A Complete Fuzzy Logic Based Real-Time Simulation of Vector Controlled PMSM Drive

A Mishra
EE Deptt, NIT Patna
Patna, India
ambrishee@gmail.com

Garima Dubey
EC Deptt
Rajkiya Plytechnic
Kanpur, India
garidubey2012@gmail.com

Dheeraj Joshi
EE Deptt
DTU Delhi
India
joshidheeraj@dce.ac.in

Pramod Agarwal
EE Deptt
IIT Roorkee
Roorkee, India
pramgfee@iitr.ac.in

S P Sriavstava
EE Deptt
IIT Roorkee
Roorkee, India
satyafee@iitr.ac.in

***Abstract*—The replacement of speed proportional plus integral (PI) controller by fuzzy logic controller is a most promising application of artificial intelligence in motion control application. The stator current divided in two components- d-axis and q-axis currents. The mathematical model of PMSM in per unit values is presented. The whole vector controlled drive has two loops; inner currents and outer speed loop. In this paper fuzzy-logic is employed for all these controllers. To execute the control rules of fuzzy inference engine, the actual error inputs to controller have been normalized by using input scaling factors. To assure that output of fuzzy logic controller is appropriate for actual system being controlled, output scaling factors are used. Each controller has different parameters like range of MFs, input-output range, so the tuning of three controllers are also different. Tuning of individual controllers is done by investigating the performance with PI controller. The exhaustive simulation is done in different operating conditions, and implemented in real time at FPGA based RT-LAB. The performance of complete fuzzy controller is compared with PI controller for PMSM drive. Simulation and experimental results validate the efficacy of proposed controllers.**

Keywords—FPGA, FLC, Modeling, PI-controller, PMSM, Per Unit, RT-LAB, SVM

I. Introduction

The 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. The benefits of PMSM on dc motor are; less audible noise, longer life, sparkless operation, higher speed, good heat transfer, higher smaller size. Advantages of PMSM on induction motors are; better efficiency, better power factor, higher power density and smaller size, and better heat transfer. Moreover popularity of PMSM comes from their desirable features; compact size, high efficiency, low noise and robustness, high torque to inertia ratio, high torque to current ratio, high air gap flux density, and high acceleration and deceleration rate.

With the recent developments in digital electronics, DSPs and ASICs PMSMs are gradually replacing the DC motors in wide range of drive applications. The development in high energy permanent magnets like NdBFe PMSM is becoming more popular in adjustable speed drive applications[1]. Due to inherent coupling effect the torque control becomes complicated. In vector controlled PMSM drives decoupled torque, flux makes the control quite easier. Speed controller used in PMSM drive plays an important role in achieving high performance[2]. In motion control applications speed controller plays an important role as it affects the efficiency, dynamic response etc of motor [3, 4]. In high performance drive (HPD) the controller exhibits a important role so it is affecting the supply of current to motor and improves the dynamic performance of motor [3, 5] [6].

One of the inherent problems with PI controller is sluggish response. The improved performance with d-q axis current controller in synchronous reference frame using PI controller are presented in [7, 8]. Both methods utilizes the complex vector to reduce complication of system to be implemented and designed. These techniques are principally move plant pole towards zero of controller or zero of controller towards pole of plant.

II. Background Theory

Scalar control is based on relationships valid in steady state. It is simple but due to the inherent coupling effect (i.e., torque and flux are proportional to the voltage or current and frequency) gives sluggish response and the system can be easily prone to instability. Vector control clearly requires instantaneous control of stator current[9]. Vector control usually realized with digital PWM controller in rotating (d-q) reference frame[10]. Aim of vector control is to control flux and torque of machine to drive the motor to accurately trace the reference command value irrespective of load, machine parameter and any external environmental changes. In vector control stator current is controlled instantaneously which reduces the torque ripples and improves overall performance of machine[11].

Among artificial intelligent techniques[12] (ANN, Fuzzy, GA), the FLC is less complex as compared to other techniques for achieving the desired performance. To improve the robustness of system, the complication of neural network controller increases and implementation becomes challenging with limited processing speed.

To reduce the torque ripples, Ref. [13]proposed a fuzzy

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logic algorithm to refine the selection of the voltage vectors. By using the space vector modulation (SVM), the torque and flux ripples can be more significantly reduced [14].

A fuzzy logic controller is a non-linear controller which provides good performance with robustness for linear and non-linear system [15]. Fuzzy logic is a mathematics based logic combination, artificial intelligence, and probability algorithms to implement the mankind way for solving problems by reasoning to combine various data and to achieve desired result.

