



TORQUE RIPPLE MINIMIZATION IN PERMANENT MAGNET SYNCHRONOUS MOTOR USING FUZZY LOGIC CONTROLLER

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ABSTRACT

This article presents a torque ripple minimization technique for permanent magnet synchronous motor (PMSM). For torque ripple minimization a fuzzy logic controller is used. The proposed controller is used to control a PMSM. The dynamic response of the PMSM with the proposed controller is studied during the starting and under loaded conditions. The effectiveness of the proposed fuzzy logic controller with FOC is then compared with other conventional controllers. Experimental results are presented to demonstrate the effectiveness of the proposed control scheme.

KEYWORDS: Permanent Magnet Synchronous Motor, Fuzzy Logic Controller, Torque Ripple, PI controller, Space Vector Pulse Width Modulation, Field Orientated Control

1. INTRODUCTION

Electric motors are machines which convert electrical energy into mechanical energy. The main categories of AC motors are asynchronous and synchronous motors. The asynchronous motors are called singly excited machines, because the stator windings are connected to AC supply whereas the rotor does not have connection from the stator or to any other source of supply. The power is transferred from the stator to the rotor only by mutual induction, so the asynchronous motors are called as induction machines. The synchronous motors needs AC supply for the stator windings and DC excitation for the rotor windings. The motor speed is determined by the frequency of AC supply and the number of poles of the synchronous machine, the rotor rotates at synchronous speed of the stator revolving field, which is constant. The variations in mechanical load within the machine's ratings will not alter the motor's synchronous speed [1]. PMSM is one of the type of synchronous motor. The PMSM consists of conventional three phase windings in the stator and permanent magnets on the rotor. One of the main advantages of PMSM over its counterpart is the removal of dc supply for field excitation. Development of PMSM has took place due to the invention of novel magnetic materials and rare earth materials. Energy efficient PMSM are designed because availability of permanent magnet materials with high magnetic flux density.

In synchronous motors the rotor rotates at synchronous speed i.e. the speed of stator field. The synchronous speed (ω_s) can be determined by the frequency of the stator input supply (f_s), and the number of stator pole pairs (p). The stator of a three phase synchronous machine consists of distributed sine three phase windings, whereas the rotor consists of the same number of pole pairs as stator, magnetized by permanent magnets or a separate DC supply source. When the synchronous machine is excited with a three phase supply, a synchronous speed is developed in the stator. The synchronous speed of this rotating

magnetic field is shown by the Eq. (1).

$$N_s = 120.f_s / P \text{ (rpm)} \quad (1)$$

where N_s is the synchronous speed, f_s is frequency of AC supply in Hz and P is the number of poles.

Permanent magnet synchronous motors (PMSM) fed by PWM inverters are widely used for industrial applications, especially servo drive applications, in which constant torque operation is desired. In traction and spindle drives, on the other hand, constant power operation is desired. These machines have the advantages like light weight, small size, simple construction, easy maintenance, good reliability, and high efficiency. The PMSM can be designed with surface mounted or interior magnets (also known as non-salient pole PMSM or salient pole PMSM respectively). It is well known that the d-axis and q-axis reactance's are very important for designing control systems, in order to maximize the efficiency, power factor, etc. There are many methods to determine the d-axis and q-axis reactance's of (PMSM) [2]. For PMSM having surface mounted magnets, the d-axis and q-axis reactance's are approximately equal (the modern permanent magnets have relative permeability close to unity, therefore the air gap seen from the stator is nearly independent of the position). Inverter circuits make it possible for different control strategies (frequency variation, voltage variation, current variation), each one with specific applications. Recent developments in power electronics have brought inverter circuits suitable for voltage, current levels and switching frequencies. Permanent magnets make unwanted rotor windings and excitation circuit. Absence of the rotor circuit improves the mechanical design.

