MODELING AND SIMULATION OF SENSORLESS CONTROL OF PMSM WITH LUENBERGER ROTOR POSITION OBSERVER AND SUI PID CONTROLLER

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Abstract: This paper presents an investigation and evaluation of the performance of the surface Permanent Magnet Synchronous Motor drive under the Simplified Universal Intelligent PID controller (SUI PID). The estimation of the rotor position and the angular speed in dynamic rate were derived by the use of the Luenberger state observer for currents and MRAS (Model Reference Adaptive System) observer. It also shows how to use a Luenberger state observer in a field oriented control (FOC) scheme to implement a sensorless vector control strategy. The mathematical descriptions of the system and simulation results have been presented in this paper.

Key words: Surface Permanent Magnet Synchronous Motor, Luenberger State Observer, SUI PID controller, MRAS observer, Sensorless vector control.

NOMECLATURE

I_d, I_q	$d-q$ Stator currents
V_d, V_q	$d-q$ Stator voltages
ω_r	Rotor angular speed (rad/s)
θ_r	Rotor position angle (rad)
R	Stator Resistance (Ω)
K_T	Motor torque constant
F	Fractional Coefficient
T_L	Load torque ($N.m$)
J	Rotor inertia ($Kg.m^2$)
P	Number of Pole Pairs
K	The matrix coefficient gain
$\wedge$	Refers to the estimated value
λ	EMF constant
K_p	Proportional gain constant
K_i	Integral gain constant
e_d	The state error in the d-axis
e_q	The state error in the q-axis
M	The SUI PI controller gain

1. Introduction

PMSM has wide application in AC servo system, compared to other machines because of its advantages like quick response, excellent control performances, small size , light weight, high power/ weight ratio, large torque/ inertia ratio, smooth torque operation, controlled torque at zero speed, high speed operation, high torque production capability, high efficiency and compact structures [1].

The motor drives need the information of rotor speed to achieve speed control loop. Rotor speed can be measured by sensors attached to rotor shaft which transmit the motor speed to the drive controller. However, using mechanical sensors placed on the machine shaft have many drawbacks [2]-[3]. First, the mechanical sensor presence increases the volume and the global system cost. Therefore it requires an available shaft end which can constitute a drawback with small sized machines. Moreover, the installation of this sensor requires a chock relating to the stator, operation which proves to be delicate and decreases the reliability of the system. This requirement leads to the paper in the field of sensorless control schemes that estimate the speed of the rotor without any sensors attached to the rotating shaft [4].

In this paper, to overcome problems related to the mechanical speed sensors, the adaptive Luenberger observer for rotor position and angular speed estimations is studied under the SUI PID controller for PMSM drive system.

2. The control system block diagram

Fig. 1 shows the block diagram of sensorless control of PMSM. The system has been built using the matlab/ simulink. The drive system consists of: - PMSM, Current controller, Adaptive Luenberger observer for estimating both rotor position & angular speed and the SUI PID controller. The estimated rotor angular speed $\hat{\omega}_r$ is compared with the reference angular speed ω_{ref} which it is set to 314 rad/sec. The resulting angular
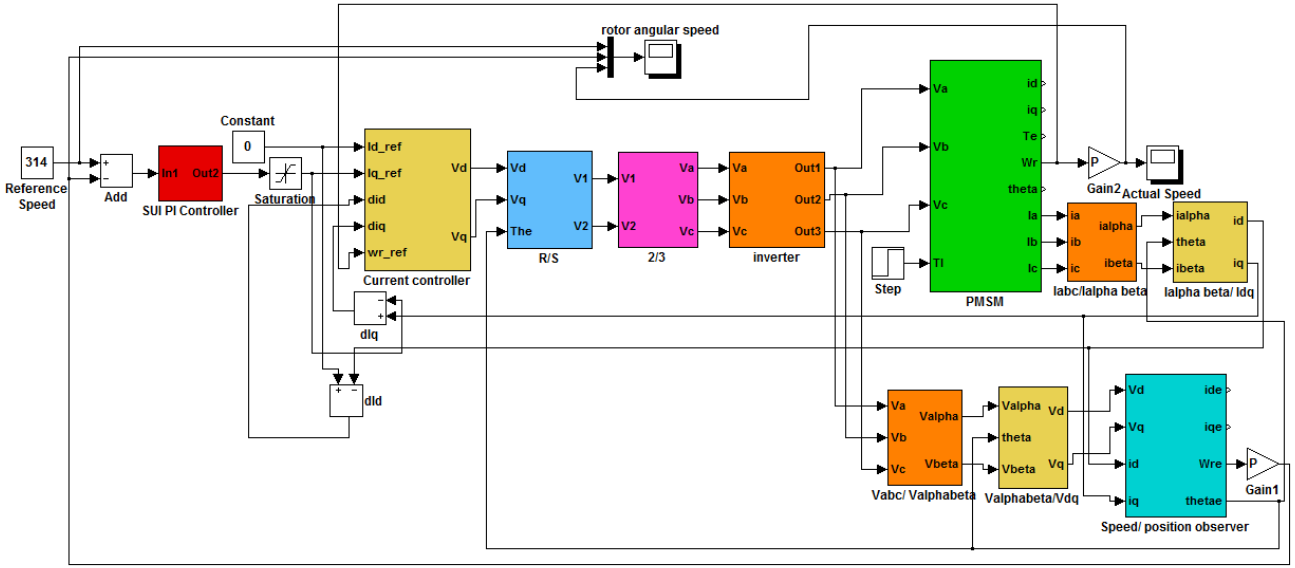
Fig. 1. Block Diagram of Sensorless control of PMSM

