Journal of Engineering and Technology Vol. 5, No. 1,2006 ISSN 1684-4114

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ABSTRACT

This paper presents design and implementation techniques of a maximum torque per ampere (MTPA) fuzzy controllers for an interior permanent magnet synchronous motor (IPMSM) drive. The complete drive system with Proportional-Integral (PI) controller and the fuzzy based MTPA controllers has been simulated and experimentally implemented in real time using a digital signal processor DS 1102 with a laboratory prototype 1 hp interior permanent synchronous motor. Contrary to the conventional control of IPMSM with d-axis current equals to zero, a non-linear expression of d-axis current has been derived and subsequently incorporated in the control algorithm for maximum torque operation of the fuzzy based IPMSM drive. In this work, it is observed that less stator current is required to produce the same amount of torque than that required for the zero d-axis current. This technique eventually overcomes the rating limitation of the inverter and motor in the drive system. Simulation and experimental results prove the efficacy of the MTPA fuzzy controller based IPMSM drive over the PI based IPMSM drive.

Key words: Synchronous motor, Interior permanent magnet synchronous motor, Fuzzy logic controller, Hysteresis current controller and Digital signal processor.

1. INTRODUCTION

Modern industrial drive applications require precision, efficient and sophisticated services, high efficiency and high performance of electric motor drives. Thus a drive system comprising intelligent control strategies with high performance motor is drawing considerable attention of researchers.

* Dept. of Electrical and Electronic Engineering, Rajshahi University of Engineering & Technology, Rajshahi-6204, Bangladesh.

** Dept. of Electrical & Electronic Engineering, Islamic University of Technology, Gazipur-1704, Bangladesh.

***Faculty of Engineering & Applied Science, Memorial University of Newfoundland, St. John's, Newfoundland A1B 3X5, Canada.

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1. INTRODUCTION

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The permanent magnet synchronous motor (PMSM) is becoming popular as compared to other types of ac motors due to some of its advantageous features including high torque to current ratio as well as high power to weight ratio, high efficiency, low noise and robust operation. Among various PMSMs, the permanent magnets may act in different ways. In case of the interior permanent magnet synchronous motor (IPMSM), the permanent magnets are buried within the rotor core, which provides a smooth rotor surface and reduces air gap. These are the favorable conditions for noise free high-speed operation and better dynamic performance. However, the operation of IPMSM is strongly affected by the rotor magnetic saliency, saturation and armature reaction effects. Particularly, the saturation of the rotor iron portion around the magnets produces air gap flux and affects the reactance parameters. Thus affects the performance of the IPMSM drive at different dynamic and steady state conditions. Fast and accurate speed responses, quick recovery of speed from any disturbances and insensitivity to parameter variation are some of the important criteria of the high performance drive (HPD) system used in robotics, rolling mills, machine tools etc. The conventional proportional integral (PI), proportional integral-derivative (PID) controllers and various adaptive controllers, such as, model reference adaptive controller (MRAC), sliding mode controller (SMC), variable structure controller (VSC) have been widely utilized as speed controllers in the IPMSM drive. However, the difficulties of obtaining the exact d-q axis reactance parameters of the IPMSM leads to cumbersome design approach for these controllers. Moreover, the conventional fixed gain PI and PID controllers are very sensitive to step change of command speed, parameter variation and load disturbance, Therefore, an intelligent speed controller demands special attention for the IPMSM drive to be used in an HPD system. Conventional adaptive controllers have some inherent disadvantages, such as, they need exact system mathematical model and accurate equations of system disturbances. On the other hand intelligent controller based systems, such as, artificial neural network (ANN) or the fuzzy logic based system prove their efficiencies in the control of ac drives [10-16]. As an intelligent controller the fuzzy logic controller (FLC) is considered in this work. In this research, a fuzzy controller with MTPA control have been designed and incorporated in the drive system. Fuzzy controllers have the ability to handle nonlinear system uncertainties, such as, step change in command speed, load compact, saturation and parameter variations. The advantages of fuzzy logic controller (FLC) over the conventional controllers are (1) the design of FLC does not need the exact mathematical model of the system; (2) the FLC is more robust than the conventional controllers; (3) it can handle nonlinear functions of any arbitrary complexity; (4) it is based on the linguistic control rules, which are also the basis of human logic. In order to achieve the high performance, vector control of IPMSM drive was employed [2] in the past. However, the control techniques become complicated due to non-linearities of the developed torque for non-zero value of d-axis current. Many researchers have focused their attention on the vector control of IPMSM drive by forcing the d-axis current equals to zero, which essentially linearizes the motor model [2-5]. In practical, the electromagnetic torque is non-linear in nature. In order to incorporate the system non-linearity in a practical IPMSM drive, a control technique known as maximum torque per ampere (MTPA) is derived which provides maximum torque with minimum stator current [6]. This MTPA strategy is very important from the limitation of IPMSM and inverter rating point of view, which optimizes the drive efficiency. Fig.1 shows the maximum torque per ampere trajectory, which provides information for the control strategy. The problem associated with MTPA control technique is that its implementation in real time becomes complicated because there exists a complex relationship between d-axis and q-axis currents. Some researchers have solved this problem by considering look-up table of d- and q-axis currents [7]. The objective of this paper is to present a simplified FLC based MTPA speed controller for the IPMSM drive where simplified expression of torque has been derived (equation 8 of section 3) and incorporated for the FLC controller based system. The system is designed in such as way as to maintain the criteria of high performance drives employing a less complex algorithm of FLC, which reduces the computational burden and allows real time implementation. The proposed IPMSM drive system with fuzzy controllers has been simulated and implemented in the laboratory. The results of FLC based IPMSM drive has been compared with those obtained from the PI based IPMSM drive. The comparisons confirm the superiority of the MTPA FLC based IPMSM drive over the PI based IPMSM drives.

