Hybrid Fuzzy Controller for Permanent Magnet Brushless DC Motor

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ABSTRACT

The paper presents simulation results of hybrid fuzzy logic with proportional plus conventional integral-derivative controller for the speed control of permanent magnet brushless dc (PMBLDC) motor. Although conventional PID controllers are widely used in the industry due to its simple control structure and ease of implementation, these controllers pose difficulties under the conditions of nonlinearity, load disturbances and parametric variations. Moreover PID controllers require precise linear mathematical models. In the paper, the performance of the permanent magnet brushless dc motor drive is examined with the aid of the hybrid controller. The hybrid controller shows improved performance compared to the conventional PID speed controller.

Key Words: Permanent Magnet Brushless DC Motor (PMBLDC), Proportional-Integral-Derivative (PID), Fuzzy Logic Proportional Plus Integral-Derivative (FP+ID), Pulse Width Modulation (PWM).

1. Introduction

Permanent magnet brushless motors have found wider applications due to their high power density and ease of control. The brushless dc motors have high efficiency, low maintaince and low rotor inertia for their increased demand in high power servo and robotic applications [1]. Several models of this drive have been presented and discussed [2-4].

The thrust is given on identification of a suitable speed controller for the PMBLDC motor. Many control strategies have been proposed [5-7] in classical linear theory. As the PMBLDC machine has nonlinear model, the linear PID may no longer be suitable. This has resulted in the increased demand for modern nonlinear control structures like self-tuning controllers, state-feedback controllers, model reference adaptive systems and use of multi-variable control structure. Most of these controllers use mathematical models and are sensitive to parametric variations. Very few adaptive controllers have been practically employed in the control of electric drives due to their complexity and inferior performance. Fuzzy controllers [8-10] have proved to be successful in recent years. These controllers are inherently robust to load disturbances. Besides, fuzzy logic controllers can be easily implemented.

The applications of fuzzy controllers are limited because of some drawbacks. In order to eliminate them, many researchers are now combining fuzzy logic [6] and conventional techniques. The present paper explores the feasibility of hybrid fuzzy proportional plus integral-derivative (FP+ID) controller for the speed control of PMBLDC motor drive. In this, the proportional term in the conventional PID controller is replaced with an incremental fuzzy logic controller improving the behavior of conventional PID [5] controllers. The drive system considered here consists of hybrid fuzzy logic [7] controller, reference current generator, PWM current controller, position sensor, motor and MOSFET based inverter. All these components are modelled and integrated for simulation in real time operating conditions. The simulation results show great improvement in both transient and steady state responses of the drive. Contrary to the PID controller, this controller makes the PMBLDC drive more robust to load variations. The key feature of this scheme is to compensate for overshoots and oscillations in the response of the PMBLDC motor. Results of this scheme are compared under starting, reversal and load perturbations for both the PID and the hybrid FP+ID controllers. Fig1 shows the starting response of the drive with both the PID controller and the FP+ID controller. The figure shows less overshoot with the present control scheme. Fig2 describes the torque response with the FP+ID controller. Final results will be available with the full paper.

In the paper, it is proposed to explore the potential and feasibility of hybrid FP+ID controller for the speed control of PMBLDC motor drive. In the proposed scheme, hybrid FP+ID controller is used to modify the command signal to compensate for the overshoots and undershoots in the speed response of the PMBLDC motor. The hybrid FP+ID controller uses fuzzy rules [11] that are based on eliminating the overshoots. The key feature of this scheme is to compensate for overshoots and undershoots in transient response. The results show that this scheme gives superior performance over the conventional PID controllers.

2. Description of the Drive System

Fig1 describes the basic building blocks of the PMBLDC motor drive. The drive consists of proposed FP+ID controller; reference current generator, PWM current controller, position sensor, motor and MOSFET based inverter. The actual speed of the motor is compared with its reference value and the error in speed is processed in hybrid FP+ID controller. The output of this controller is considered as the reference torque. A limit is put on the speed controller output depending on maximum winding currents. The reference current generator block generates the three phase reference currents (i_a^*, i_b^*, i_c^*) using the limited peak current magnitude decided by the controller and the position sensor. The reference currents have the shape of quasi-square wave in phase with respective back emfs to develop constant unidirectional torque. The PWM current controller regulates the winding currents (i_a, i_b, i_c) in the small band around the reference currents (i_a^*, i_b^*, i_c^*). The motor currents are compared with the reference currents and the switching commands are generated to drive the inverter devices.

