Sensorless Field oriented control of PMSM Drive System for Automotive Application

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***Abstract*-This paper presents an analysis and hardware implementation of a Sensorless Field oriented control method for Permanent Magnet Synchronous Motor drive using 3-Phase Permanent Magnet Synchronous Low-Voltage Motor Control Drive. The Sensorless Field oriented control Permanent Magnet Synchronous Motor drive system is designed, simulated and implemented using the standard setup by free scale. The experimental setup is designed and implemented based on a six-pole, 2 *kW* permanent magnet synchronous motor. The 3-ph permanent magnet synchronous motor LV(low voltage)motor control drive board consists of all the required circuitry needed for development of motor control applications. It incorporates a complete 3-phase power stage, a communication interface, feedback signal handling and the user's interface. Power circuit consists of metal oxide semiconductor field effect transistor based voltage source inverter and gate driver circuit. The control hardware consists of power supplies, resolver demodulation circuit, current sensors and interfacing circuits. The reference speed, rotor speed estimation using sensed position signals, speed controller, reference frame transformation, vector controller and PWM current controller for gating pulse generation of voltage source inverter are implemented using the standard GUI interface of the software where high level language coding is used. The simulated performances along with test results of the permanent magnet synchronous motor drive are studied for starting, steady-state condition, speed reversal and load perturbation. Experimental results show that the drive system has a good dynamic response particularly in terms of torque ripple and speed response.**

Key words: Permanent Magnet Synchronous Motor, FOC, Implementation, Microcontroller processor, Voltage source inverter

I. INTRODUCTION

Several types of AC&DC electric motors have been used in the automotive application for various purposes. [3]. AC&DC machines are broadly used in Electrical drives & are subject of study for every research scholar [4,13]. The main aim of this paper is to design and implement a normal PMSM drive. The stator has double set of winding as explained in [12]. The drive system simulation and the hardware implementation is explained. The simulations are carried out in Matlab/Simulink software. Microcontroller based control system is used to control the whole PMSM drive system.

In recent years, Permanent magnet synchronous motors have attracted increasing interest for industrial drive applications [3]. The controller of the PMSM drives compared to the induction motor drives make them a good alternative in automotive industry due to high efficiency, high steady state torque density.

The main advantages of the permanent magnet synchronous motor are low inertia, high efficiency, reliability and low cost of the power electronic converters required for controlling the machine [1]. All these facts make the permanent magnet synchronous motor an excellent candidate for being used in many industrial applications.

Sensorless Field oriented control of PMSM is one of the widely used schemes in drive applications [14] that is considered in this paper. A mathematical model of permanent magnet synchronous motor is introduced and the FOC method is explained. Finally Matlab/Simulink based simulation results are presented for this method.

II. MATHEMATICAL MODEL OF PMSM

Considering a two-pole three phase surface-mounted Permanent Magnet Synchronous Motor , the voltage equation in the dq domain.

$$\overline{u_{dqos}} = R_s.\overline{i_{dqos}} + p\overline{\lambda_{dqos}} \tag{1}$$

Where
p →differentiating operator.
d, q and 0 →d axis, q axis and zero component.

Equation (2) shows the flux linkage in the *dq* frame.

$$\overline{\lambda_{dqos}} = L_{dqo}.\overline{i_{dqos}} + \overline{\lambda_{dqo,m}} \tag{2}$$

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Inductance matrix

$$(L_{dqo}) = \begin{bmatrix} L_d & 0 & 0 \\ 0 & L_q & 0 \\ 0 & 0 & L_o \end{bmatrix} = \begin{bmatrix} L_s & 0 & 0 \\ 0 & L_s & 0 \\ 0 & 0 & L_s \end{bmatrix} \qquad (3)$$

For Surface mounted permanent magnet, $L_d = L_q$

The magnetizing flux

$$(\lambda_{dqo,m}) = \begin{bmatrix} \lambda_{pm} & 0 & 0 \end{bmatrix}^T \qquad (4)$$

