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INTELLIGENT CONTROL OF INTERIOR PERMANENT MAGNET SYNCHRONOUS MOTOR DRIVE

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ABSTRACT

This paper presents a novel fast speed response control strategy for the interior permanent magnet synchronous motor (IPMSM) drive system using intelligent control. As an intelligent controller, the Fuzzy Logic Controller (FLC) is considered in the present work. In this paper, a closed loop control system with FLC in the speed loop has been designed where the motor is fed from a six switch three phase (6S3Ph) pulse width modulation (PWM) inverter. The closed loop vector control technique is used in this work. The approach proposed here is based on a comparison between PI controller and FLC. Simulation of the drive system was carried out to study the performance of the motor drive. It is observed that the proposed fuzzy logic control methodology provides faster response than the conventional PI controller incorporated system.

Keywords: *Interior permanent magnet synchronous motor, fuzzy logic control, hysteresis current controller, vector control and inverter.*

1. INTRODUCTION

In the present world, it is necessary to control the speed of motor for better production and quality control in any industry where rotating machines are used. Hence, different control schemes are adopted for speed controlling purposes. Now, IPM motor drives have been a topic of interest. Different authors have carried out modeling and simulation of such drives.

A permanent magnet synchronous motor (PMSM) is a motor that uses permanent magnets to produce the air gap magnetic field rather than using electromagnets. PM machines generally have two classifications [1]: (1) the popularly used surface permanent magnet (SPM) machine where magnets are mounted on the rotor surface and (2) the buried or interior permanent magnet (IPM) machine where magnets are mounted inside the rotor. IPM motors have saliency with q-axis inductance greater than the d-axis inductance ($L_q > L_d$).

Nasir Uddin *et al.* [2], in their paper developed a cost effective interior permanent magnet (PM) synchronous motor drives. But the main shortcomings of four-switch (4S) topology are [3]:
1) decreased voltage gain and thereby increased current rating for the devices at the same output power;

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2) increased voltage stress on both power devices if the same output voltage should be kept;
3) large variations of the voltage across the two dc-link capacitors caused by one phase current circulating through the capacitive bank which will also load the capacitors more.

Those shortcomings are the major reasons for that the 4S inverter is rarely used compared with the six switch (6S) inverter. If the inverter needs a wide fundamental frequency range, the capacitors in the 4S inverter will be loaded heavily at low fundamental frequency.

Conventionally, a 2-phase equivalent circuit model (d-q model) has been used to analyze reluctance synchronous machines. This theory is now applied in analysis of other types of motors [4] & [5] including PM synchronous motors, induction motors etc.

The conventional controllers are very sensitive to parameter variations and load disturbance. Therefore, an intelligent speed controller demands special attention for the IPMSM drive to be used in high performance drive (HPD) systems [6]. Advanced control based on artificial intelligence techniques is called intelligent control. The advantages of FLC are given in [7].

PM synchronous motors are now very popular in a wide variety of industrial applications. These motors have significant advantages like, medium construction complexity, multiple fields, delicate magnets, elimination of copper loss, high reliability (no brush wear), high efficiency , high torque-to-current ratio, can be driven by multi-phase inverter controllers, smooth rotation and appropriate for position control. These advantages are attracting the interest of researchers and industry for use in many applications. IPMSM motors are used in a wide range of industrial applications due to their robustness and simplicity [8−11].

This paper investigates the application of the fuzzy logic control scheme to improve the transient and steady state performances of the IPMSM drive system. Moreover, the hysteresis controller is used to control the current in such a way that it can follow the command current as close as possible to the sinusoidal reference. The performances of the proposed drive have also been compared with those obtained from the conventional PI controller.

2. MATHEMATICAL MODEL

Detailed modeling of PM motor drive system is required for proper simulation of the system. The equivalent circuit for the IPMSM can be developed for d-q axis as shown in Fig.1. The following assumptions are made in the modeling of the IPMSM:

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.