speed error is processed in the SUI PID controller to regulate the rotor speed. The output of this controller is $i_{q\,ref}$. The state frame transformations of Clark, Park, and inverse-Park are used to transform the currents and voltages.

2 PMSM model

The stators of the PMSM and wound rotor synchronous motor are similar. In addition, there is no difference between the back EMF produced by a permanent magnet and that produced by an excited coil. Hence, the mathematical model of a PMSM is similar to that of the wound rotor SM [5]. The electrical dynamic equation of the motor in the dq rotor reference frame can be written as:-

$$\frac{di_d}{dt} = \frac{V_d}{L_d} - \frac{R}{L_d}i_d + \frac{L_q}{L_d}P\,\omega_r\,i_q \qquad (1)$$

$$\frac{di_q}{dt} = \frac{V_q}{L_q} - \frac{R}{L_q}i_q - \frac{L_d}{L_q}P\,\omega_r i_d - \frac{\lambda P\,\omega_r}{L_q} \qquad (2)$$

Both stator currents in the rotor reference frame I_d & I_q can be obtained by integrating equations (1) & (2).

The electro-magnetic torque:-

$$Te = \frac{3}{2}P\left[\lambda\,I_q + (L_d - L_q)I_q I_d\right] \qquad (3)$$

For constant flux operation I_d maintained at zero, which produce electric torque

$$Te = \frac{3}{2}P\left[\lambda I_q\right] = K_T I_q \qquad (4)$$

This torque equation of the PMSM similar to the regular dc machine and hence provides ease of control where, the torque depends only on the quadrature component of the stator current.

The torque balanced equation is:-

$$T_e = J\frac{d\omega_r}{dt} + F\omega_r + T_L \qquad (5)$$

$$\frac{d\omega_r}{dt} = \frac{\left[T_e - F\omega_r - T_L\right]}{J} \qquad (6)$$

The rotor position θ_r in state space derivative form is:-

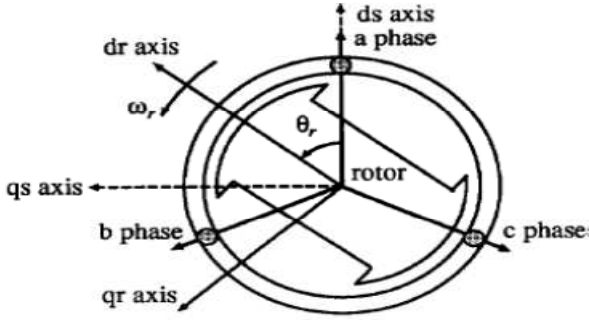$$\frac{d\theta_r}{dt} = \omega_r \qquad (7)$$

Fig. 2. Analytical model of PMSM

3. Coordinate transformations

In order to study the performance of PMSM model under sensorless control, two different transformations were made: The first one is Clarke-transformation while the second is Park transformation.

