



Predictive Field Oriented Control of PMSM Using Fuzzy Logic

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Keywords : Permanent magnet synchronous motor, fuzzy logic, predictive current control, field oriented control, space vector modulation, constant switching frequency

Abstract :

This paper deals with two popular and powerful methods in electrical drive applications. The first one is field oriented control (FOC) and the other one is space vector modulation (SVM). The proposed FOC-SVM method is incorporated with a predictive current control (PCC) based technique. The proposed method estimates the desirable electrical torque to track mechanical torque at fixed speed operation of permanent magnet synchronous motor (PMSM). The estimated torque is used to calculate the reference current based on FOC. In order to increase the performance of the traditional SVM, predictive current control (PCC) is established as switching pattern modifier. In addition, to manage the uncertainty of the estimated values and their error, a fuzzy inference system is cooperated with the proposed FOC-SVM-PCC controller. The performance of the proposed technique is evaluated in terms of torque and current ripple and transient response to step variations of the torque command. The presented method has been simulated with MATLAB-SIMULINK

model. Simulation results confirm the ability of this technique in minimizing of torque and speed ripples and fixing switching frequency, simultaneously.

1. Introduction

In recent years, permanent magnet synchronous motors (PMSM) have gained an increasing popularity in a variety of industrial applications [1]. In addition, many researchers have tried to reduce the torque pulses and harmonics in PMSM. There are many ways to use power converters to fix the voltage or current in a PMSM driver to desired set point. There are two popular modulation methods for inverter voltage control. The first one is voltage control (such as six-step, sinusoidal, and space-vector modulation) and the other one is current control (such as hysteresis and delta modulation) [2]. Since important improvements have been made regarding the control techniques of the special machines, adequate operation for any industrial application is obtained with the appropriate supplying-motor assembly. In the same time, two of the control techniques, which are

widely used in this industrial environment, are the field oriented and the direct torque control (FOC and DTC, respectively) [3]. These control strategies are different on the operation principle but their objectives are the same. They aim both 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. Both control strategies have been successfully implemented in industrial products [4].

DTC is able to produce very fast torque and flux control, if the torque and the flux are correctly estimated, and will be robust with respect to motor parameters and perturbations. By controlling stator current by FOC it reduces torque ripple for quieter motor operation. The supporters of field-oriented control and direct torque control claim the superiority of their strategy versus the other. Up to now, the question of which strategy is superior the other, has not been clearly answered [5]. Nonetheless the DTC based controllers are very little sensible to the parameters detuning in comparison with FOC, operation with variable switching frequency and large torque ripple (due to the hysteresis comparators) are the disadvantages of these controllers [6].

The idea of combining the advantages of DTC and PMSMs into a highly dynamic drive appeared in the late 1990's [7], [8]. In the past decade several authors have proposed ways to adapt DTC to work with PMSMs [9]. In 1989 Pillay and Krishnan [10] presented the PMSM which was one of several types of permanent magnet ac motor drives available in the drives industry. They did not consider the damper windings and designed the motor drive system in field-oriented control. Qianad and Rahman [11] developed FOC in PMSM they presented a microprocessor-based FOC for PM hysteresis synchronous motor.

Recently, some researches have been devoted on the torque and flux ripple reduction and fixing the switching frequency of the DTC system [12-16]. A modified DTC scheme

with fixed switching frequency and low torque and flux ripple was introduced in [14] and [16]. With this design, however, two PI regulators are required to control the flux and torque and they need to be tuned properly. To reduce the torque ripples, Sun et al. [17] proposed a fuzzy logic algorithm to refine the selection of the voltage vectors. Fuzzy control is a way for controlling a system without the need of knowing the plant mathematic model. It uses the experience of people's knowledge to form its control rule base. There has appeared many applications of fuzzy control on power electronic and motion control in the past few years. A fuzzy logic controller was reported being used with DTC [18]. The fuzzy controller is designed to have three fuzzy state Variables and one control variable for achieving direct torque Control of the induction machine [19]. However there arises the problem that the rule numbers it used is too many which would affect the speed of the fuzzy reasoning [20].