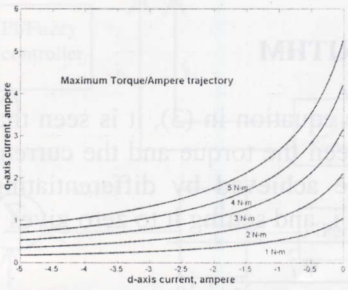

Fig.1 Maximum torque per ampere (MTPA) trajectory on constant torque loci

2. IPMSM DYNAMICS

The mathematical model of an IPMSM drive can be described by the following equations [2] in a synchronously rotating rotor d-q reference frame as,

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} R + pL_d & -P\omega_r L_q \\ P\omega_r L_d & R + pL_q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 \\ P\omega_r \psi_f \end{bmatrix} \tag{1}$$

$$T_e = T_L + J_m p\omega_r + B_m \omega_r \tag{2}$$

$$T_e = \frac{3P}{2}\left(\psi_f i_q + (L_d - L_q) i_d i_q\right) \tag{3}$$

where, v_d, v_q = d- and q-axis stator voltages;
i_d, i_q = d- and q-axis stator currents;
R = stator per phase resistance;
L_d, L_q = d- and q-axis stator inductances;
J_m = moment of inertia of the motor and load;
B_m = friction coefficient of the motor;
P = number of poles of the motor;
ω_r = rotor speed in angular frequency;
p = differential operator (=d/dt);
ψ_f = rotor magnetic flux linking the stator;
T_e, T_L = electromagnetic and load torques;

Equation (1) is the d- and q-axis voltage equations which can be obtained from the IPMSM equations using Park's transformation. Equation (2) presents the motor dynamic equation and (3) is the equation of the developed torque for the IPMSM. Equations (1) and (2) have been used to simulate the proposed drive system.