As far as the stator windings are star-connected and supplied with balanced three phase currents, the zero-axis components can be neglected. The voltage equations for direct and quadrature axes are

$$u_{ds} = R_s i_{ds} + L_s \frac{di_{ds}}{dt} - \omega_r L_s i_{qs} \qquad (5)$$

$$u_{qs} = R_s i_{qs} + L_s \frac{di_{qs}}{dt} - \omega_r (L_s i_{ds} + \lambda_{pm}) \qquad (6)$$

Where

Rs → stator resistance,

Ls → stator inductance,

ωr → rotor rotational speed

λpm → permanent magnet flux.

Electromagnetic torque of PMSM in the *dq* frame $(T_e) = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\left(\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}\right)$ (7)

From equation (2) & (7),

$$T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\left(\lambda_{pm} i_{qs} - (L_q - L_d) i_{qs} i_{ds}\right) \qquad (8)$$

Considering a non-salient rotor, where the inductances are equal, the final expression of the electromagnetic torque is:

$$T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\left(\lambda_{pm} i_{qs}\right) \qquad (9)$$

Equation (9) shows that the production of the torque in a Permanent Magnet Synchronous Motor without saliency is directly proportional to the stator q-axis current.

The direct and quadrature axes variables are related with a, b, c variables through the Park's transformation defined as:

$$\begin{bmatrix} Vq \\ Vd \\ Vo \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos(\theta - 2\pi/3) & \cos(\theta + 2\pi/3) \\ \sin\theta & \sin(\theta - 2\pi/3) & \sin(\theta + 2\pi/3) \\ 1/2 & 1/2 & 1/2 \end{bmatrix}$$

The inverse Parks transformation is defined below:

$$\begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos(\theta - 2\pi/3) & \sin(\theta - 2\pi/3) & 1 \\ \cos(\theta + 2\pi/3) & \sin(\theta + 2\pi/3) & 1 \end{bmatrix} . \begin{bmatrix} Vq \\ Vd \\ Vo \end{bmatrix}$$

A. *Principle of FOC*

The stator currents & rotor angle are measured. The stator currents are transformed into a $\alpha\beta$ -axis reference frame with the Clark Transformation. The $\alpha\beta$ currents are converted into a dq reference frame using Park Transformation. This *dq* values are invariant in steady-state conditions. With the speed regulator, a q-axis current reference is obtained when the d-axis reference is zero for operation below rated speed. The direct axis-current controls the air gap flux, the quadrature axis current control the electromagnetic torque production. The current error signals are used in controllers to generate reference voltages for the inverter. The voltage references are transformed into *abc* domain. With these values are calculated the PWM signals required for driving the inverter.

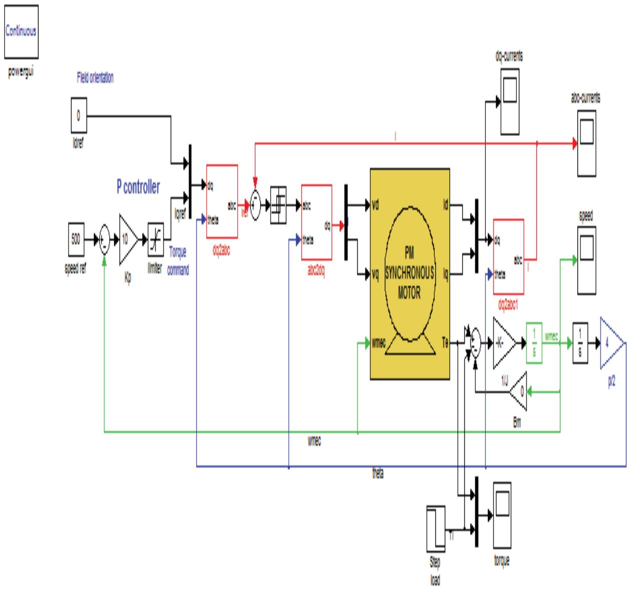


Fig.1 Simulink Block Diagram of FOC

III.SIMULATION RESULTS

Sensorless Field oriented control of PMSM method are simulated using MATLAB/Simulink.