3. Analysis of PMBLDC Drive

The drive system considered in the paper here consists of hybrid FP+ID controller, the reference current generator, PWM current controller, PMBLDC motor and MOSFET inverter. All these components are modelled and integrated for simulation in real time conditions**.**

3.1 FP+ID controller structure

Fig.1 illustrates the basic control structure. This scheme consists of FP+ID speed controller. The hybrid fuzzy controller has the advantages of classical action. The control signal of conventional PID speed described below:

$$\omega_{e(n)} = \omega_{r(n)}^{*} - \omega_{r(n)}.$$

$$\Delta\omega_{e(n)} = \omega_{e(n)} - \omega_{e(n-1)}$$

$$T^{*}_{(n)} = T^{*}_{(n-1)} + K_P\{\omega_{e(n)} - \omega_{e(n-1)}\} + K_I\,\omega_{e(n)} + K_D\,\{\omega_{e(n)} - 2\,\omega_{e(n-1)} + \omega_{e(n-2)}\} \quad (1)$$

where K_P, K_I and K_D are the proportional, integral and derivative gains of the speed controller and n is the sampling index

$$T^{*}_{(n)} = T^{*}_{(n-1)} + K_P \times \Delta\hat{u}(k) + K_I\,\omega_{e(n)} + K_D\{\omega_{e(n)} - 2\,\omega_{e(n-1)} + \omega_{e(n-2)}\} \quad (2)$$

where K_P, K_I and K_D are identical to the fixed gain PID speed controller, $\Delta\hat{u}$ (k) is the output of the fuzzy logic controller. The output of the above equation T^{*} is considered as the reference torque of the PMBLDC motor. The dominating term in the hybrid FP+ID controller is the proportional gain which is the responsible to reduce overshoot and rise time.

The fuzzy logic control output $\Delta\hat{u}(k)$ is a function is the function of $w_{e(n)}$ and $\Delta\omega_{e(n)}$ and is expressed as

$$\Delta\hat{u}(k) = FLC\,[w_{e(n)} \text{ and } \Delta\omega_{e(n)}] \quad (3)$$

where $w_{e(n)}$ is the error between reference speed and speed of the motor and $\Delta\omega_{e(n)}$ is the change in speed error.

The fuzzy members are chosen as follows:

Positive Big: PB — Negative Big: NB
Positive Medium: PM — Negative Medium: NM
Positive Small: PS — Negative Small: NS
and zero: ZO

The triangular shaped functions are chosen as the membership functions due to the resulting best control performance and simplicity. The height of the membership functions in this case is one, which occurs at the points –1, -0.57, -0.27, 0, 0.27, 0.57, 1 respectively as shown in Fig.2(c). An overlap of 50% is provided for neighboring fuzzy subsets. Therefore, at any point of the universe of discourse, no more than two fuzzy subsets will have non-zero degrees of membership. The realization of the function FLC [$w_{e(n)}$ and $\Delta\omega_{e(n)}$], based on the standard fuzzy method, consists of three stages: fuzzification, interference, and defuzzification.

Fuzzification: This converts point-wise (crisp) data into fuzzy sets (linguistic variable), making it compatible with fuzzy representation.

Interference method: A linguistic rule table according to the dynamic performance of the drive is shown in table 2. The first two linguistic values are associated with the input variables $w_{e(n)}$ and $\omega_{e(n-1)}$, while the third linguistic value is associated with the output. For example, if error in speed is ZO and change in speed error is NS, then output is NM.

Defuzzification: The reverse of fuzzification is called defuzzification. The rules of FLC produce required output in a linguistic variable. Linguistic variables have to be transformed to crisp output. By using the center of gravity defuzzification method, crisp output is obtained.

3.2 Reference Current Generator

The input to the reference current generator are reference torque (T^*) and the rotor position signal (θ_r) .The magnitude of the three phase current (I^*) is determined by using reference torque (T^*) and the back emf constant (K_b) is as:

$$I^* = T^* / K_b$$

Depending on the rotor position, the reference current generator generates the reference currents (i_a^*, i_b^*, i_c^*) by taking the value of reference current magnitude as I^*,$-I^*$ and zero.

3.3 Rotor Position Signal and Reference currents

	i_a^*	i_b^*	i_c^*
0 – 60	I^*	$-I^*$	0
60 – 120	I^*	0	$-I^*$
120 – 18	0	I^*	$-I^*$
180 – 240	$-I^*$	I^*	0
240 – 300	$-I^*$	0	I^*
300 – 360	0	$-I^*$	I^*

These reference currents are fed to the PWM current controller.

3.4 PWM Current Controller Modelling

The switching logic is formulated as given below.