3. CONTROL ALGORITHM

According to the torque equation in (3), it is seen that there exists a non-linear relationship between the torque and the currents. Maximum torque per unit current can be achieved by differentiating equation (3) with respect to q-axis current i_q and setting it to zero gives

$$i_d = \frac{\psi_f}{2(L_q - L_d)} - \sqrt{\frac{\psi_f^2}{4(L_q - L_d)^2} + i_q^2} \tag{4}$$

Substituting equation (4) in (3), one can get a non-linear lationship between i_q and T_e as

$$T_e = \frac{3P}{2}\left(\psi_f i_q - \frac{\psi_f i_q}{2} - \left(L_d - L_q\right)\sqrt{\frac{\psi_f^2 i_q^2}{4\left(L_q - L_d\right)^2} + i_q^4}\right) \tag{5}$$

Real time implementatation of the drive system becomes complex and it overburdens the DSP with expressions in (4) and (5). In order to solve this problem, this work presents a simplier relationship between d- and q-axis currents which is obtained by expanding the square root term of equation (4) using Taylor series expansion at a point approahing zero, which gives

$$i_d = -0.11825\ (i_q - 0.001)^2 \tag{6}$$

Numerical values of equation (6) are obtained by using the parameters of the motor in appendix-A. Substituing (6) in (3), the following relationship can be obtained

$$i_q = 0.001 - 1.06157 * T_e \tag{7}$$

which leads to $T_e = \frac{1}{1.06157}(0.001 - i_q)$ (8)

Equations (6) and (7) are the key equations used for the MTPA control of IPMSM. Block diagram in Fig.2 shows the control scheme of the motor drive. The command torque is obtained from the designed speed controller. Using equation (7), reference q- axis current i_q^* is computed first, subsequently reference d-axis current i_d^* is calculated using equation (6).

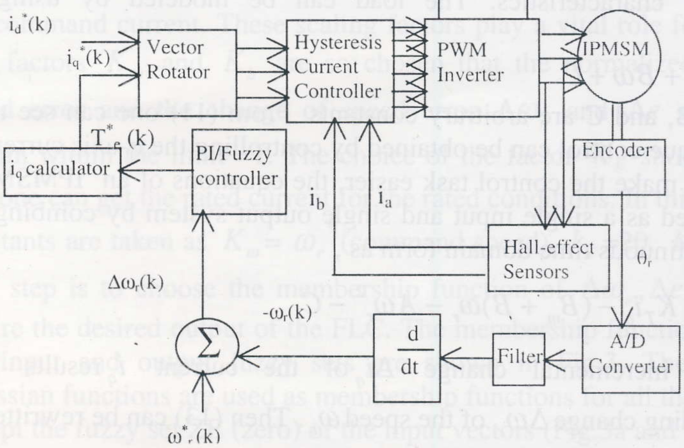

Fig.2 Block diagram for the proposed controller based IPMSM Drive.

Using these reference currents, three phase currents are determined by the vector rotator block. The hysteresis current controller compares the reference three phase currents with the actual currents and generates the base signals for the transistorized inverters.

4. FLC STRUCTURE

In this work, unlike the conventional approach of controlling the speed, the vector control technique is incorporated with the FLC to obtain the highest torque response of the IPMSM drive. The vector control technique is formulated within the d-q synchronously rotating rotor reference frame so that the reactance parameters are no longer dependent on the rotor position or speed. The complexity of the control arises due to the non-linear nature of the torque expressed by (3), Moreover, the values of L_d and L_q undergo significant variation at various steady state and dynamic loading conditions. In order to operate the motor in the vector control scheme, d-axis current (i_d) is set to zero such that the motor is operated like a separately excited dc motor. The dynamic model of the IPMSM may be rewritten from (1-4) setting i_d=0, as

$$PL_q = (V_q - ri_q - K_b\omega_r)/L_q \quad (9)$$

$$p\omega_r = (T_e - T_L - B_m\omega_r)/L_q \quad (10)$$

$$T_e = K_T i_q \quad (11)$$

where K_T=(3/2) K_b and K_b=p φ_r . As the FLC can handle any type of non-linearity, one can consider the load of non-linear unknown mechanical characteristics. The load can be modeled by using the following

