IJCTA
Vol.8, No.1, Jan-June 2015, Pp.96-108
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Field Oriented Control of PMSM with Model Reference Adaptive Control Using Fuzzy-PI Controller

Ch.Uma Maheswara Rao[1], Bala Murali Krishna.V[2], A.Laxmi Soundarya[3] , N.Krishna Kumari[4]

[1]Assistant Professor, Vignan's University, Andhra Pradesh,
[2]Assistant Professor, Regency Institute of Technology, Pondicherry
[3&4]Department of EEE, VNRVJIET, JNTUH, Telangana
[1]maheshsrkr@gmail.com;[2] balamuralikrishna.vk@gmail.com

ABSTRACT
This paper proposes to describe Field oriented control (FOC) of Permanent Magnet Synchronous motor (PMSM) using Model Reference Adaptive control System (MRAS) speed observer for sensorless control of drive. The objective of the proposed sensorless control is to improve the speed control performance and robustness of PMSM drive under load variations. In this work, the conventionally used PI controller in adaption mechanism of the MRAS observer is replaced by a FLC. The improvement in speed response during load variations is shown by comparative study between conventional PI and fuzzy PI. The effectiveness and validity of the proposed control approach is verified by simulation results.
Index Terms—permanent magnet synchronous motor (PMSM), speed control, Field oriented control (FOC), model reference adaptive system (MRAS), Fuzzy logic controller (FLC).

1. INTRODUCTION

Nowadays, permanent magnet synchronous motor (PMSM), has been widely used in high performance variable speed in many industrial applications, due to its high efficiency, high ratio of torque-to-inertia ratio, high power factor, fast response and rugged construction .The PMSM has increasingly used in electrical vehicles , aircraft, nuclear power station ship engines, robotic automation, escalators and industrial servo drives [5]. The control methods used for the permanent magnet synchronous motors are: V/f control, field oriented control and direct torque control [4]. Field oriented control is one of the control methods of the PMSM, which achieve fast dynamic response and the flexibility normally obtained in control of separately excited dc motor.

Position sensor with higher quality is a necessary component part of the drive system employed in industrial and automotive applications. But the high cost and strict requirement extremely limit the application in the drive system. Moreover, there are some applications, where there is no room to put the speed sensor or the nature of the environment does not allow the use of any additional speed sensor. So that it is highly desired to develop the position sensorless technology and elimination of the speed encoder is highly encouraged to increase the mechanical robustness of the system.

The sensorless technology can make drive cheaper and also increase the reliability of the drive system. This paper adopts the MRAS scheme, which uses the PMSM itself as the reference model to estimate the speed of the motor. [1]

2. MODELING OF PMSM

A primitive version of a PMSM with wound-rotor synchronous motor, the stator of a PMSM has winding similar to those of the conventional wound-rotor synchronous motor which is generally three-phase, Y-connected, and sinusoidally distributed. The motor is fed from inverter which gets pluses from HPWM for better stator voltages. [2]

In a PMSM, the inductances vary as a function of the rotor angle, the two-phase (d-q) equivalent circuit model is a perfect solution to analyze the multiphase machines because of its simplicity and intuition. [5]

$$V_d = R_s i_d + p\lambda_d - \omega\lambda_d \tag{1}$$

$$V_q = R_s i_q + p\lambda_q + \omega\lambda_d \tag{2}$$

$$\lambda_d = L_d i_d + \lambda_f \tag{3}$$

$$\lambda_q = L_q i_q \tag{4}$$

$$v_d = R_s i_d + L_d \frac{d}{dt} i_d - L_q \omega_e \frac{d}{dt} i_q \tag{5}$$

$$v_q = R_s i_q + L_q \frac{d}{dt} i_q + L_q \omega_e \frac{d}{dt} i_d + \omega_e \lambda_f \tag{6}$$

$$T_e = \frac{3}{2} p\left[\left(L_d - L_q\right) i_d i_q + \lambda_f i_q\right] \tag{7}$$

