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FPGA IMPLEMENTATION TO MINIMIZE TORQUE RIPPLES IN PERMANENT MAGNET SYNCHRONOUS MOTOR DRIVEN BY FIELD ORIENTED CONTROL USING FUZZY LOGIC CONTROLLER

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ABSTRACT

The Permanent Magnet Synchronous motor is a rotating electrical machine where the stator produces a sinusoidal flux density distribution in the air gap and the rotor has permanent magnets. A substantial air gap magnetic flux generated by permanent magnet makes it reliable to design highly efficient motors. However, the main disadvantage is the non-uniform variance in the developed torque. These torque ripples causes speed oscillations and vibrations and perverts the system performance. Since the construction of permanent magnet synchronous motor lacks rotor coil which will provide mechanical damping during transient conditions, these motors are inefficient with open-loop V/Hz control and rely on Vector Control for better dynamic response. Fuzzy logic controllers which does not requires any modeling of a system based on mathematics and are they are working on the linguistic rules. It also improves the performance of PI controllers which are affected by load turbulence, parameter variations and speed disturbances. This project presents the Fuzzy logic approach for a vector controlled PMSM drive for minimizing torque ripples. Also, Space vector modulation is employed to overcome the periodic torque pulsations generated by hysteresis controllers. The design analysis and the hardware control are implemented by using FPGA controller and discussions on the hardware results are done.

Keywords: *Permanent Magnet Synchronous Motor (PMSM), Field Oriented Control (FOC), PI controller, Fuzzy Logic Controller (FLC), Field Programming Gate Array (FPGA), Space Vector Pulse Width Modulation (SVPWM).*

1. INTRODUCTION

Permanent magnet synchronous motor (PMSM) is a hybrid of an AC induction motor and a Brushless DC motor. They have rotor which contain permanent magnets and it is similar to that of a BLDC motors. These PMSMs are extensively utilized in small and medium power applications such as Robotics, Computer peripheral equipment's, Adjustable speed drives and Electric vehicles due to the advantages like high efficiency, high power factor, high power density, compactness and maintenance free operation. Also these motors are preferred over the traditional brush-type dc motors because of the absence of mechanical commutators, which reduces mechanical wear and tear of the brushes and increases the life span of the motor. However, the main disadvantage of PMSMs is the parasitic torque pulsations. Presence of these torque pulsations results in instantaneous torque that pulsates periodically with rotor position. These pulsations are reflected as periodic oscillations in the motor speed, especially for low-speed operation.There are various sources of torque pulsations in a PMSM such as the cogging, flux harmonics, errors in current measurements, and phase unbalancing. In view of the increasing popularity of PMSMs in industrial applications, the suppression of pulsating torques has received much attention in recent years.

Many techniques based on both motor designs and control techniques have been proposed in literature to diminish the torque ripples in the PMSM [10]. Nonlinear torque controller centered on flux/torque estimate is introduced to reduce the influence of the flux harmonics. The influence of the cogging torque is significantly condensed at low motor speed by means of internal model principle and adaptive feed forward compensation technique. The disadvantage

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is that the practical implementation of the model requires additional work [9].

The torque ripples are parasitic and can lead to torque pulsations, vibrations and noise. The complex state variable technique is used for modeling and analyzing the effects of parasitic torque. The compensation of parasitic torque ripples is by producing high frequency electromagnetic torque components through current control system [8]. A numerical predetermination of the current waveform is imposed in phases of machine to attain a steady torque. Torque regulation scheme is based on-line instant estimation. The optimization of the current and minimization of copper losses is done by current modulus minimization and the results are compared. The optimization of current function optimizes the mean torque, such that torque ripple is minimized [5].

A new inverter output filter topology is designed to reduce the high frequency harmonics which reduces the breakdown strength of insulation and reduces insulation life and causes severe damage to the motor bearings. These output filters reduce the phase shift in the current regulating system and torque ripple respectively and improves the filter efficiency [17].

An embedded phase domain model of PMSM, which reduces instabilities due to numerical. Both the conventional and embedded phase domain models of PMSM shows indistinguishable results in the steady state and transient conditions, however the conventional model of PMSM becomes unstable if the time-step is increased [6].