2. CONTROL TECHNIQUES FOR TORQUE RIPPLE MINIMIZATION

Many techniques based on both design of motor as well as

control techniques have been proposed in literature to minimize the torque ripples in the PMSM. (Fig. 1)

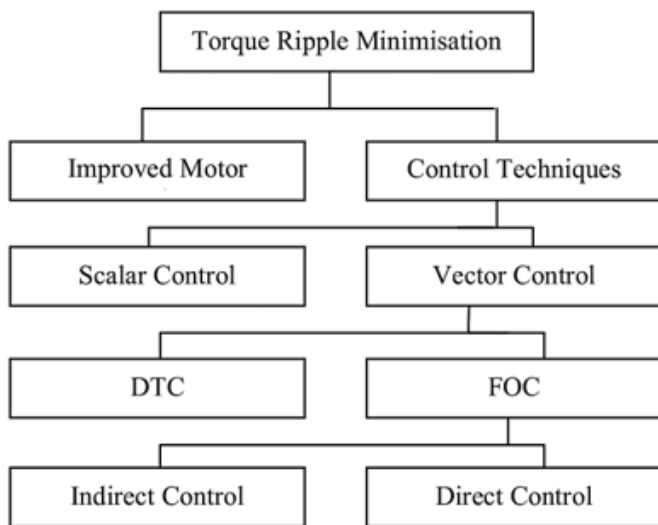


Fig (1). Classification of various control techniques

i. Scalar Control

The open-loop scalar control technique, which is the most prevalent control method for squirrel cage AC motors, is one way to control AC motors for variable speed applications. It is now employed in applications where the angular speed does not need to be known. It's appropriate for a wide range of drives since it ensures robustness at the expense of dynamic performance. Because the control algorithm does not require information about the angular speed or actual rotor position, this basic technique can run in a sensorless mode.

ii. Vector Control

Vector control of a brushless AC electric motor control system enables the rotation speed and torque on the motor shaft to be adjusted independently and with little inertia. Vector control is based on the idea of controlling not only the magnitude and frequency of the supply voltage, but also the phase. In other words, the space vector's magnitude and angle are regulated. In comparison to scalar control, vector control offers a better performance [3]. Vector control solves practically all of scalar control's drawbacks. There are two types of vector control techniques:

- **Direct torque control (DTC):** The DTC is one among the best performance control strategies for the control of AC machines. In a DTC drive applications, flux linkage and electromagnetic torque are controlled directly and independently by the selection of optimum inverter switching modes of operation. The required optimal switching vectors can be selected by using the optimum switching voltage vector look-up table. This can be obtained by simple physical considerations involving the position of the stator-flux linkage space vector, with available switching vectors, and the necessary torque flux linkage.
- **Field Oriented Control (FOC):** For the control of

PM motors, FOC technique is used for synchronous motor to evaluate as a DC motor. The stator windings of the motor are fed by an inverter that generates a variable frequency variable voltage scheme. Instead of controlling the inverter frequency independently, the frequency and phase of the output wave are controlled using a position sensor.

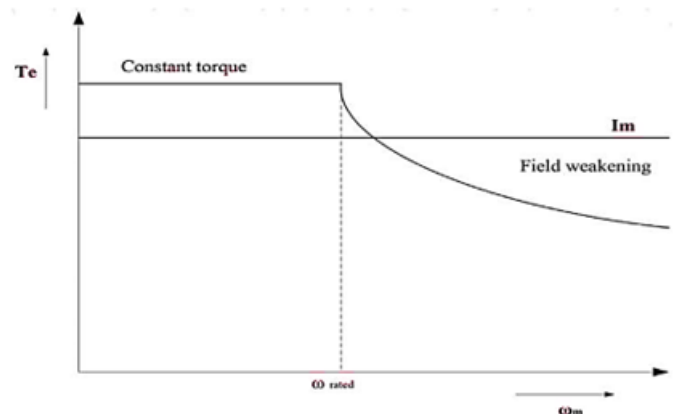


Fig. 2 Steady state torque versus speed.