$$J \frac{d\omega_m}{dt} + B\omega_m + T_L = T_e \tag{8}$$

Block representation PMSM is shown by Figure.1

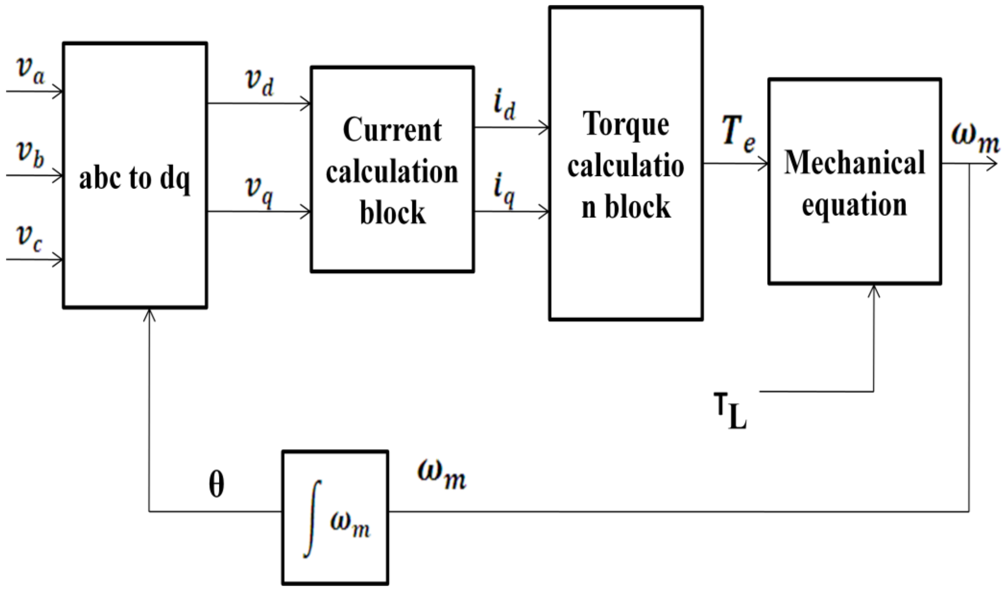

Figure.1. Block representation of PMSM

It is apparent from the above equations (1)-(8), that the produced torque is composed of two distinct mechanisms. The first term corresponds to "the mutual reaction torque" occurring between I_q and the permanent magnet, while the second term corresponds to "the reluctance torque" due to the differences in d-axis and q-axis reluctance.[4]

3. FIELD ORIENTED CONTROL (FOC) OF PMSM

Vector control techniques are usually also referred to as the field-oriented control (FOC) [4] . The basic idea of the FOC algorithm is to decompose a stator current into a magnetic field-generating part and a torque-generating part. Both components can be controlled separately after decomposition. The structure of the motor controller is then as simple as that for a separately excited DC motor. If the permanent magnets are mounted on the rotor surface, and there is no significant internal asymmetry in the iron parts of the rotor, the direct-axis and quadrature-axis inductances of the machine are approximately equal, $L_d=L_q$. In the steady state, the torque equation is given by equation (9). Thus, the direct-axis current does not show any effect on the torque, and at $i_d = 0$, the minimum stator current is reached with corresponding constant torque and reference current is given by equation (10)

$$T_e = \frac{3}{2} p \lambda_f i_q \qquad (9)$$

$$i_{qref} = \frac{T_{eref}}{\frac{3}{2} p \lambda_f} \qquad (10)$$

The torque control is implemented similarly as in a fully compensated DC machine. Most low-power servo machines fall in this category. Hence, i_d=0 control is best adapted to machines, the armature reaction of which is small. Figure.2 shows the Block diagram of FOC of PMSM

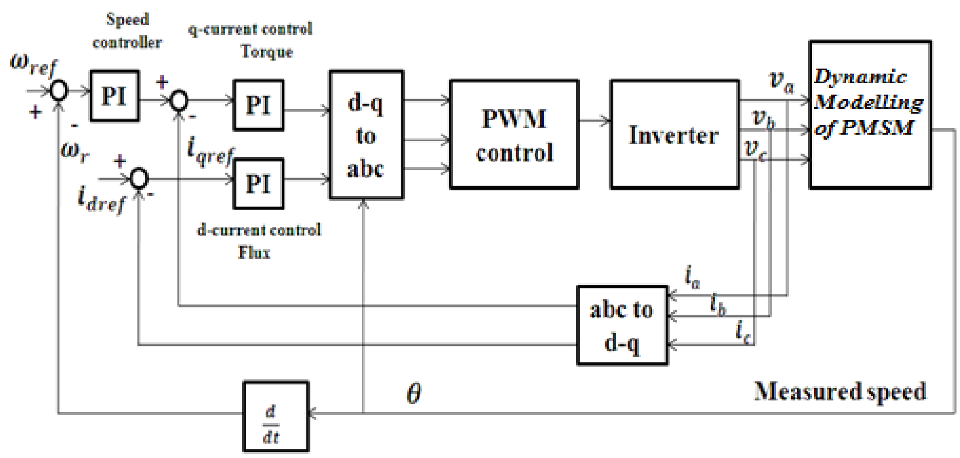

Figure.2. Block diagram of FOC of PMSM

4. MODEL REFERENCE ADAPTIVE CONTROL SYSTEM (MRAS)

This paper proposes a novel sensorless control algorithm based on the MRAS. In general, the MRAS algorithm is based on the comparison between the output of two estimators. The error between the estimated quantities obtained by two models is used to drive a suitable adaptation mechanism which generates the estimated rotor speed. The MRAS algorithm is based stator currents of PMSM motor, and has been proved to be effective [1], [9].

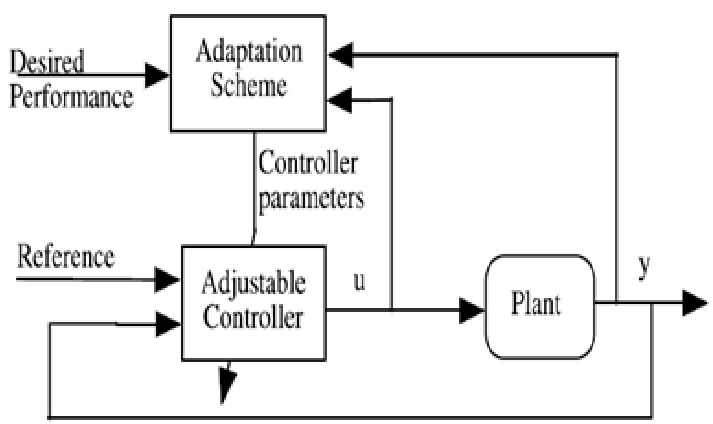

Figure.3. An adaptive control system

Selecting current as state variable, the state equation is given by Equations (11) & (12)

$$\frac{di_d}{dt} = -\frac{R_s}{L_s} i_d + \omega_e i_q + \frac{v_d}{L_s} \qquad (11)$$

$$\frac{di_q}{dt} = -\frac{R_s}{L_s} i_q - \omega_e i_d - \frac{\lambda_f}{L_s}\omega_e + \frac{v_q}{L_s} \qquad (12)$$