A. Transient Performance

The transient & Steady State response of the Sensorless FOC of permanent magnet synchronous motor are evaluated by simulating step changes in the torque responses. Fig.2 & fig 3 shows transient & Steady State response of FOC, at 500 rpm.TableII shows the torque ripple analysis of FOC of Permanent Magnet Synchronous Motor at different speed. & TableIII shows that specification of Permanent Magnet Synchronous Motor.

Torque ripple analysis of FOC,.Calculated by formula

Torque ripple (%) = $(Tmax - Tmin)/Tavg * 100$

Table I Torque Ripples analysis

Controller Speed	FOC
100 rpm	27.9538%
200 rpm	18.9723%
500 rpm	10.9823%

Table II Specification of Permanent Magnet Synchronous Motor

Sr. No.	Permanent Magnet Synchronous Motor Parameter	Value
1.	Stator Resistance Rs	2.875Ω
2.	d-axis Inductance Ld	8.5×10^{-3}H
3.	q-axis Inductance Lq	8.5×10^{-3} H
4.	Permanent Magnet Flux	0.175Wb
5.	No of Pole pairs	4
6.	Torque	0.051Nm
7.	Movement of Inertia(J)	2.26×10^{-5}Kg/m^2
8.	Viscous coefficient(f)	1.349×10^{-5}Nms

