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Torque Ripple Reduction in Permanent Magnet Synchronous Motor using Fuzzy Logic Control

[1]B.Adhavan, [1]M.S.Birundha, [1] Dr.C.S.Ravichandran, [2] Dr.V.Jagannathan

[1]Department of EEE(PG), Sri Ramakrishna Engineering College, Coimbatore, India
[2]Department of EEE, Coimbatore Institute of Technology, Coimbatore, India

Abstract: Permanent Magnet Synchronous Motor (PMSM) drives are widely used in applications where smooth torque is required. However, the main disadvantage of PMSM is torque ripple that leads to mechanical vibration and acoustic noise. For applications that require precise tracking, the machine should be free of torque ripples. Vector controlled PMSM drive provides better dynamic response and lesser torque ripples, and necessitates only a constant switching frequency. The outer loop in vector control greatly affects the system performance. Proportional plus integral (PI) controllers are usually preferred, but due to its fixed proportional gain and integral time constant, the performance of the PI controllers are affected by parameter variations, load disturbances and speed variations. These problems can be overcome by the fuzzy logic controllers, which do not require any mathematical model and are based on the linguistic rules obtained from the experience of the system operator. This paper describes two new instantaneous torque control schemes 1) Fuzzy Logic Controller (FLC) with Hysteresis Pulse Width Modulation (HPWM) 2) Fuzzy Logic Controller (FLC) with Space vector Pulse Width Modulation (SVPWM) respectively to reduce torque ripples in PMSM driven by Field oriented control. The design, analysis and simulation of the proposed system is done using MATLAB version R2009a and the simulation results are discussed.

Key words: Permanent Magnet Synchronous motor (PMSM), Torque ripple, Field oriented Control (FOC), Proportional plus (PI) Controller, Fuzzy Logic Controller (FLC), Hysteresis PWM (HPWM), Space Vector Pulse Width modulation (SVPWM).

INTRODUCTION

Permanent magnet synchronous motors (PMSMs) have been widely used in many industrial applications. Due to their compactness, high efficiency and high torque density, the PMSMs are particularly used in high-performance drive systems. PMSM eliminates the use of slip rings for field excitation, resulting in low maintenance and low losses in the rotor. One of the major disadvantages of the PMSM drive is the torque ripple produced which is due to the following sources:

1) Mutual torque, due to the interaction of the rotor field and stator currents;
2) Reluctance torque, due to rotor saliency;
3) Cogging torque, due to the existence of stator slots.

In applications such as the conveyor belt control, torque pulsations are highly undesirable and must be eliminated. Presence of these torque pulsations results in instantaneous torque that pulsates periodically with rotor position changing. The torque ripple of the PMSM can also bring the problems such as speed fluctuation, resonance and acoustic noise, and then affect the machine's reliability, accuracy and degree of comfort. So it is important to suppress the torque ripple.

In order to minimize torque ripple, many techniques based on both motor design and control schemes have been proposed in literature (Jahns,T.M *et al.*, 1996). An inverter output filter system for PWM motor drives can reduce harmonics of PMSM (Sozer,Y *et al.*, 2000). This method is composed of conventional RLC filter cascaded with an LC trap filter tuned to the inverter switching frequency. The scheme shows some effectiveness in reducing switching harmonics, but however, very large circulating current between inverter output and filter elements is required to reshape the motor terminal voltage which violate current limitation of the inverter.

An iterative learning control (ILC) is utilized for torque/speed ripple minimization of a brushless surface-mounted PMSM drive (Qian,W *et al.*, 2004). However, the ILC scheme has its own limitation for real-time applications, particularly at high-speed operating conditions. A complicated and expensive filter topology has been used in PMSM which consists of an insulated-gate bipolar transistor AF and two RLC filters (Gulez,K *et al.*, 2008). Although complex filter topologies are beneficially capable to reduce torque ripple and current harmonic noises, and provide an almost sinusoidal voltage to the motor terminals, online filter tuning causes more complexity and hardware implementation is relatively expensive. An application of fuzzy logic control is

Corresponding Author: B.Adhavan, M.S.Birundha, Department of Electrical and Electronics Engineering, Sri Ramakrishna Engineering College, Coimbatore, India.
E-mail: adhav14@gmail.com, birundha001@gmail.com

used to improve the torque ripple associated with the direct torque control when used in control of a PMSM (Li,N *et al.*, 2010).

