Full Length Research Paper

Design and development of fuzzy logic controller to control the speed of permanent magnet synchronous motor

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The paper presents a fuzzy logic controller (FLC) for permanent magnet synchronous motor (PMSM). The fuzzy logic controller is used for speed control of this type of motor. The dynamic response of (PMSM) with the proposed controller is studied under different load disturbances. The effectiveness of the proposed fuzzy logic controller is compared with that of the conventional PI and PID controllers. The proposed controller is used in order to overcome the nonlinearity problem of PMSM and also to achieve faster settling response.

Key words: Speed control, plus integral controller, fuzzy logic controller, permanent magnet synchronous motor.

INTRODUCTION

Traditionally commutator motors, also known as direct current (dc) motors were preferred for variable speed drives while induction motors were used for constant speed applications. Advances in solid state devices helped in development of suitable controllers possessing provision of vector control. Such controllers made it possible to incorporate in the induction motor almost all the characteristics of a dc motor. In vector control scheme, torque and flux are decoupled from each other like in dc motors (Benchouia et al., 2004). Industry automation is mainly developed around motion control systems in which controlled electric motors play as a heart of the system a crucial role. The high performance motor control systems thus, contribute to a great extent, to the desirable performance of automated manufacturing sector by enhancing the production rate and the quality of products. In fact the performance of modern automated systems, defined in terms of swiftness, accuracy, smoothness and efficiency, mainly depends on the motor control strategies (Sung et al., 2004). The advancement of control theories, power electronics and micro-electronics in connection with new motor designs and materials has contributed largely to the field of electric motor control for high performance systems. Newly developed permanent magnet synchronous motors (PMSM) with high energy permanent magnet materials particularly provide fast dynamics, efficient operation and very good compatibility with the applications but only if they are controlled properly (Nour et al., 2006). However, the ac motor control including control of PMS motors is a challenging task due to very fast motor dynamics and highly non-linear models of the machines. Therefore, a major part of motor control development consists of deriving mathematical models in suitable forms.

The dynamic models of the motors can be presented in different reference frames to lay down a basis for the motor control design. The mathematical formulations and the equivalent circuit models can be provided to help in better controller design for PMSM drives. There are two competing control strategies for ac motors viz vector control (VC) and direct torque control (DTC) for PMSM

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(Rahideh et al., 2007). Vector control scheme with several benefits is the most applied control strategy. The decoupling of torque control and flux linkage control are the basis of vector control technique. The motor phasor diagrams can provide better understanding of different control schemes used for PMSM drives. It is the most straightforward approach for motor modelling and control. It also reduces the analytical burden (Cao and Fan, 2009). Even though equipped with modern solid state devices and suitable controller, the vector controlled induction motor drives are still not able to cope up with the more stringent requirements of loads used in some high performance applications. Pump, fan and compressor drive motors in industrial applications that operate large percentage of the time necessitate highly efficient and reliable service.

Also in aerospace applications as well as in robotics, superior power density ratio and reduction in size become prime requirements (Wang et al., 2007; Cao et al., 2008; Kamel et al., 2009). Moreover in some industries, the presence of dust particles are extremely damaging to the brushes and commutator of the dc motor. These requirements paved the way for the evolution of permanent magnet brushless motors. These motors use permanent magnet to produce the air gap magnetic field rather than field coils. These motors are showing increasing popularity in recent years for industrial drive applications (Wang et al., 2008; Cao and Fan, 2008).

The momentum of this popularity will considerably increase in the near future due to the recent availability of the high-energy low-cost neodymium-iron-boron (NdFeB) permanent magnet (Kung et al., 2009).

MODEL OF THE PMSM

The model of PMSM without damper winding has been developed on rotor reference frame using the following assumptions:

1) Saturation is neglected.
2) The induced EMF is sinusoidal.
3) Eddy currents and hysteresis losses are negligible.
4) There are no field current dynamics.