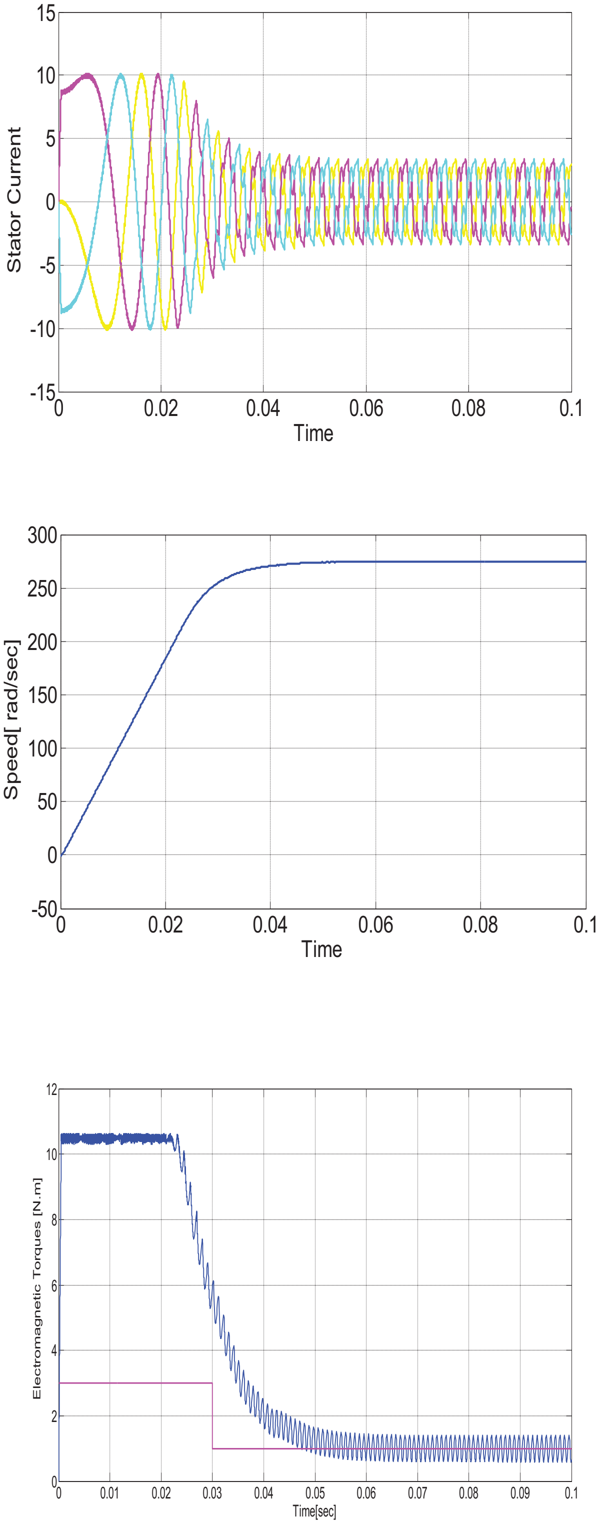


Fig 2 Transient response of FOC, at 500 rpm

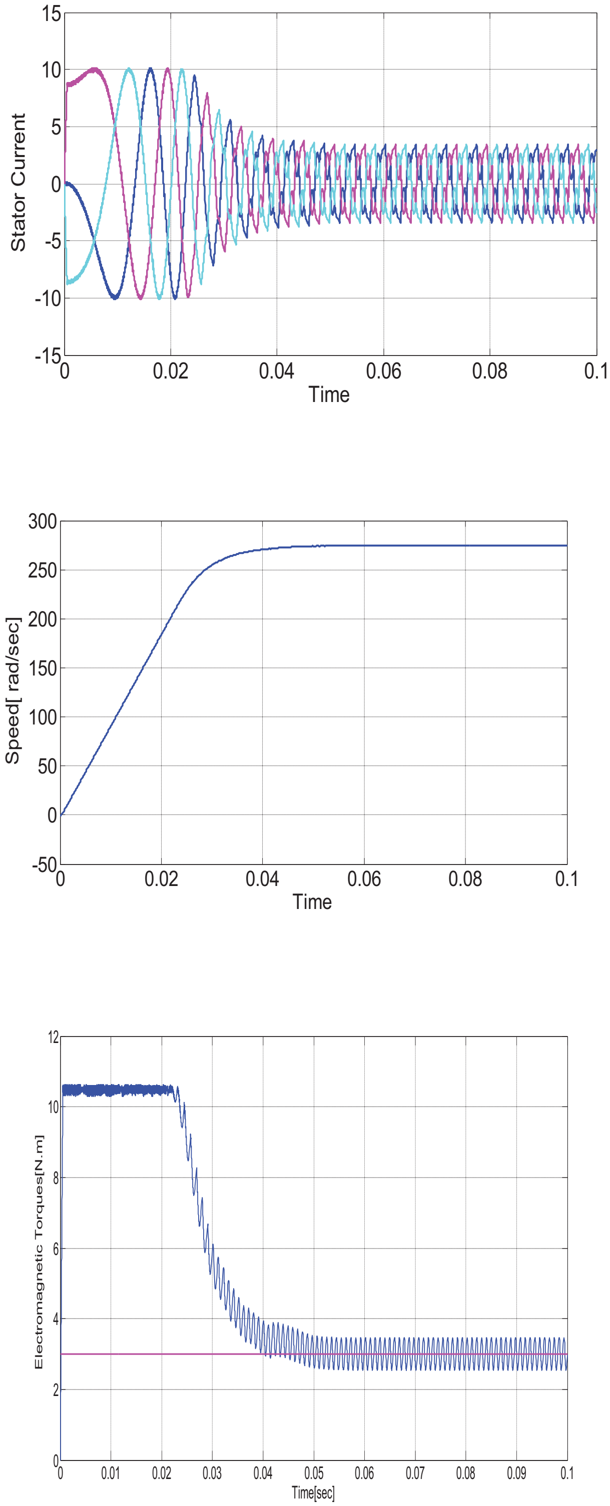


Fig 3 Steady State response of FOC, at 500 rpm

IV. HARDWARE IMPLEMENTATION

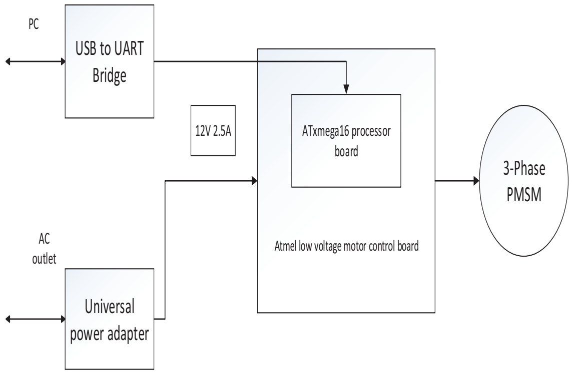


Fig.4 Block Diagram of Three Phase Permanent Magnet Synchronous Motor Low-Voltage Motor Control Drive

The system consists of a 3-phase PMSM, Atmel ATxmega16D4 processor board, USB-UART bridge cable a 12V universal power adapter and Atmel LV motor control board,. The firmware also provides the control structure for Permanent magnet synchronous motor sensorless Field oriented control. The sensorless control method calculates back EMF to form a back EMF PLL . Speed control is provided by a PI controller. Three Phase Permanent Magnet Synchronous Motor Low-Voltage Motor Control Drive consists of a Three-phase, 8-pole PMSM. The three motor leads, consisting of red, black and yellow(1 no.) 20 AWG wire, are brought out for connection to the LV motor control board. The motor have three Hall sensors leads and a common sensor power and ground. These wires are left disconnected because they are not used in the sensorless algorithm. The ATxmega processor board consists of Atmel ATxmega16D4 AVR µC, 3.3V regulator , 6 pin header (2x3) PDI interface connector & 6 pin header (1x6) for USB-UART bridge. The LV motor control board consists of a Socket for Atmel ATxmega16D4 AVR