With these assumptions, voltage equations are given by:

$$v_q = Ri_q + p\lambda_q + P\omega_r\lambda_d + P\omega_r\psi_f \quad (1)$$

$$v_d = Ri_d + p\lambda_d + P\omega_r\lambda_q \quad (2)$$

Flux Linkages are given by:

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

$$\lambda_d = L_d i_d \quad (4)$$

Where v_d and v_q are the d-q axis voltages, i_d and

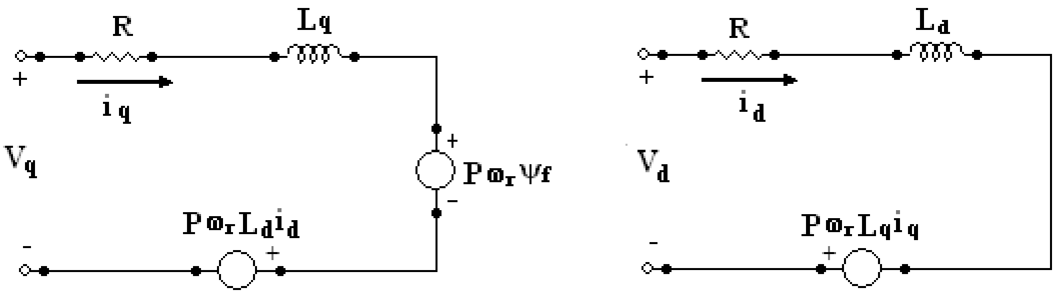


Figure 1. IPMSM d-q model

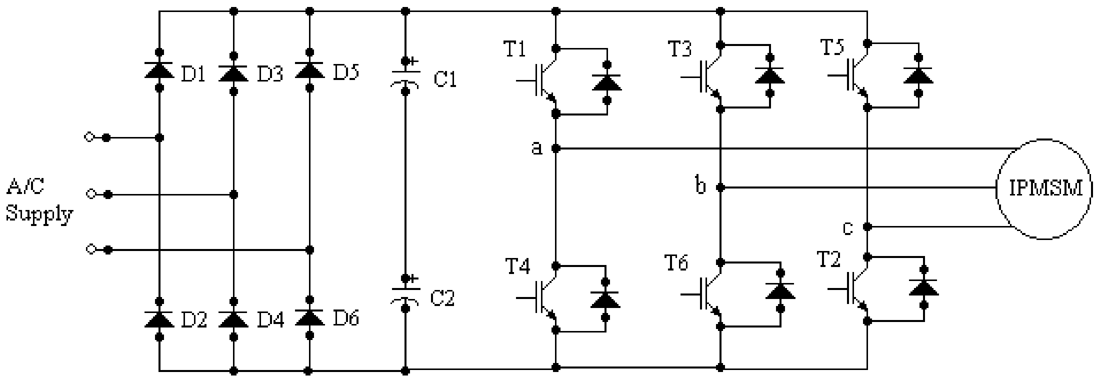


Figure 2. Power circuit of the drive system.

i_q are the d-q axis stator currents, L_d and L_q are the d-q axis inductances, λ_d and λ_q are the d-q axis stator flux linkages, R is the stator resistance per phase, ω_r is the rotor speed, ψ_f *is the* magnetic flux constant, P is the number of pole pairs and p is the derivative operator.

The developed electromagnetic torque is given as:

$$T_e = \frac{3P}{2}(\psi_f i_q + (L_d - L_q) i_d i_q) \quad (5)$$

The torque balance equation for the motor dynamics is given as

$$T_e = T_L + J_m p\omega_r + B_m \omega_r \quad (6)$$

For dynamic simulation, the model equations of the PMSM must be expressed in state space derivative form as:

$$L_q \frac{di_q}{dt} = v_q - Ri_q - P\omega_r L_d i_d - P\omega_r \psi_f \quad (7)$$

$$L_d \frac{di_q}{dt} = v_d - Ri_d + P\omega_r L_q i_q \quad (8)$$

$$J_m \frac{d\omega_r}{dt} = T_e - T_L - B_m \omega_r \quad (9)$$

and

$$\omega_r = P * \omega_m \quad (10)$$

where ω_m is the rotor mechanical speed.

