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Research Article

Sensorless Field Oriented Control of Permanent Magnet Synchronous Motor

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Abstract

This paper presents a controller which consists of a Proportional, Integral (PI) and fuzzy speed controller for the sensorless speed control of Permanent Magnet Synchronous Motor (PMSM) using Model Reference Adaptive System (MRAS). In this paper the sensorless control of PMSM is studied. The study contains two main purposes; the first is to find a simple effective method to estimate the rotor position and angular speed of the PMSM, The second is to regulate the speed of the motor with varying the load using the PI controller and the fuzzy controller. The simulation of the system is established using MATLAB package. This paper mainly focuses on designing the MRAS algorithm in order to estimate rotor speed. When the load torque changes suddenly this algorithm decreases the rise time to reach the speed reference.

Keywords: *PMSM, FOC, Sensorless control, MRAS, Fuzzy, PI.*

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1. Introduction

PMSM has been widely used in high performance drive applications for its advantages such as compactness, high efficiency, reliability, suitability to environment, high power density, and smaller size. It widely used in machine tools and robots. In order to overcome the inherent coupling effect and the sluggish response of scalar control the field oriented control (FOC) is employed. By using the FOC in this paper, the performance of the AC machine can be made similar to that of a DC machine (M. A. Rahman *et al*, 1985; R. Gabriel *et al*, 1980). In this work to achieve high performance the sensorless FOC of the PMSM drive is employed. Using shaft sensors presents some disadvantages as reliability, machine size, noise interferences and cost. Therefore, using MRAS scheme eliminating the rotor position sensor mounted on the rotor of the PM machine and reduces this disadvantage (A. R. Wheeler, 1984; P. B. Allan *et al*, 1979).

1.1 Classification of PMSM

1.1.1 Direction of field flux: PM motors are broadly classified by the direction of the field flux. The first field flux classification is radial field motor meaning that the flux is along the radius of the motor. The second is axial field motor meaning that the flux is perpendicular to the radius of the motor (E. Richter *et al*, 1985; V. B. Honsinger, 1982).

1.1.2 Flux density distribution

PM motors are classified on the basis of the flux density distribution and the shape of current excitation. The PMSM has a sinusoidal-shaped back EMF and is designed to develop sinusoidal back EMF waveforms. They have the following:
A. Sinusoidal distribution of magnet flux in the air gap
B. Sinusoidal current waveforms
C. Sinusoidal distribution of stator conductors.

1.1.3 Permanent magnet radial field motors

In PM motors, the magnets can be placed in two different ways on the rotor. Depending on the placement they are called either as surface permanent magnet motor or interior permanent magnet motor.

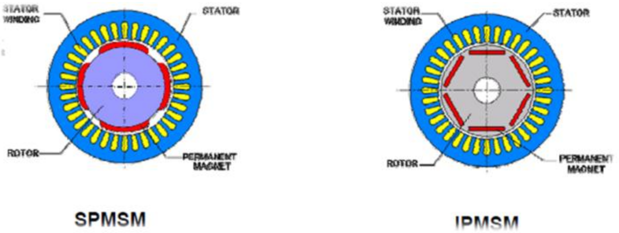

Fig.1 Cross -section of surface mounted and interior PM motor

A- Surface mounted PM motors have a surface mounted permanent magnet rotor as shown in figure 2. Each of the PM is mounted on the surface of the rotor. For a surface permanent magnet motor Ld = Lq.

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B- Interior PM motors have interior mounted permanent magnet rotor as shown in figure2. Each permanent magnet is mounted inside the rotor. For interior PM (Lq > Ld) (M. A. Rahman *et al*, 1985; T. Sebastian *et al*, 1986).

2. Proposed Control System

Figure1 shows the proposed control system. It consists of five main parts are.
1-PMSM, 2-FOC, 3-Controller, 4-Three- phase inverter, 5-MRAS filter

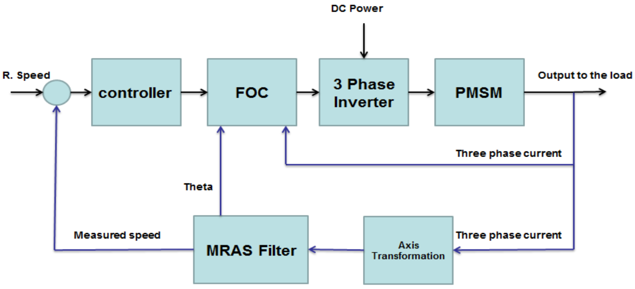

Fig.2 The proposed control system

3. Modeling of PMSM

The model of PMSM without damper winding has been developed on rotor reference frame using the following assumptions (T. Sebastian *et al*, 1986; P. Pillay *et al*, 1988):
1) Saturation is neglected.
2) The induced EMF is sinusoidal.
3) Eddy currents and hysteresis losses are negligible.
4) There are no field current dynamics.
5) The constants of the machine do not vary with temperature