Voltage equations are given by (Wang and Liu, 2009; Song and Peng, 2009; Sant and Rajagopal, 2009):

$$V_q = R_s i_q + \omega_r \lambda_d + \rho \lambda_q \quad \ldots\ldots\ldots\ldots\ldots \quad (1)$$

$$V_d = R_s i_d - \omega_r \lambda_q + \rho \lambda_d \quad \ldots\ldots\ldots\ldots\ldots \quad (2)$$

Flux linkages are given by:

$$\lambda_q = L_q i_q \quad\quad\quad \ldots\ldots\ldots\ldots\ldots \quad (3)$$

$$\lambda_d = L_d i_d + \lambda_f \quad\quad \ldots\ldots\ldots\ldots\ldots \quad (4)$$

Substituting Equations 3 and 4 into 1 and 2:

$$V_q = R_s i_q + \omega_r (L_d i_d + \lambda_f) + \rho L_q i_q \quad \ldots\ldots\ldots \quad (5)$$

$$V_d = R_s i_d - \omega_r L_q i_q + \rho (L_d i_d + \lambda_f) \quad \ldots\ldots\ldots \quad (6)$$

Arranging Equations 5 and 6 in matrix form:

$$\begin{bmatrix} V_q \\ V_d \end{bmatrix} = \begin{bmatrix} R_s + \rho L_q & \omega_r L_d \\ -\omega_r L_q & R_s + \rho L_d \end{bmatrix} + \begin{bmatrix} \omega_r \lambda_f \\ \rho \lambda_f \end{bmatrix} \quad \ldots\ldots \quad (7)$$

The developed torque (Liu et al., 2009; Febin and Subbiah, 2009; Yang and Wang, 2009) motor is being given by:

$$T_e = 3/2 \, (P/2) \, (\lambda_d i_q - \lambda_q i_d) \quad \ldots\ldots\ldots\ldots \quad (8)$$

The mechanical Torque equation is:

$$T_e = T_L + B \, \omega_m + J \frac{d\omega_m}{dt} \quad \ldots\ldots\ldots\ldots \quad (9)$$

Solving for the rotor mechanical speed form Equation 9:

$$\omega_m = \left(\int \frac{T_e - T_L + B \, \omega_m}{J} \right) dt \quad \ldots\ldots\ldots \quad (10)$$

And

$$\omega_m = \omega_r \left(\frac{2}{P} \right) \quad\quad\quad \ldots\ldots\ldots\ldots \quad (11)$$

In the aforementioned equations ω_r is the rotor electrical speed where as ω_m is the rotor mechanical speed.

SPEED CONTROL OF PMSM WITH THE PROPOSED CONTROLLER

For the speed control of PMSM, many controllers are used. In conventional P, PI and PID controllers, very fine tuning is required which cannot cope up with system's parameter variations. Also the performance of such controllers is affected due to variations in physical parameters like temperature, noise, saturation etc. Many control systems use adaptive controllers for PMSM, which can track only linear systems. Therefore, fuzzy logic based controller may be used to achieve more accurate and faster solutions and to handle complicated non-linear characteristics.