3. SYSTEM OPERATION AND CONTROL SCHEME

Fig. 3 illustrates the basic building blocks of the IPMSM drive considered in this paper. The drive system consists of a fuzzy speed controller, hysteresis current controller, IGBT based current

Table 1. Inverter Modes Of Operatıon

Switching function			Switch on			Output voltage		
S_a	S_b	S_c				V_a	V_b	V_c
0	0	0	T4	T6	T2	$-V_{dc}$	$-V_{dc}$	$-V_{dc}$
0	0	1	T4	T6	T5	$-V_{dc}$	$-V_{dc}$	V_{dc}
0	1	0	T4	T3	T2	$-V_{dc}$	V_{dc}	$-V_{dc}$
0	1	1	T4	T3	T5	$-V_{dc}$	V_{dc}	V_{dc}
1	0	0	T1	T6	T2	V_{dc}	$-V_{dc}$	$-V_{dc}$
1	0	1	T1	T6	T5	V_{dc}	$-V_{dc}$	V_{dc}
1	1	0	T1	T3	T2	V_{dc}	V_{dc}	$-V_{dc}$
1	1	1	T1	T3	T5	V_{dc}	V_{dc}	V_{dc}

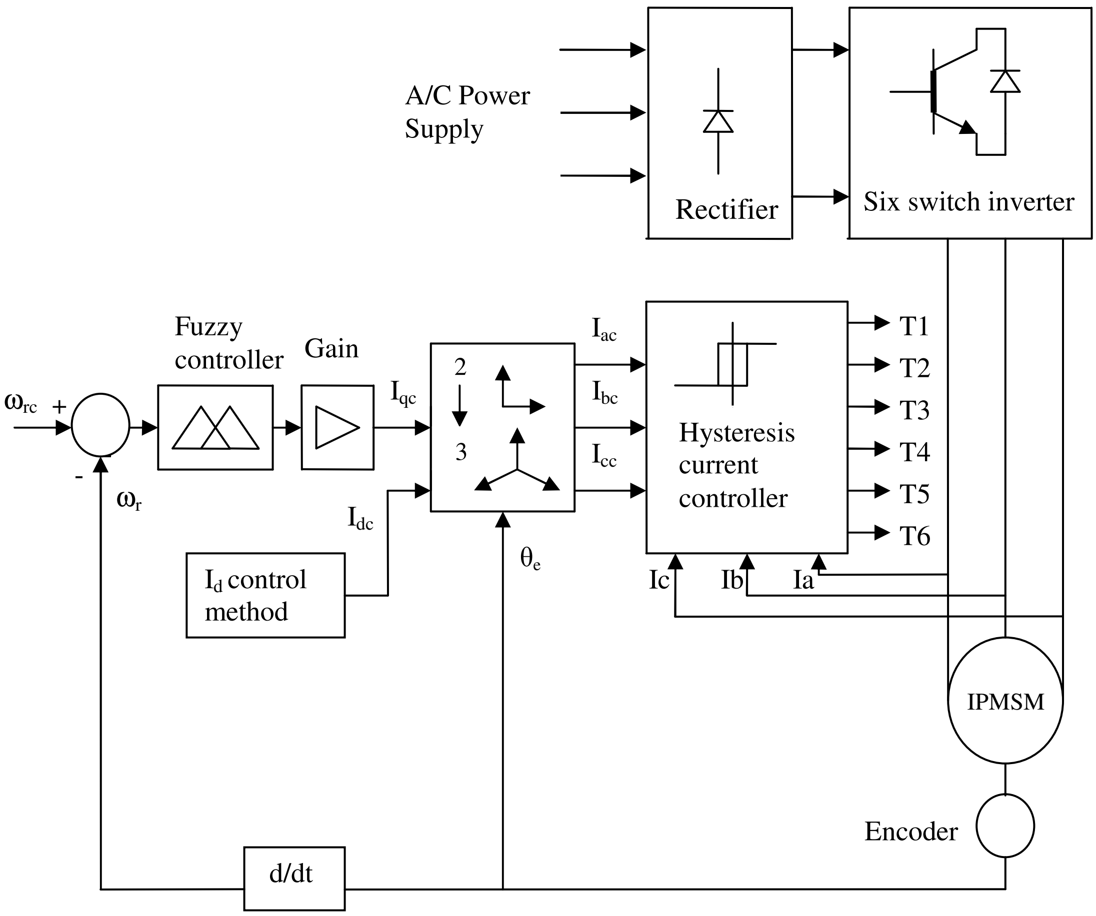


Figure 3. Control scheme of the IPMSM fed from a six-switch inverter.

controlled voltage source inverter and IPMSM. The power circuit of the drive system is shown in Fig.2.

The speed error and rate of change speed error are processed in the fuzzy speed controller for each sampling interval. The output of this is considered as the quadrature axis reference current i_q^*. The d-q axis reference currents i_d^* and i_q^* are used to generate the reference currents i_a^*, i_b^*, and i_c^*. These reference currents are then compared with the actual motor currents i_a, i_b, and i_c to generate PWM signals, which will fire the power semiconductor devices of the three-phase inverter to produce the actual voltages to the motor. Table 1 shows the different modes of operation and the corresponding output voltage