If $i_a < (i_a^* - h_b)$ switch 1 ON and switch 4 OFF
If $i_a < (i_a^* + h_b)$ switch 1 OFF and switch 4 ON
If $i_b < (i_b^* - h_b)$ switch 3 ON and switch 6 OFF
If $i_b < (i_b^* + h_b)$ switch 3 OFF and switch 6 ON
If $i_c < (i_c^* - h_b)$ switch 5 ON and switch 2 OFF
If $i_c < (i_c^* + h_b)$ switch 5 OFF and switch 2 ON

where h_b is the hysteresis band around the three phase reference currents.

3.5 Modelling of back emf using rotor position

The per phase back emf in the PMBLDC motor is trapezoidal in nature and are the functions of the speed and rotor position angle (θr). The normalized function of back emfs are shown in Fig.2 (a). From this, the phase back emf e_{an} can be expressed as:

$$e_{an} = E \qquad 0° < \theta r < 120°$$
$$e_{an} = (6E/\pi)(\pi-\theta) - E \qquad 120° < \theta r < 180°$$
$$e_{an} = -E \qquad 180° < \theta r < 300°$$
$$e_{an} = (6E/\pi)(\theta-2\pi) + E \qquad 300° < \theta r < 360°$$

where $E = K_b\ \omega$ and e_{an} can be described by E and normalized back emf function $f_a(\theta_r)$ shown in Fig.2(a). $e_{an} = E\ f_a(\theta r)$. The back emf function of other two phases e_{bn} and e_{cn} are defined in similar way using E and the normalized back emf function $f_b(\theta_r)$ and $f_c(\theta_r)$ as shown in Fig.2 (a).

3.6 Modelling of PMBLDC Motor and Inverter

The PMBLDC motor is modeled in the stationary reference frame using 3-phase abc variables. The general volt -ampere equation for the circuit shown in the Fig.2 (b) can be expressed as:

$$\nu_{an} = Ri_a + p\lambda_a + e_{an} \quad (4)$$

$$\nu_{bn} = Ri_b + p\lambda_b + e_{bn} \quad (5)$$

$$\nu_{cn} = Ri_c + p\lambda_c + e_{cn} \quad (6)$$

where ν_{an}, ν_{bn} and ν_{cn} are phase voltages and may be designed as:

$$\nu_{an} = \nu_{ao} - \nu_{no},\ \nu_{bn} = \nu_{bo} - \nu_{no} \text{ and } \nu_{cn} = \nu_{co} - \nu_{no}. \quad (7)$$

where ν_{ao}, ν_{bo}, ν_{co} and ν_{no} are three phase and neutral voltages referred to the zero reference potential at the mid- point of dc link (o) shown in the Fig.2(b). R is the resistance per phase of the stator winding, p is the time differential operator and e_{an}, e_{bn} and e_{cn} are phase to neutral back emfs. The λ_a, λ_b and λ_c are total flux linkage of phase windings a, b and c respectively. These values can be expressed as:

$$\lambda_a = L_s i_a - M(i_b + i_c) \quad (8)$$

$$\lambda_b = L_s i_b - M(i_a + i_c) \quad (9)$$

$$\lambda_c = L_s i_c - M(i_a + i_b) \quad (10)$$

where L_s and M are the self and mutual inductance, respectively The PMBLDC motor has no neutral connection and hence this result:

$$i_a + i_b + i_c = 0 \quad (11)$$

Substituting equation (11) into equations (8), (9) and (10) the flux linkages are given

$$\lambda_a = i_a(L_s + M),\ \lambda_b = i_b(L_s + M) \text{ and } \lambda_c = i_c(L_s + M) \quad (12)$$

By substituting equation (12) in volt ampere equations (4) - (6) and rearranging these equations in a current derivative of state space form, one gets

$$pi_a = 1/(L_s+M)\ [\nu_{an} - Ri_a - e_{an}] \quad (13)$$

$$pi_b = 1/(L_s+M)\ [\nu_{an} - Ri_b - e_{bn}] \quad (14)$$

$$pi_c = 1/(L_s+M)\ [\nu_{cn} - Ri_c - e_{cn}] \quad (15)$$

The developed electromagnetic torque may be expressed as:

$$T_e = [e_{an}i_a + e_{bn}i_b + e_{cn}i_c]/\omega_r \quad (16)$$

where ω_r is the rotor speed in electrical rad/sec.

$$p\omega = (P/2)\ (T_e - T_l - B\ \omega)\ /J \quad (17)$$

where P is the number of poles, T_l is the load torque in N-m, B is the frictional coefficient in N-ms/rad, and J is the moment of inertia, kg-m^2.