Three FLCs are used in this paper for vector controlled PMSM drive and investigated. The FLCs are used with scaling factors. The values of these scaling factors are distinct for speed and current controllers based on their input error range, required output range, and interval of membership function defined for that individual controller. The tuning of controller is with system parameter to achieve better performance. The fuzzy based drive is implemented in Simulink. Simulation and experimental results validate the effectiveness of the controllers.

III. Mathematical Model of PMSM in P.U.

Mathematical modeling of motor is presented and simulation and analysis of drive system is done. The equations of PMSM are given d-q reference frame[16].
It is assumed that nominal power of motor as base power. Peak per phase voltage is assumed as base voltage. Peak value of instantaneous stall current is base current. Base voltage is derived from nominal power and continuous stall current. Here the motor equations are derived in p.u. Base values of PMSM is based on,

$$V_b=\sqrt{2}V_{rms};\ ib=\sqrt{2}i_{rms};\ S_b=\frac{3}{2}V_b i_b;\ T_b=\frac{S_b}{\omega_{bm}}$$

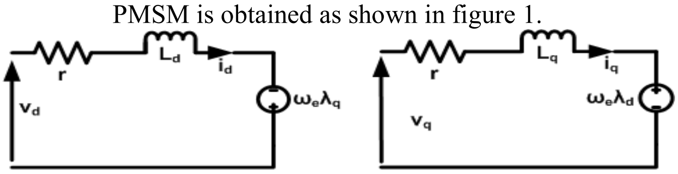
ω_{bm} = Base mechanical speed in Rad. /sec. $\omega_{be}=\frac{P}{2}\omega_{bm}$

ω_{be} = Base electrical speed in Rad. /sec.
Motor d-q axis rotor reference frame equations are,

$$V_{ds}=i_{ds}r+l_d\frac{di_d}{dt}-\omega_s l_q i_q \qquad (1)$$

$$V_{qs}=i_{qs}r+l_q\frac{di_q}{dt}+\omega_s l_d i_d+\lambda_{af}\omega_s \qquad (2)$$

Equation (1) and (2) are the voltage equations of PMSM used in vector control, based on that equivalent circuit of PMSM is obtained as shown in figure 1.



(a) d-axis equivalent circuit (b) q-axis equivalent circuit

Fig.1.PMSM equivalent circuit

Dividing both sides of equations (1) and (2) by base voltage V_b

$$\frac{V_{ds}}{V_b}=\frac{ri_{ds}}{V_b\frac{i_b}{i_b}}+\frac{l_d}{V_b\frac{i_b\,\omega_{be}}{i_b\,\omega_{be}}}\frac{di_d}{dt}-\frac{l_q}{V_b\frac{i_b\,\omega_{be}}{i_b\,\omega_{be}}}\omega_s i_q \qquad (3)$$

$$\frac{V_{ds}}{V_b}=\frac{ri_{ds}}{V_b\frac{i_b}{i_b}}+\frac{l_d}{V_b\frac{i_b\,\omega_{be}}{i_b\,\omega_{be}}}\frac{di_d}{dt}-\frac{l_q}{V_b\frac{i_b\,\omega_{be}}{i_b\,\omega_{be}}}\omega_s i_q \qquad (4)$$

Hence, equations in P.U. (taking time in actual values) are;

$$V_{ds\_p.u.}=i_{ds\_p.u.}r_{\_p.u.}+l_{d\_p.u.}\frac{di_{d\_p.u.}}{\omega_{be}dt}-\omega_{s\_p.u.}l_{q\_p.u.}i_{q\_p.u.} \qquad (5)$$

$$V_{qs\_p.u.}=i_{qs\_p.u.}r_{\_p.u.}+l_{q\_p.u.}\frac{di_{q\_p.u.}}{\omega_{be}dt}+\omega_{s\_p.u.}l_{d\_p.u.}i_{d\_p.u.}+\lambda_{af\_p.u.}\omega_{s\_p.u.} \qquad (6)$$

Torque equation of motor is given as;

$$T_e=T_L+B\frac{2}{P}\omega_s+J_m\frac{2}{P}\frac{d\omega_s}{dt} \qquad (7)$$

Dividing by base torque in both sides

$$\frac{T_e}{T_b}=\frac{T_L}{T_b}+\frac{2}{P}\frac{B}{T_b\frac{\omega_{be}}{\omega_{be}}}\omega_s+\frac{2}{P}\frac{J_m}{T_b\frac{\omega_{be}^2}{\omega_{be}^2}}\frac{d\omega_s}{dt} \qquad (8)$$