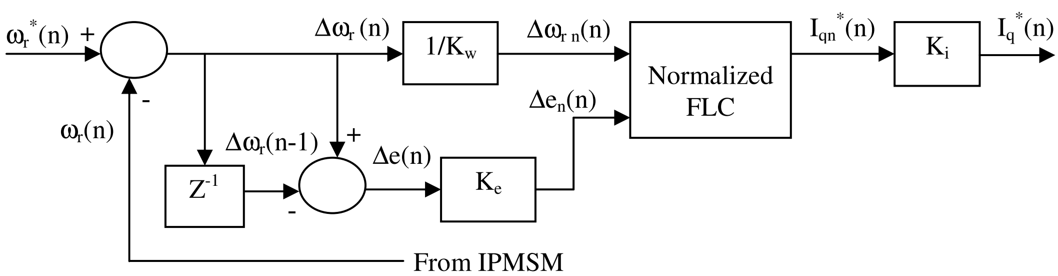


Figure 4. Fuzzy speed controller [2].

vector of the inverter. For PI controller, the proportional and integral constants are adjusted by trial and error method.

2.1 Fuzzy Logic Control Scheme

Fuzzy logic control algorithms can be used to solve problems that are difficult to address with traditional control techniques. Fuzzy logic defines rules that determine the behavior of the system using word descriptions instead of mathematical equations. The algorithm consists of three steps: (1) fuzzification (2) rule evaluation and (3) defuzzification. Descriptions of these steps will be found in [6].

Table 2. Fuzzy Rule Based Matrıx [7]

Δe_n \ $\Delta\omega_{rn}$	NH	NL	ZE	PL	PH
NE	NH	NL	NC	PM	PH
ZE	NH	NL	NC	PM	PH
PS	NH	NL	PL	PM	PH

The block diagram of FLC is shown in Fig. 4. For the proposed FLC, the speed error and rate of change speed error are considered as the input linguistic variables and the torque producing current component (i_{qn}*) is considered as the output linguistic variable. For the proposed control scheme, the d-axis component of the stator current i_d is set to zero so that the torque equation becomes linear [11].

Various scaling factors (k_w, k_e, and k_i) were tuned by trial and error to get an optimum drive performance. The membership functions are given in Fig.5. The fuzzy rule base matrix is shown in Table 2. In this study, Mamdani-type fuzzy inference and center of gravity defuzzification is used.