The stator voltage equations in d-q axis are

$$V_{qs} = R_s\, i_{qs} + \omega_r\, \lambda_{ds} + P\, \lambda_{qs} \quad (1)$$
$$V_{ds} = R_s\, i_{ds} - \omega_r\, \lambda_{qs} + P\, \lambda_{ds} \quad (2)$$

The d and q axes Flux Linkages equations are

$$\lambda_{ds} = L_d\, i_{ds} + \lambda_f \quad (3)$$
$$\lambda_{qs} = L_q\, i_{qs} \quad (4)$$

The voltage equations of PMSM can be written as

$$V_q = R_s\, i_q + P\, L_q\, i_q + \omega_r\, L_d\, i_d + \omega_r\, \lambda_f \quad (5)$$
$$V_d = R_s\, i_d - \omega_r\, L_q\, i_q + P\, L_d\, i_d \quad (6)$$

Where Rs is the stator resistance, Ld the d-axis inductance, Lq the q-axis inductance, ωr the rotor rotational speed and λf the permanent magnet flux.

Arranging equations 5 and 6 in matrix form

$$\begin{bmatrix} V_q \\ V_d \end{bmatrix} = \begin{bmatrix} R_s + P L_q & \omega_r L_d \\ -\omega_r L_q & R_s + P L_d \end{bmatrix} \begin{bmatrix} i_q \\ i_d \end{bmatrix} + \begin{bmatrix} \omega_r \lambda_f \\ 0 \end{bmatrix} \quad (7)$$

$$T_{em} = 3p/2(\lambda_d\, i_q - \lambda_q\, i_d) = T_L + B\, \omega_m + J\frac{d\omega_m}{dt} \quad (8)$$

Where Tem is the developed torque

Using Parks transformation then

$$\begin{bmatrix} V_q \\ V_d \\ V_o \end{bmatrix} = 2/3 \begin{bmatrix} \cos\theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \sin\theta & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (9)$$

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ \cos(\theta - \frac{2\pi}{3}) & \sin(\theta - \frac{2\pi}{3}) \\ \cos(\theta + \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} V_q \\ V_d \\ V_o \end{bmatrix} \quad (10)$$

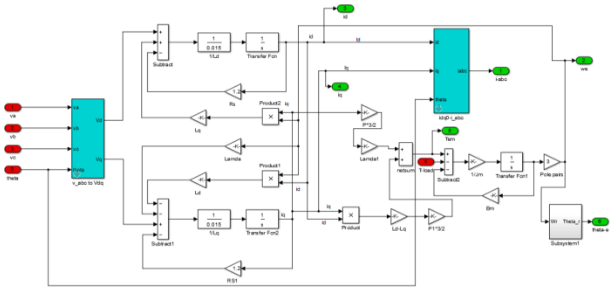

Fig.3 Complete Simulink model of PMSM

4. Field Oriented Control (FOC)

The FOC consists of controlling the stator currents. It is based on transform three phase's currents time and speed dependent system into a two co-ordinates (d and q) time invariant system. These projections lead to a structure similar to that of a DC machine control (Z. Bingyi *et al*, 2003). FOC needs two input references, the torque component (aligned with the q co-ordinate) and the flux component (aligned with d co-ordinate). This control is more accurate in transient and steady state and independent of the limited bandwidth mathematical model (P. P. Acarnley *et al*, 2006; R. Gabriel *et al*, 1980).

5. Model Reference Adaptive System (MRAS)

MRAS is one of the most popular adaptive control method used in motor control applications for tracking and observing system parameters and states. It may be parallel model, series model, direct model and indirect model. Figure 4 shows a Rotor speed estimation structure using MRAS (Y. Zhao *et al*, 2013; G. Wei *et al*, 2013).