Torque ripple diminishing in a permanent magnet synchronous motor with non ideal back electromotive force. In order to achieve constant torque with reduced torque ripples improved current tracking in the presence of periodic reference signals and disturbances is proposed by the application of current repetitive techniques in a field-oriented PMSM drive [13].

To diminish the torque ripples and harmonic noises in PMSM an active filter topology. The hysteresis voltage control method is used in active filter, while the motor current uses the hysteresis current control method. The simulation results show that the total harmonic distortion goes below 13% with EMI noise damping down to nearly to -10 dB [7].

An application of computational intelligence techniques like fuzzy logic is used to reduce the torque ripples associated with direct torque control in PMSM [12].

2. FIELD ORIENTED CONTROL

The primary limitation of sinusoidal commutation is controllig motor currents which are time variant in nature. This breaks down as speeds and frequencies increases due to the restricted bandwidth of PI controllers. This problem can be solved by controlling the current space vector directly in the d-q reference frame of the rotor which is known as Vector Control or Field Oriented control or Decoupling control.

Field-oriented control is an efficient method to control a PMSM in adjustable speed drive applications with quickly changing load in a wide range of speeds including high speeds where field weakening is required. It demonstrates a synchronous motor to be controlled like a separately excited dc motor by the orientation of the stator mmf or current vector in relation to the rotor flux.

Field oriented control consists of vectors to control the stator currents. The field oriented control is based on transforming a three phase coordinates systems which are time and speed dependent into d and q co-ordinates (two co-ordinate system) time invariant system. The DC machine type control is achieved through these projections of three phases to two phase conversions.

Field oriented controlled machines require two constant input references; they are the torque component which is aligned with the q coordinate and the flux component which is aligned with d co-ordinate. This makes the field oriented control system precise in all working modes (transient and steady state) and unlimited bandwidth compared to limited bandwidth in mathematical model. The Field Oriented Control solves the following steps:

1. Finding the constant reference of flux component and torque component of the stator current.

2.Calculation of torque from (d,q) reference frame by applying direct torque control and the expression of torque is given by

$$T \alpha \Psi_R i_{sq} \quad (1)$$

The linear relationship of torque and torque component (i_{sq}) can be maintained by controlling the amplitude of rotor flux (Ψ_R) at a fixed value. By controlling the torque components of stator current vectors the torque can be controlled. The three phase currents, fluxes and voltages of PMSM can be analyzed in stipulations of composite space

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vectors. Assuming that i_a, i_b, i_c are the instantaneous stator phase (a, b, c) currents respectively.

$$i_a+i_b+i_c=0 \tag{2}$$

These stator currents space vectors depict the three phase sinusoidal system. It still wants to be altered into a time invariant co-ordinate system. This conversion can be divided into two steps:

1. Clarke transformation ((a, b, c) to (α, β))

$$\begin{cases} i_{s\alpha} = i_a \\ i_{s\beta} = \frac{1}{\sqrt{3}} i_a + \frac{2}{\sqrt{3}} i_b \end{cases} \tag{3}$$

The inverse Clarke transformation transforms from a 2-phase (α,β) to a 3-phase (i_{sa},i_{sb},i_{sc}) system.

$$\begin{cases} i_{sa} = i_{s\alpha} \\ i_{sb} = -\frac{1}{2} i_{s\alpha} + \frac{\sqrt{3}}{2} i_{s\beta} \\ i_{sc} = -\frac{1}{2} i_{s\alpha} - \frac{\sqrt{3}}{2} i_{s\beta} \end{cases} \tag{4}$$

2. Park transformation ((α,β) to (d,q))

$$\begin{cases} i_{sd} = i_{s\alpha}\cos\theta + i_{s\beta}\sin\theta \\ i_{sq} = -i_{s\alpha}\sin\theta + i_{s\beta}\cos\theta \end{cases} \tag{5}$$

where θ is the rotor flux position.

These components depend on the current vector (α,β) components and on the rotor flux position. Inverse Park transformation modifies the voltages in d,q rotating reference frame in a two phase orthogonal system.

$$\begin{cases} V_{s\alpha ref} = V_{sdref}\cos\theta - V_{sqref}\sin\theta \\ V_{s\beta ref} = V_{sdref}\sin\theta + V_{sqref}\cos\theta \end{cases} \tag{6}$$

The proposed block diagram of PMSM driven by FOC using Fuzzy logic controller with SVPWM is described in the Figure 1.