The rules used for the proposed FLC algorithm are as follows [7]:

i) if $\Delta\omega_{rn}$ is PH (positive high), i_{qn}* is PH (positive high)

ii) if$\Delta\omega_{rn}$ is PL (positive low), i_{qn}* is PM (positive medium) iii) if $\Delta\omega_{rn}$ is ZE (zero) and Δe_n is PS (positive), i_{qn}* is PL (positive low)

iv) if $\Delta\omega_{rn}$ is ZE (zero) and Δe_n is NE (negative), i_{qn}* is NC (no change)

v) if $\Delta\omega_{rn}$ is ZE (zero) and Δe_n is ZE (zero), i_{qn}* is NC (no change)

vi) if $\Delta\omega_{rn}$ is NL (negative low), i_{qn}* is NL (negative low)

vii) if $\Delta\omega_{rn}$ is NH (negative high), i_{qn}* is NH (negative high)

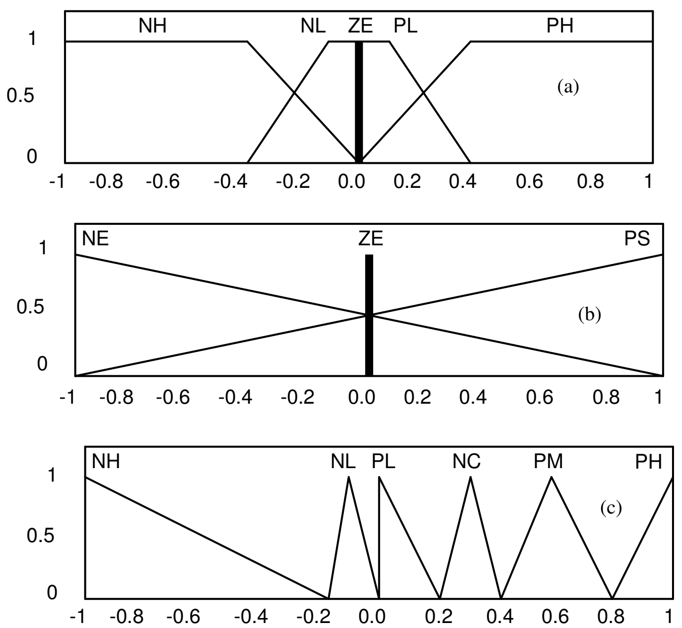


Figure 5. Membership functions for [7]: (a) Speed error ($\Delta\omega_{rn}$) (b) Change of speed error (Δe_n) and (c) q-axis command current i_{qn}*.

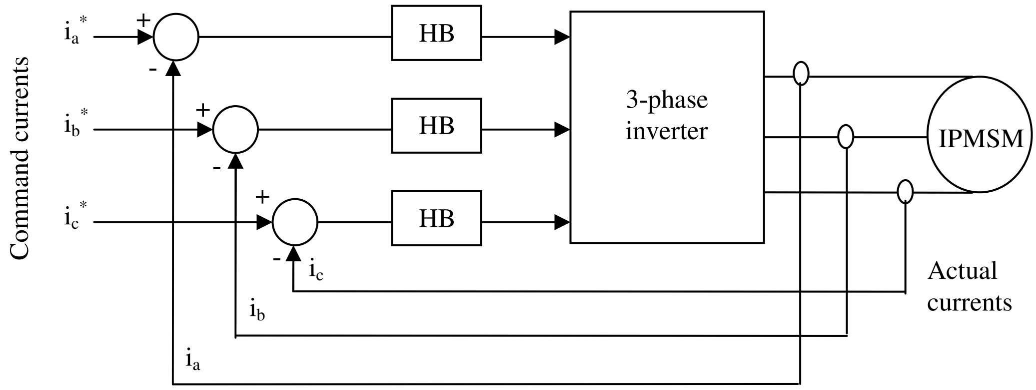


Figure 6. Hysteresis-Band (HB) current controller block diagram.