Here, p is the differentiate.

$$p\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_d} & \omega_e \frac{L_q}{L_d} \\ -\omega_e \frac{L_d}{L_q} & -\frac{R_s}{L_q} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} \frac{v_d}{L_d} \\ \frac{v_q}{L_q} - \omega_e \frac{\lambda_f}{L_q} \end{bmatrix} \qquad (13)$$

Suppose:

$$i_d^* = i_d + \frac{\lambda_f}{L_d}, i_q^* = i_q, v_d^* = v_d + \frac{R_s}{L_d}\lambda_f, v_q^* = v_q \qquad (14)$$

From equations (14) & (13)

$$p\begin{bmatrix} i_d^* \\ i_q^* \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_d} & \omega_e \frac{L_q}{L_d} \\ -\omega_e \frac{L_d}{L_q} & -\frac{R_s}{L_q} \end{bmatrix} \begin{bmatrix} i_d^* \\ i_q^* \end{bmatrix} + \begin{bmatrix} \frac{1}{L_d} v_d^* \\ \frac{1}{L_q} v_q^* \end{bmatrix} \qquad (15)$$

Equation (8) is obtained by shortening (7), than

$$p\widehat{i^*} = \hat{A}\widehat{i_d^*} + Bv^* \qquad (16)$$

Generalized error is given by equation (17) and from equations (13) & (14)

$$e = i^* - \widehat{i^*} \qquad (17)$$

$$\begin{bmatrix} \frac{de_d}{dt} \\ \frac{de_q}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L} & \omega_e \\ -\omega_e & -\frac{R_s}{L} \end{bmatrix} \begin{bmatrix} e_d \\ e_q \end{bmatrix} - J(\omega_e - \widehat{\omega_r}) \begin{bmatrix} \widehat{i_d^*} \\ \widehat{i_q^*} \end{bmatrix} \qquad (18)$$

Where, $e_d = i_d^* - \widehat{i_d^*}$, $e_q = i_q^* - \widehat{i_q^*}$ and $J = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$

By using the Popov hyper stability theorem, the speed of adaptive mechanism is given by equation (19)[5],[6]

$$\widehat{\omega_e} = \left(K_P + \frac{K_i}{p}\right)\left[i_d \widehat{i_q} - i_q \widehat{i_d} - \frac{\lambda_f}{L_s}(i_q - \widehat{i_q})\right] + \widehat{\omega_e}(0) \quad (19)$$

$$\hat{\theta} = \int \widehat{\omega_e} + \theta_e \quad (20)$$

Figure.4 shows the simulation block diagram of sensorless MRAS of PMSM [9]

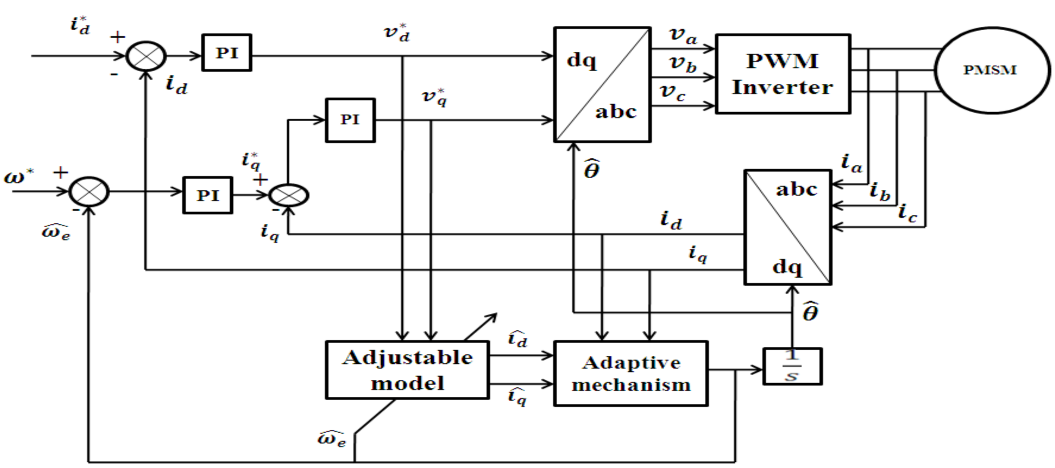

Figure.4. Sensorless MRAS simulation block diagram of PMSM

A. *Fuzzy adaptive PI Controller :*

The dynamic response of the PMSM motor transformed to the estimated rotor frame are nonlinear, thus the observer and observer error dynamics are nonlinear. The stability of control system is analyzed as a linearized error model. But the conventional PI control method could not solve the nonlinear problems of strongly nonlinear system. Fuzzy control method has a strong adaptive ability for complex nonlinear systems and can be effectively controlled.[9] By combining these two control strategies together the controller is able to achieve precise control and obtain strong self adaptability. This control suits for the system, where the model is unknown and the system parameters variation problems. The adaptive control with PI is applied to PMSM to control the speed range and giving robust performance under load disturbance effect. This method is carried out by the MATLAB Simulation for various operating conditions. Figure.5 shows the PI controller based on Fuzzy Logic Controller.