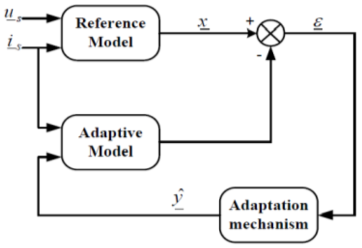

Fig.4 Rotor speed estimation structure using MRAS

Where:

ε Represents the error between the reference model and the adaptive model
X is the state vector, u the system input vector, y is the output vector (A. S. Mohamed *et al*, 2011; Y. Liang *et al*, 2003).
The estimated speed equation is

$$\hat{\omega}=\int_0^t K1[(id\,\hat{iq}-iq\,\hat{id}-\psi f/L(iq-\hat{iq}))]d\tau+K2[(id\,\hat{iq}-iq\,\hat{id}\,\psi f/L(iq-\hat{iq}))]+\hat{\omega}(0) \qquad (11)$$

And the position equation is $\hat{\theta}=\int_0^t \hat{\omega}\,dt$ (12)

Where: K1 and K2 is the proportional and integral coefficients. Figure 5 shows a control block scheme of a MRAS and Figure 6 shows a complete Simulink model of MRAS filter.
Figure 7 shows a complete Simulink model of FOC of PMSM.

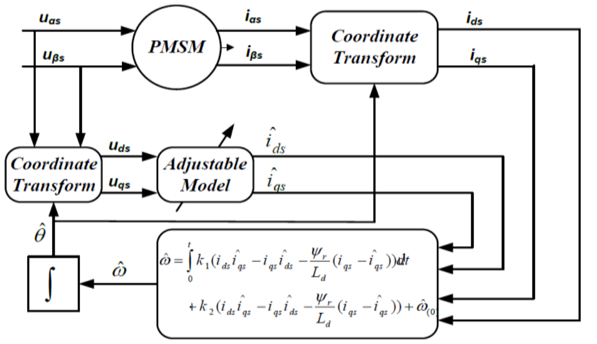

Fig.5 Control block scheme of MRAS

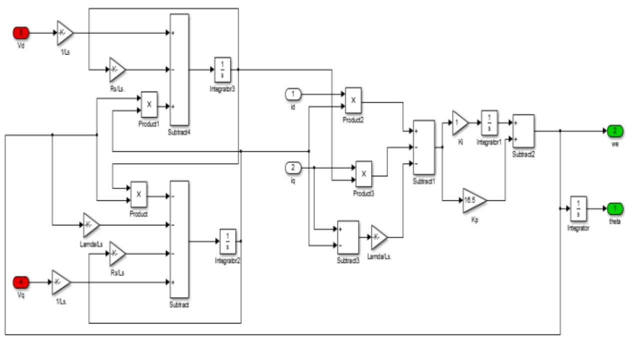

Fig.6 Complete Simulink model of MRAS filter

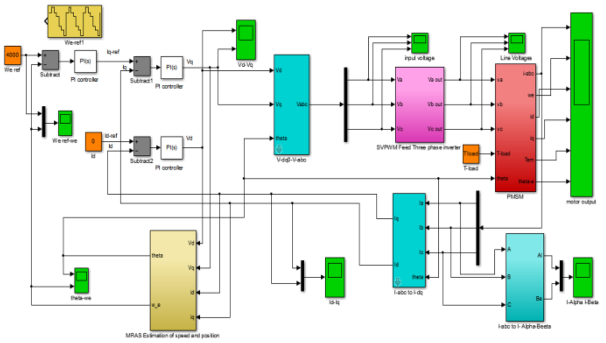

Fig.7 Complete Simulink model of FOC of PMSM

Motor parameters are shown in Table 1.

Table 1 motor parameters

S. No	Parameters	Values
1	Stator resistance Rs	1.2 ohm.
2	Stator inductance Ls = Ld = Lq	0.015 H.
3	Moment of inertia jm	0.000176 Kg.m2
4	Friction coefficient Bm	0.00038815 Nm/rad/sec.
5	Rotor magnet flux λf	0.2865 V/rad/sec.
6	Rated speed Nr	4000 rpm
7	Rated torque=TL	3.2 N.M
8	Vdc	310.61 v
9	Number of pole pairs P	3 pair of pole.

6. Simulation Results

Simulation results using PI controllers without loading are shown in figures from 8 to 15; Simulation results using PI controllers with full loading (TL=3.2 NM) are shown in figures from 16to 23, Simulation results using fuzzy controllers without loading are shown in figures from 24 to 31. And Simulation results using fuzzy controllers with full loading (TL=3.2 NM) are shown in figures from 32to 39.