Vector controlled PMSM drive provides better dynamic response and lesser torque ripples, and necessitates only a constant switching frequency. The outer loop in vector control greatly affects the system performance. Proportional plus integral (PI) controllers are usually preferred, but due to its fixed proportional gain and integral time constant, the performance of the PI controllers are affected by parameter variations, load disturbances and speed variations. These problems can be overcome by the fuzzy logic controllers, which do not require any mathematical model and are based on the linguistic rules obtained from the experience of the system operator.

In this paper, Fuzzy Logic Control based Field Oriented Control is presented to minimize the torque ripples in PMSM. Also, Hysteresis and Space vector Pulse Width Modulation techniques are used for effective switching of inverter and the proposed system with both the techniques is simulated using MATLAB and are compared.

Field Oriented Control:

Field-oriented control (FOC), also known as vector control or decoupling control aims to control effectively the motor torque and flux in order to force the motor to accurately track the command trajectory regardless of the machine and load parameter variation or any extraneous disturbances. It is based on three major points:

- Machine current and voltage space vectors
- Transformation of a three phase speed and time dependent system into a two co-ordinate time invariant system and
- Effective Pulse Width Modulation pattern generation.

Field orientated controlled machines need two constants as input references: the torque component (aligned with the q coordinate) and the flux component (aligned with d co-ordinate). As FOC is simply based on projections, the control structure handles instantaneous electrical quantities. This makes the control accurate in every working operation (steady state and transient) and independent of the limited bandwidth mathematical model. The FOC thus solves the classic scheme problems, in the following ways:

1. The ease of reaching constant reference (torque component and flux component of the stator current)
2. The ease of applying direct torque control, because in the (d,q) reference frame the expression of the torque is:

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

By maintaining the amplitude of the rotor flux (Ψ_R) at a fixed value, we have a linear relationship between torque and torque component (i_{sq}). We can then control the torque by controlling the torque component of stator current vector.

Proposed Method Of Foc Of Pmsm Using Flc:

The block diagram of proposed FOC with the Fuzzy logic based controller for the PMSM drive is shown in the Fig. 1.

Single phase AC supply is given to the inverter through the rectifier. The Inverter feeds the PMSM which drives the load. The 3 phase stator currents i_a,i_b,i_c are measured. i_c is calculated from i_a and i_b using the relationship

$$i_a+i_b+i_c=0$$

The Clarke transformation is applied to determine the stator current projection in the two co-ordinates a,b stationary frame. The transformation from the three phase system into the (α,β) two dimension orthogonal system is given by the relations

$$i_\alpha= i_a$$
$$i_\alpha= (i_a+2i_b)/\sqrt{3}$$

The Park transformation is then applied in order to obtain this projection in the d, q-rotating frame. The relationship between the two reference frames can be obtained from the following equations.

$$i_d = i_\alpha\cos\theta+ i_\beta\sin\theta$$
$$i_q = -i_\alpha\sin\theta+ i_\beta\cos\theta$$