2.2 Hysteresis Current Control Scheme

The main task of the current controller is to force the current vector in the three phase load according to a reference trajectory. The block diagram of a three-phase hysteresis current controller is shown in Fig.6. Three independent hysteresis current controllers are used to force phases “a”, “b” and “c” currents to follow their commands.

The hysteresis current controller contributes the switching pattern to the inverter devices. The switching logic is formulated as given below.

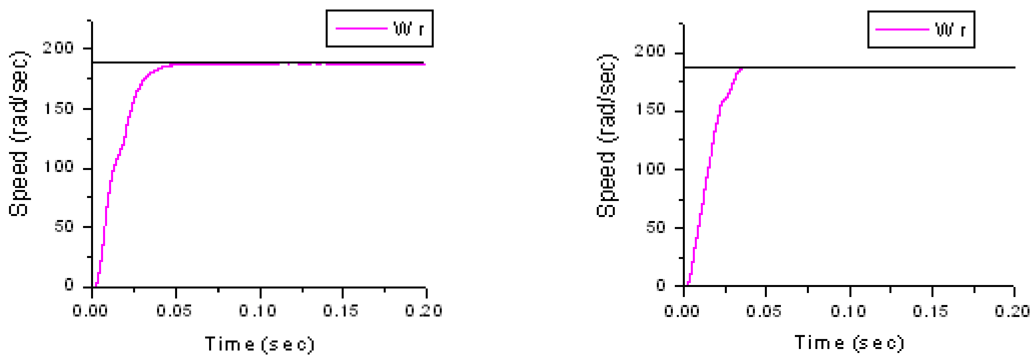
if $i_a < (i_a^* - hb)$ T1 on and T4 off
if $i_a > (i_a^* + hb)$ T1 off and T4 on
if $i_b < (i_b^* - hb)$ T3 on and T6 off
if $i_b > (i_b^* + hb)$ T3 off and T6 on
if $i_c < (i_c^* - hb)$ T5 on and T2 off
if $i_c > (i_c^* + hb)$ T5 off and T2 on

where hb is the hysteresis band around the reference currents.

4. SIMULATION RESULTS

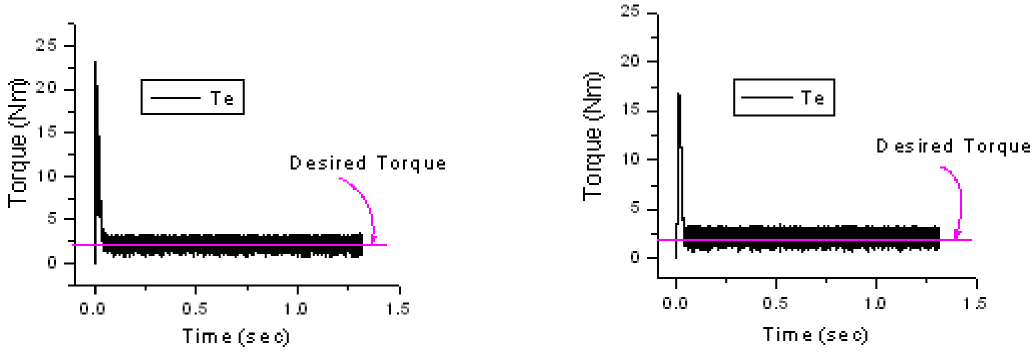
Simulation studies have been conducted in order to test the performance of the drive system. The motor parameters used in this simulation are given in Table 3. Figures 7(a)

and 7(b) show the simulated speed responses of the drive at rated load and rated speed conditions for PI and FLC based drive systems, respectively. For PI controller steady-state speed response occurs at 0.055 sec but for FLC it is 0.035 sec. So, the FLC yielded better performances in terms of faster response time.