As mentioned in literature, the high current and torque ripple in DTC are due to the presence of hysteresis comparators together the limited number of available voltage vectors [21]. Due to this disadvantage of conventional current control, the current control of a PMSM by a predictive current control (PCC) technique based on the space vector modulation is presented in [22]. Other references applied predictive current control technique to PMSM drive system and voltage source inverter in [20-23] and [26-27] respectively. Wipasuramonton et al. [24] proposed a technique to reduce the current errors that exist due to the inaccuracies in the system parameters and the non ideal behavior of the inverter. In addition to these, Moon et al. [23] discretized the PMSM module to improve transient and steady state, better than the conventional predictive current controllers.

The significant advantages of space vector modulation are the ease of microprocessor implementation [28]. Also, one advantage of field oriented control 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 [29]. Therefore, in order to utilize the capabilities of FOC and SVM techniques and eliminate the problems of variable switching frequency, a predictive current control based method (compatible with both FOC and SVM methods) is proposed. Also, in order to mitigate the uncertain values of the proposed controller (the input values) a fuzzy system is added to the predictive based field oriented controller. In addition, to the constant switching frequency the proposed predictive technique is employed to reduce speed and torque ripple (by predicting the proper vector of the applied voltage at the PMSM terminal). The proposed method uses the d-q form of motor equations and discretizes the equations to have controlled torque with lower error. The discretizing process in constant time period (T), leads to operate the proposed PMSM driver with constant switching frequency (1/T Hz). The electromechanical relations of PMSM are used to estimate the desired currents and proper voltage vectors in synchronous speed terms.

2. Analytic Mode of PMSM

Permanent magnet synchronous motor has been studied since two last decades widely. In majority of devoted method on PMSM there is a set of equations depended on rotor position. By representing the motor equations in rotor reference frame, we have a set of equations independent of rotor position. The d and q axis currents will be obtained from two transformations. The first part transfers the three phase to two phase (abc to $\alpha\beta$). The second part carries over the quantities at stationary frame to rotational frame.

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (2)$$

where, θ represents the rotor position. According to the mentioned above, electromechanical behavior of the PMSM in the dq-frame is as below:

$$V_q = R i_q + \omega_r \lambda_d + \frac{d \lambda_q}{dt} \quad (3)$$

$$V_d = R i_d - \omega_r \lambda_q + \frac{d \lambda_d}{dt} \quad (4)$$

$$V_o = R i_o + \frac{d \lambda_o}{dt} \quad (5)$$

$$\lambda_q = L_q i_q \quad (6)$$

$$\lambda_d = L_d i_d + \lambda_m \quad (7)$$

$$\lambda_o = L_o i_o \quad (8)$$

$$T_e = \frac{3}{2} P \left(\lambda_m i_q + (L_d - L_q) i_d i_q \right) \quad (9)$$

$$\frac{d \omega_r}{dt} = \frac{P}{J} (T_e - B \omega_r - T_m) \quad (10)$$

If the angle between stator and rotor field flux is kept at 90° we have:

$$i_d^* = 0 \quad (11)$$

So, by this assumption and set $i_o = 0$, determining i_q leads to control the electrical torque directly.

$$T_e = \frac{3}{2} P \lambda_m i_q \quad (12)$$

It should be mentioned that a predictive process will be present to have constant motor speed accompanied with low error torque tracking procedure.

3. Traditional Space Vector Modulation

Space vector modulation for three phase voltage source inverter is based on the representation of the three phase quantities as vectors in a two-dimensional (α, β) plane. The reference voltages are given by space voltage vector and the output voltages of the inverter are considered as space vectors. There are eight possible output voltage

vectors, six active vectors V_2-V_7 , and two zero vectors V_1, V_8 (Fig. 1).

The reference voltage vector is realized by the sequential switching of active and zero vectors. According to the SVM method, the inverter will switch between switching vectors (V_1-V_8) with consideration of angle of desirable voltage (θ). However a disadvantage of SVM is that it requires complex online computation that limits the inverter switching frequency [28].