Torque equation in p.u. (taking time in actual values)

$$T_{e\_p.u.}=T_{L\_p.u.}+\frac{2}{P}B_{\_p.u.}\omega_{s\_p.u.}+\frac{2}{P}J_{m\_p.u.}\frac{d\omega_{s\_p.u.}}{dt} \qquad (9)$$

The torque developed by motor is;

$$T_e=\frac{3}{2}\frac{P}{2}\left[\lambda_{af}i_{qs}+\left(l_q-l_d\right)i_{qs}i_{ds}\right] \qquad (10)$$

Dividing by base torque on both sides

$$\frac{T_e}{T_b}=\frac{3}{2}\frac{P}{2}\left[\frac{\lambda_{af}i_{qs}}{T_b\frac{i_b}{i_b}}+\frac{\left(l_q-l_d\right)i_{qs}i_{ds}}{T_b\frac{i_b^2}{i_b^2}}\right] \qquad (11)$$

Equation in p.u. (time in actual value) is;

$$Te=\left(\frac{P}{2}\right)\left[\lambda_{af\_p.u.}i_{qs\_p.u.}+\left(l_{q\_p.u.}-l_{d\_p.u.}\right)i_{qs\_p.u.}i_{ds\_p.u.}\right] \qquad (12)$$

Electrical rotor Angle can be calculated from;

$$\theta_{re}=\int\omega_s dt \qquad (13)$$

$$\theta_{re}=\int\omega_{s\_p.u.}\omega_{be}dt \qquad (14)$$

Normally the drive is considered with standard PI controllers. For the research in area of drives to design most of the controllers, first of all the performance of the drive system is analyzed with PI controllers. Then based on the performance of drive, speed error, current error, speed of motor, torque generated by motor etc. provides a basic understanding of the required control actions. By using this knowledge as base criteria the controller design is being started.
Equation of PI controller;

$$T^* = K_p d\omega_s + K_i \int d\omega_s dt \tag{15}$$

Dividing by base torque on both sides

$$\frac{T^*}{T_b} = \frac{K_p}{T_b \frac{\omega_{be}}{\omega_{be}}} d\omega_s + \frac{K_i}{T_b \frac{\omega_{be}}{\omega_{be}}} \int d\omega_s dt \tag{16}$$

The equation in p.u. is

$$T^*_{\_p.u.} = K_{p\_p.u.} d\omega_{s\_p.u.} + K_{i\_p.u.} \int d\omega_{s\_p.u.} dt \tag{17}$$

For the simulation of the motor with actual parameter values Eq. (1), (2), (7), (10), (13) and (15) are used. Generally to perform more accurate calculations normalized or p.u. values of parameter are used for this Eq. (5), (6), (9), (12), (14), and (17) are used.

IV. Synthesis of Fuzzy Logic Controller

Fig. 2 shows the block diagram of FLC. The design steps for fuzzy logic controller for speed and current control of PMSM are as follows

1. Find out input and output variables.
2. Select membership functions and specify control rules.
3. Specify possible inference with membership functions and control rules.
4. Translate the fuzzy set into crisp set.
5. Tune the input and output gains appropriately to get the desired performance.

To control the speed of PMSM using FLC in this paper error (e) and change in error (ce) in corresponding variables are considered as input crisp variables and are defined as[17]

Error in speed is defined as

$$\Delta\omega_r(n) = \omega^*_r(n) - \omega_r(n) \tag{18}$$

Error in d-axis current is defined as

$$\Delta i_d(n) = i^*_d(n) - i_d(n) \tag{19}$$

Error in q-axis is defined as

$$\Delta i_q(n) = i^*_q(n) - i_q(n) \tag{20}$$

Change in error for all three variables is defined as

$$\Delta e(n) = e(n) - e(n-1) \tag{21}$$

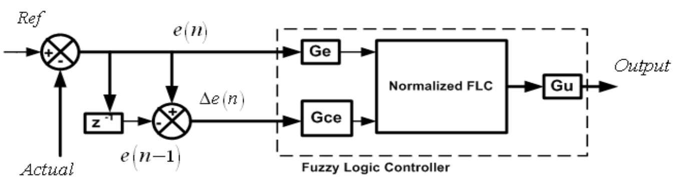


Fig. 2: Block Diagram of FLC.