The derivative of the rotor position (θ_r) in state space form is expressed as:

$$p\theta_r = \omega \quad (18)$$

The potential of the neutral point with respect to the zero potential (ν_{no}) is required to be considered in order to avoid imbalance in the applied voltage and simulate the performance of the drive. This is obtained by substituting equation (11) in the volt-ampere equations (4) to (6) and adding them together give as:

$$\nu_{ao} + \nu_{bo} + \nu_{co} - 3\nu_{no} = R(i_a + i_b + i_c) + (L_s + M)\ (pi_a + pi_b + pi_c) + (e_{an} + e_{bn} + e_{cn}) \quad (19)$$

Substituting equation (11) in equation (19) we get:

$$\nu_{ao} + \nu_{bo} + \nu_{co} - 3\nu_{no} = (e_{an} + e_{bn} + e_{cn})$$

Thus,

$$\nu_{no} = [\nu_{ao} + \nu_{bo} + \nu_{co} - (e_{an} + e_{bn} + e_{cn})]\ /\ 3$$

The set of differential equations mentioned in eqns (13), (14), (15), (17) and (18) define the model developed in terms of the variables i_a, i_b, i_c, ω_r, T and time as an independent variable.

4. Discussion of Results

A program is developed using C language to simulate the PMBLDC drive model with both the FP+ID speed controller and the fixed gain PID controller. The equations governing the model of the drive system are given in the above section. A numerical technique namely Rung-Kutta method was used to get the solution of these equations for the variables such as i_a, i_b, i_c, ω and T. The speed controller and switching logic of current controller are used in this simulation. The transient and steady state responses of a 4 pole, 1500 rpm, 3 phase, 2.0 hp, 4A PMBLDC motor are shown in Figs 3 to 6. The performance of the FP+ID controller for speed control of PMBLDC motor is judged during different operating conditions. The parameters used for our real time simulation are listed in Appendix-I. The same values of gains are used in both the controllers to examine the performance of drive with these two controllers. The specifications of the PMBLDC motor are given in table1.

4.1 Starting Response

The starting response of the PMBLDC drive system using hybrid fuzzy logic controller is shown in Fig.3 with the motor at rest, the reference speed is set at 157rad/s (1500rpm) Within 152ms the motor speed reaches the reference speed without any appreciable overshoot and zero steady state error in speed Fig.3 (b). The starting response of the PMBLDC drive with conventional PID controller is shown in Fig.4. The response of the drive is slower than that of FP+ID speed controller. The former controller shows an overshoot in speed response, which is undesirable. The drive takes maximum permissible current to start the motor from standstill. The results prove that the response of the drive is faster with FP+ID controller than the conventional PID controller. Improved response in case of FP+ID controller is of immense help to industrial applications.

4.2 Speed Reversal Response

The motor running under steady state with a speed of 157rad/s (1500 rpm) which is suddenly changed to other direction at t=0.75 sec. The controller makes the motor speed coincide with the reference speed. Fig.3 shows that the speed response of the drive takes 245ms to reach the speed of –157 rad/s. The response is smooth and free from oscillations in the case of FP+ID control scheme. This is due to robust and accurate control of the structure of the controller. The speed reversal response of the drive with PID controller is shown in Fig.4. The drive takes 325msec for speed reversal. The results show the superiority of the FP+ID controller over PID controller.

4.3 Response under load perturbation

Fig. 5 shows the response of the FP+ID speed controller under load perturbations. The sudden application of load at t=1.0sec and removal at 1.05sec on the motor shaft causes a negligible change in the speed response of the drive. The FP+ID controller makes the drive robust to load variations. The torque rises to 5 Nm and remains at the same value till the load is removed. The response of the drive under load perturbations introduced at t =1.0 sec and removal at 1.05 sec with fixed gain PID controller is shown in Fig.5. The dip in speed is around 4 rad/sec (38.2 rpm) with the conventional PID controller. The drive takes 110 msec to recover to the original speed. Under sudden removal of load, the rise in speed is 4rad/sec. The results show significant improvement in the response of the drive with the FP+ID speed controller.