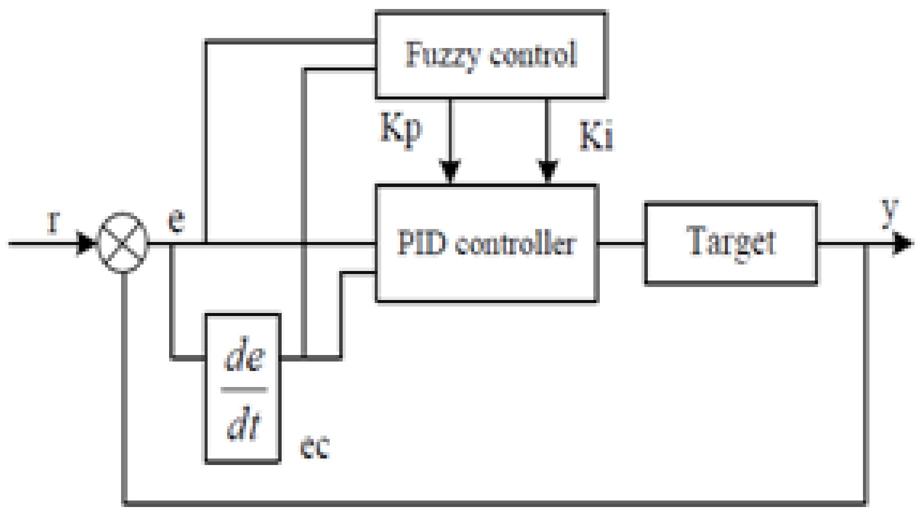

Figure.5. PI controller based on Fuzzy Logic Controller

5. SIMULATION RESULTS & DISCUSSIONS

The implementation of the MRAS sped identification for PMSM based on fuzzy PI control has been carried out using MATLAB/Simulink. The performance of PMSM speed control using Fuzzy PI is compared to a conventional PI controller by extensive simulation for various operating conditions. The simulation parameters are given in Table.1

Table.1. Simulation Specification

Name of the Parameter	Rating of the Parameter
Stator resistance (R_s)	2.8750 Ω
Inductance d-axis (L_d)	0.0085H
Inductance q-axis (L_q)	0.0085H
Dc voltage (V_{dc})	120 V
Rotor flux (λ)	0.1750Wb
Moment of inertia (J)	0.0008kgm^2
Friction (B)	0.001Nm/rad
Poles (P)	4
Load Torque(T_L)	2 N-m
Speed (N)	1500 r.p.m

There are three test cases, at first FOC without sensorless MRAS, second case FOC with sensorless MRAS using PI controller and finally replacing PI controller in adaptive mechanism with fuzzy-PI controller. These three cases were tested under constant speed with varying torque and constant torque with varying speed. For first mode, keeping speed constant the load torque of 2-Nm was applied at 0.1sec after reaching motor to rated speed of 1500rpm, the load torque was decreased to 1.5Nm at 0.4sec and finally decreased to 1Nm at 0.5sec. The response of torque, speed and flux for three cases are shown in Fig.6, Figure.7 and Figure.8. In second, keeping torque constant the speed is decreased after reaching to rated speed. The speed is decreases to 1000rpm at 0.1sec and finally decreases to 800rpm at 0.4sec. The response of torque, speed and flux for three cases are shown in Figure. 9, Figure.10 and Figure.11. In three cases FOC with sensorless control using fuzzy logic controller with PI gives better results with reduced harmonics, torque ripples due load impact and steady state error also got reduced to low value. These three cases are shown by the fallowing sections (5.1 to 5.5)

1.1 ***Torque, Speed and Flux Responses under Constant Speed and varying torque :***

1.2 (T= 2Nm at t= 0.1sec,   T=1.5Nm at t= 0.4 sec, T=1Nm at t=0.5sec) :