3.1 Clarke transformation

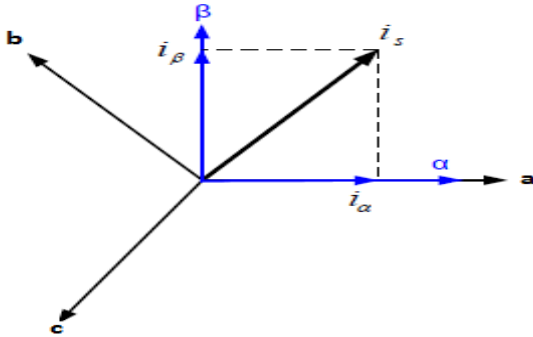Clarke-transformation transforms the 3-phase system into a 2- phase time or vice versa.
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Fig. 3. Clark transformation

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & \dfrac{-1}{2} & \dfrac{-1}{2} \\ 0 & \dfrac{\sqrt{3}}{2} & \dfrac{-\sqrt{3}}{2} \end{bmatrix} \times \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (8)$$

The inverse Clark transformation can also be found as:

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ \dfrac{-1}{2} & \dfrac{\sqrt{3}}{2} \\ \dfrac{-1}{2} & -\dfrac{\sqrt{3}}{2} \end{bmatrix} \times \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (9)$$

3.2. Park transformation

Park-transformation produces the system model; the current and voltage vectors onto a rotating coordinate time invariant system as shown on Fig.4.
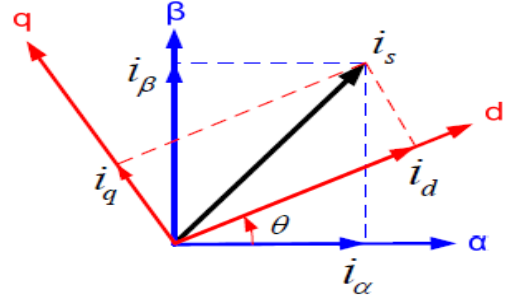

Fig. 4. Park transformation

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos\theta_r & \sin\theta_r \\ -\sin\theta_r & \cos\theta_r \end{bmatrix} \times \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (10)$$

And the inverse Park transformation is:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} \cos\theta_r & -\sin\theta_r \\ \sin\theta_r & \cos\theta_r \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} \quad (11)$$

4. Current controller

The current controller block used to regulate the stator current and it has five inputs: $i_{d\,ref}, i_{q\,ref}, \Delta i_d, \Delta i_q$ & $\hat{\omega}_r$ and two outputs; V_d & V_q. The current controller has been implemented according to the current controller equations;

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} R & -P\omega_r \\ P\omega_r & R \end{bmatrix} \times \begin{bmatrix} i_{dref} \\ i_{qref} \end{bmatrix} + \frac{1}{\Delta t} \times \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix}$$

$$\times \begin{bmatrix} \Delta i_d \\ \Delta i_q \end{bmatrix} + \begin{bmatrix} 0 \\ P\omega_r \lambda \end{bmatrix} \tag{12}$$

Where; $i_{d\,ref}$ is maintained at zero since there is no flux weakening operation in this paper.

$$\Delta i_d = i_{d\,ref} - I_d \tag{13}$$

$$\Delta i_q = i_{q\,ref} - I_q \tag{14}$$

5. The SUI PID speed controller

The speed controller was implemented to regulate the rotor speed by comparing the reference angular speed with the estimated angular speed. The output of this controller is $i_{q\,ref}$.

The PID controller consists of three terms [6]:-

The first controller term: $P = K_P * error$ (15)

The second controller term: $I = K_I * \int error.dt$ (16)

The third controller term: $D = K_d * \dfrac{derror}{dt}$ (17)

The following values can then be substituted into the PID controller equation:-

$$K_P = ABS(error) \tag{18}$$

$$K_I = ABS\left(\int error.dt\right) \tag{19}$$

$$K_d = ABS\left(\frac{derror}{dt}\right) \tag{20}$$

Selecting the controller constants from the above explanation leads to a simple design algorithm and simplified adaptive weighting for the three terms.