6.1 Simulation Result using PI Controller without Loading

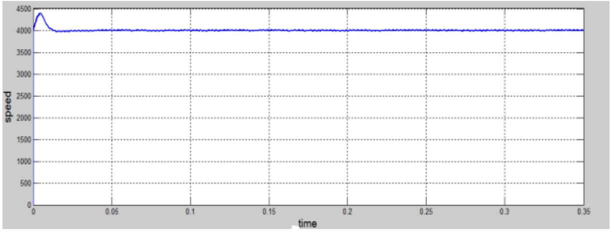

Fig.8 Actual speed

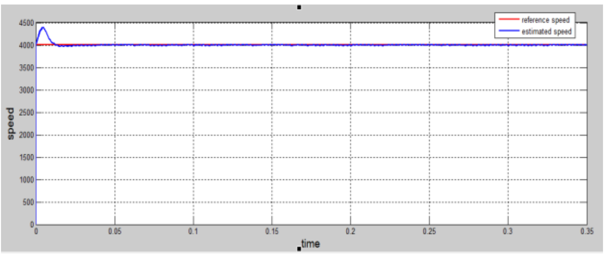

Fig.9 Actual and reference speed

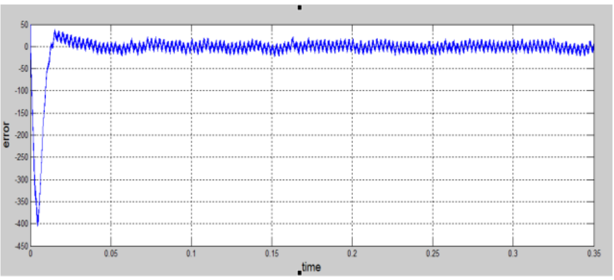

Fig.10 Error between actual and reference speed

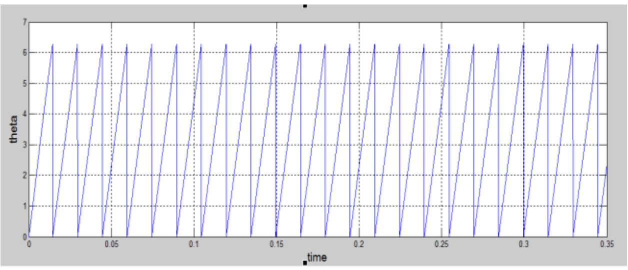

Fig.11 Rotor position (Theta)