3. PROPOSED TORQUE MINIMIZATION TECHNIQUE

One of the major disadvantages of the PMSM drive is the torque ripple produced which can be attributed to the following sources like mutual torque, due to the interaction of the rotor field and stator currents, reluctance torque, due to rotor saliency and cogging torque, due to the existence of stator slots. In this section presents an application of fuzzy logic control to denigrate the torque ripple associated with the field oriented control when used in control of a PMSM. A SVPWM based FOC with fuzzy logic control is proposed to produce an effective selection of the stator voltage vector to obtain smooth torque performance. The significant advantages of space vector modulation are the ease of microprocessor implementation. Also, one advantage of FOC is that it increases efficiency, letting smaller motors replace larger ones without sacrificing torque and speed. Another advantage is that it offers higher, more dynamic performance in the case of speed and torque controlled ac drives.

The block diagram of proposed FOC with the fuzzy logic based controller for the PMSM drive is shown in Fig. 3.

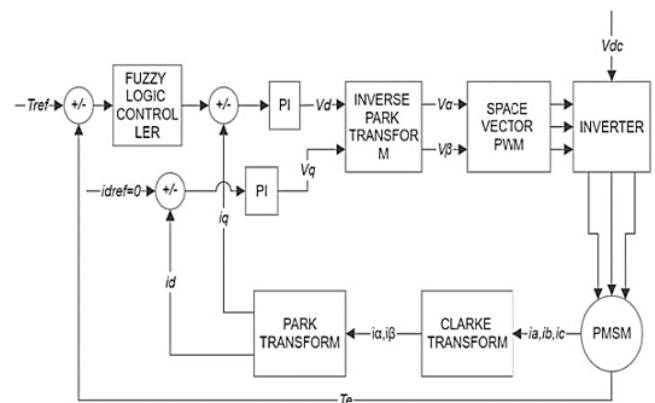


Fig. 3 Block diagram for proposed torque ripple minimization technique using FLC

i. Space Vector Pulse Width Modulation Technique

Space vector PWM (SVPWM) refers to a special technique of determining the switching sequence of the upper three power transistor so for three-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 PWM technique controls the motor based on the switching of space voltage vectors, by which an approximate circular rotary magnetic field is obtained [4].

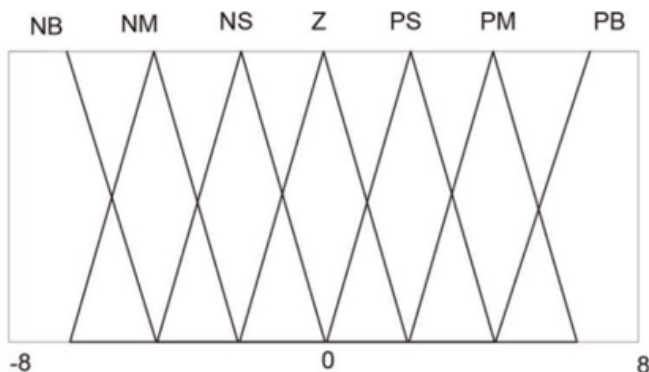
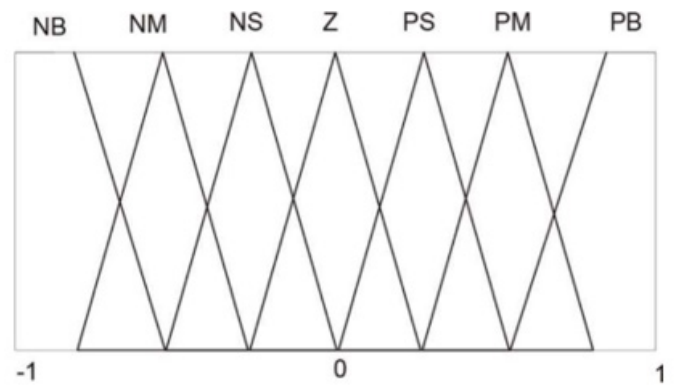
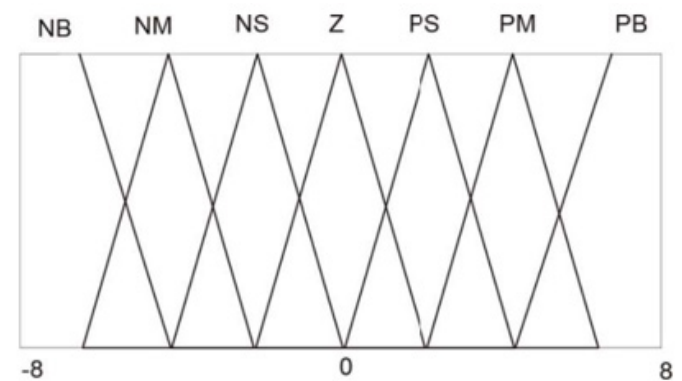
ii. PI controller tuning