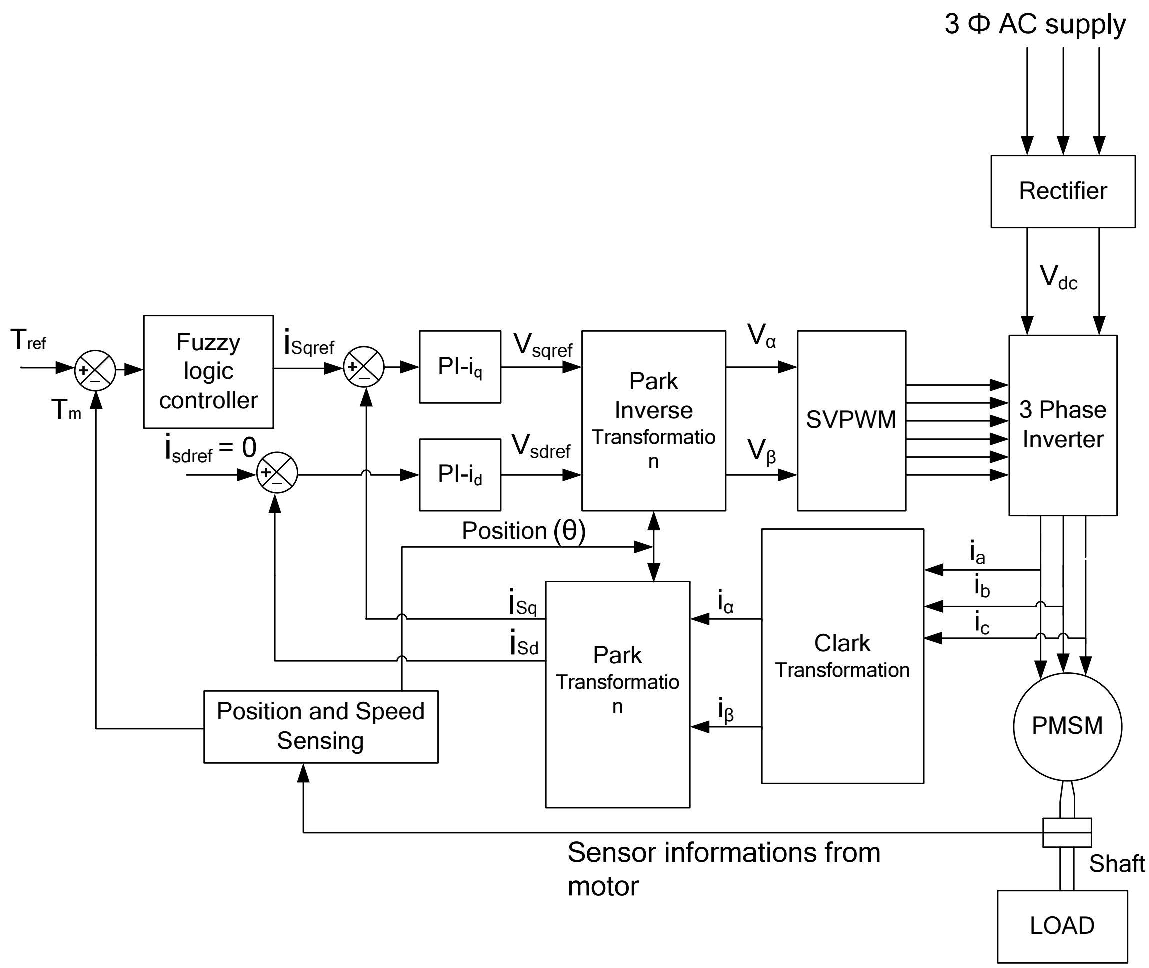

Figure 1 Proposed Block Diagram Of PMSM driven by FOC Using FLC With SVPWM

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3. SPACE VECTOR PULSE WIDTH MODULATION

The space vector PWM method is an advanced, computation-intensive PWM method which is the best among all the PWM techniques for variable-frequency drive applications. There are eight possible combinations for the switch commands which determine eight phase voltage configurations. This PWM technique approximates the reference voltage V_{ref} by a combination of the eight switching patterns (V_0 to V_7) are described in the Figure 2 with the Switching patterns and output voltages of a three-phase power inverter in Table 1. To implement the space vector PWM, the voltage equations in the abc reference frame can be transformed into the stationary αβ reference frame that consists of the horizontal (α) and vertical (β) axes, as a result, six non-zero vectors and two zero vectors are possible.