Based on the prior experience of the system, the membership functions and control rules defined are defined. The normalized inputs and output are obtained for fuzzy logic controller by using gain blocks as scaling factors G_e, G_{ce} and G_u [18]as shown in fig. 2.

In this paper for current controller only five variables are chosen 1) negative medium (NM); 2) negative small (NS); 3) zero (Z); 4) positive small (PS); 5) positive medium (PM); as shown in figure 3. For speed controller 7 variable are considered: 1) Negative Large (NL); 2) Negative Medium (NM); 3) Negative Small (NS); 4) Zero (Z); 5) Positive Small (PS); 6) Positive Medium (PM); 7) Positive Large (PL) as shown in figure 4.In case of speed controller more variables chosen because the variation and range of speed error is more as compared to current error.

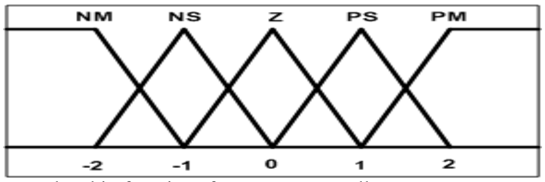


Fig. 3: Membership functions for current controllers

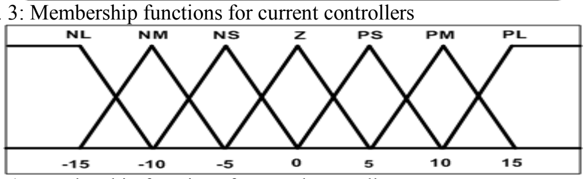


Fig. 4: Membership functions for speed controller

In the second stage of FLC, variables E and CE executed by inference engine of FLC that executes control rules stored in (7 × 7) rule base for speed controller and (5×5) rule base for current controller. Every rule is expressed in form of

Rule: IF 'E' is A and 'CE' is B, THEN 'Output' is C

Where 'E', 'CE', and 'Output' are fuzzy subsets. The control rules are formulated using behavior of PMSM. Derivation of control rules are based on following criteria for PMSM.

- When speed error is more positive then to catch up the reference speed, current reference has to be more.
- When speed error is small positive and change in speed error is large then current reference has to be kept constant to avoid overshoot
- At zero speed error current reference has to be unchanged.
- At negative speed error current reference has to be negative.

A robust controller with FLC requires tuning of parameter [19]. As shown in block diagram of FLC, there are three (two input and one output) scaling factors G_e, G_{ce} and G_u used. Depending upon the parameter of PMSM, inverter, load, and reference speed these scaling factors are tuned.

The current controller is same as speed controller shown in fig.2. Scaling factors for different controller is different, because input and output requirement of every controller is different. For example fuzzy speed controller has speed error as input and, q-axis current controller has q-axis current error (difference of i^*_q and i_q), and d-axis current controller has d-axis current error (difference of i^*_d and i_d). So the gains have to be different to normalize them into range specified by respective MFs. In this paper for the linguistic variable of current controller triangular MFs are selected in the interval [-2 2], for speed controller the interval is [-15 15]. To obtain the normalized error and change in the error in range defined for corresponding controller gains blocks have to be used. The control rules will be executed only when the inputs E and CE are normalized using gain blocks, in the range specified for the corresponding controller. In this paper max-min algorithm is implemented to obtain output from inputs executed by control rules. In centroid algorithm of defuzzification crisp values are achieved from center of gravity of MFs.

V. OPAL-RT LAB TECHNOLOGY

Real time simulation of full fuzzy controlled PMSM drive on FPGA based real time simulator which produce the actual results. RT-LAB, from Opal-RT Technologies, is a real-time simulation platform that enables real time and HIL (hardware in loop) simulation of controllers, electric plants or both, through automatic code generation methods. The entire process occurs without the need for handwritten 'C' code, enabling very rapid deployment of prototyped controllers or HIL-simulated plants. The process is notably very efficient when applied to I/O code because RT-LAB provides a set of simulink blocks that automatically configure common I/O functions, like analog input/outputs and time-stamping capable digital I/Os, with a 10 nanosecond resolution. Special interpolating models use this timing information to greatly increase simulation accuracy [23]. RT-LAB simulator is equipped with a user-programmable FPGA card. The FPGA card can be programmed with the Xilinx System Generator blockset for Simulink enabling implementation of complex sensor models like resolvers, Resolver-To-Digital and FM resolvers or even complex motor drives [24]. RT-Lab is used as real time hardware-in-loop controller in this implementation for easy and flexibility [20]. Table I summarizes the characteristics of FPGA board used in this paper.