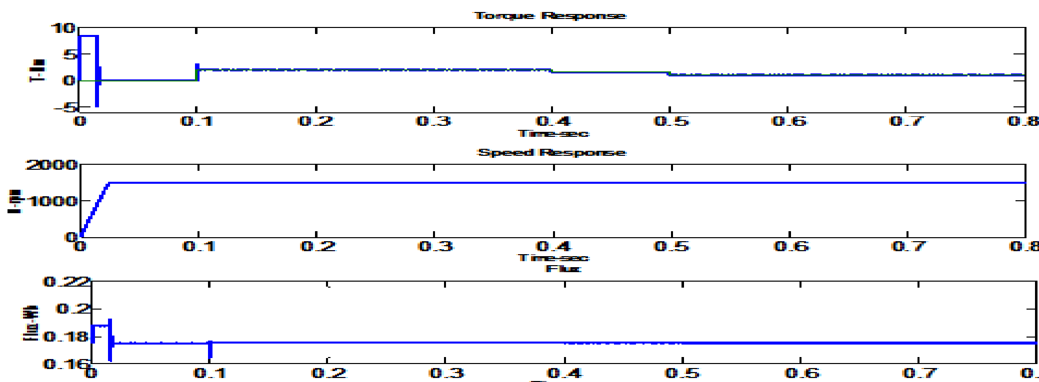

Figure.6.Torque, Speed and Flux response results of FOC of PMSM without MRAS

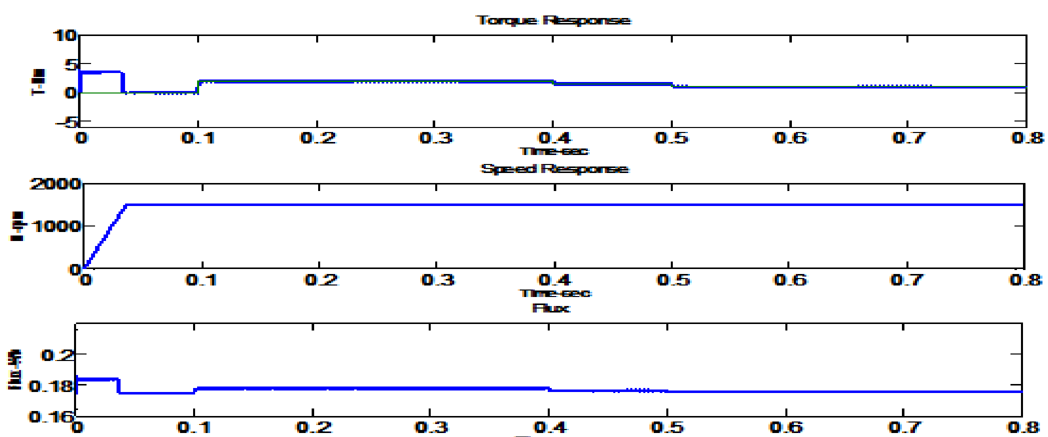

Figure.7. Torque, Speed and Flux response of FOC with MRAS using PI controller

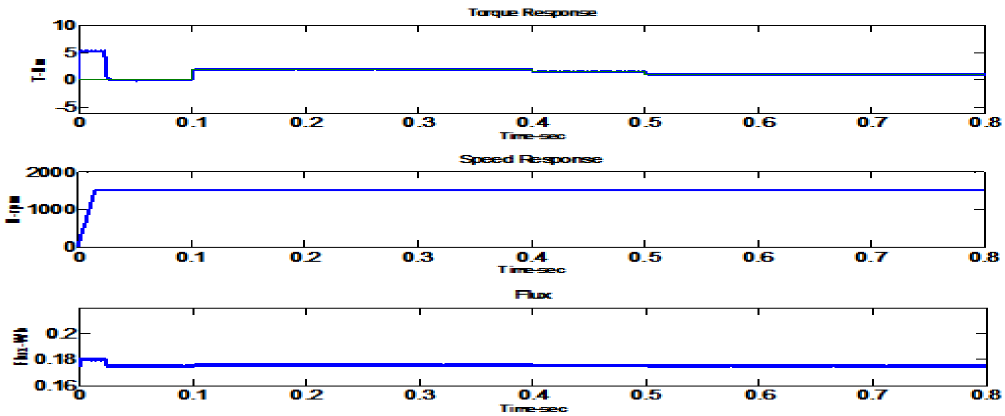

Figure.8. Torque, Speed and Flux response of FOC with MRAS using Fuzzy-PI controller

5.2 ***Torque, Speed and Flux Responses under Constant Torque and Varying Speed:***
(T= 2Nm at t=0.05sec , N=1000 till t=0.1sec, N=800 till t= 0.4sec)