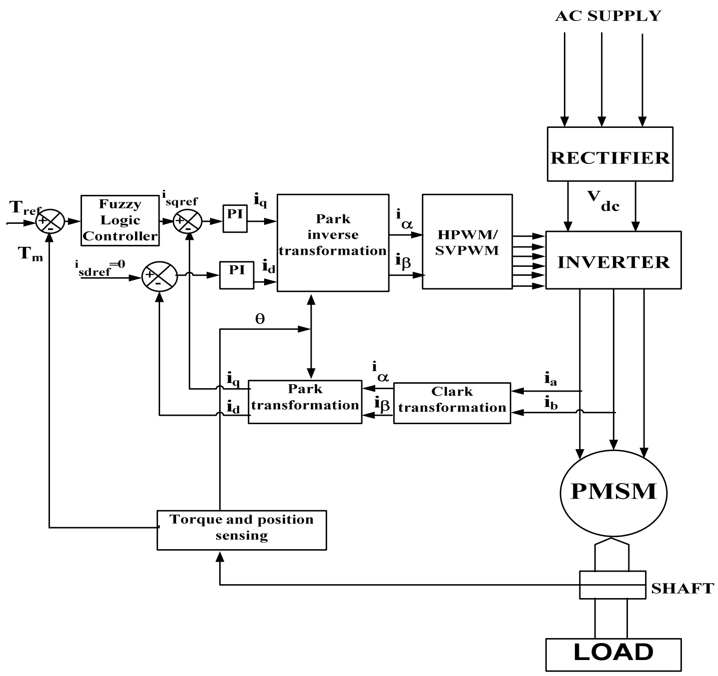


Fig. 1: Block Diagram of PMSM drive with FOC using FLC controller

The torque is sensed from the motor and it is compared with the reference torque. The error signal is given to the Fuzzy Logic Controller. The inputs to the FLC are Torque error (e) and change in torque error (Δe). The FLC initially converts the crisp error and change in torque error into fuzzy variables and then are mapped into linguistic labels. The FLC calculates a reference torque, which is proportional to the quadrature-axis stator current component i_{sqref}.

Membership functions are associated with each label which consists of two inputs and one output. The linguistic labels are divided into seven groups. They are: NB-Negative Big; NM-Negative Medium; NS-Negative Small; Z-zero; PS-Positive Small; PM-Positive medium; PB-Positive Big. Each of the inputs and the output contain membership functions with all these seven linguistics. Each of the inputs and the output contain membership functions with all these seven linguistics. The Fig. 2(a) shows the speed error, Fig. 2(b) shows the change in speed error and Fig. 2(c) shows the torque limit of the FLC.