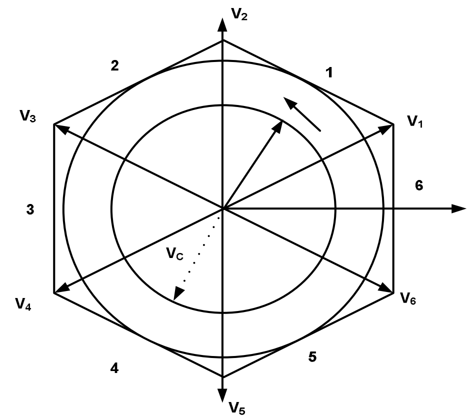

Figure 2 Switching Vectors And Sectors

Table 1: Switching Patterns And Output Voltages Of A Three-Phase Power Inverter

Vector	Va	Vb	Vc	Vab	Vbc	Vca
V_0={000}	0	0	0	0	0	0
V_1={100}	2/3	−1/3	−1/3	1	0	-1
V_2={110}	1/3	1/3	−2/3	0	1	-1
V_3={010}	− 1/3	2/3	−1/3	-1	1	0
V_4={011}	−2/3	1/3	1/3	-1	0	1
V_5={001}	− 1/3	−1/3	2/3	0	-1	1
V_6={101}	1/3	− 2/3	1/3	1	-1	0
V_7={111}	0	0	0	0	0	0

4. FUZZY LOGIC CONTROLLER (FLC) [1]

Fuzzy logic (FL) is defined as multi-valued logic which deals with problems that have fuzziness or vagueness.

Fuzzy logic is a methodology used for problem solving in any type of control system and it can be implemented in microprocessors, embedded microcontrollers, FPGA chips and PC based data acquisition and control systems. FL provides a trouble-free way to get at a definite conclusion based upon unclear, vague, inaccurate, noisy, or absent input information. Fuzzy Logic approach towards a control system problem mimics how a person would make decisions.

The inputs to the FLC are error of torque and change in torque error and the output is torque limit are described in the Figure 3, 4 and 5. The inputs and outputs contains seven linguistics membership functions, they are as follows PB- Positive Big, PM- Positive Medium, PS- Positive Small, Z- Zero, NS- Negative Small, NM- negative medium, NB- Negative Big, are described in Table 2.

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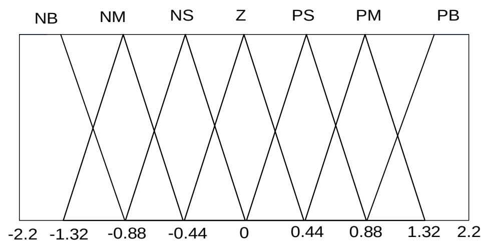

Figure 3 Inputs To FLC- Torque Error

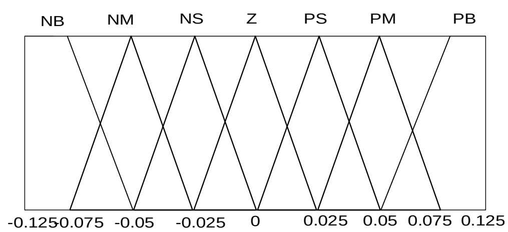

Figure 4 Inputs to FLC- Change In Torque Error

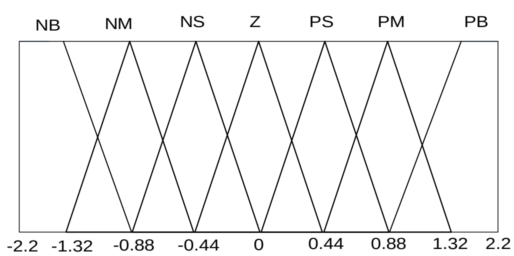

Figure 5 Torque Limit Output Of FLC

Table 2: Rules for FLC

e / Δe	B	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NM	NM	NS	Z
NM	NB	NB	NB	NM	NS	Z	PS
NS	NB	NM	NS	NS	Z	PS	PM
Z	NM	NM	NS	Z	PS	PM	PM
PS	NM	NS	Z	PS	PS	PM	PB
PM	NS	Z	PS	PM	PM	PB	PB
PB	Z	PS	PM	PM	PB	PB	PB