5.0 Conclusions

A hybrid controller (FP+ID) has been employed for the speed control of PMBLDC motor drive and analysis of results of the performance of a hybrid fuzzy controller is presented. The modelling and simulation of the complete drive system is described in the paper. Effectiveness of the model is established by performance prediction over a wide range of operating conditions. A performance comparison between the hybrid FP+ID controller and the conventional PID controller has been carried out by several simulation runs confirming the validity and superiority of the hybrid FP+ID controller. The results have shown that the hybrid FP+ID controller is robust to external load disturbances. For implementing the hybrid fuzzy controller, proportional gain constant needs to be adjusted such that manual tuning time of the classical controller is significantly reduced. The performance of the PMBLDCM drive with reference to both the steady state and the dynamic conditions is improved with the application of the hybrid FP+ID speed controller.

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APPENDIX-I

The controller gains of both the controllers are same and given here with:

$K_P = 0.12$, $K_I = 0.0005$ and $K_D = 0.0012$

Table 1: PMBLDC motor specifications

HP	2
No. of Poles	4
No. of Phases	3
Type of connection	Star
Rated Speed	1500 rpm
Rated current	4A
Resistance/Ph	2.8Ω
Back EMF Constant	1.23V-Sec/rad
Self & Mutual Inductance	0.00521 H/phase
Moment of Inertia	0.013 N/m^2

Table 2: **Fuzzy Logic Rules For FP+ID controller**

e\ce	NB	NM	NS	ZO	PS	PM	PL
NB	NB	NB	NB	NB	NM	NS	ZO
NM	NB	NB	NB	NM	NS	ZO	PS
NS	NB	NB	NM	NS	ZO	PS	PM
ZO	NB	NM	NS	ZO	PS	PM	PB
PS	NM	NS	ZO	PS	PM	PB	PB
PM	NS	ZO	PS	PM	PB	PB	PB
PB	ZO	PS	PM	PB	PB	PB	PB