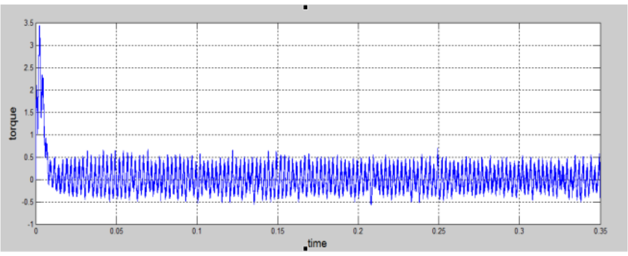

Fig.12 Actual torque

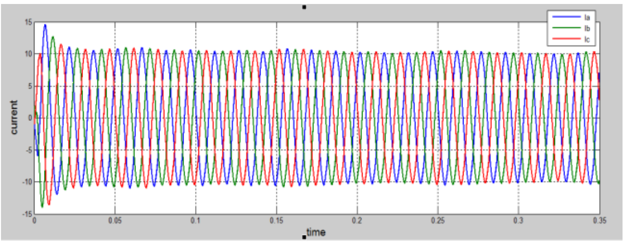

Fig.13 Three phase currents

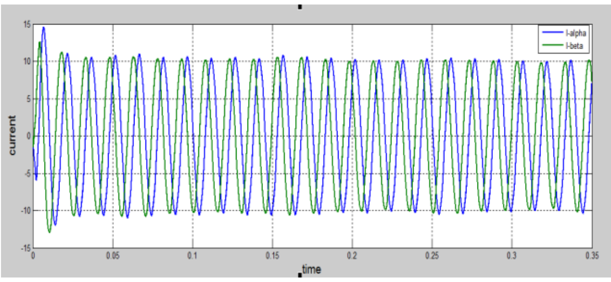

Fig.14 I alpha and I beta

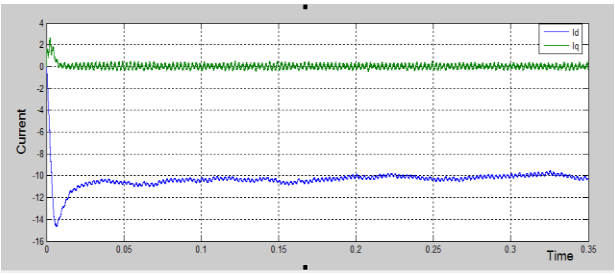

Fig.15 Id and Iq

6.2 Simulation Result using PI Controller With full Loading (TL=3.2N.M)

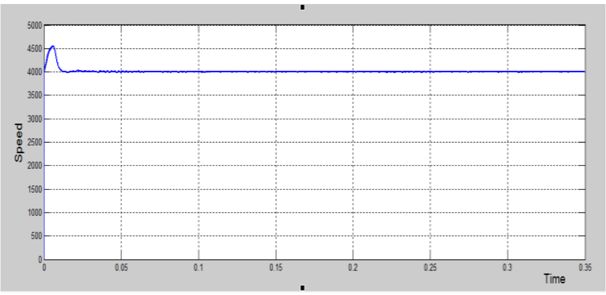

Fig.16 Actual speed

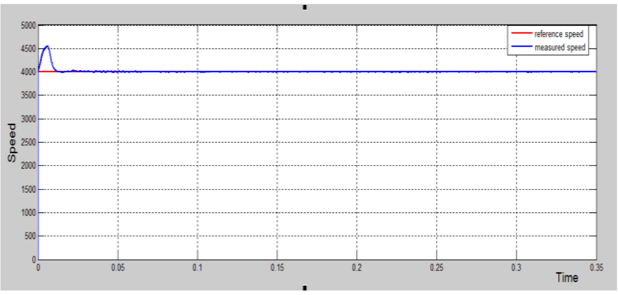

Fig.17 Actual and reference speed

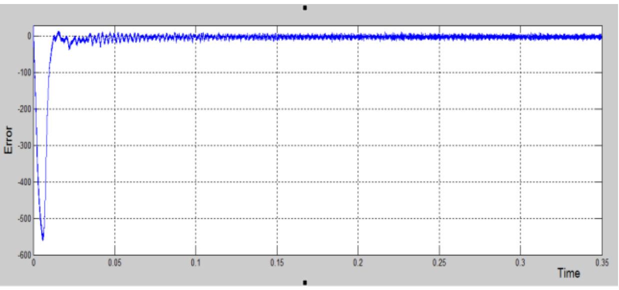

Fig.18 Error between actual and reference speed

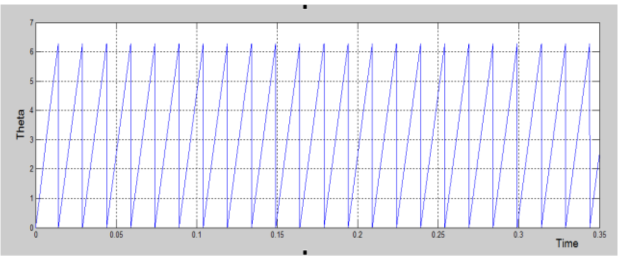

Fig.19 Rotor position (Theta)