processor board, Gate drive circuitry, Current sense resistor, 3-phase power stage consisting of three N-channel MOSFETs as lower switches and three P-channel MOSFETs as upper switches, DC bus bypass capacitor,2-pin header for 12V power adapter connector & a 3-pin header for motor phase connections.

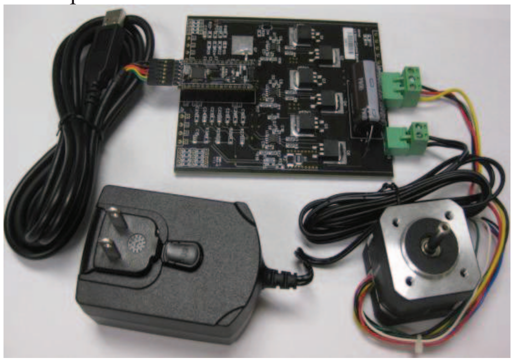


Fig.5 Configurable 3-phase PMSM with a USB-UART bridge and universal power adapte

Now,after powering of Atmel ATxmega16D4 processor board via USB ,the PMSM phase leads are connected to the 3-pin connector J2. The motor phase leads are the 20 RYB wires from the motor. Connecting the motor phase leads in the order shown in Figure.5 provides clockwise rotation for a positive and anticlockwise rotation for a negative command. Interchanging any two phases reverses the rotation direction for both commands. DC input voltage 0 to 15V is connected to J3 . Under voltage lockout is provided by gate drive ICs below 10.1V so that at least 12V nominal is recommended to run the motor. 12V power can be supplied from the universal power adapter or a variable lab supply can be used that is capable of supplying 12V and 2.5A

V. EXPERIMENTAL RESULTS

TABLE III

Actual Speed	Measured speed	Actual current	Measured current	Actual D.C voltage	Torque ripple
500 rpm	497.182 rpm	0.21 A	0.17 A	24.5 V	0.08
1500 rpm	1494.8rpm	-0.02 A	0.10 A	24.5 V	0.06
3000 rpm	3000 rpm	0.01 A	0.04 A	24.5 V	0.02