The proposed intelligent PID controller is constructed by using the multi degree of freedom controller (MDOF) concept [7], [8]. Applying the intelligent PID controller eliminates the need to know the system steady state gain.

$$C_m = C * M * error + C * \frac{1}{M}(1 - error) \tag{21}$$

$$C_m = C * error * (M - \frac{1}{M}) + \frac{C}{M} \tag{22}$$

For $M \succ\succ 1 \Longrightarrow C_m = C * error * M$ (23)

The proposed SUI PI controller is a classical PI with a universal PID constant, so no specific design is needed and therefore no need for a system model. The SUI PID controller constants K_P and K_I are the absolute values of errors and integration of errors as shown in Fig.5.
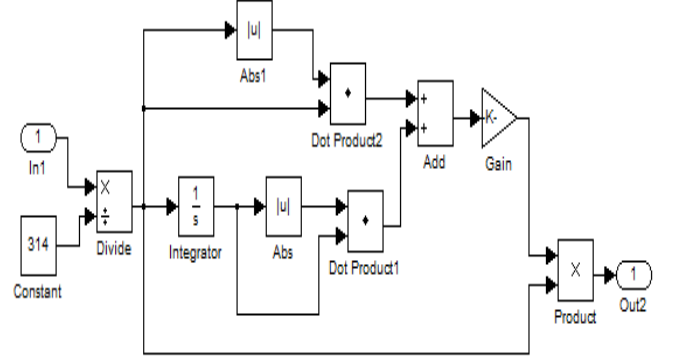

Fig. 5. SUI PID controller

6. Luenberger Adaptive Observer

The state space of PMSM model of equations 1&2 is constructed according to the following relations based on the knowledge of inputs and outputs of the system:

$$\begin{cases} \dfrac{dX}{dt} = AX + BU \\ \quad Y = CX \end{cases} \tag{24}$$

Where;

$$X = \begin{bmatrix} i_d & i_q \end{bmatrix}^T ; U = \begin{bmatrix} V_d & V_q & \lambda \end{bmatrix}^T ;$$

$$Y = \begin{bmatrix} i_d & i_q \end{bmatrix}^T ;$$

$$A = \begin{bmatrix} \dfrac{-R}{L_d} & P\omega_r \\ -P\omega_r & \dfrac{-R}{L_d} \end{bmatrix} ; B = \begin{bmatrix} \dfrac{1}{L} & 0 & 0 \\ 0 & \dfrac{1}{L} & \dfrac{-P\omega_r}{L} \end{bmatrix} ;$$

$$C = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

For SPMSM, $L_d = L_q = L$. To estimate the rotor position and the angular speed; the stator current in d &

q directions (i_d & i_q) in the rotating frame are used as the estimated variables and the rotor speed ω_r as the regulated variable.

The second order Luenberger observer is given by:

$$\begin{cases} \dfrac{d\,\hat{X}}{dt} = A_1(\hat{\omega}_r)\,\hat{X} + B_o U + K(Y - \hat{Y}) \\ \hat{Y} = C\,\hat{X} \end{cases}$$

(25)

Where; $\hat{\omega}_r$ is the estimated angular speed (rad/sec) and K is a constant coefficient matrix which is characterized by an equation containing a term which corrects the current state estimates by an amount proportional to the prediction error. The prediction error is the difference between the estimated and actual current. This correction ensures stability and convergence of the observer even when the system being observed is unstable [9].

$$\hat{X} = \begin{bmatrix} \hat{i}_d & \hat{i}_q \end{bmatrix}^T ; \hat{Y} = \begin{bmatrix} \hat{i}_d & \hat{i}_q \end{bmatrix}^T ;$$

$$A_1(\hat{\omega}_r) = \begin{bmatrix} \dfrac{-R}{L} & P\,\hat{\omega}_r \\ -P\,\hat{\omega}_r & \dfrac{-R}{L} \end{bmatrix} ;$$

$$B_o = \begin{bmatrix} \dfrac{1}{L} & 0 & 0 \\ 0 & \dfrac{1}{L} & \dfrac{-P\hat{\omega}_r}{L} \end{bmatrix}.$$

7. Rotor angular speed observation

The rotor angular speed is reconstructed using the model reference adaptive system (MRAS). The MRAS principle is based on the comparison of the outputs of the two estimators. The first one is independent of the observed variable named as model reference, while the second is the adjustable one. The error between the two models feeds an adaptive mechanism to turn out the observed variable [10].

In this paper, the actual system is considered as the model reference and the observer is used as the

adjustable one. The rotor angular speed is built around the following adaptive mechanism:

$$\hat{\omega}_r = K_p(\hat{i}_d\,i_q - i_q\,\hat{i}_d - \dfrac{\lambda}{L}e_q) + K_i\int_0^t (i_d\,\hat{i}_q - i_q\,\hat{i}_d - \dfrac{\lambda}{L}e_q)dt$$

(26)

Where;

$$e_d = i_d - \hat{i}_d \qquad \& \qquad e_q = i_q - \hat{i}_q .$$

Where; e_d & e_q are the state errors.