TABLE I.
RECONFIGURABLE FPGA BOARDS

Model Name	FPGA	Bus type	Gate	I/O lines	Logic cells	FPGA clock	
OP5142	Xilinx Spartan 3 XG3S500	PCI-Express 1x	5M	296	74.880 ((74k)	100 MHz	

VI. PERFORMANCE EVALUATION

The vector control of PMSM is applied to obtain the performance as of dc-machine. The stator current is devided in d-axis and q-axis currents[3]. The voltage reference is generated by current controllers for both axis. The schematic diagram of PMSM drive is shown as in fig. 5.

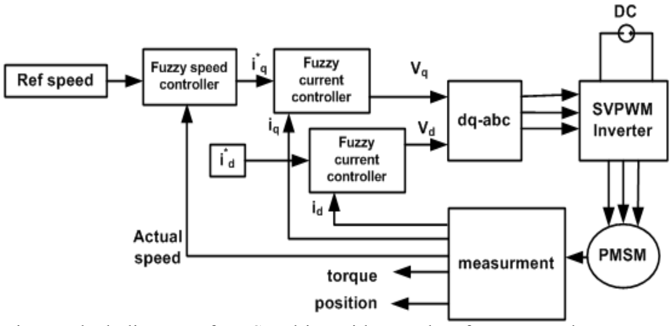


Fig. 5: Block diagram of PMSM drive with complete fuzzy control

As explained in previous section scaling factors initially estimated by using PI controller for selected input and output interval for individual controllers [21]. SVPWM inverter is feeding power to PMSM[22]. The speed control loop gives the reference torque, voltage reference for SVM inverter is generated by current controllers. The dc link voltage used here is 250V.

Table II: Parameters of PMSM

Motor Parameters		
Symbol	***Parameter***	***Value***
R_s	Resistance	2.0 ohm
L_d	d-axis inductance	4.5 mH
L_q	q-axis inductance	4.5 mH
J	Inertia	0.8×10-3 kgm2
P	No of Poles	8

A. Simulation Performance

The vector controlled PMSM drive simulated with PI, speed fuzzy controller, and full fuzzy (fuzzy speed and fuzzy current controller). The parameter of PMSM is given in table II. For a step change in load torque (0-5 Nm) the drive with PI speed and PI controller, fuzzy speed and current PI, and full fuzzy logic takes different times to generate desired load torque as given in table III.

Table III.

Controller	Time (sec)
PI speed +PI current	0.25
Speed fuzzy +PI current	0.17
Full fuzzy	0.11

The waveforms of electromagnetic torque for a step change of 0-5 Nm, in load torque with these three controllers based PMSM drive are shown in figure 6, figure 7, and figure 8 respectively.

Torque response of PMSM with PI controllers is shown in fig 6. During zero load torque ripples are more. Figure 7 shows the torque performance with fuzzy speed and PI current controllers. The ripples in torque are less with fuzzy speed controller as compared to PI speed controller. Torque response with full fuzzy logic controller is shown in figure 8. It has less torque ripples and takes less time to reach load torque as compared to other two controllers.

The torque response of drive is governed by q-axis current controller, and speed response is governed by d-axis current controller. The speed controller just generates the q-axis current reference for q-axis current controller. Speed response of full fuzzy logic controlled PMSM drive with 760-500 rad/sec step change in speed is shown in figure 9.