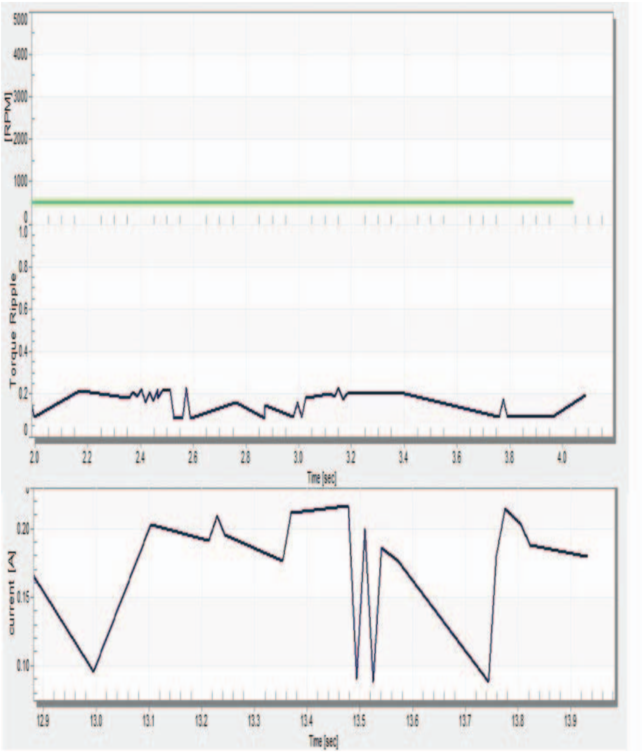
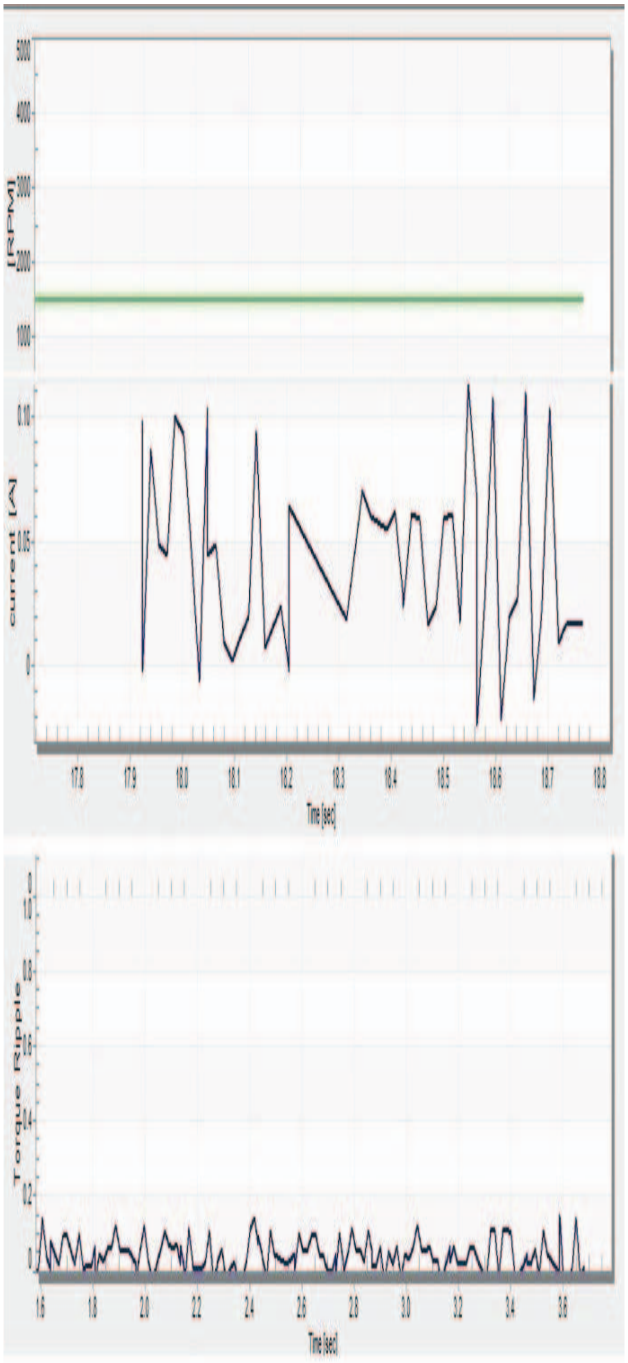