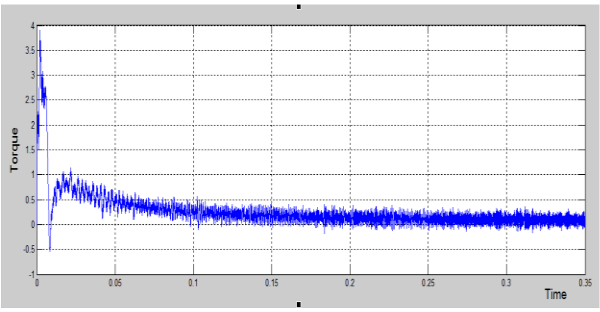

Fig.20 Actual torque

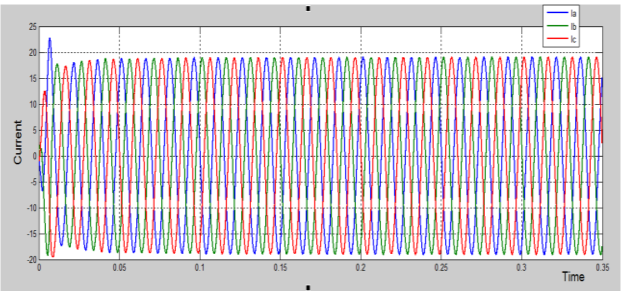

Fig.21 Three phase currents

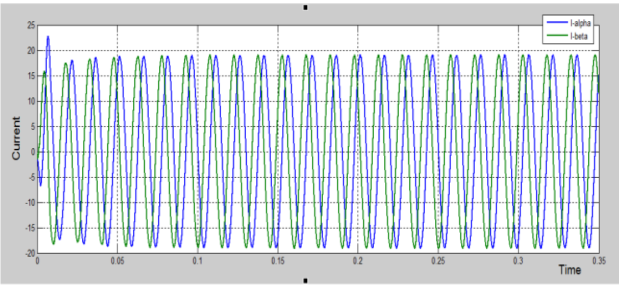

Fig.22 Ialpha and Ibeta

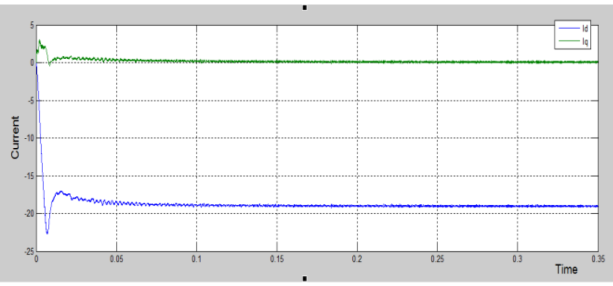

Fig.23 Id and Iq

6.3 Simulation Result using Fuzzy Controller without Loading

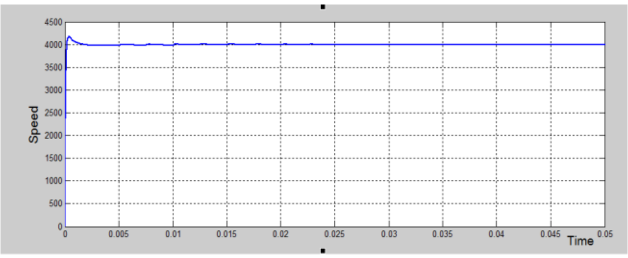

Fig.24 Actual speed

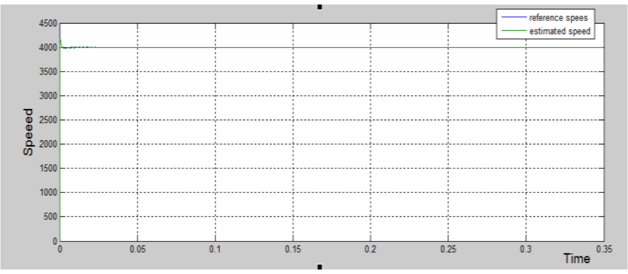

Fig.25 Actual and reference speed

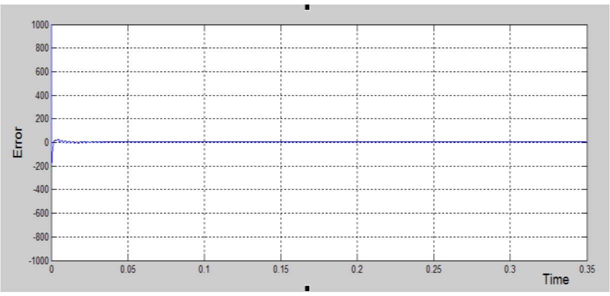

Fig.26 Error between actual and reference speed

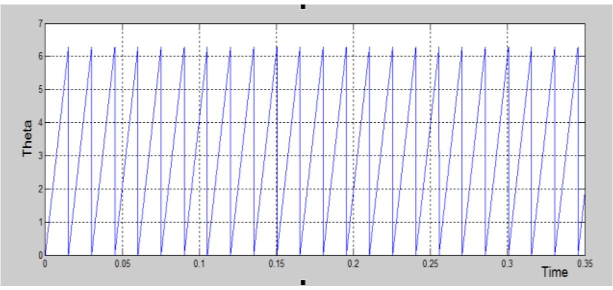

Fig.27 Rotor position (Theta)