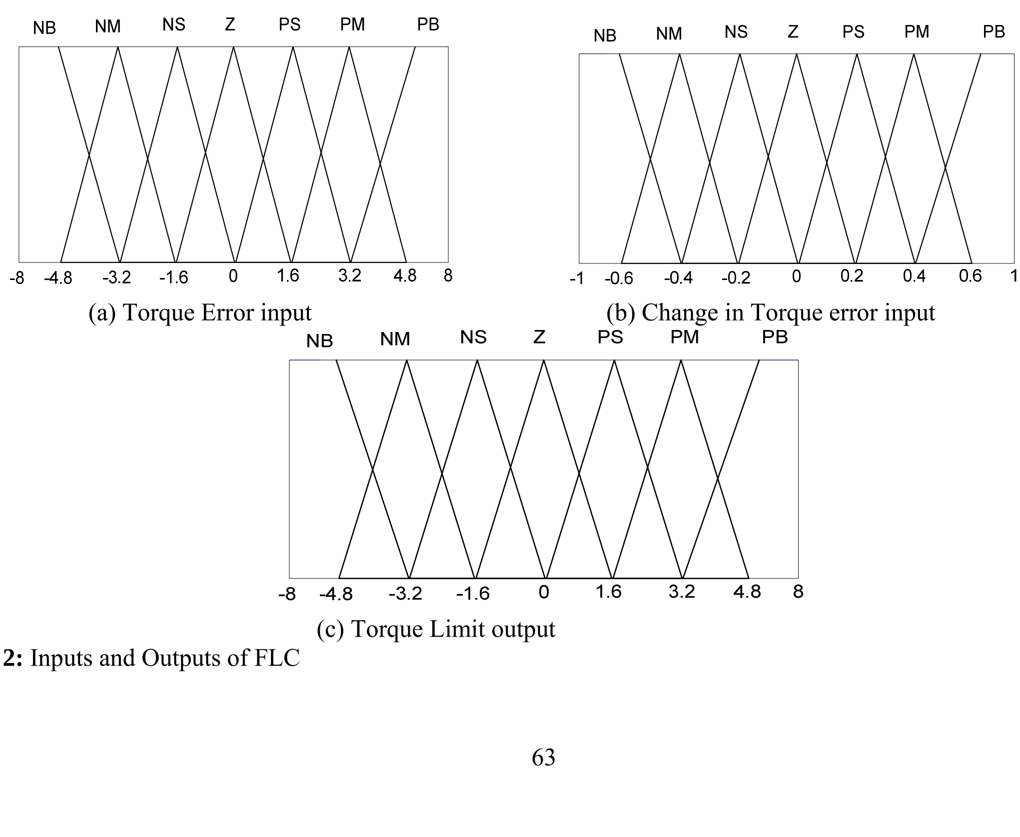


Fig. 2: Inputs and Outputs of FLC

The mapping of the fuzzy inputs into the required output is derived with the help of a rule base as given in Table 1.

Table 1: Rules for FLC

Δe \ e	NB	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

The d, q projections of the stator phase currents are then compared to their reference values i_{sqref} and i_{sdref} and corrected by means of PI current controllers. The outputs of the current controllers are passed through the inverse Park transform and a new stator voltage vector is impressed to the motor using the Hysteresis/Space Vector Modulation technique.

Hysteresis PWM:

In this method of PWM, the deviation of the current between the upper and lower in the hysteresis band (HB) is limited. In any phase, if the actual current becomes more than the upper limit of hysteresis band (i_{ref}+HB) the upper switch of the inverter arm is turned off, the lower switch is turned on and the current starts to decay. In contrast if the actual current reaches lower limit or less than of hysteresis band (i_{ref} -HB) the lower switch of the inverter arm is turned off, the upper switch is turned on and the current comes back into the hysteresis band. The six switches of the PWM inverter are driven by the hysteresis current controller in order to produce the desired motor currents.

Space Vector Modulation:

Space Vector PWM (SVPWM) refers to a special technique of determining the switching sequence of the upper three power transistors of a three-phase voltage source inverter (VSI). There are eight possible combinations of on and off states for the three upper power transistors which determine eight phase voltage configurations. This PWM technique controls the motor based on the switching of space voltage vectors, by which an approximate circular rotary magnetic field is obtained. It approximates the reference voltage Vref by a combination of the eight switching patterns (V_0 to V_7). The vectors (V_1 to V_6) divide the plane into six sectors (each sector: 60 degrees). Vref is generated by two adjacent non-zero vectors and two zero vectors. The switching sector is shown in Fig. 3 and Table 2 shows the switching vector for inverter. This technique allows having a higher torque at high speeds, and a higher efficiency.

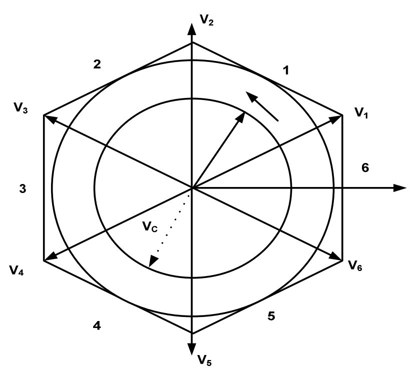


Fig. 3: Switching vectors and sectors

Table 2: Switching vectors for inverter

Vector	A+	B+	C+	A-	B-	C-	V_{AB}	V_{BC}	V_{CA}
V_0={000}	OFF	OFF	OFF	ON	ON	ON	0	0	0
V_1={100}	ON	OFF	OFF	OFF	ON	ON	$+V_{dc}$	0	$-V_{dc}$
V_2={110}	ON	ON	OFF	OFF	OFF	ON	0	$+V_{dc}$	$-V_{dc}$
V_3={010}	OFF	ON	OFF	ON	OFF	ON	$-V_{dc}$	$+V_{dc}$	0
V_4={011}	OFF	ON	ON	ON	OFF	OFF	$-V_{dc}$	0	$+V_{dc}$
V_5={001}	OFF	OFF	ON	ON	ON	OFF	0	$-V_{dc}$	$+V_{dc}$
V_6={101}	ON	OFF	ON	OFF	ON	OFF	$+V_{dc}$	$-V_{dc}$	0
V_7={111}	ON	ON	ON	OFF	OFF	OFF	0	0	0

RESULTS AND DISCUSSION

A PMSM fed from DC supply via inverter and FOC using FLC with HPWM and SVPWM techniques is simulated using MATLAB version R2009a and the results are compared. The parameters of PMSM used in the simulation are given below.