Fig.6.Speed, Stator current & torque ripple response of FOC, at 500 rpm



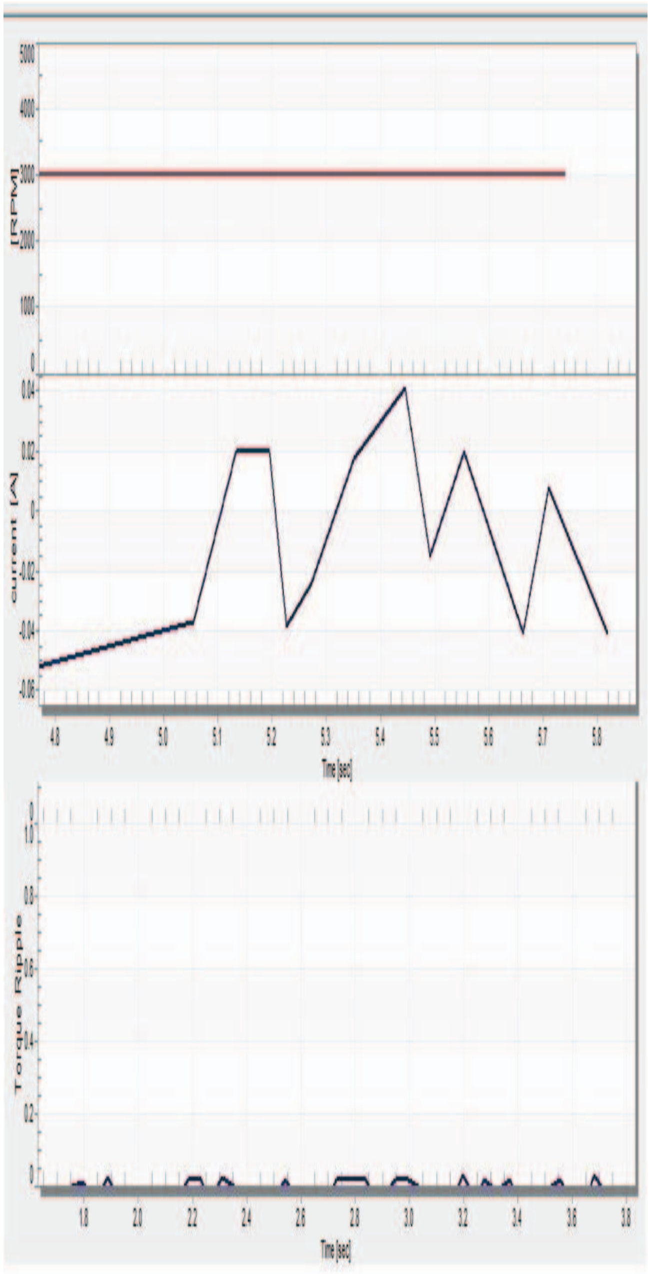


Fig.8.Speed, Stator current & torque ripple response of FOC, at 3000 rpm

Fig.7.Speed, Stator current & torque ripple response of FOC, at 1500 rpm

VI. CONCLUSIONS

This paper presented FOC of a PMSM .It is designed, simulated and implemented. Firstly, the model of FOC control of a permanent magnet synchronous motor drive system has been developed& simulated in Matlab/Simulink. The percentage of torque ripples are 10.98% at 500 rpm in transient and steady state response.

Afterwards the hardware was implemented using a 2 kW,6 pole Permanent Magnet Synchronous Motor and μC with computer-system interface. After the calibration of every measuring device and the proper corrections of the controller model, some results were carried up to check the validity of the simulation results. The percentage of torque ripples are 0.02% at 3000 rpm in hardware implementation. Hence the output results show that the system has a good dynamic response for software and hardware implementation at high speed & suitable for automotive application.

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