Figure 1 shows the block diagram of the proposed control system. A simple structure fuzzy logic controller (FLC) is used in the speed control loop to regulate the motor speed. The inputs to the FLC are the speed error (e) and the change of speed (Δe).
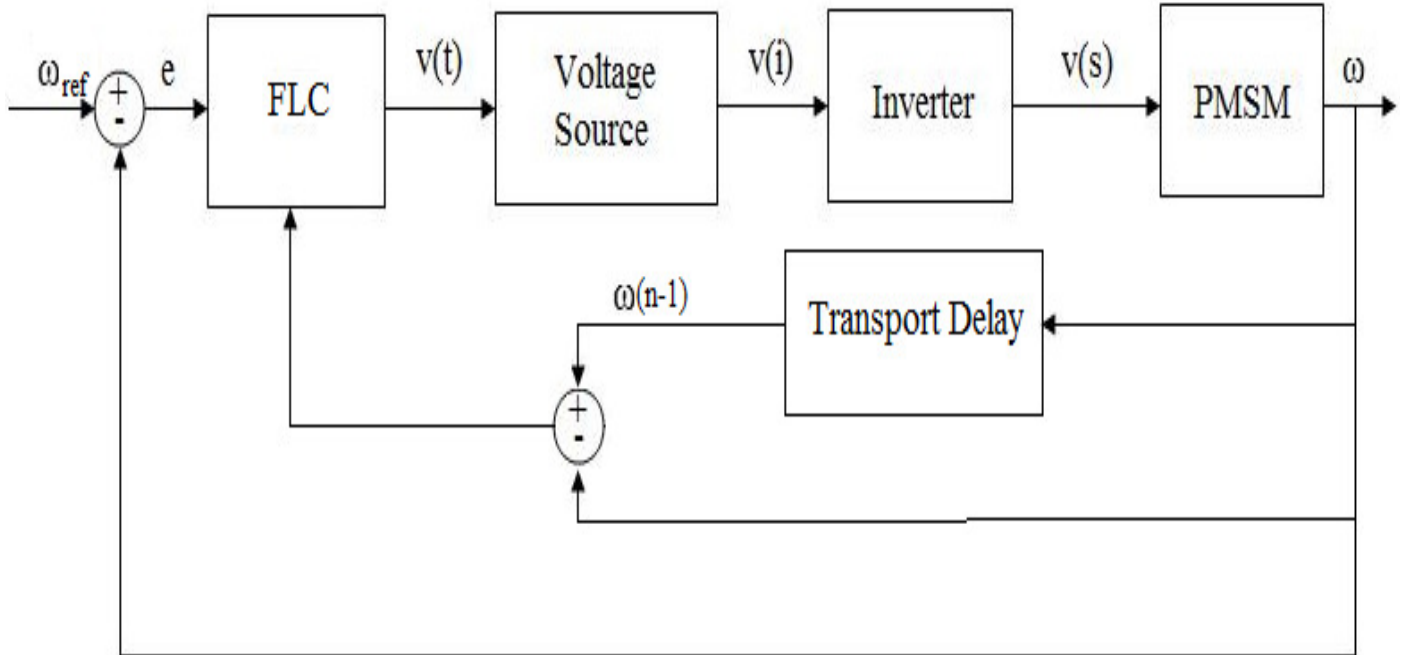
Figure 1. Speed control using FLC for PMSM.

The motor speed error (e) may be given by the following equation:

$$e(t) = \omega_{ref} - \omega(t) \qquad \dots\dots\dots\dots \qquad (12)$$

The change of error (Δe) may be described by the following equation:

$$\Delta e = e(t) - e(t-1) \qquad \dots\dots\dots\dots \qquad (13)$$

Where $e(t-1) = \omega_{ref} - \omega(t-1)$ and $\Delta e = \omega(t-1) - \omega(t)$.

The conventional PI controller

The proportional plus integral (PI) controller is one of the famous controllers used in a wide range in the industrial applications. The output of the PI controller in time domain is defined by the following equation:

$$v_c(t) = k_p e(t) + k_c \int_0^t e(t)\, dt \qquad \dots\dots\dots\dots \ (14)$$

Where $v_c(t)$ is the output of the PI controller, k_p is the proportional gain, k_i is the integral gain, and $e(t)$ is the instantaneous error signal. The main advantage of adding the integral part to the proportional controller is to eliminate the steady state error in the controller variable. However, the integral controller has the serious drawback of getting saturated after a while if the error does not

change its direction.

This phenomenon can be avoided by introducing a limiter to the integral part of the controller before adding its output to the output of the proportional controller. The input to the PI is the speed error (e), while the output of the PI is used as the input of controlled voltage source inverter. And finally the controlled voltage obtained from inverter is fed to the motor for controlling its speed. The dynamic response of the PMSM driven by the PI controller is shown in Figure 2.

PID controller

In PID controller scheme only change is the replacement of PI controller block with PID controller block. The dynamic response of the PMSM driven by the PID controller is shown in Figure 3.