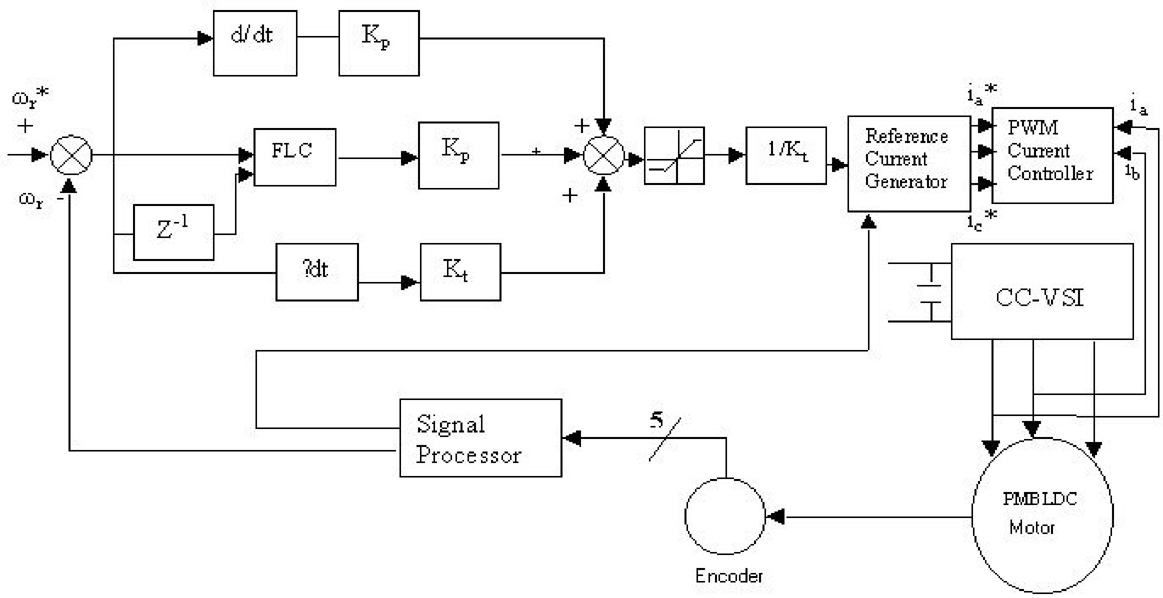


Fig. 1 Basic Block Diagram of PMBLDC motor drive system

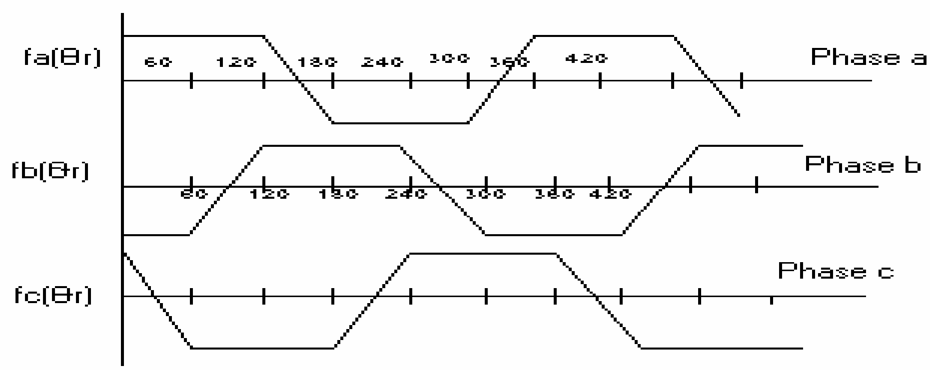
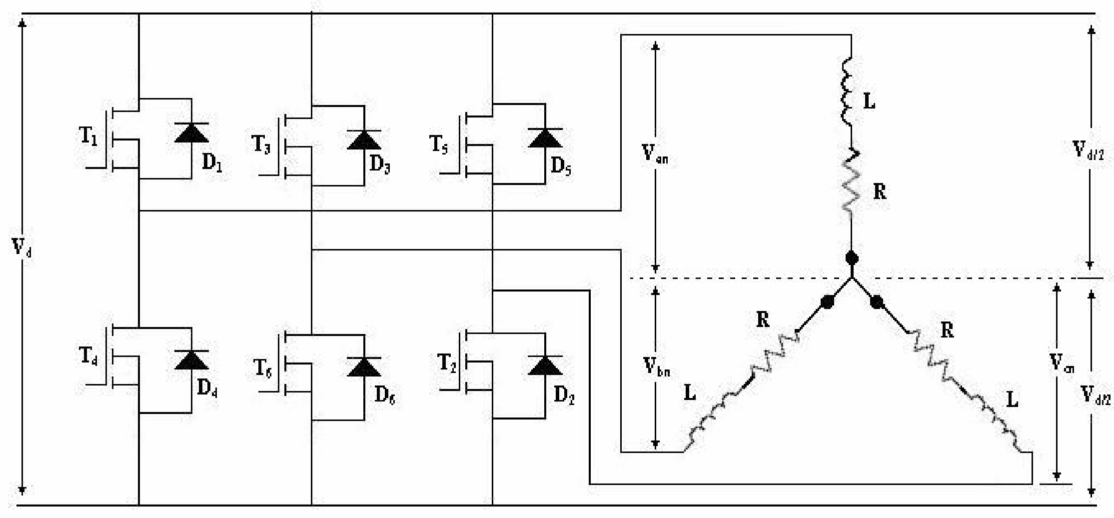


Fig. 2(a) Function of backemfs of PMBLDC drive



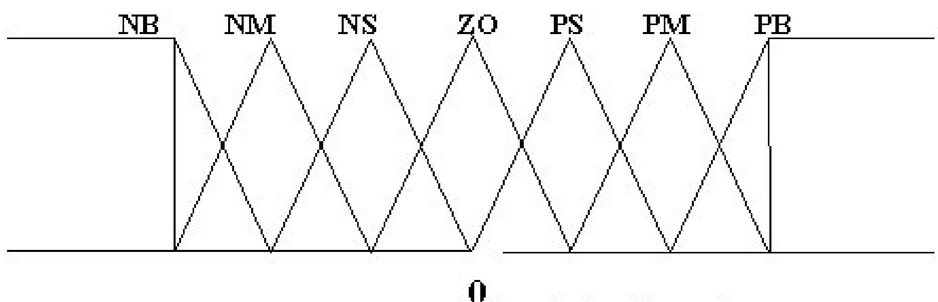


Fig. 2(c) Membership functions

Performance with the hybrid FP+ID controller during starting and speed reversal

Performance with PID controller during starting and speed reversal

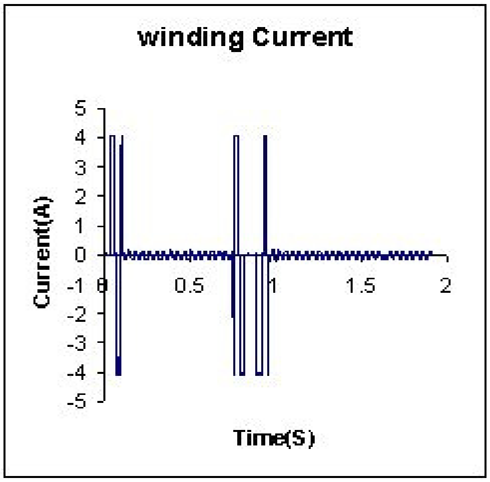


Fig.3 (a)