5. FIELD PROGRAMMABLE GATE ARRAY

Field Programmable Gate Array (FPGA) is low cost, high-performance DSP solution for high-volume, cost-conscious applications. Their efficiency in concurrent applications is achieved by using multiple parallel processing blocks. Due to parallel processing paths, different tasks do not want to compete for the same resources. In a single FPGA device multiple control loops can be executed at different rates. Because of parallel processing the speed is very high. The FPGAs gives limitless flexibility to the designers due to reconfigurable option. It distributes memory throughout the device, so the dedicated memory needed by each task is permanently allocated. This provides a high degree of isolation between tasks. The designer of an FPGA controller has complete flexibility to select any combination of peripherals and controllers.

6. RESULTS AND DISCUSSION

The simulation parameters of PMSM used in the simulink matlab and hardware are shown in table 3 with the Hardware block diagram and Hardware setup in Figure 6 and Figure 7. The Figure 8 and Figure 9 shows Inverter Line to line Voltage waveform and current waveform at 75% loading. The Figure 11 and Figure 12 shows Inverter Line to line Voltage waveform and current waveform at 100% loading. The Figure 10 and Figure 13 shows the torque waveform for 75% and 100% loading.

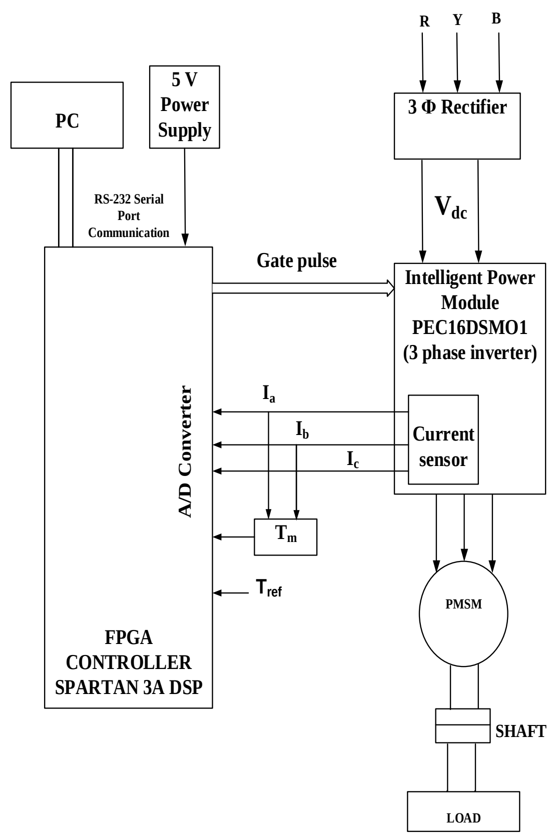

Figure 6 Hardware Block Diagram of Field Oriented Control Of PMSM Using FPGA Controller

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Table 3: Parameters Of PMSM

Rated Power	1.1HP
Rated Torque	2.2Nm
Rated Voltage	220 V
Rated Current	3.69A
Rated Speed	4600 rpm
Torque Constant	0.6 Nm/Arms
Terminal To Terminal Resistance	3.07Ω
Terminal To Terminal Inductance	6.57 mH
Moment of Inertia	1.8 $kgcm^2$