The fuzzy logic controller (FLC)

In FLC scheme the output of the FLC is used as the input of the controlled voltage source which converts the input signal into an equivalent voltage in order to regulate the motor speed. All membership functions are iteratively adjusted and the result of the FLC corresponds to the minimum training error. The resultant MAMDANI-type FIS has only 21 rules which was found to provide sufficient accuracy after optimization. The membership functions of
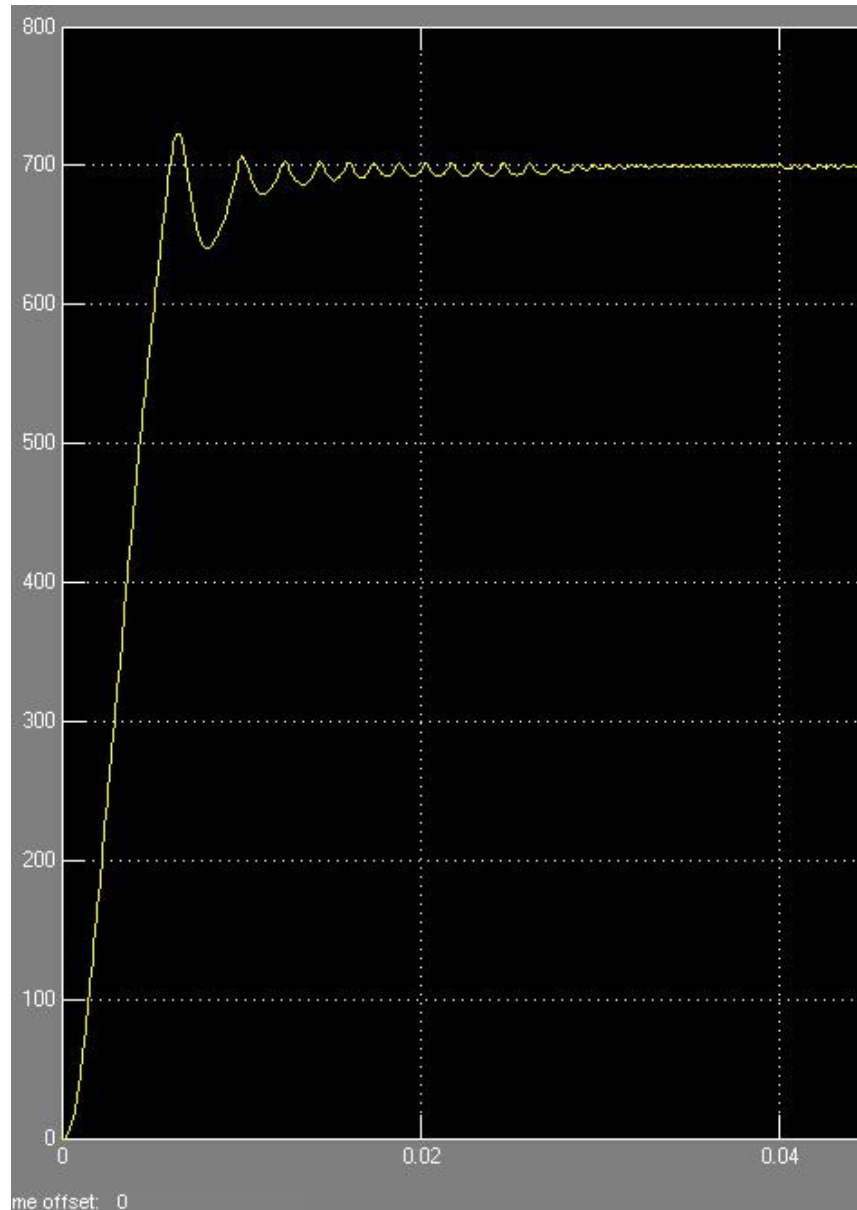
Figure 2. The dynamic response of the drive system using a PI controller.

the inputs are shown in Figures 4, 5 and 6. The dynamic response of the PMSM driven by the Fuzzy Logic Controller is shown in Figure 7.