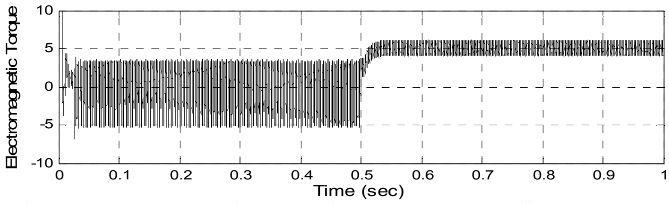


Fig. 6: Torque response with PI speed and PI current controller

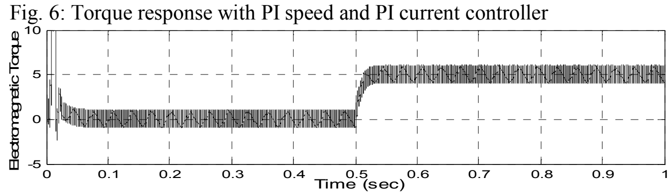


Fig. 7: Torque response with fuzzy speed and PI current controller

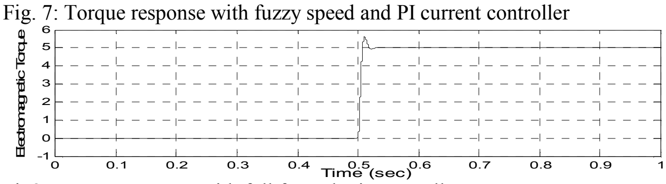


Fig8: Torque response with full fuzzy logic controller

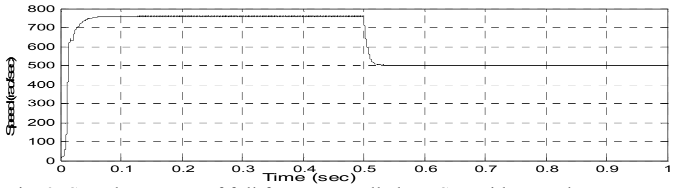


Fig. 9: Speed response of full fuzzy controlled PMSM with step change (760-500 rad/sec) in speed.

B. *Real time implementation*

The full fuzzy logic based PMSM drive is simulated in RT-LAB of OPAL-RT. The implementation of computer controlled RT-LAB based on MALAB is shown in Figure 10.

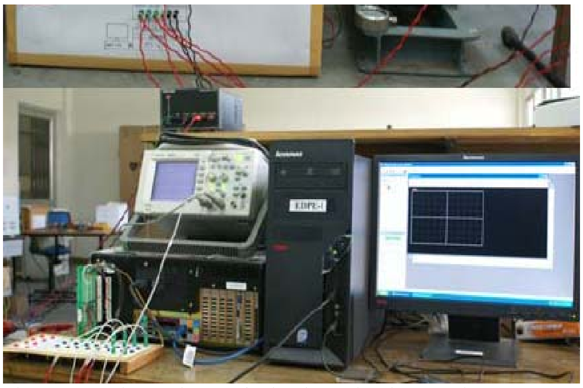


Fig. 10 Experimental setup for hardware implementation

Figure 11 shows the speed and torque response wit first speed is changed from 0-500 rad/sec, then after some time 0-4 Nm load torque is applied. Figure 12 shows the speed and torque response when speed is changed in step of 0-200-500 rad/sec at no load. At the transition moment of speed peak is generated in torque and vice versa. At positive step change in speed a positive peak is appearing in torque and at positive step change in torque causes negative peak in speed as shown in figure 12.

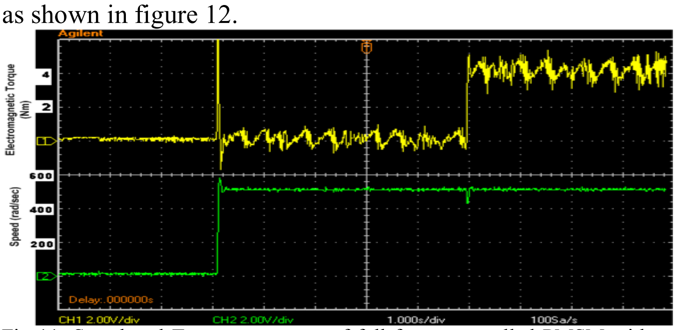


Fig 11: Speed and Torque responses of full fuzzy controlled PMSM with step change (0-500 rad/sec) in speed and (0-4 Nm) in torque at different instant.

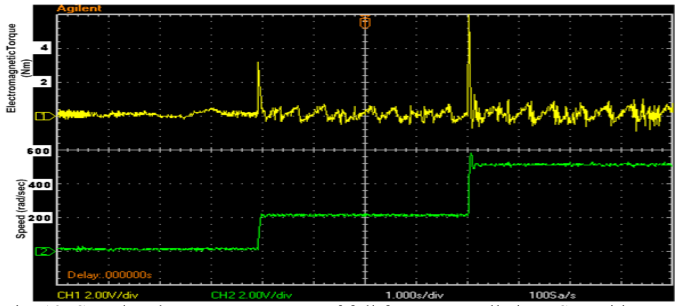


Fig. 12: Speed and Torque responses of full fuzzy controlled PMSM with step change (0-200-500 rad/sec) in speed at no load.

VII. CONCLUSION

To evade the enslavement of PI controllers on machine parameter and operating conditions a full fuzzy logic for PMSM drive is proposed with adequate gain tuning for a robust performance. Simulation performance is observed in MATLAB software, further the controller is implemented in real time using FPGA based RT-LAB system, which provides the real time performance of full fuzzy logic controlled drive.

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