Figure 7 Snapshot Of Hardware Setup

6.1 Waveforms Of Inverter Line To Line Voltage, Current And Torque (75% Loading)

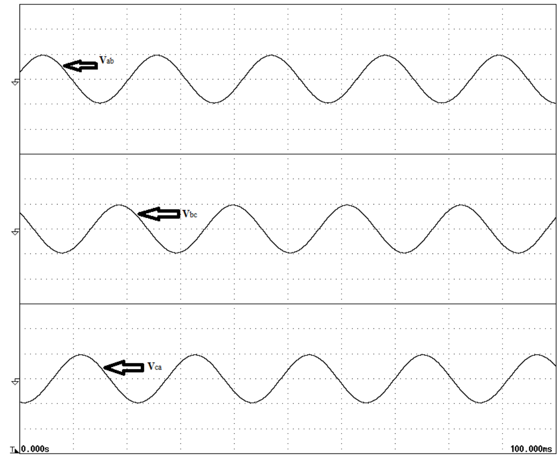

Figure 8 Inverter Line To Line Voltage Waveform For 75% Loading (X-Axis: Time In Ms: 1 Div= 10 Ms, Y-Axis (Vab, Vbc, Vca): Voltage In Volts: 1 Div= 325 V)

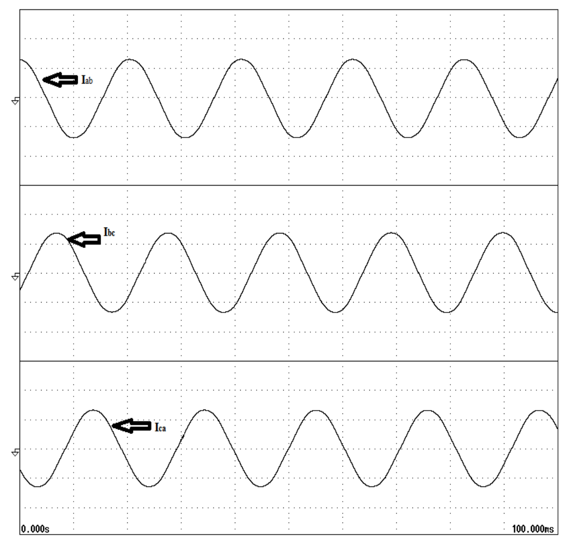

Figure 9 Current Waveform For 75% Loading (X-Axis: Time In Ms: 1 Div= 10 Ms, Y-Axis (Iab, Ibc, Ica): Current In Amps: 1 Div= 2 A)

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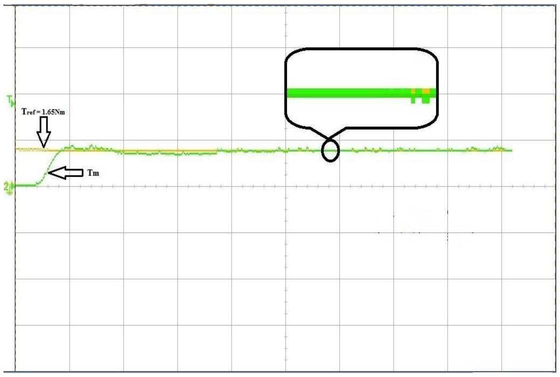

Figure 10 Torque Waveform For 75% Loading(X-Axis: Time In S, 1 Div= 10s, Y-Axis: Torque In Nm, 1 Div= 2.2Nm)

$$\text{Torque Ripple Factor(TRF\%)}= \frac{T_{\text{peak-peak}}}{T_{\text{ave}}} \times 100 \quad (7)$$

From the Figure 10 the motor torque(Tm) follows the reference motor torque (Tref) with less torque ripples and it is shown in the circled portion of waveform which is zoomed and shown inside the figure 10. The torque ripple factor for the proposed scheme as per equation (7) is given below for figure 10.

$$\text{Torque Ripple Factor (TRF \%)} = \frac{1.65 - 1.62}{1.65}$$
$$=1.81\%$$

6.2 Waveforms Of Inverter Line To Line Voltage, Current And Torque (100% Loading)

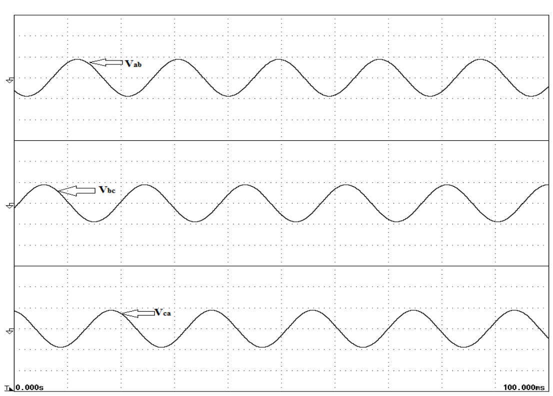

Figure 11 Inverter Line To Line Voltage Waveform For 100% Loading(X-Axis: Time In 1 Div= 10 Ms, Y-Axis: Voltage In Volts: 1 Div= 325 V)