PERFORMANCE EVALUATION

For PI controller

The PMSM starts in closed-loop because speed and current control are in cascade. The load torque applied to the machine's shaft is set to its nominal value. Two control loops are used: the inner loop regulates the motor's stator currents and the outer loop controls the motor's speed. Using a PWM inverter, a noise is observed in the electromagnetic torque waveform. However, the motor's inertia prevents this noise from appearing in the motor's speed waveform (Figure 2). The stator currents are quite "noisy," which is to be expected when using PWM inverters. The rotor speed increases fast to its synchronous value after few oscillations and preserves its value (Figure 2). The current takes initially a high value in order to develop the kinetic energy to accelerate the rotor. After a certain delay the current
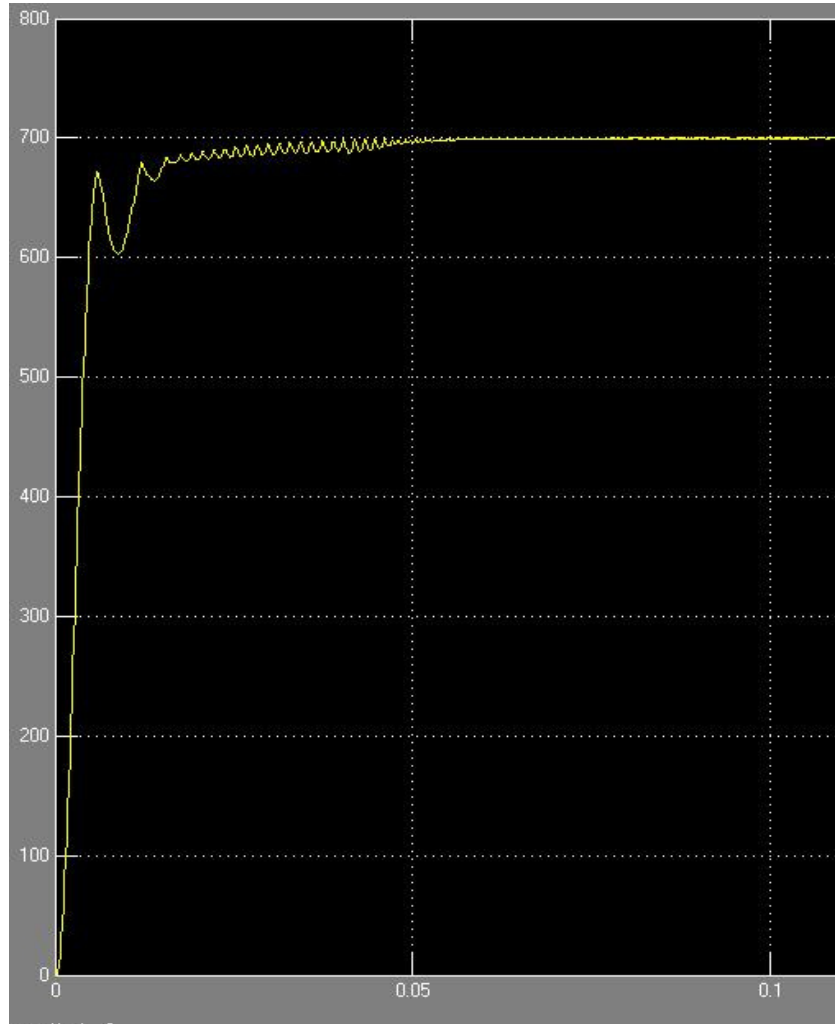
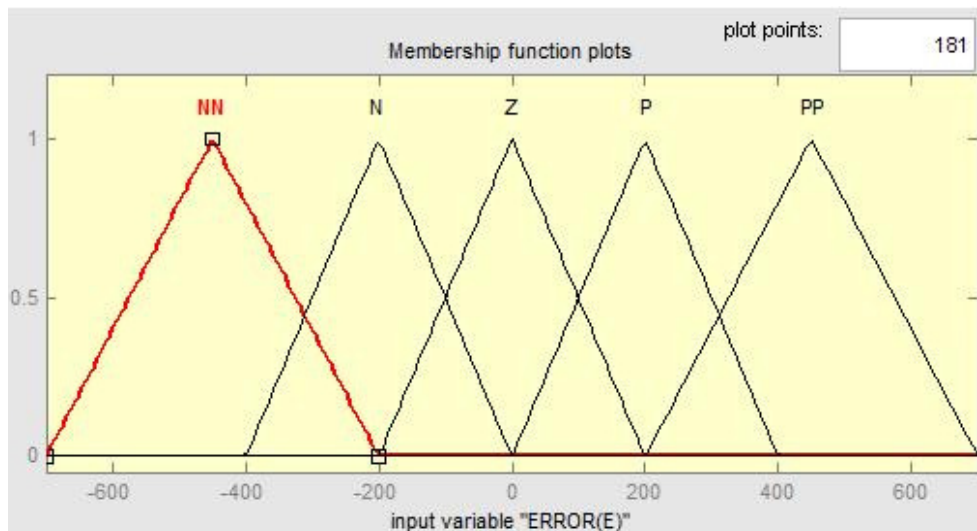**Figure 3.** The dynamic response of the drive system using a PID controller.
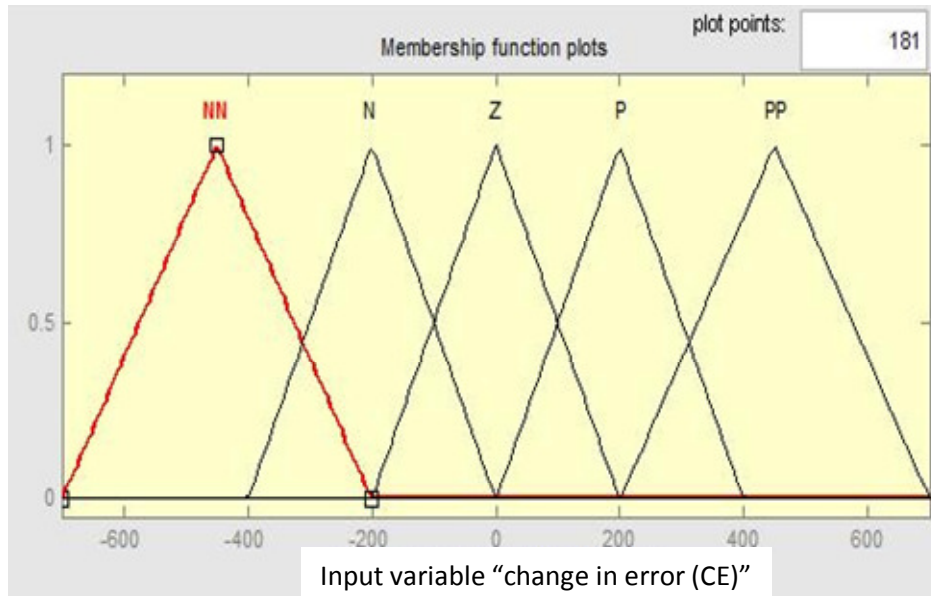