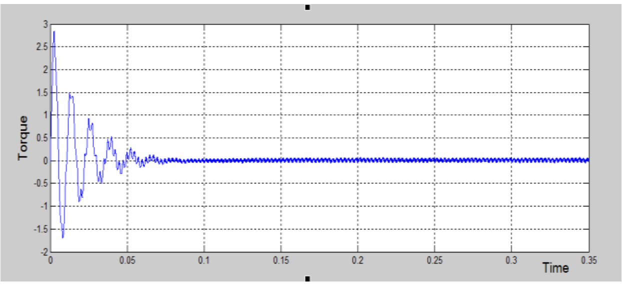

Fig.28 Actual torque

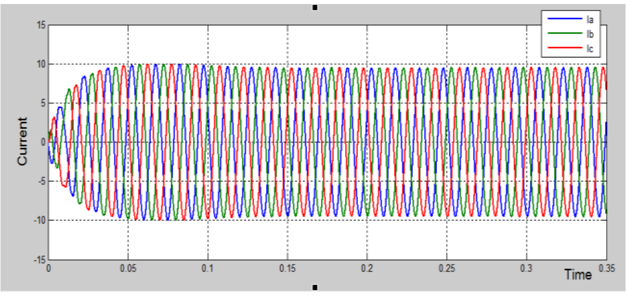

Fig.29 Three phase currents

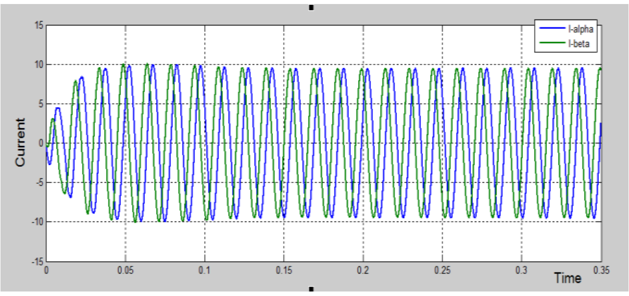

Fig.30 I alpha and I beta

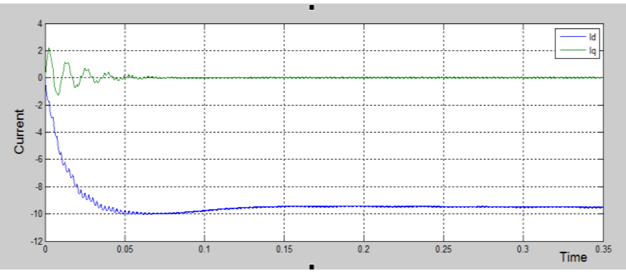

Fig.31 Id and Iq

6.4 Simulation Result using Fuzzy Controller With full Loading (TL=3.2N.M)

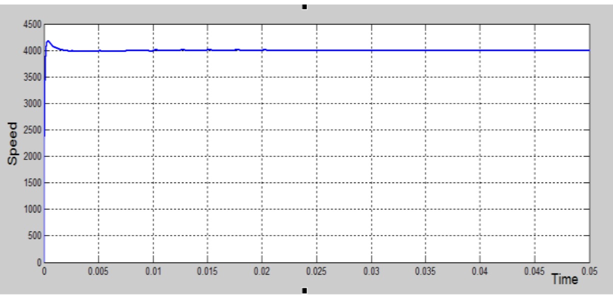

Fig.32 Actual speed

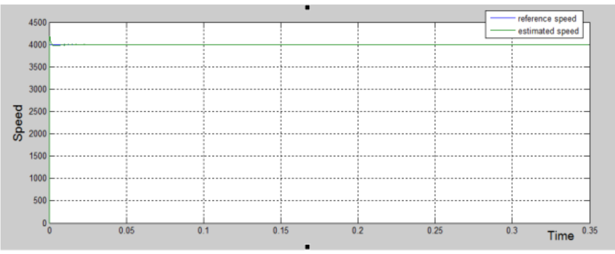

Fig.33 Actual and reference speed

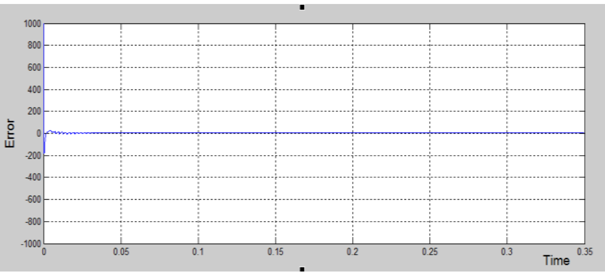

Fig.34 Error between actual and reference speed

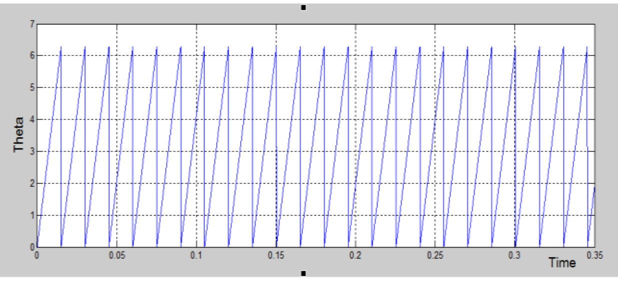

Fig.35 Rotor position (Theta)