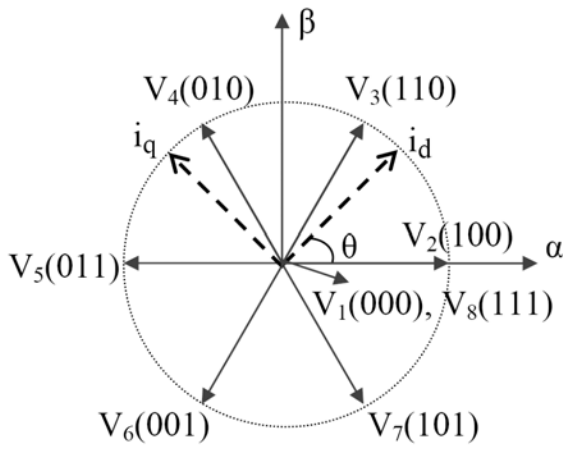


Fig. 1. Output voltage represented as space vectors

4. Proposed Predictive FOC-SVM Method

PMSM control techniques can be divided into scalar and vector control. The problem with scalar is that motor flux and torque in general, are coupled. The vector control theory provides a control strategy to regulate the instantaneous rotational torque in electrical machines. In this control technique, the magnitude of stator and rotor flux and their mutual angle are considered.

The vector control of currents and voltages results in control of the spatial orientation of the electromagnetic fields in the machine and it has led to the field, called orientation-field. Oriented control usually refers to controllers which maintain a 90° orientation referred to as field angle control or angle control. To have an independent controlled orthogonal special angle (electrical) between stator and rotor flux, the angle between stator and rotor field flux should be kept at 90° which leads to:

$$\begin{aligned} i_d = 0 &\rightarrow i_d^* = 0 \\ i_q &= i_s \end{aligned} \quad (13)$$

In other words, the desired value of i_d is zero. Therefore, the d axis reference current is taken as zero ($i_d^* = 0$). In order to calculate the q axis reference current the following relations are suggested. The equation 10 represents in discrete state:

$$\begin{aligned} \frac{d\omega_r}{dt} = \frac{p}{J}(T_e - B\omega_r - T_m) &\rightarrow \frac{\omega_r(n+1) - \omega_r(n)}{T} = \\ \frac{p}{J}(T_e(n) - B\omega_r(n) - T_m(n)) \end{aligned} \quad (14)$$

By considering this fact that the synchronous motor has a fixed speed, then we would have $\omega_r(n+1)$ as a known parameter of the next sample condition. So, the desired value of $T_e(n)$ will be derived as following:

$$\omega_r(n+1) = \omega_r^* \quad (15)$$

$$T_e^*(n) = B\omega_r(n) + T_m(n) + \frac{J}{p} \left(\frac{\omega_r^* - \omega_r(n)}{T} \right) \quad (16)$$

Regarding to the equations 12 and 16, the q axis reference current can be obtained as:

$$i_q^* = \frac{2}{3p\lambda_m} \left(B\omega_r(n) + T_m(n) + \frac{J}{p} \left(\frac{\omega_r^* - \omega_r(n)}{T} \right) \right) \quad (17)$$

Substituting the equations 6, 7 and 8 in the equations 3, 4 and 5 represents the equations of PMSM in dq-frame as:

$$V_q = Ri_q + L_d\omega_r i_q + \lambda_m\omega_r + L_q \frac{di_q}{dt} \quad (18)$$

$$V_d = Ri_d - L_q\omega_r i_q + L_d \frac{di_d}{dt} + \frac{d\lambda_m}{dt} \quad (19)$$

We can write Eq.18 and Eq.19 in discrete time, by considering the concept of derivation in discrete time, as:

$$\begin{aligned} V_d(n) = Ri_d(n) + L_q\omega_r(n)i_q(n) + \\ L_d \frac{i_d(n+1) - i_d(n)}{T} \end{aligned} \quad (20)$$

$$\begin{aligned} V_q(n) = Ri_q(n) - L_d\omega_r(n)i_d(n) - \omega_r(n)\lambda_m + \\ L_q \frac{i_q(n+1) - i_q(n)}{T} \end{aligned} \quad (21)$$

The subscript (n) represents the present time values and (n+1) values in the next sample. Note that the duration between two samples is equal with T.