Figure 4. Error (E).
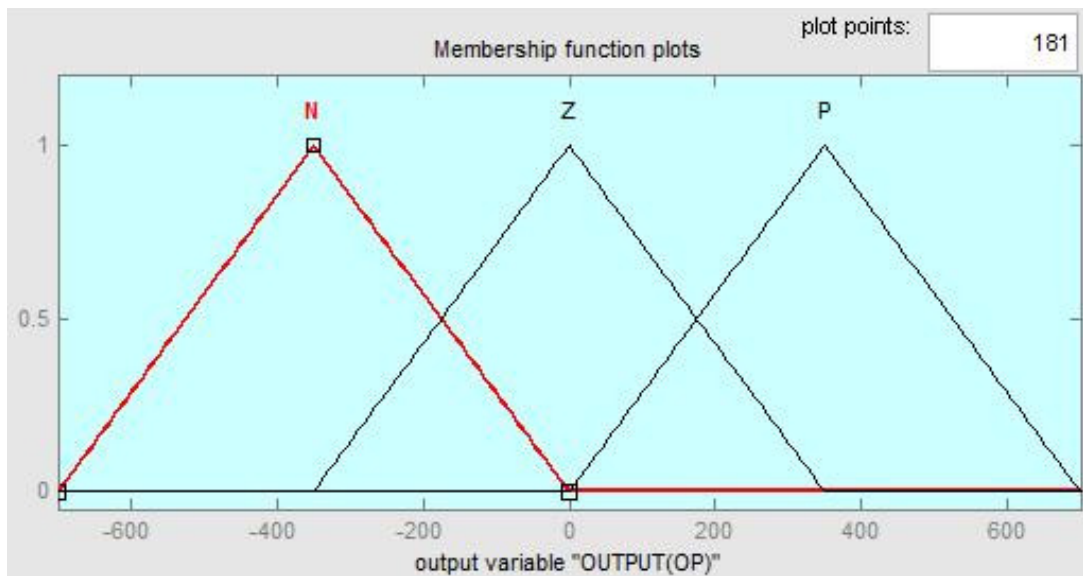
Figure 5. Change in error (CE).