The tracking performance of the speed estimation and the sensitivity to noise are depending on proportional and integral coefficient gains. The integral gain K_i is chosen to be high for fast tracking of speed. While, a low proportional K_p gain is needed to attenuate high frequency signals denoted as noises [11].

By estimating the rotor angular speed, the estimated rotor position $\hat{\theta}_r$ can be obtained by:

$$\hat{\theta}_r = \int \hat{\omega}_r \,.dt$$

(27)

MRAS structure for estimating the rotor angular speed and the rotor position is illustrated in Fig. 6.

The scheme consists of 2 models; reference model and adjustable model with adaptation mechanism. The reference model block represents the actual system having unknown parameters values. The adjustable model block has the same structure of the reference one, but with adjustable parameters instead of the unknown ones. The adaptation mechanism block updates the adjustable model with the estimated parameter until satisfactory performance is achieved. The PMSM model was considered to be the reference model and the Luenberger observer was considered as adjustable model to obtain the estimated stator currents [12].
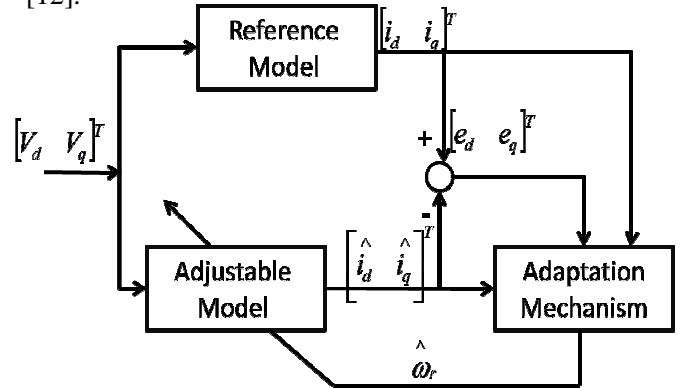

Fig. 6. MRAS Structure

8. Simulation results

Based on the motor parameters indicated in the appendix, the simulation of the sensorless control of PMSM has been carried out using the Simulink in Matlab. The stator current is decoupled using the field oriented control into both $i_d \& i_q$. In this paper the motor was tested at no load and sudden loading conditions with constant stator resistance at 2Ω.

The PWM switching frequency of the inverter is set to 10 KHz. The DC link voltage of the inverter is maintained at 200 V. The reference angular speed of the motor is set to 314 rad/sec.

Using only the three phase stator currents the quadrature and direct axis currents, rotor angular speed and position are estimated by the Luenberger state observer.

The estimated angular speed was regulated via conventional PI controller with low K_p =2 and above K_i =5000 and the constant coefficient matrix K =1000.

Fig. 7 shows the actual, estimated and the reference angular speeds.

At starting, the motor has rapid changing, both the actual and the estimated speeds track the target speed at t=0.062 sec. The system response converges to the model reference one.

The estimated rotor angular speed $\hat{\omega}_r$ tracks the actual rotor angular speed ω_r in a very short time nearly 0.003 sec by the virtue of the SUI PI controller.

After loading, both the estimated and actual rotor angular speeds dropped but in a very short time and by the virtue of the SUI PI controller they returned back again to the reference value (target) in less than 0.002 sec.

At t=0.04 sec an error occurs with angular speed error=65 rad/sec and at t=0.04 sec the error converges to zero in 0.0572 sec thanks to the adaptive control algorithm as shown on Fig. 8.

At t=1 sec, with a sudden loading, the speed error decreases and then return back again to zero as both Actual and estimated speeds are equal.

The speed error between the estimated and the reference is the input to the SUI PI controller to regulate it and the output of the controller is $i_{q_{ref}}$.

Fig. 9 shows the motor electromagnetic torque, T_e which starts smoothly and at t=0.05 sec it becomes 1.8 $N.m$ then from t=0.06 sec to t=0.128 sec, the electromagnetic torque was oscillating around 0 $N.m$ and then it returned back again to 1.8 $N.m$ when load and then it returned back again to 1.8 $N.m$.