Regarding to the equations 20 and 21, the estimated values of i_d and i_q at the next sample ($i_d^{(n+1)}, i_q^{(n+1)}$), can be obtained as:

$$i_d^{(n+1)} = i_d^{(n)} + \frac{T}{L_d} (V_d^{(n)} - R i_d^{(n)} - L_q \omega_r^{(n)} i_q^{(n)})$$

$$i_q^{(n+1)} = i_q^{(n)} + \frac{T}{L_q} (V_q^{(n)} - R i_q^{(n)} + L_d \omega_r^{(n)} i_d^{(n)} + \omega_r^{(n)} \lambda_m)$$

According to the equations 22 and 23, by keeping the existing voltage vectors (V_d, V_q) to the d-q currents at the next sample are obtained.

In order to reduce the speed error and torque ripple, the estimated d and q axis currents ($i_d^{(n+1)}$ and $i_q^{(n+1)}$) must track the reference d and q axis currents (i_d^* and i_q^*) accurately. The error between the references and (n+1) states currents (calculated currents in the equations 13, 17 and 22, 23 respectively) motor are defined as:

$$\begin{cases} \Delta i_d = i_d^* - i_d^{(n+1)} \\ \Delta i_q = i_q^* - i_q^{(n+1)} \end{cases} \quad (24)$$

With the above definition, we can establish the SVM technique in the proposed predictive field oriented control method. Regarding to the Fig. 1, by having the rotor angle (θ), Δi_d and Δi_q the proper switching state (correspondingly the proper voltage vector) will be chosen.

As a matter of fact, the negative amounts of Δi_d and Δi_q indicate that the proper vector must increase the i_d and i_q through the next sample. Also, the positive amounts of Δi_d and Δi_q indicate that the proper vector must decrease the i_d and i_q through the next sample. As an example, for $\theta = 45^\circ$, the proper voltage vector is selected in terms of probable values of Δi_d and Δi_q . In this case, there is two possible switching vectors (110,010 and 001,101 respectively). In this situation the desirable vector is selected in term of more increase or decrease of i_q (when the $\Delta i_q > \varepsilon$ and $\Delta i_d > 0$, the 010 switching vector lead to increase of i_d and when

the $\Delta i_q < -\varepsilon$ and $\Delta i_d < 0$, the 010 switching vector lead to increase of i_q . On the similar way, the switching pattern, in terms of $0 < \theta < 2\pi$ can presented as table I. It should be mentioned that the obtained switching vectors are applied through a sample (T). Due to this scheme, the switching frequency is fixed in 1/T Hz. Therefore, the constant switching frequency reduces the switching losses.

Table I
The selecting pattern of proper voltage vectors

Voltage vectors	$\Delta i_q < -\varepsilon$	
	$\Delta i_d > 0$	$\Delta i_d < 0$
$-\pi/6 < \theta < \pi/6$	101	001
$\pi/6 < \theta < \pi/2$	100	101
$\pi/2 < \theta < 5\pi/6$	110	100
$5\pi/6 < \theta < 7\pi/6$	010	110
$7\pi/6 < \theta < 3\pi/2$	011	010
$3\pi/2 < \theta < 11\pi/6$	001	011

Voltage vectors	$-\varepsilon < \Delta i_q < \varepsilon$	
	$\Delta i_d > 0$	$\Delta i_d < 0$
$-\pi/6 < \theta < \pi/6$	111	000
$\pi/6 < \theta < \pi/2$	111	000
$\pi/2 < \theta < 5\pi/6$	111	000
$5\pi/6 < \theta < 7\pi/6$	111	000
$7\pi/6 < \theta < 3\pi/2$	111	000
$3\pi/2 < \theta < 11\pi/6$	111	000

Voltage vectors	$\Delta i_q > \varepsilon$	
	$\Delta i_d > 0$	$\Delta i_d < 0$
$-\pi/6 < \theta < \pi/6$	110	010
$\pi/6 < \theta < \pi/2$	010	011
$\pi/2 < \theta < 5\pi/6$	011	001
$5\pi/6 < \theta < 7\pi/6$	001	101
$7\pi/6 < \theta < 3\pi/2$	101	100
$3\pi/2 < \theta < 11\pi/6$	100	110

5. Improved Predictive FOC Method with Fuzzy System

The proposed control strategy in the previous section has the property of hysteresis, which only takes one control status for the very big or small error of the torque. That means the control action will be the same in the whole error range. To get a better control

performance, introducing a fuzzy logic controller replace the hysteresis controller should be proper.