Figure 6. Output (O).

stabilizes to their nominal value. The reference speed of the motor is set at 700 rad/s. As soon as the speed reaches the reference speed the PI speed controller forces the speed to remain steady at reference speed. During starting period torque climbs to maximum capability of the motor after that it settles down to steady state value of 3 N-M. Also the current rises to its maximum value and after that comes back to nearly 2 A. A detailed Simulink model for a PMSM drive system with field oriented control has been developed and operation

below and above rated speed has been studied using one current control scheme. Simulink has been chosen from several simulation tools because of its flexibility in working with analog and digital devices. Mathematical models can be easily incorporated in the simulation and the presence of numerous tool boxes and support guides simplify the simulation of large system as compared to other simulation tools. Simulink is capable of showing real time results with reduced simulation time and debugging. In the present simulation measurement of
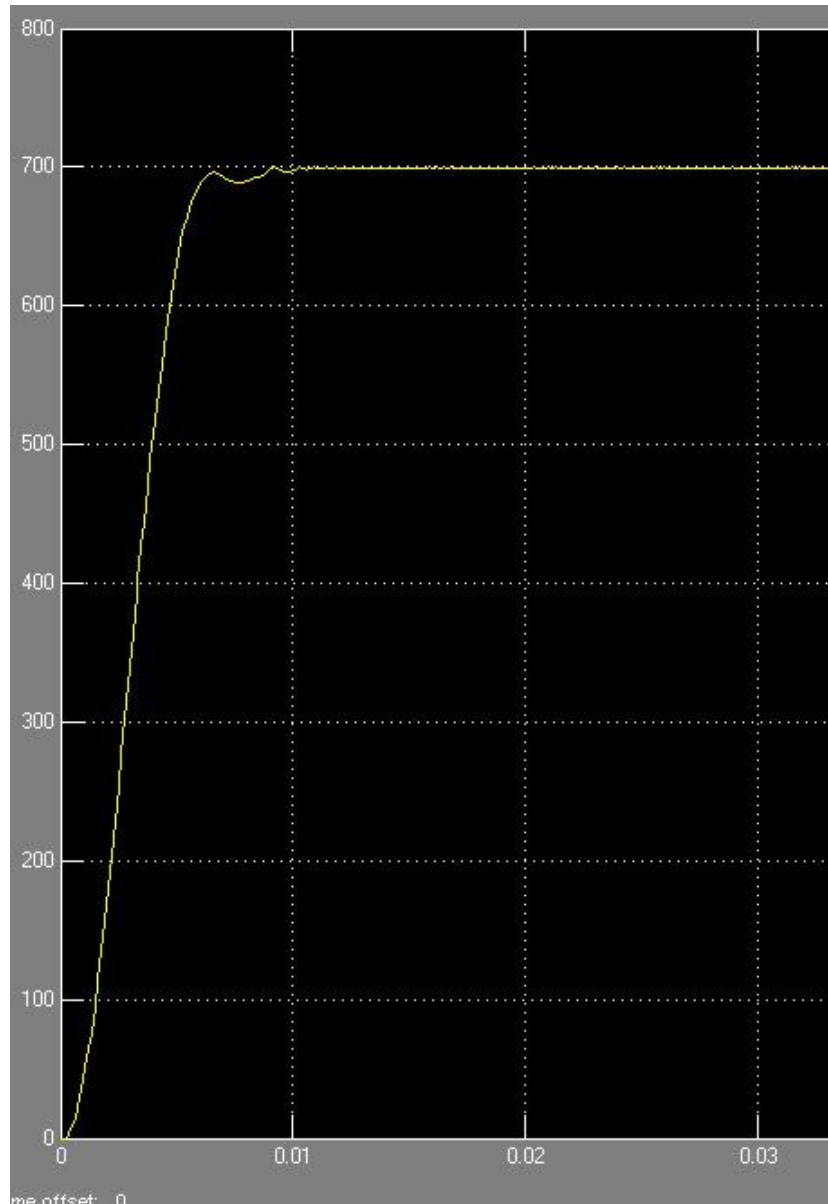
Figure 7. The dynamic response of the drive system using FLC.