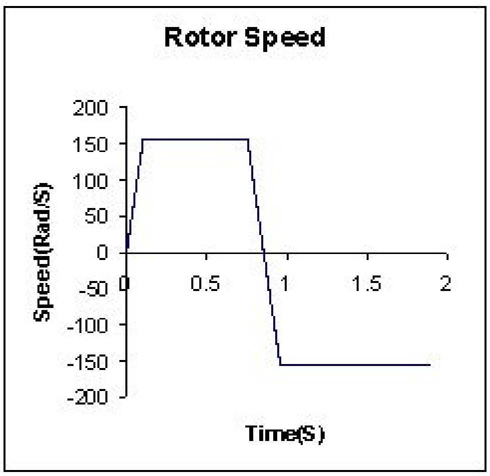


Fig.3 (b)

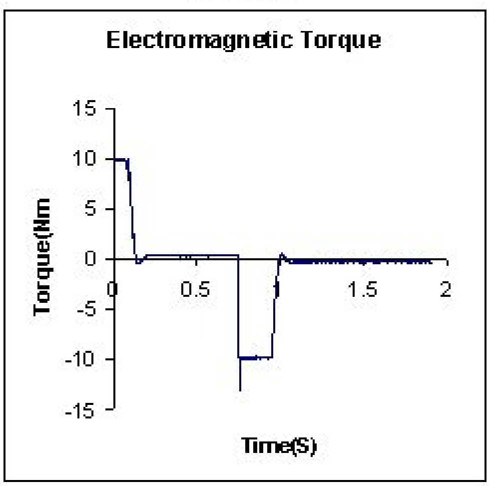


Fig.3 (c)

Performance with the hybrid FP+ID controller during load perturbations

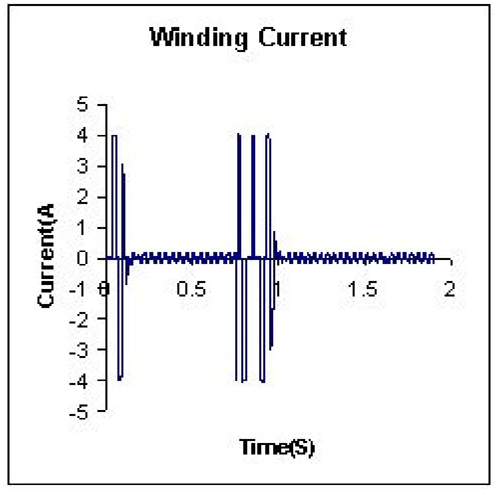


Fig.4 (a)

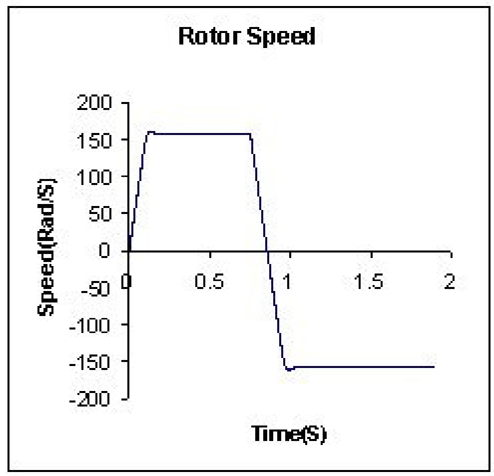


Fig.4 (b)

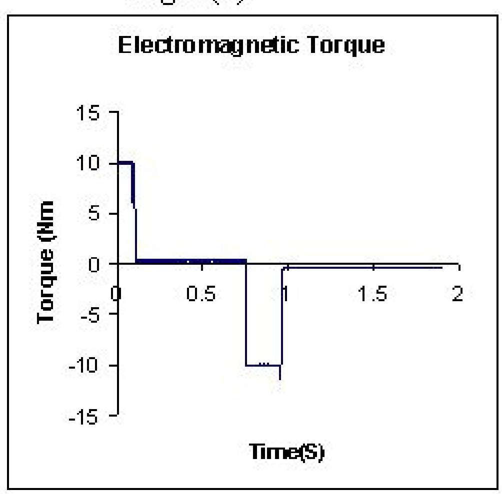


Fig.4 (c)