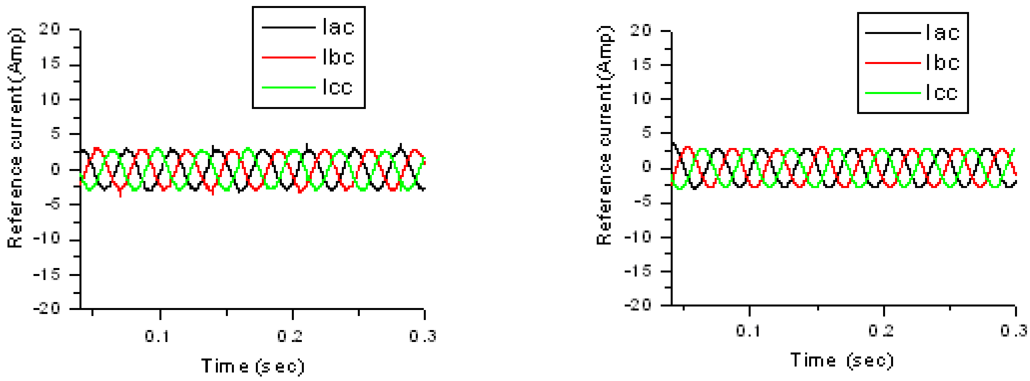
(a) (b)

Figure 7. Simulated speed responses for the IPMSM drive at rated condition. (a) PI, (b) FLC.



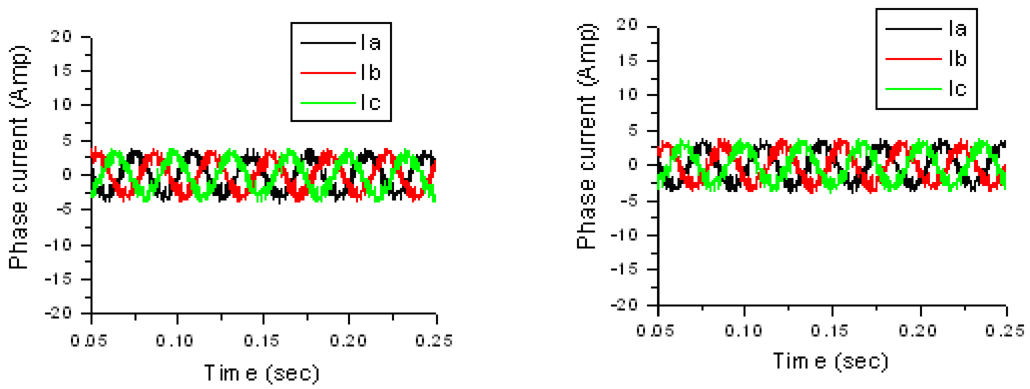
(a) **(b)**

Figure 8. Developed torques of the drive system. (a) PI, (b) FLC.



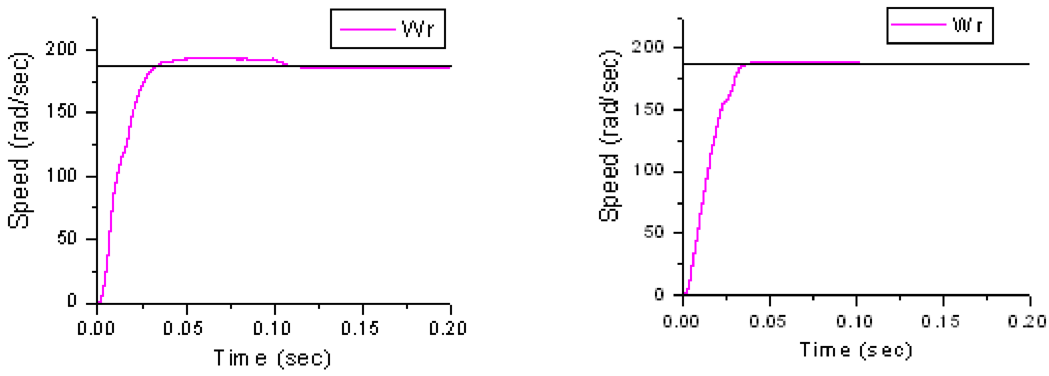
(a) **(b)**

Figure 9. Three phase reference currents for (a) PI, (b) FLC.