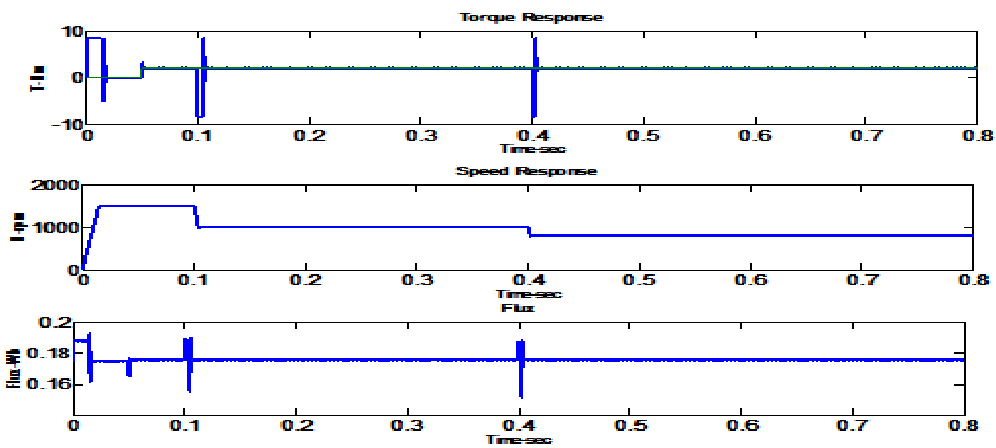

Figure.9. Torque, Speed and Flux response of FOC without MRAS

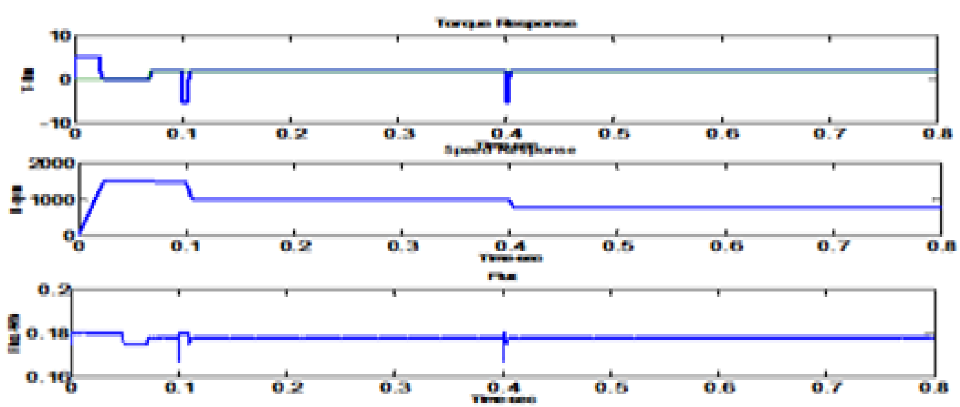

Figure.10. Torque, Speed and Flux responses of FOC with MRAS using PI Controller

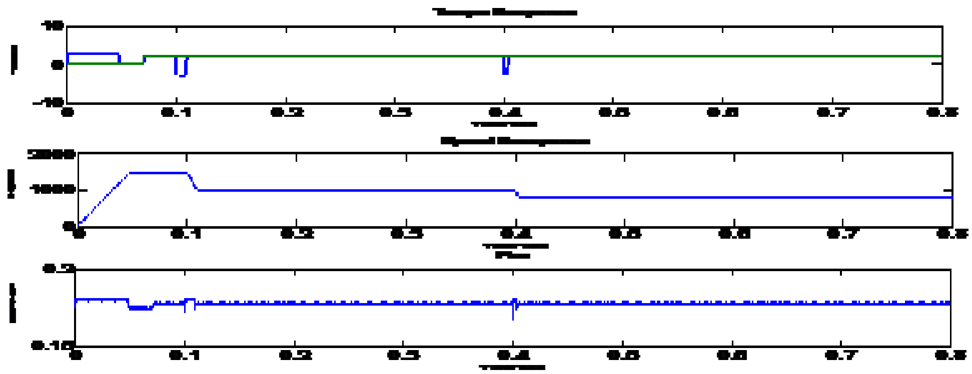

Figure.11.Torque, speed and Flux response of FOC with MRAS using Fuzzy-PI controller

5.3 ***Stator currents Responses under Constant Speed and varying torque :*** *(T= 2Nm at t = 0.1sec, T=1.5Nm at t= 0.4 sec, T=1Nm at t=0.5sec)* :