Performance with PID controller during load perturbations

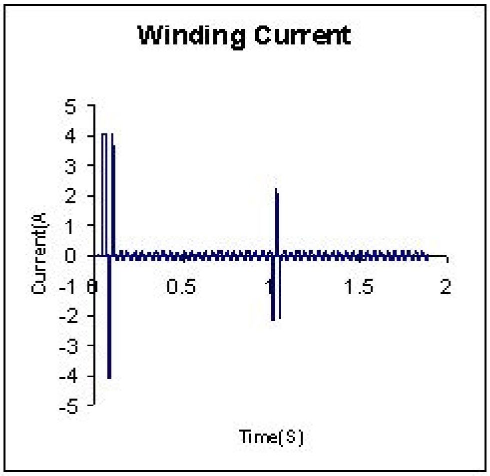
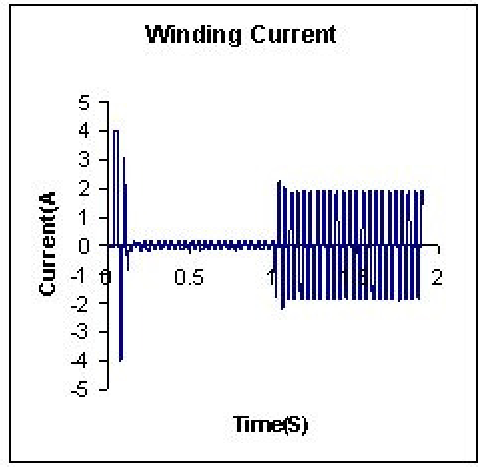


Fig.5 (a)



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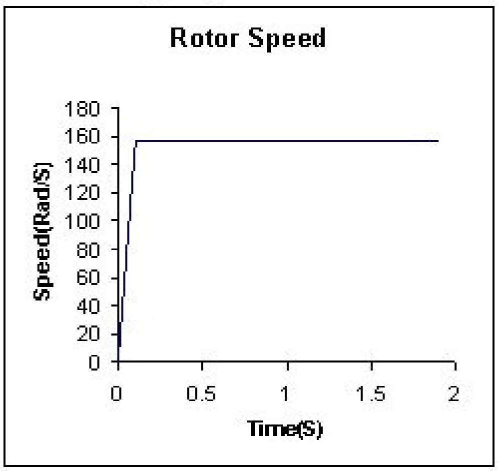


Fig.5 (b)

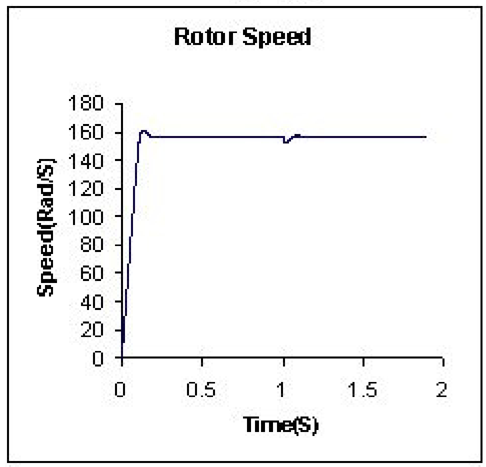
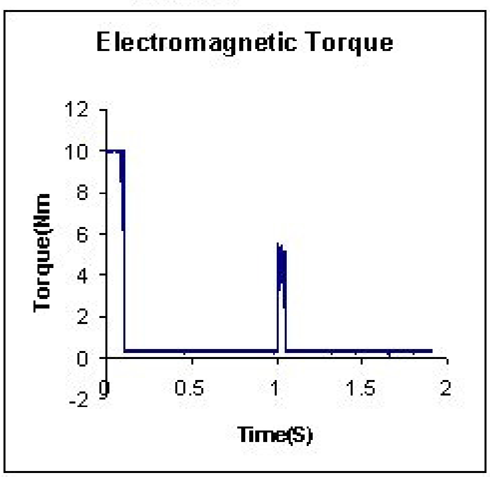


Fig.5 (b)



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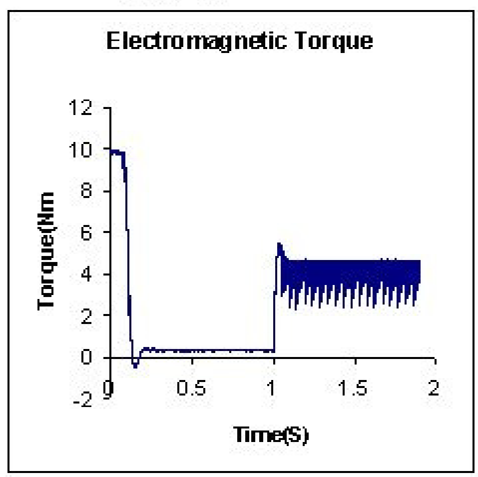

Fig.5 (c)