The current loop PI controllers compare the actual current with reference current and produce i_q and i_d current, respectively. PI tuning can be done by trial and error method.

iii. Fuzzy logic controller

The basic concept behind FLC is to utilize the knowledge and experience of a human operator for designing a controller an application process whose input output relationship is given by a collection of fuzzy control rules using linguistic variables instead of a complicated dynamic model. The FLC initially converts the crisp error and change in error variables into fuzzy variable are mapped into linguistic labels. Membership functions are associated with each label as shown in which consists of two inputs and one output. The inputs are Torque error and change in torque error and the output is torque limit.

Fuzzy Inference System uses “IF... THEN...” statements, and the connectors present in the rule statement are “OR” or “AND” to make the necessary decision rules. The linguistic labels are divided into seven groups. They are: NB negative big; NM-negative medium; NS-negative; Z-zero; PS-positive small; PM-positive medium; PB-positive big. Each of the inputs and the output membership functions with all these seven linguistics. Fig 4 shows the speed error, Fig. 5 shows the change in speed error and Fig. 6 shows the torque limit. The mapping of the fuzzy inputs into the required output is derived with the help of a rule base as given in Table 1.

**Fig. 4 Torque error input to FLC****Fig. 5 Change in torque error input to FLC****Fig. 6 Torque limit output from FLC**

	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	NS	Z	PS	PM	PB	PB
PB	Z	PS	PM	PM	PB	PB	PB

Table 1**4. CONTROL TECHNIQUES FOR TORQUE MINIMIZATION**

The Simulink model of FLC with FOC using SVPWM PMSM is shown in Fig. 7 and that of inverter output is shown in Fig. 8. The FOC of PMSM is done using conventional PI controller and FLC using techniques using MATLAB results are compared with other reported results in Table 2.