Designing of the fuzzy logic controller needs to two consecutive steps:

A)Choice of membership functions for input and output variables.

B)Rule knowledge-based structure based on previous error procedure.

Consequently, worthy fuzzy operators and defuzzification method are assigned to obtain the decision on the fuzzy logic controller output. According to the previous section, the fuzzy controller is designed to have three fuzzy state Variables and one control variable. The input set consists of the d-Axis current error, q-Axis current error and the rotor position (rotor angle). The output is the voltage space vector shown Fig. 1. The input and output sets of fuzzy system are shown in Fig. 2 to 5. These rules are described by language variables.

The 1n input (d-Axis current error):

P means that the d-Axis current error is positive, so the d-Axis current must make increase.

Z means that the d-Axis current error is zero, so the d-Axis current no needs to make change.

N means that the d-Axis current error is negative, so the d-Axis current must make decrease.

The 2n input (q-Axis current error):

PL means that the q-Axis current error is positive large, so the q-Axis current must make increase rapidly.

PS means that the q-Axis current error is positive small, so the q-Axis current must make increase slowly.

Z means that the q-Axis current error is zero, so the q-Axis current no needs to make change.

NS means that the q-Axis current error is negative small, so the q-Axis current must make decrease slowly.

NL means that the q-Axis current error is negative large, so the q-Axis current must make decrease rapidly.

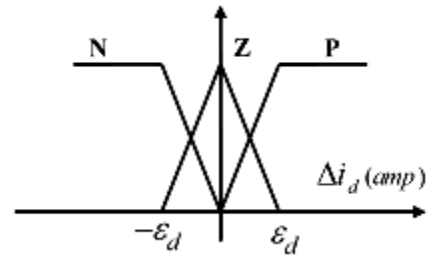


Fig.2. Membership functions of d-Axis current error (1n input)

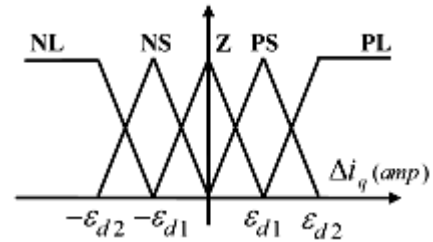


Fig.3. Membership functions of q-Axis current error (2n input)

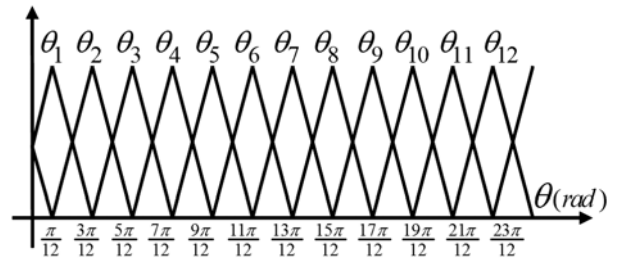


Fig.4. Membership functions of rotor angle (3n input)

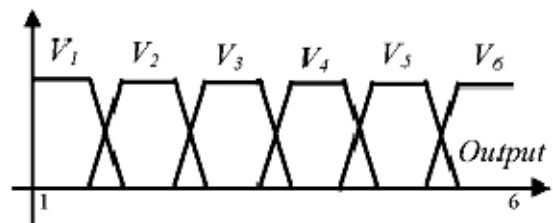


Fig.5. Membership functions voltage space vector (output)

The control rules are established using literature and table I. The inference method used in this system is Mamdani's procedure based on min-max decision [20]. Therefore, Fuzzy rule base that causes FOC improvement can be found in Table II. As

mentioned in table II, each angle has specified rule.

Table II
Fuzzy rule for the stator voltage switching state selector

Δid	Δiq	$\theta 1$	$\theta 2$	$\theta 3$	$\theta 4$	$\theta 5$	$\theta 6$
N	NL	001	101	101	100	100	110
	NS	000	111	111	000	000	111
	Z	000	111	111	000	000	111
	PS	010	011	011	001	001	101
	PL	011	011	001	001	101	101
Z	NL	101	100	100	110	110	010
	NS	111	111	000	000	111	111
	Z	111	111	000	000	111	111
	PS	110	110	010	010	011	011
	PL	110	010	010	011	011	001
P	NL	101	100	100	110	110	010
	NS	100	111	110	000	010	111
	Z	111	111	000	000	111	111
	PS	110	110	010	010	011	011
	PL	110	010	010	011	011	001