Rated Power	2.25HP
Number of phases	3
Number of poles (P)	8
Base current	5.6 A
Rated voltage	300 V
Rated speed	2000 rpm
Rated torque	8 N.m
Stator resistance per phase(R)	0.9585 ohm
q-axis inductance(Lq)	0.00525 H
d-axis inductance (Ld)	0.00525 H
Stator flux linkages per phase due to rotor magnet (A f)	0. 1827V/ (rad/s)
Moment of inertia (J)	0.0006329Kg.m^2
Friction Factor (F)	0.0003035 N.m/(rad/s)

The torque ripple can be calculated by using the relation

Torque Ripple Factor = Peak to peak torque/Rated Torque

The simulink model of FLC with HPWM based FOC of PMSM is shown in Fig. 4 and that of HPWM pulse production is shown in Fig. 5. The simulation result is shown in Fig. 6. The Hysteresis band selected for simulation is h=0.1.

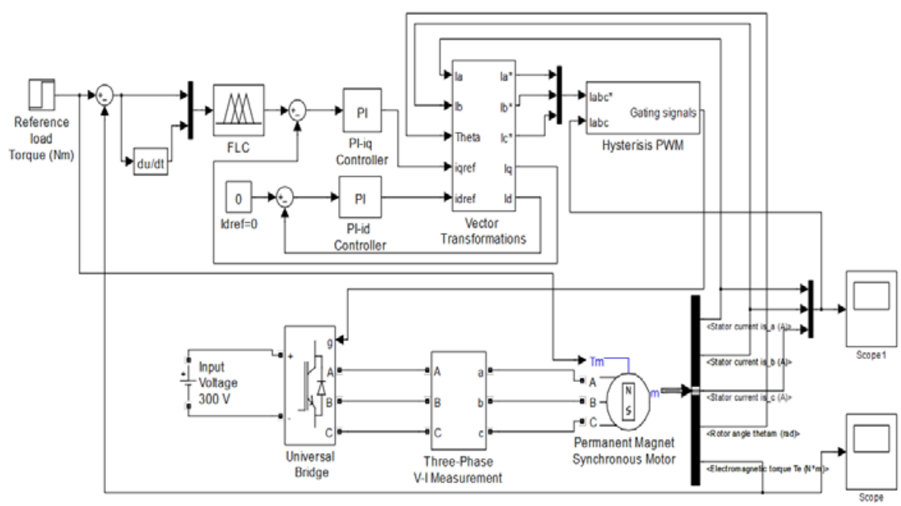


Fig. 4: Simulink model of FLC with HPWM based FOC of PMSM

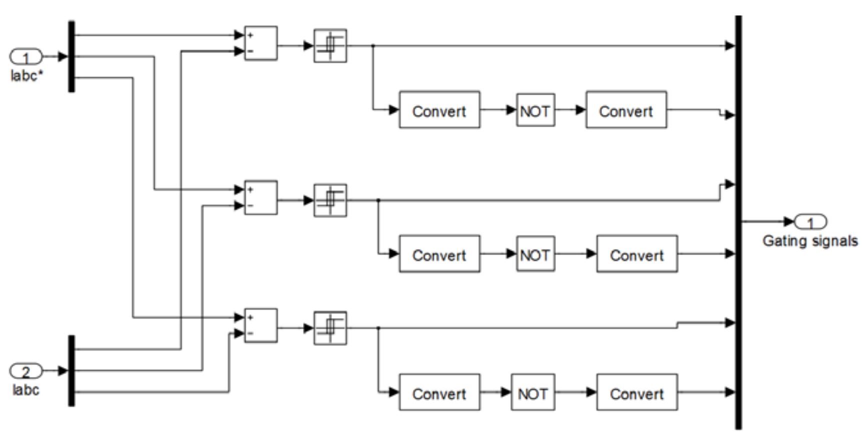
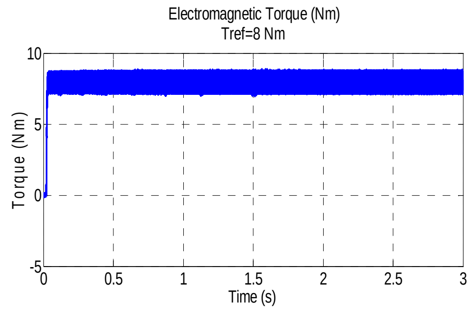
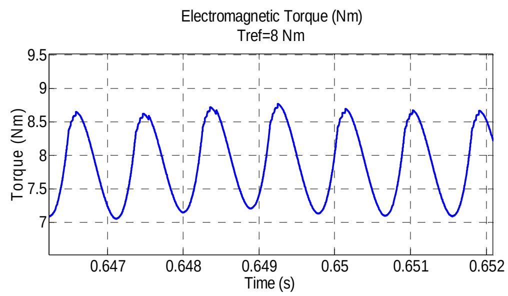


Fig. 5: Simulink model of HPWM pulse production



(a) Torque output



(b) Torque ripples

Fig. 6: Output Waveforms for PMSM driven by FOC using FLC and HPWM

Similarly, the simulink model of FLC with SVPWM based FOC of PMSM is shown in Fig. 7 and that of SVPWM pulse production is shown in Fig. 8.