$$T_L = A\omega^2 + B\omega + C \quad (12)$$

where A, B, and C are arbitrary constants. From (11) one can see that a precise torque control can be obtained by controlling the q-axis current i_q . In order to make the control task easier, the equations of an IPMSM can be expressed as a single input and single output system by combing (9)-(11) in continuous time domain form as ,

$$J_m \frac{d\omega_r}{dt} = K_T i_q - (B_m + B)\omega_r - A\omega_r^2 - C \quad (13)$$

A small incremental change Δi_q of the current i_q results in a corresponding change $\Delta\omega_r$ of the speed ω_r . Then (13) can be rewritten as

$$J_m \frac{d\omega_r}{dt} = K_T\Delta i_q - (B_m + B)\Delta\omega_r - A\Delta\omega_r^2 \quad (14)$$

By replacing all the continuous equations of (14) by their finite differences, the discrete time small signal model of the simplified IPMSM with load can be given as,

$$\Delta i_q(n) = -\frac{J_m}{K_T T_L}\Delta e(n) + (B_m + B)\Delta\omega_r(n) + A[\Delta\omega_r(n)]^2 \qquad (15)$$

$$\text{Hence,} \quad i_q(n) = \int_{discreate} \Delta i_q(n) = f[\Delta e(n), \Delta\omega_r(n)] \qquad (16)$$

where $\Delta e(n) = \Delta\omega_r(n) - \Delta\omega_r(n-1)$ is the change of speed error, $\Delta\omega_r(n) = \omega_r^*(n) - \omega_r(n)$ is the present sample of speed error , $\Delta\omega_r(n-1)$ is the past sample of speed error, $\omega_r(n)$ is the present sample of actual speed, $\omega_r^*(n)$ is the present sample of command speed and f denotes the nonlinear function. The purpose of using the proposed FLC is to map the nonlinear functions relationship between q –axis current i_q and speed ω_r .

One of the most important tasks of designing an FLC is to determine the input and output linguistic variables. The equation of the q-axis current expressed by (16) defines the input and output linguistic variables for the FLC of the IPMSM drive. According to (16) the inputs of the proposed FLC are the change of speed error and change of speed. Thus the input vectors of the FLC are $\Delta\omega_r(n)$ and $\Delta e(n)$ and output vector in the q-axis command current $i_q^*(n)$. The block diagram of proposed FLC based IPMSM drive shown in Fig.2. The next step is to choose the scaling factors K_ω, K_b and k_T for fuzzification and obtaining the actual output of the command current. These scaling factors play a vital role for the FLC. The factors K_ω and K_b are so chosen that the normalized values of speed error and the change of speed error $\Delta\omega_r$ and Δe respectively remain within the limit =1. The choice of the factor K_b should be such that one can get the rated current for the rated conditions. In this paper, the constants are taken as $K_\omega = \omega_r^*$ (command speed), k_T=20, K_ω=10. The next step is to choose the membership function of $\Delta\omega_r$, Δe and i_q^* to ensure the desired output of the FLC. The membership functions used for the input and output fuzzy sets are shown in Fig.3. The combined Gaussian functions are used as membership functions for all the fuzzy sets except the fuzzy set ZE (zero) of the input vectors (Fig.3a and Fig.3b) and fuzzy sets of the output vectors (Fig.3c). Based on the above rules the fuzzy rule base matrix is formulated, which is show in Table I where input vectors are speed error ($\Delta\omega_r$) and change of speed error (Δe) and output vector is q-axis current (i_q).