Δid	Δiq	$\theta 7$	$\theta 8$	$\theta 9$	$\theta 10$	$\theta 11$	$\theta 12$
N	NL	110	010	010	011	011	001
	NS	111	000	000	111	111	000
	Z	111	000	000	111	111	000
	PS	101	100	100	110	110	010
	PL	100	100	110	110	010	010
Z	NL	010	011	011	001	001	101
	NS	000	000	111	111	000	000
	Z	000	000	111	111	000	000
	PS	001	001	101	101	100	100
	PL	001	101	101	100	100	110
P	NL	010	011	011	001	001	101
	NS	011	000	001	111	101	000
	Z	000	000	111	111	000	000
	PS	001	001	101	101	100	100
	PL	001	101	101	100	100	110

According to the table II, the fuzzy rule for each rotor angle (based on Fig. 4) is determined.

For example, for the rotor angle $\theta 1$, if the control process is to increase the q-Axis current rapidly (PL) and increase the d-Axis current (P), the desired decision for the output switching vector is 110 (V3) or the rotor angle $\theta 8$, if the control process is to decrease the q-Axis current slowly (NL) and increase the d-Axis current (P), the desired decision

for the output switching vector is 011 (V5). In the similar way, these (5×3×12=180) rules could be checked clearly.

6. Simulation Result

The performance of the proposed fuzzy drive is investigated through computer simulation with MATLAB/SIMULINK. In the proposed PMSM drive the SVM technique is incorporated with the proposed predictive field oriented controller and improved with fuzzy inference system. The d-q axis currents and voltages, speed and mechanical load of the PMSM are applied to the predictive field oriented controller. Thereupon, the difference between estimated and reference d-q currents are utilized to the fuzzy based SVM rules (established in the Table II). Consequently, the obtained switching vectors are applied to the voltage source inverter through a constant switching period.

Table II
PMSM parameters in simulation model

P	Number of pole pairs	4	
R	Stator resistance	1	Ω
Ld,Lq	Stator inductance	6	mH
λm	Rotor magnet flux	0.2	Wb
J	Rotor inertia	0.001	Kg.m ²
B	Damping coefficient	0.0004	
wr	Rated speed	2000	rpm
T _N	Rated torque	10	N.m
fr	Switching frequency	20	kHz
	DC voltage	300	Volt
	Power switches	IGBT	

It is clear that the high switching frequency leads to proper operation of the proposed drive. Simulation parameters (such as PMSM, voltage source inverter) are listed in Table III. In order to show the performance of the proposed controller the result without and with fuzzy inference system is illustrated.

The controller (without fuzzy inference system) is tested with a sudden load change applied to the PMSM. Regarding to the Fig. 6, the electrical torque tracks the mechanical load torque properly. This figure depicts that the electrical torque response has minimum error (mechanical torque changes: 5 N.m to 8 N.m at 0.8 second). Furthermore, the

electrical speed in terms of the arbitrary reference speed (exhibited in Fig. 7) has low ripple, error. Also, according to the Fig. 5 the fast transient response of electrical torque is a result of the proposed method. In fact, a considerable step up in mechanical load will cause to a considerable speed reduction. Therefore, the duty of a controller is reducing motor speed drop at minimum transient time. Furthermore, the motor drive must keep the speed error in the steady-state at admissible range.

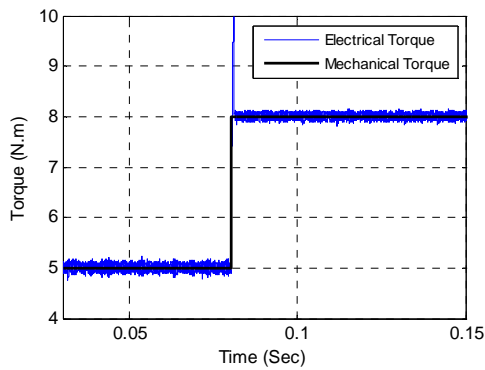


Fig. 6. Dynamic change in load torque: electrical and mechanical torque without fuzzy controller