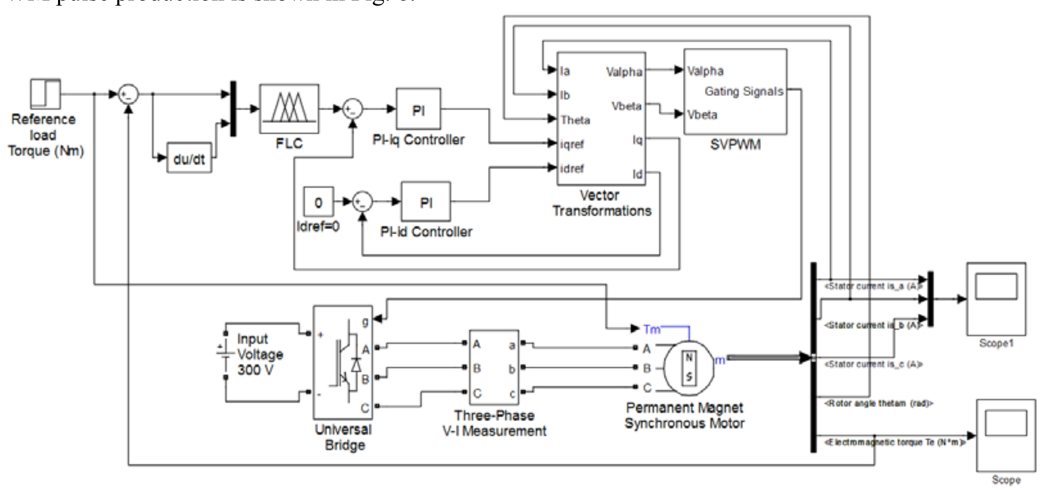


Fig. 7: Simulink model of FLC with SVPWM based FOC of PMSM

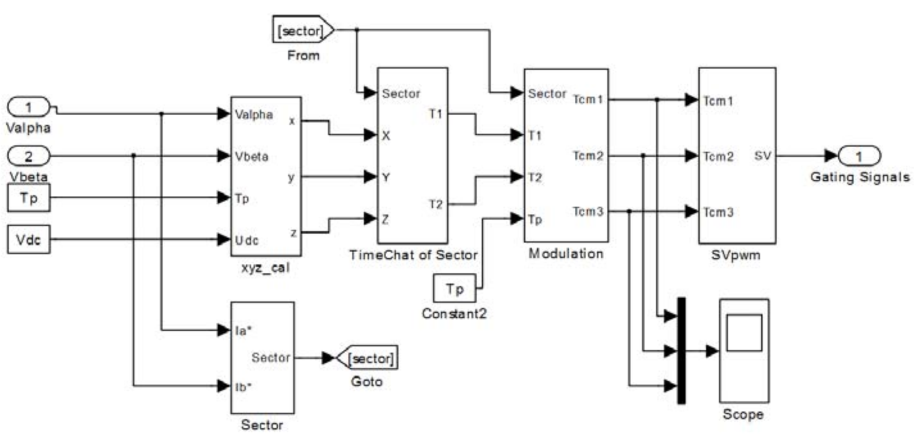
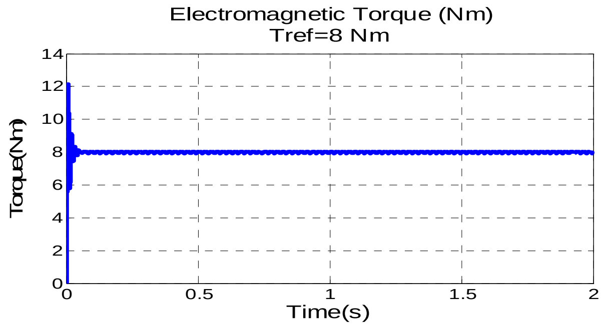
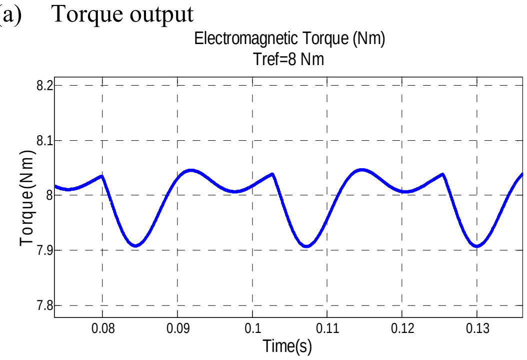


Fig. 8: Simulink model of SVPWM pulse production

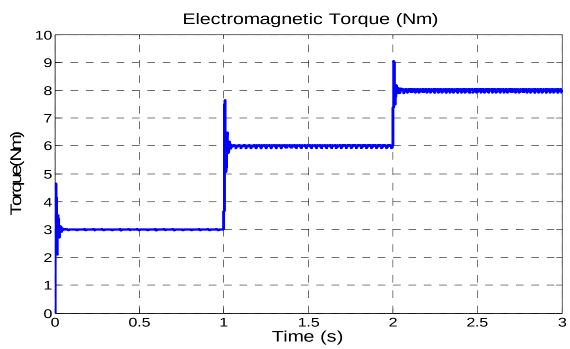
The simulation results of SVPWM based control is shown in Fig. 9.



(a) Torque output



(b) Torque ripples



(c) Dynamic torque output

Fig. 9: Output waveforms for FOC based PMSM using FLC and SVPWM

The comparative results of field oriented control of PMSM using both HPWM and SVPWM techniques and is shown in Table 3.

Table 3: Comparative Results of Control techniques of PMSM

FIELD ORIENTED CONTROL	TORQUE RIPPLE FACTOR (%)
FLC with HPWM	19
FLC with SVPWM	1.75

From the waveforms it is inferred that the torque ripples in the case of FLC with HPWM is 19% and by SVPWM technique the ripple is 1.75%. Thus by SVPWM, the ripples is reduced completely.

Conclusion:

A FOC method of minimizing the torque ripple in PMSM drives using FLC is simulated and the results are obtained. The simulated results of Fuzzy Logic Controller have shown the improved performance over the PI Torque controller and hence it can be effectively used in place of PI Torque controller. And particularly the accuracy of SVPWM technique has been proved.

ACKNOWLEDGEMENT

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