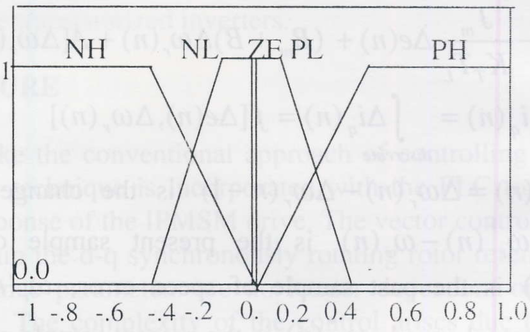

Fig.3 (a) Membership function for speed error $\Delta\omega_r$

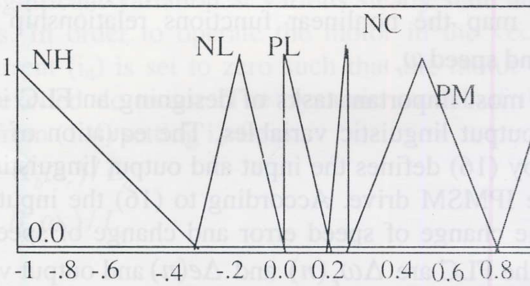

Fig. 3(b) Membership function for change of speed error Δe (n)

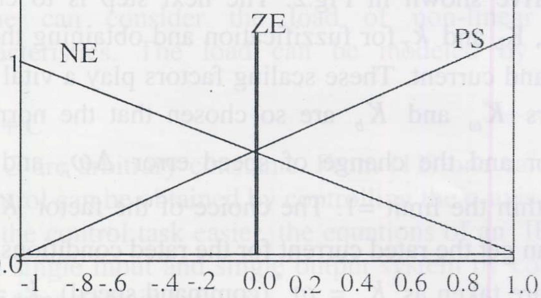

Fig.3 (c) Membership function for quadrature-axis current. i_q

Table-I: Fuzzy rule from matrix.

Δe / $\Delta\omega_r$	NH	NL	ZE	PL	PH
NE	NH	NL	NC	PM	PH
ZE	NH	NL	NC	PM	PH
ZE	NH	NL	PL	PM	PH

For the present work, Mamdani type [17] fuzzy inference is used. The values of the constants, membership functions, fuzzy sets for the input and output variables and the rules used in this paper are selected by trial and error to obtain the optimum drive performance. The rules used for the proposed FLC algorithms are shown in Table II.

Table-II: (Fuzzy Rules)

(1) If $\Delta\omega_r$ is PH, i_q is PH.

(2) If $\Delta\omega_r$ is PL, i_q is PM.

(3) If $\Delta\omega_r$ is ZE and Δe is PS, i_q is PL.

(4) If $\Delta\omega_r$ is ZE and Δe is not PS, i_q is NC.

(5) If $\Delta\omega_r$ is NL, i_q is NL.

(6) If $\Delta\omega_r$ is NH, i_q is NH.

where PH=positive high, PL=positive low, PM=positive medium, ZE=zero, PS=positive, PL=positive low, NC=no change, NL=negative low and NH=negative high.

5. REAL-TIME IMPLEMENTATION

The complete IPMSM drive system has been implemented in the laboratory for a 1-hp laboratory IPMSM using DSPACE DSP controller board [8]. The DSP board is installed in a PC with uninterrupted communication capabilities through dual-port memory. The DSP has been supplemented by a set of on-board peripherals used in digital control systems, such as A/D, D/A converters and incremental encoder interfaces. The DS 1102 is also equipped with a TI TMS320P14, 16-bit micro controller DSP that acts as a slave processor and is used for some special purposes. In this work, slave processor is used for digital I/O configuration. The actual motor currents are measured by the Hall-effect sensors which have good frequency response and fed to the DSP board through an A/D converter. As the motor neutral is isolated, only two-phase currents are fed back to an A/D converter and the other phase current is calculated from them. Three phase reference currents are generated utilizing reference q- and d-axis currents and rotor position angle obtained through encoder mounted on the shaft of the motor. Computed three phase reference currents are converted to upper and lower hysteresis by adding and subtracting a reselected band. Hysteresis currents are compared with actual motor currents and PWM base drive signals are generated.