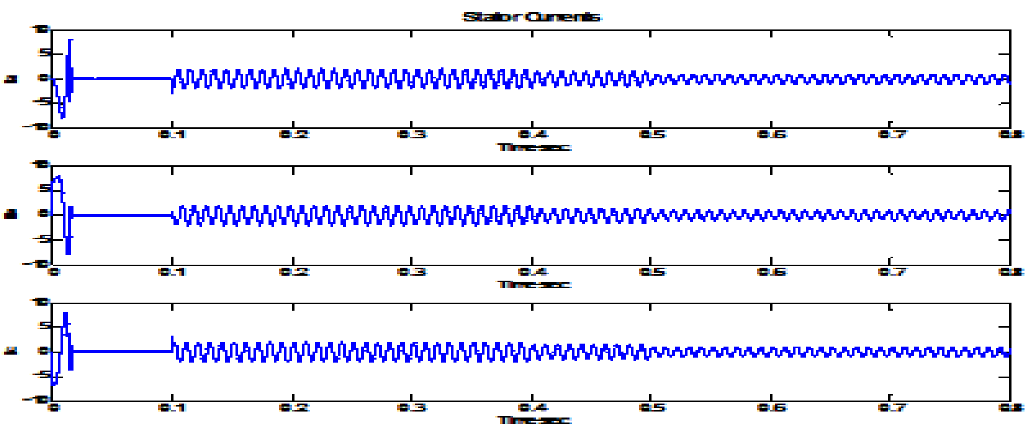

Figure.12. stator currents I_{abc} of FOC without MRAS

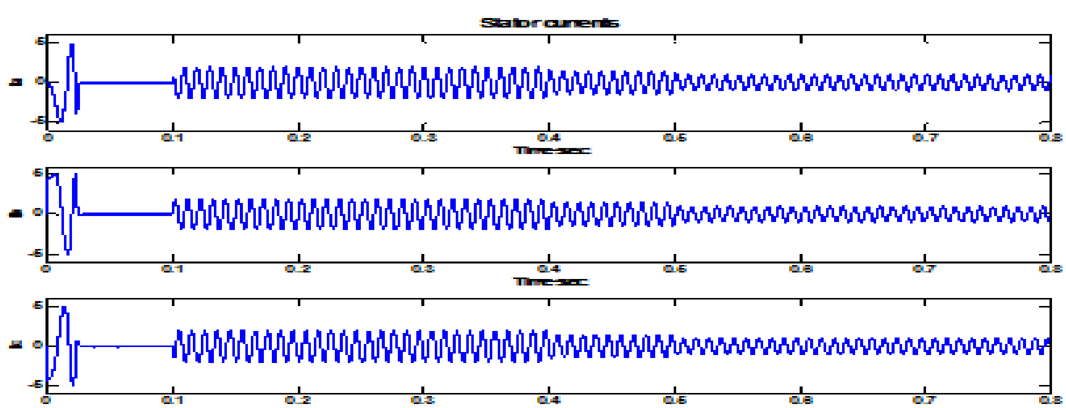

Figure.13. Stator currents I_{abc} of FOC with MRAS using PI controller

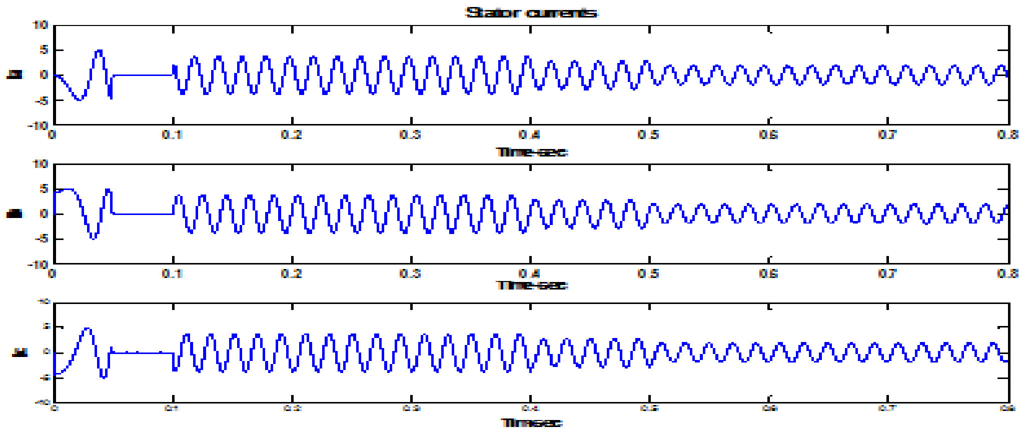

Figure.14.Stator currents I_{abc} of FOC with MRAS using fuzzy-PI controller

5.4 ***Stator Currents Responses under Constant Torque and Varying Speed:*** *(T= 2Nm at t=0.05 , N=1000 till t=0.1, N=800 till t= 0.4)* **:**