currents and voltages in each part of the system is possible, thus permitting the calculation of instantaneous or average losses, efficiency of the drive system and total harmonic distortion. Usually in such a drive system the inverter is driven either by hysteresis or by PWM current controllers.

For PID controller

In this control scheme, proportional control (K_p) is used to improve the rise time, derivative control (K_d) to improve the overshoot, an integral control (K_i) to eliminate the steady-state error. The stator currents are here less "noisy", as compared to PI speed controller, which is to be expected when using PWM inverters. The rotor speed increases fast to its synchronous value after a few oscillations and preserves its desired value (Figure 3). The current takes initially a high value in order to develop the kinetic energy to accelerate the rotor. After a delay, the current stabilizes to their nominal value. The present model takes into consideration the movement equations in the PMSM model and the operating principle of the PWM voltage converter associated with the current controller. The reference speed of the motor is set at 700 rad/s. As soon as the speed reaches the reference speed

the PID speed controller forces the speed to remain steady at reference speed. During starting period torque climbs to maximum capability of the motor after that it settles down to steady state value of 3 N-M. Also the current rises to its maximum value and after that comes back to nearly 2 A.

For fuzzy logic controller

The FLC has exhibited high performance in tracking the speed reference. The stator current, flux and torque response of PMSM with fuzzy controller is faster than PI and PID controllers during start up and during a step change in torque. At the same time, dynamic behaviour of PMSM with fuzzy logic controller is more stable than PI and PID controllers. A performance comparison between the fuzzy logic controller and conventional PI and PID controllers has been carried out by several simulations confirming the superiority of the Fuzzy logic controller.

Comparison of different types of speed controllers

In this work, three different types of speed controllers namely, PI, PID and FLC are used to investigate the dynamic behaviour of the PMSM drive. On the basis of simulated results, following important observations are made which are listed as:

1. Among all the speed controllers considered in this study, PI takes maximum starting time. Though PID controller takes nearly 39 ms to reach a speed of 698.79 rad/s but finally settles for 698.54 in nearly 55 ms. Fuzzy takes nearly 7.96 ms to reach 692.42 rad/s and settles for 699.75 in nearly 11 ms.
2. In case of PI controllers, there is some overshoot present in the speed response while FLC has very small steady state error.
3. The spikes during transient period in speed response are more with PI while less in PID and minimum in FLC. Also in FLC, minimum oscillations are observed.
4. The speed recovers very quickly when Fuzzy logic controller is used during the operation.

CONCLUSIONS

The overall idea of this work is to compare the performance of different speed and current controllers for PMSM drive. For this purpose, the motor drive system simulation model was developed and verified through the SIMULINK toolbox of the MATLAB software package. For current controller, PWM is examined and for speed controller, performance of PI, PID and Fuzzy controllers are compared. The simulated results confirmed the viability of the model used in this work and it has been

shown that the model is suitable for transient as well as steady state condition. These results also confirmed that the transient torque and current never exceed the maximum permissible value. Among all the speed controllers discussed, Fuzzy logic controller makes the system robust as there is no speed overshoot and also minimum pulsation in torque and current are observed.

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APPENDIX

The specifications of the permanent magnet synchronous motor are listed in Table 1.

Table 1. The motor specifications.

No of phases	Three
Rated Torque	3 N-M
Rated Speed	3000 RPM
The Stator Phase Resistance	2.8750 ohm
The Stator Phase Inductance	8.5 mH
The Motor Inertia	0.00008 kg-m^2