All computations for generating reference currents and consequently base drive signals for the inverter are done by developing a program in

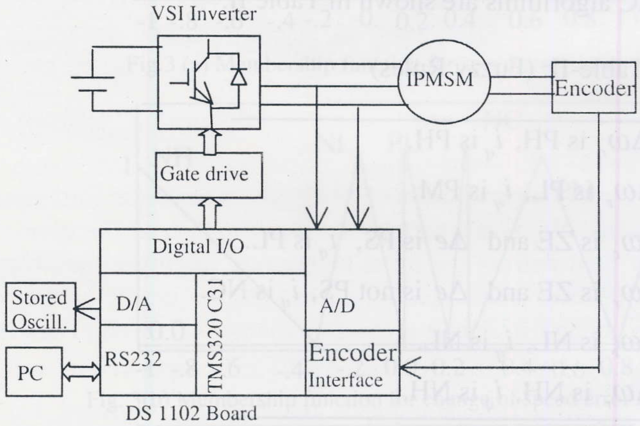

Fig.4 Hardware schematic for real time implementation.

ANSI C programming language. The program is compiled using Texas Instrument C compiler and downloaded to the DSP controller board. The sampling frequency for experimental implementation of the proposed drive is 10 kHz.

6. RESULTS AND DISCUSSIONS

Before implementing the IPMSM drive in real-time, numerous simulations have been carried out to test the performance of the proposed FLC based drive. The simulation is carried out using the Matlab Fuzzy Logic Toolbox. The speed and current responses are observed under different operating conditions, such as, various command speeds, sudden application of load, step change in command speed and at different loading conditions. Some of the sample results are presented in this paper. Fig.5 and 8 show the simulated starting performance of the drive with PI- and FLC-based drive systems respectively with reference speed (rated speed of the motor) of 188.5 rad/sec at a load of 2 N-m. Although the PI controller is tuned to give an optimum response, the fuzzy controller yielded better performances in terms of faster response time without any overshoot and lower starting current. Fig.6 and 7 show the experimental speed and steady state current response of the drive with PI/ i_d=0 and MTPA drive systems respectively at a reference speed of 188.5 rad/sec at the same loading condition. The speed response of the MTPA control is clearly superior while requiring less stator current. Fig.9 (a) and (b) show experimental speed and steady state current response of the fuzzy based IPMSM drive system with the reference speed at a load of 2 N-m. Fig.10 (a) and (b) show simulated speed responses of the drive system using PI and FLC, respectively with a step change in the reference speed. It is evident from Fig.10 (b) that the proposed FLC based drive system can follow the command speed without any overshoot and steady state error. Thus, the FLC-based drive system is not affected by the sudden change of command speed. So, a good tracking has been achieved for the FLC, whereas the PI-controller based drive system is affected with sudden change in command speed. Fig.11 and 12 show speed and current responses of the drive system using PI and FLC, respectively with a sudden change in loading torque. The motor was started with no load and this value was increased to 2 N-m after two seconds causing a drop in motor speed. The PI took less than 0.5 second and fuzzy logic controller took negligible time to respond to this change in torque for operating the motor at the command speed. All the experimental results show that the proposed FLC based IPMSM drive can follow the command speed perfectly at different dynamic operative conditions without overshoot and almost zero steady state error. This clearly proves the robustness of the fuzzy logic controller. Thus the proposed fuzzy logic MTPA IPMSM drive system its efficacy both in simulation and real time implementation.