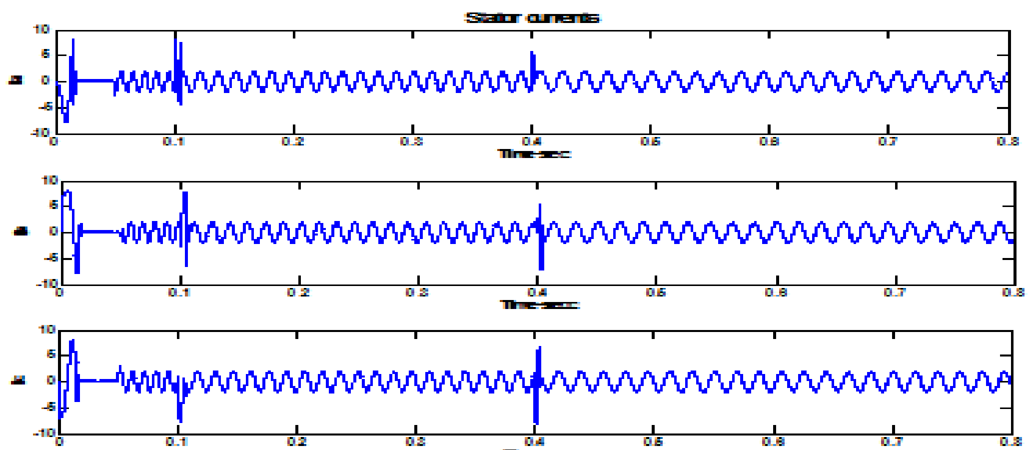

Figure.15. stator currents I_{abc} of FOC without MRAS

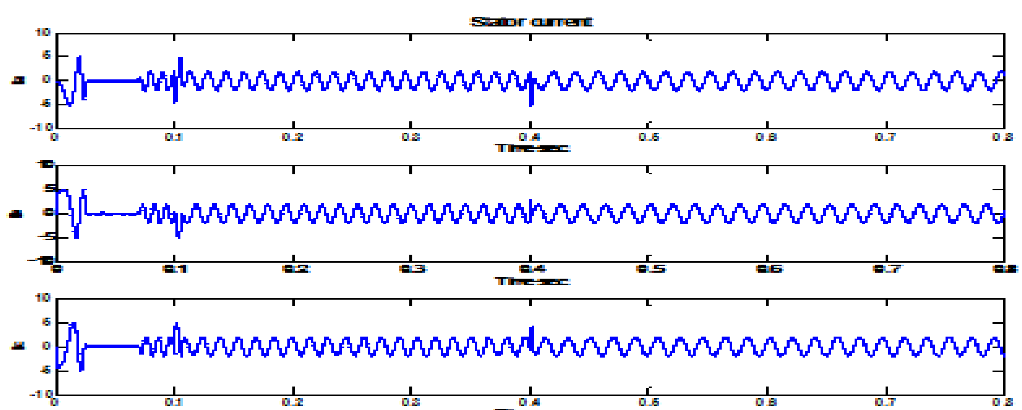

Figure.16. Stator currents I_{abc} of FOC with MRAS using PI

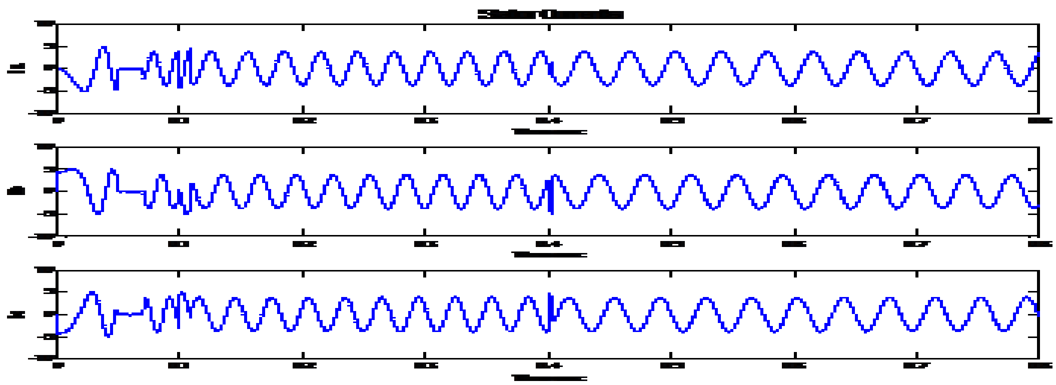

Figure.17. Stator current I_{abc} of FOC with MRAS using Fuzzy-PI controller

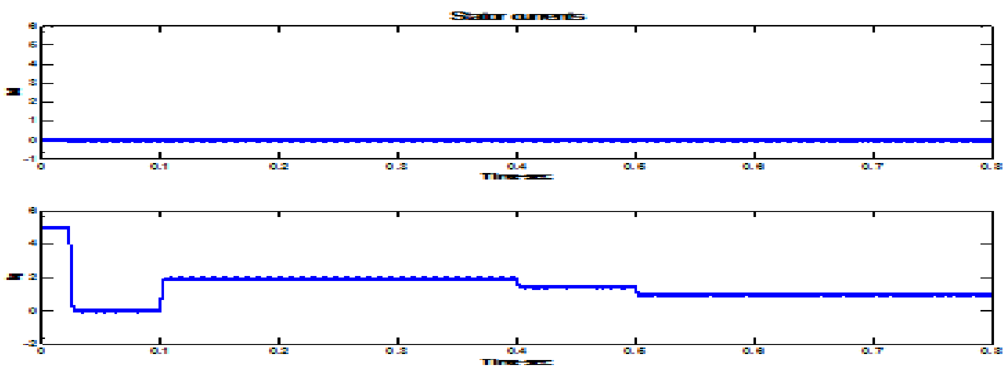

Figure.18. Stator currents I_{dq} of FOC with MRAS using Fuzzy-PI controller

5.5 ***Stator Flux Locus under Constant Speed and Varying Torque:*** *(T= 2Nm at t= 0.1sec, T=1.5Nm at t= 0.4 sec, T=1Nm at t=0.5sec) :*

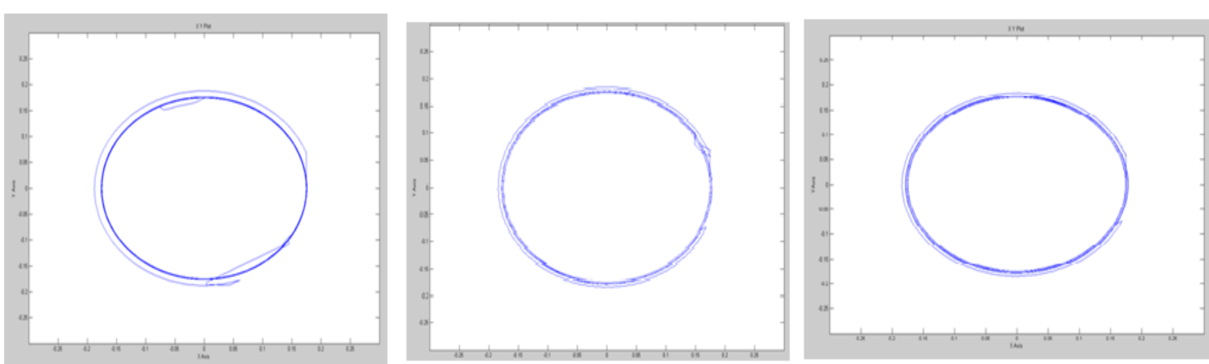

Fig : Stattor flux of FOC without MRAS

Fig : Stattor flux of FOC with MRAS using PI Controller

Fig : Stattor flux of FOC with MRAS using Fuzzy-PI Controller

Figure.19. Stator flux comparison between without MRAS, with MRAS and MRAS using Fuzzy-PI Controller

6. CONCLUSION

Hence, in this paper, the synthesis of fuzzy adaptive PI Controller has been developed for speed control method of PMSM drive. The control scheme was developed by using 2009a MATLAB / Simulink in GUI environment. The proposed control algorithm has good position and speed estimation precise, preferable dynamic performance, as well as strong immunity. The obtained results proved that the proposed control method much superior than the conventional PI Controller under no-load and applied load variations.

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