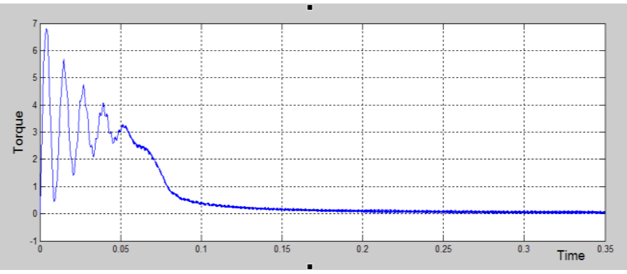

Fig.36 Actual torque

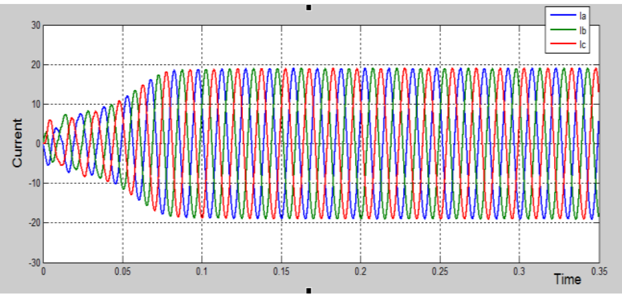

Fig.37 Three phase currents

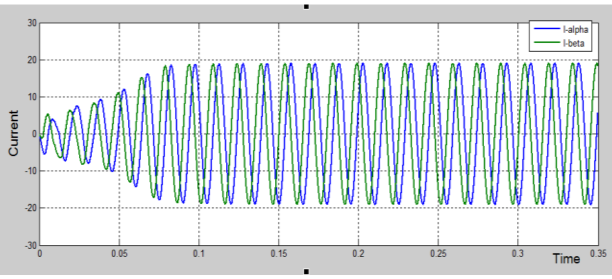

Fig.38 Ialpha and Ibeta

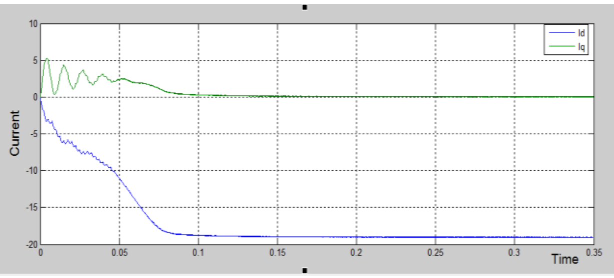

Fig.39 Id and Iq

6.5 Comparison of Results

The aims of this paper is to analysis, modeling sensorless FOC of PMSM and compare the performances of sensorless FOC based on MRAS using PI and fuzzy controllers when applied to PMSM drives the comparison results shown in table2 and table3

A-Comparison of Results without loading: the comparison results without loading are shown in table2.

B-Comparison of Results with full loading: the comparison results with full loading are shown in table3.

Table 2 The comparison results without loading

S. No	Response	PI Controllers	Fuzzy Controllers
1	Settling Time	.002 sec	.001 sec
2	Peak Over Shoot	10%	4.25%
3	Torque Ripples	Very low	No torque ripples
4	Steady State Error	Very low	V.Very low

Table 3 The comparison results with full loading

S. No	Response	PI Controllers	Fuzzy Controllers
1	Settling Time	.0025 sec	.0012 sec
2	Peak Over Shoot	12.63%	5.3%
3	Torque Ripples	Very low	V.Very low
4	Steady State Error	Very low	V.Very low

Conclusion

This paper explained the mathematical equations related to the application of the FOC of PMSM. The proposed sensorless FOC of PMSM is more stable and high accuracy because the produced error in the speed (by using PI and fuzzy controllers) is eliminated and torque ripples is very low. Results obtained show that the sensorless FOC strategy based on MRAS can be applied successfully in PMSM drives with low cost.

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