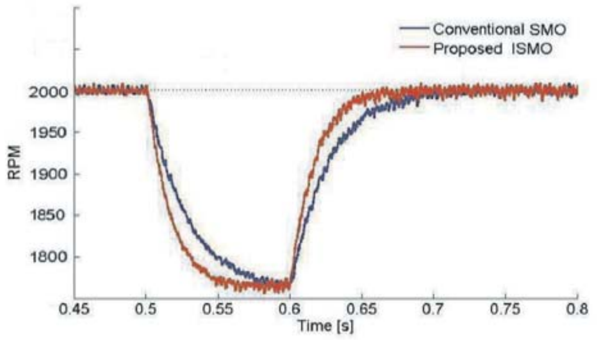

Fig. 16. Comparison of responses against disturbances.

III. INTELLIGENT CONTROL ANALYSIS

In this Research work, the merits of the neuro fuzzy controller can be observed as following. Neuro fuzzy controller for its unique characteristics emerges as a replacement for the previous existing controllers. The neuro fuzzy controller has improved control quality. The aim of control of heated barrel is to bring the set points during startup as soon as possible while avoiding large overshoots in order to maintain it at current temperature set value. The Figures 4 and 9-16 gives various timing specification for the four controllers. From the analysis of the neuro fuzzy controller on the basis of delay time it gives efficient output differences 8.5 times to that of PID controller, 6.35 times than that of neural controllers and 1.5times to that of Fuzzy. Consequently the neuro fuzzy controller produces an output which is 5 times ahead of that of PID, 3 times efficient than neural controller and 1.6 times than that of fuzzy in the rise time analysis. The peak time results states that neuro fuzzy output 6.66 times efficient than PID, 2 times than neural network and 1.66 times than that of Fuzzy controller. With consideration over the settling time the neuro fuzzy controller is 1.15 times efficient than PID, 1.10 times efficient than neural controller and 1.09 times than that of Fuzzy. The set points tracking and disturbance rejection is obtained in the proposed method.

IV. SIMULATION MODEL OF PMSM BASED ON MATLAB

In this Research paper, MATLAB simulation module, two control loops are used which are inner current loop using PI controller and the outer speed loop using Fuzzy based PI controller is built based on $id = 0$. This PMSM control system mainly includes; PMSM module, three phase voltage inverter module, co-ordinate transformation module, speed loop controller, current loop controller.

V. PWM CONTROLLER

MATLAB simulation model, PMSM fed by a current controlled PWM (Pulse Width Modulation) inverter is built by using six power semiconductor devices. The PWM current controllers are widely used in low and mid power applications by PMSM. The switching frequency is usually kept constant. They are based on the principle of triangular carrier wave of desired switching frequency and are compared with the error of controlled signal. The difference between reference signal generated in controller and the actual current are compared with the carrier signal. The obtained voltage signal triggers the gates of the voltage source inverter to generate the desire output. If the error command is greater than the carrier, the inverter leg is held switched to the positive polarity. When the error command is less, the inverter leg is switched to negative polarity. This will generate the PWM signal and the output voltage of the inverter is proportional to the current error command.

VI. PMSM MODULE

The inner structure of PMSM subs system which is used to the sub system which used to calculate the quadrature axis current. The subsystem is used to calculate torque (Te), electrical speed (ωe) and mechanical speed of rotor (ωm) and position signals (θ). The mechanical speed is converted into electrical speed by using number of pole pairs. The d-axis current and q-axis currents are converted into three phase currents by using transformation module. The input of PMSM module is three phase voltage which is responsible for loading torque Tm. The three phase voltages are transformed into direct axis voltage and quadrature axis voltage using transformation module. The quadrature axis current produces electromagnetic torque. The difference between electromagnetic torque and load torque is used to calculate acceleration by assuming damping co-efficient is zero. The speed can be obtained from first integral of acceleration and position signals are obtained from the first integral of speed. The Figure.8 shows the complete simulation model of a PMSM drive with Intelligent Hybrid Fuzzy controller in the outer loop and PI current controllers in the inner loops.

VII. CONCLUSION

The proposed Research work Intelligent Control Design of PMSM Servo Drive for neuro fuzzy controller eliminates sudden input disturbance and maintain the set point temperature in the plastic extrusion system. The simulation results shows neuro fuzzy controller reduces the timing specifications of Fuzzy, Neural and PID controllers. This Research work demonstrates the effectiveness of intelligent controller Design of PMSM Servo Drive on non linear system particular for temperature control in plastic extrusion system. The comparison of performance of the three controllers reveals that the neuro fuzzy controller is superior to the other controllers. From the results the proposed controller is good for set point changes and for stability. With the aid of the supervisory technique, the proposed controller identifies the process variations quickly and provides good controller performance for the set point changes and sudden disturbances. Therefore neuro fuzzy controller will prove Intelligent Control especially efficacious in the case of plastic extrusion temperature control system of PMSM Servo Drive.

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