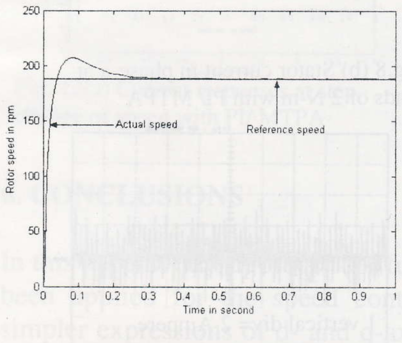

Fig. 5(a) Speed responses at a load of 2 N-m with PI controller/ MTPA

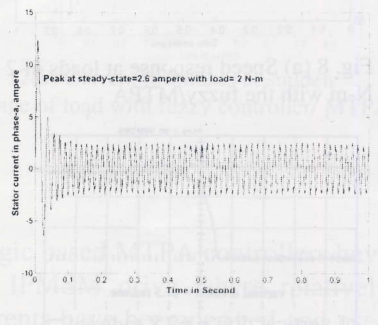

Fig. 5 (b) Stator current in phase-a at a load of 2 N-m with PI/ MTPA

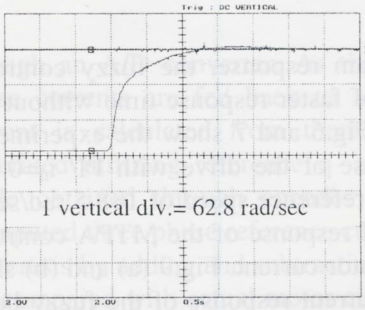

Fig.6 (a) Experimental speed response at a load of 2 N-m with $PI/i_d=0$

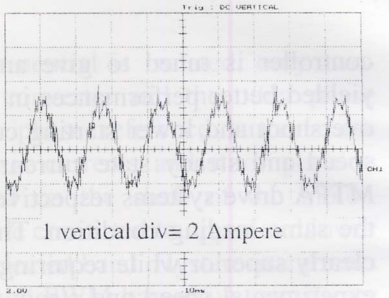

Fig.6 (b) Experimental current response at a load of 2 N-m with $PI/i_d=0$

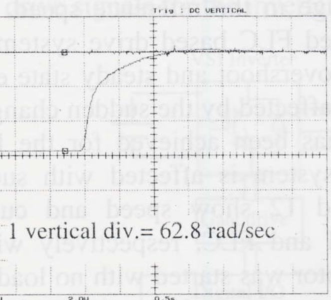

Fig.7 (a) Experimental speed response at a load of 2 N-m with PI/MTPA

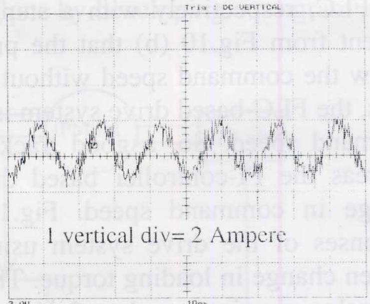

Fig.7 (b) Experimental current response at a load of 2 N-m with PI/MTPA

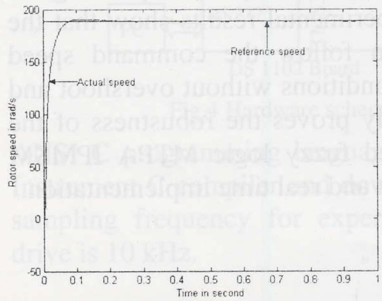

Fig. 8 (a) Speed response at loads of 2 N-m with the fuzzy/MTPA

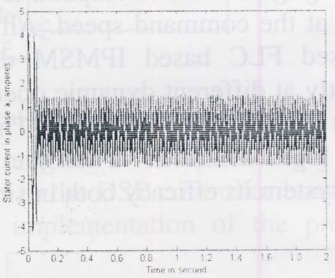

Fig.8 (b) Stator current in phase-a at loads of 2 N-m with PI/ MTPA

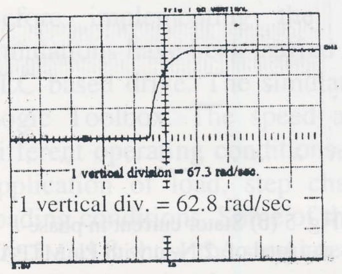

Fig. 9(a) Experimental speed response a load of 2 N-m with the fuzzy/MTP

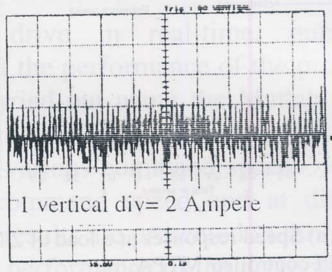

Fig. 9(b) Experimental current response at a load of 2 N-m with the fuzzy/MTPA

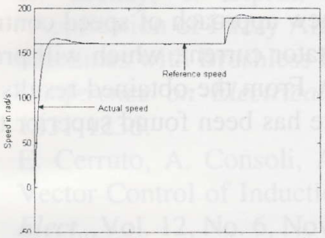

Fig. 10 (a) Speed response with a step change of reference speed at loads of 2 N-m using PI/MTPA

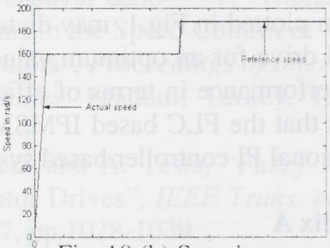

Fig. 10 (b) Speed response with a step change of reference speed at loads of 2 N-m using the fuzzy/MTPA

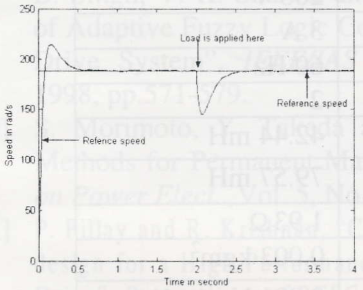

Fig. 11 (a) Speed responses at sudden change of load with PI/ MTPA