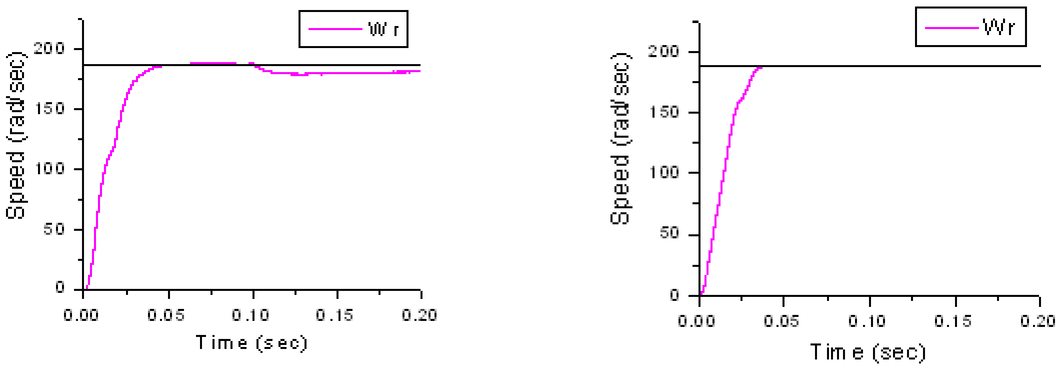
(a) **(b)**

Figure 10. Actual phase currents for (a) PI, (b) FLC.



(a) **(b)**

Figure 11. Speed responses for change in load torque. (a) PI, (b) FLC.



(a) **(b)**

Figure 12. Speed responses with change of stator resistance (R to 2R). (a) PI, (b) FLC.

Moreover, there is small ripple in the speed response for PI controller aided system.

Figures 8(a) and 8(b) show the developed torques for PI and FLC, respectively. The initial torque ripple is more in PI controller than FLC. Figures 9(a) and 9(b) show the reference currents and Figures 10(a) and 10(b) show the actual phase currents for PI and FLC, respectively.

The speed response with change of load at t=0.1 sec is given in Figures 11(a) and 11(b) for PI and FLC, respectively. Sudden application of load torque causes a very small speed oscillation for FLC. The steady-state error is almost negligible.

On the other hand, the PI controller-based system shows a larger speed oscillation. Figures 12(a) and 12(b) show the effects of stator resistance for

PI & FLC, respectively. The stator resistance has increased to double at t=0.1 sec. Figure 12 shows that the proposed FLC based drive is almost insensitive to the load disturbance. But the PI controller based system is sensitive to parameter variation.

5. CONCLUSIONS

In this paper a novel fast speed response control strategy for the interior permanent magnet synchronous motor (IPMSM) drive system using fuzzy logic controller is successfully developed. The fuzzy logic controller is used as a substitute for the conventional PI controller. The obtained simulation results show that the proposed FLC based control scheme provides faster response and improve performance than that of the conventional PI controller.

APPENDIX

Table 3. Parameters Of IPMSM [2]

Motor rated power	3-phase, 1 hp
Rated voltage (rms)	208 V
Rated current (rms)	3 A
Rated frequency	60 Hz
Pole pair number (P)	2
d-axis inductance, L_d	42.44 mH
q-axis inductance, L_q	79.57 mH
Stator resistance, R	1.93 Ω
Motor inertia, J_m	0.003 Kgm^2
Friction co-efficient, B_m	0.001 Nm/rad/sec
Magnetic flux constant, ψ_f (rms)	0.311 volts/rad/sec

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