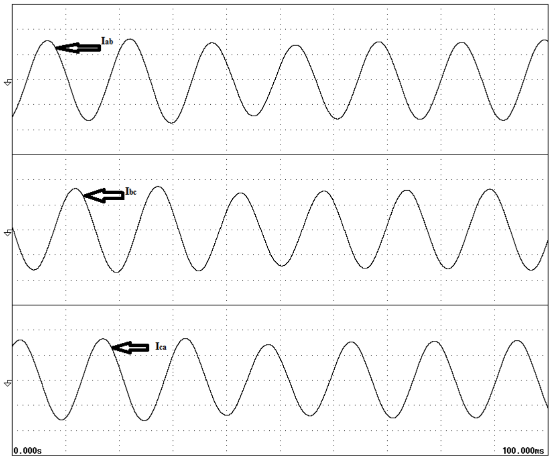

Figure 12 Current Waveform For 100% Loading(X-Axis: Time In Ms: 1 Div= 10 Ms, Y-Axis: Current In Amps(Iab, Ibc, Ica): 1 Div= 3 A)

From the Figure 13 the motor torque(Tm) follows the reference motor torque (Tref) with less torque ripples and it is shown in the circled portion of waveform which is zoomed and shown inside the figure 13.

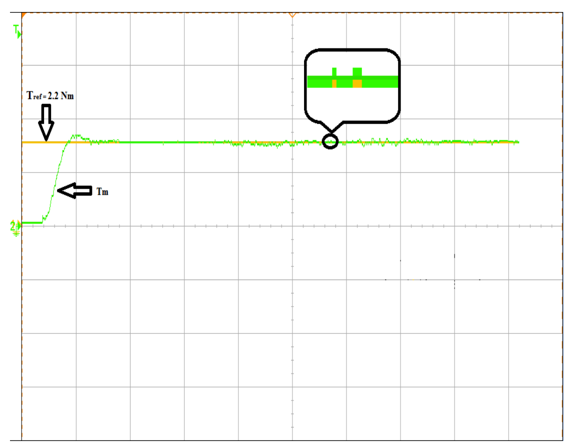

Figure 13 Torque Waveform For 100% Loading(X-Axis: Time In S, 1 Div= 10s, Y-Axis: Torque In Nm, 1 Div= 1.46 Nm)

The torque ripple factor for the proposed scheme as per equation (7) is given below for figure 13.

$$\text{Torque Ripple Factor (TRF \%)} = \frac{2.24 - 2.2}{2.2}$$
$$=1.81\%$$

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Table 4: Comparison Of Control Strategies In PMSM

CONTROL STRATEGIES	TORQUE RIPPLE (%)
Proposed FLC with SVPWM	1.81
P. Mattavelli, L.Tubiana, and M. Zigliotto,2005 [13]	3.8
W. Qian and K. Panda, 2004 [14]	3.9
M.Tarnik and J.Murgas, 2011 [20]	4
H. Hasanien, 2010 [19]	12

It is clear that variation in Torque shown in table 4 is less in case of Fuzzy logic controllers and they can achieve a minimum torque ripple than other control techniques. It has been viewed that the proposed control strategy has helped in reducing the torque ripples to 1.81%. Thus by using FLC based controller, ripples are reduced completely.

7. CONCLUSION

Fuzzy logic controller based Torque controller model of PMSM motor drive have been modeled and implemented using FPGA and the results have been presented to demonstrate the proposed FLC based control. The implemented hardware result of Fuzzy Logic Controller has shown that it is better over the PI Torque controller in reducing the torque ripples to 1.81%. And therefore it can be successfully used in position of PI Torque controller. In future implementation, Hybrid Neuro-Fuzzy controllers can be used to replace the PI controller.

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