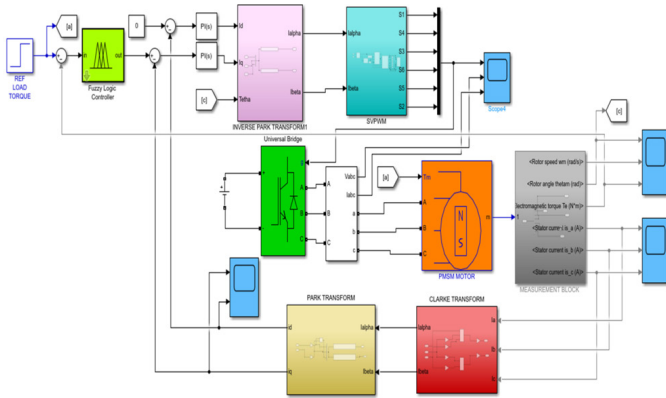


Fig. 7 Simulink Model of FLC with FOC for torque minimization

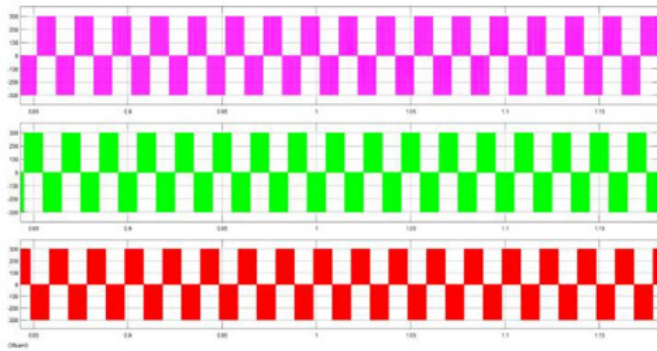


Fig. 8 Three phase inverter output

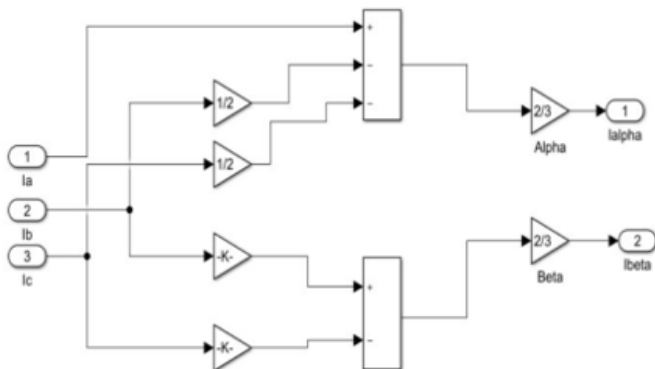


Fig. 9 Simulink model of Clarke transform

The Clarke transformation is applied to determine the stator projection of current in the two coordinates (α , β) stationary frames. The transformation from the three phase system into the two dimension orthogonal system is shown in Fig. 9. and Fig. 10. The Park transformation is then applied in order to obtain the projection in the d, q- rotating frame. Relationship between the two reference frames obtained and is shown in Fig. 11 and Fig. 12.

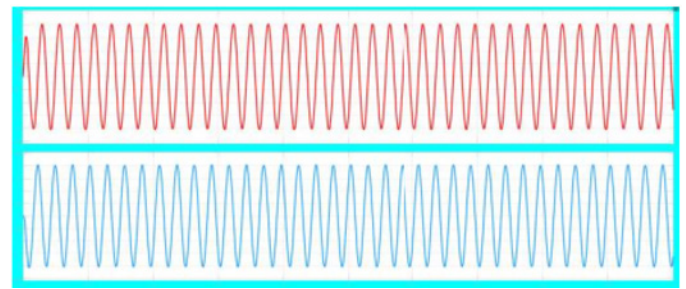


Fig. 10. Waveform after Clarke transform

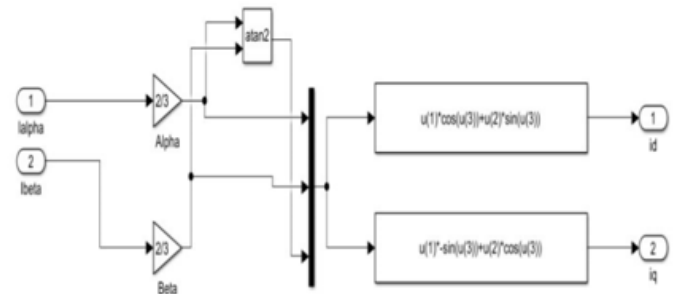


Fig. 11 Simulink Model of a Park transform

Then electromagnetic torque is sensed from the motor and is compared with the reference torque. The generated error signal is given either to the fuzzy LOGIC or PI Controller. The PI controller or FLC calculates reference torque, which is proportional to the q-axis stator current component iqref. The d-q projections of the stator phase currents are compared to their reference values idref and iqref and are corrected by means of PI controller. The outputs of the current controllers go through the inverse Park transform and voltage vector will be impressed to the motor with the help of space vector pulse width modulation (SVPWM).

Control Strategies	Torque Ripple Factor
Proposed FLC with SVPWM	1.75%
Mattavelli et al. [5]	3.8%
Qian et al. [6]	3.9%
Tarnik and Murgas [7]	4%
Hasanien [8]	12%