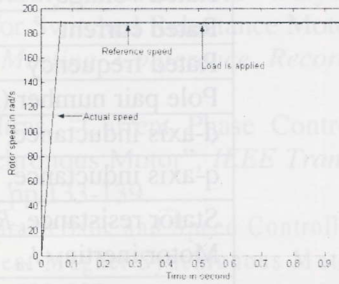

Fig. 11 (b) Stator current in phase-a at loads of 2 N-m with the fuzzy/MTPA

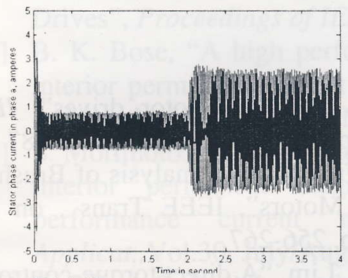

Fig. 12(a) Current responses at step change of speed with PI/ MTPA

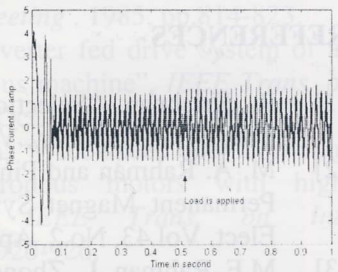

Fig. 12(b) Current responses at sudden change of load with fuzzy controller/ MTPA

6. CONCLUSIONS

In this paper a new approach for fuzzy logic based MTPA controllers have been applied for the speed control of IPMSM drive where relatively simpler expressions of d- and q-axis currents have been derived and used in the IPMSM drive system. Simplified fuzzy controller for the IPMSM has also been designed and implemented in the laboratory. The fuzzy based IPMSM drive system is efficient enough to operate in no load and also under various loading conditions. Derived equation of MTPA, which has been plotted in Fig.1, may dictate a new approach of speed control of IPMSM drive for an optimum value of stator current, which will provide better performance in terms of efficiency. From the obtained results, it is obvious that the FLC based IPMSM drive has been found superior to the conventional PI controller based system.

Appendix A

Table-III: Machine parameters

Motor rated power	3-phase, 1 hp
Rated voltage	208 V
Rated current	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 coefficient, B_m	0.001 Nm/rad/sec
Magnetic flux constant, ψ_f	0.311 volts/rad/sec

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