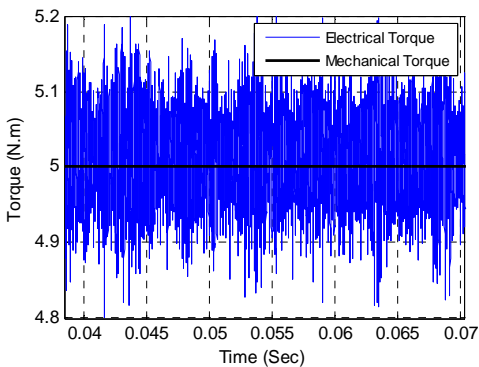


Fig. 7. Electrical speed of PMSM during a dynamic change in load torque without fuzzy controller

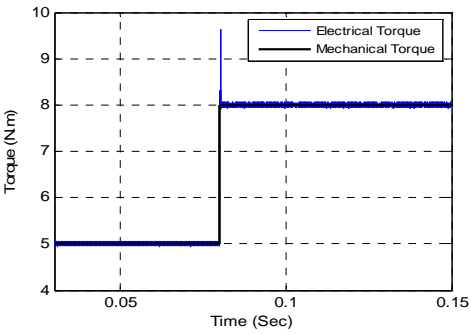
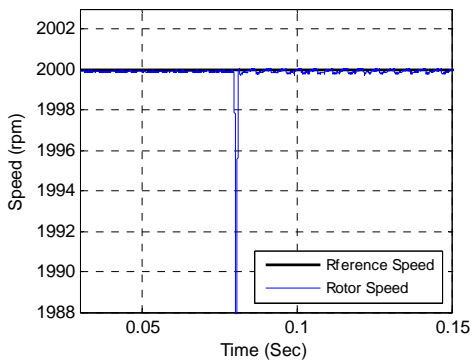


Fig. 8. Dynamic change in load torque: electrical and mechanical torque with fuzzy controller

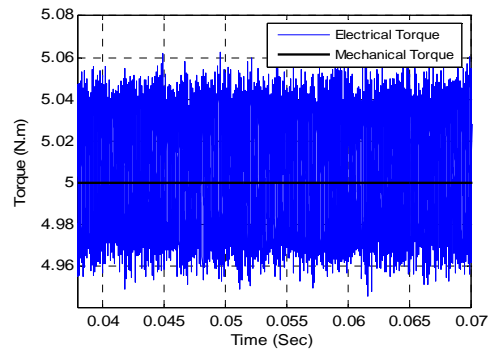


Fig. 9. Electrical speed of PMSM during a dynamic change in load torque with fuzzy controller

The results of the improved controller with fuzzy system are shown in Fig. 8 and Fig. 9. As shown in these figures the electrical torque ripple and error of the rotor speed are lower than the similar case in the controller that is not improved by fuzzy system. According to the Fig. 6, the error of the electromagnetic torque produced by the motor in steady-state is around 8% and 5% at 5 N.m and 8 N.m of the mechanical load torque, respectively.

The amounts achieved errors are reduced to 2% and 1.25% at mentioned reference speeds for the fuzzy improved controller. Therefore,

the PMSM torque can be tuneable in a tolerable range of mechanical torque with fast transient response and low error at steady-state.

7. Conclusion

The aim of this paper is to propose an accurate method in PMSM drive. A new control technique based on FOC technique is suggested. The proposed control strategy uses space vector modulation technique is used to reduce switching losses. In order to have an optimum switching control strategy, the FOC-SVM based method is modified with fuzzy inference system. The proposed FOC-SVM method is incorporated with a predictive current control (PCC) based technique. The proposed method estimates the desirable electrical torque to track mechanical torque at fixed speed operation of permanent magnet synchronous motor (PMSM). The proposed FOC-SVM-PCC controller predicts the desirable stator current as reference value. The error between this current and estimated stator current at the next sample with existing switching vector, is applied to the modified fuzzy table. The performance of the proposed technique is evaluated in terms of torque and current ripple and transient response to step variations of the torque command. The presented method has been simulated with MATLAB-SIMULINK model. According to the results, the proposed technique is able to reduce torque ripple and its transient-states at mechanical torque variations. The advantages of the proposed method are fixed switching frequency, fast response and low harmonic current.

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