Table 2

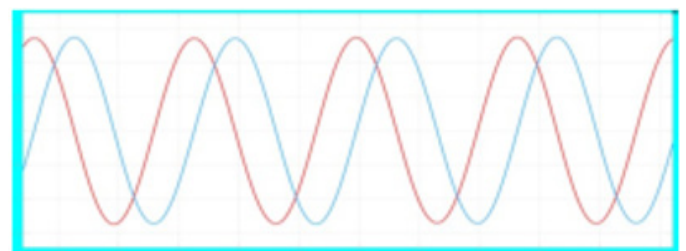


Fig. 12 Waveform of Park's transform

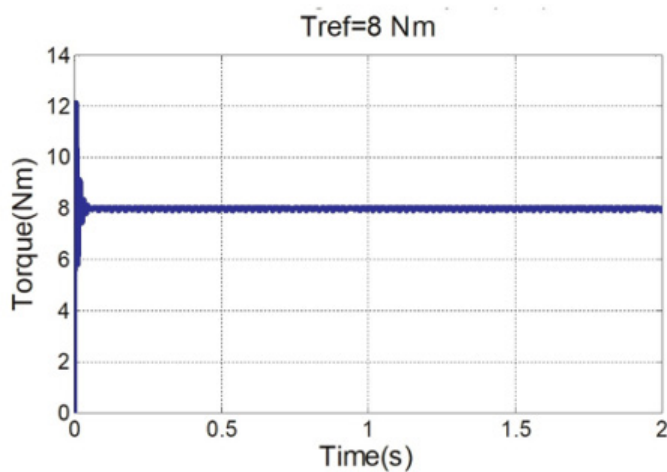


Fig. 13 Torque Output

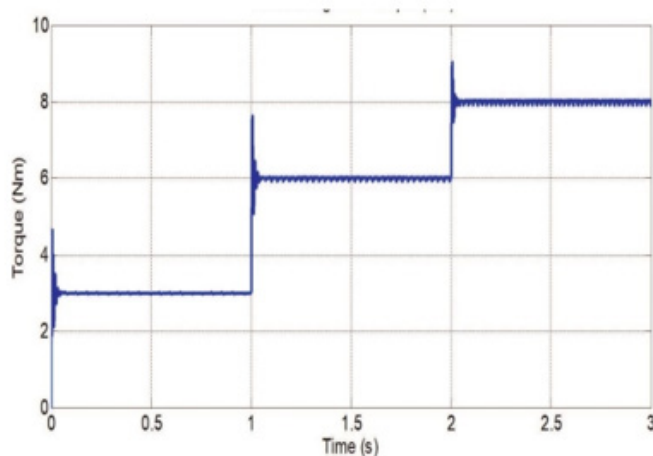


Fig. 14 Torque for various load torques

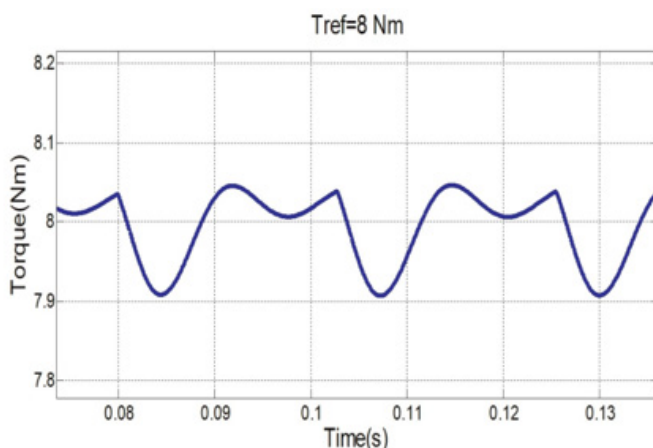


Fig. 15 Torque Ripples zoomed in view

The torque ripple can be calculated by using the relation,

$$\text{Torque Ripple factor} = \frac{\text{Peak to peak torque}}{\text{Rated Torque}}$$

The simulation results are shown in Figures 13–15.

Torque ripple factor (%) can be calculated as $= ((8.05 - 7.91)/8) * 100 = 0.14/8 * 100 = 1.75$. It is clear that variation in torque shown in Table 2 is less in case of fuzzy logic controller it can

achieve a minimum torque ripple compared to other control techniques. It can be seen that the discussed control strategy has helped in reducing the torque ripples to 1.75%. Thus by using FLC based controller, ripples are reduced completely.

5. CONCLUSION

Torque minimization technique of PMSM motor drive using fuzzy logic controller is analyzed and simulated using MATLAB Simulink and the results have been presented to visualize the comparison with techniques in the literature. The results obtained from fuzzy logic controller show fast and satisfactory response under different load torque.

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