After loading the motor torque oscillates around T_e = 1.8 $N.m$.

Fig. 10 shows the d-axis current, the actual and estimated stator current at d axis I_d . The estimated current $\hat{I}_d$ tracks the actual d axis current I_d of the motor at t=0.05 sec and both become 0 A at t=0.06 sec and both oscillate around the zero axis.

After loading at t=1 sec, both estimated and actual i_d are equal to zero.

Fig. 11 shows the q-axis current, the actual and estimated stator current at the q axis, I_q: the estimated q axis current $\hat{I}_q$ tracks the actual q axis current I_q at t=0.06 sec and both of them have the same characteristics of the motor electromagnetic torque T_e in both cases during the stating up with no load and after loading at t=1 sec and both oscillates around 4A.

Fig. 12 shows the rotational parameters (Sin and Cos of the estimated rotor position).
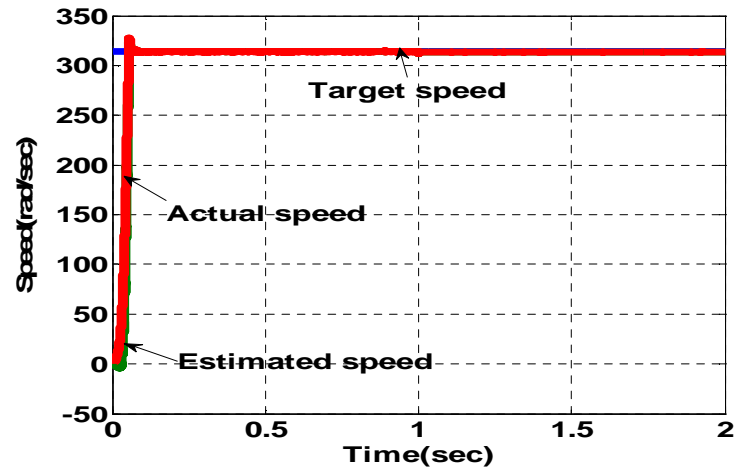

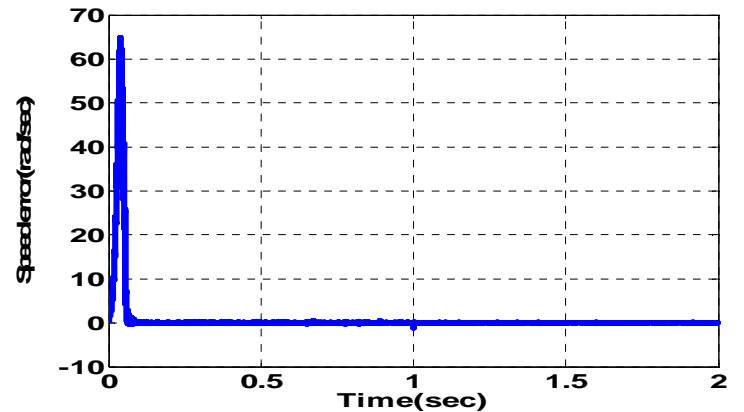Fig. 7. The actual, target and estimated angular speeds at starting and then a sudden loading
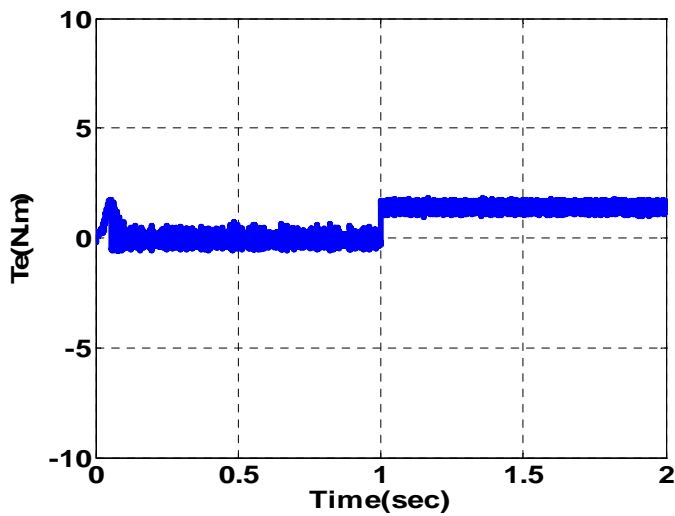

Fig. 8. The angular speed error
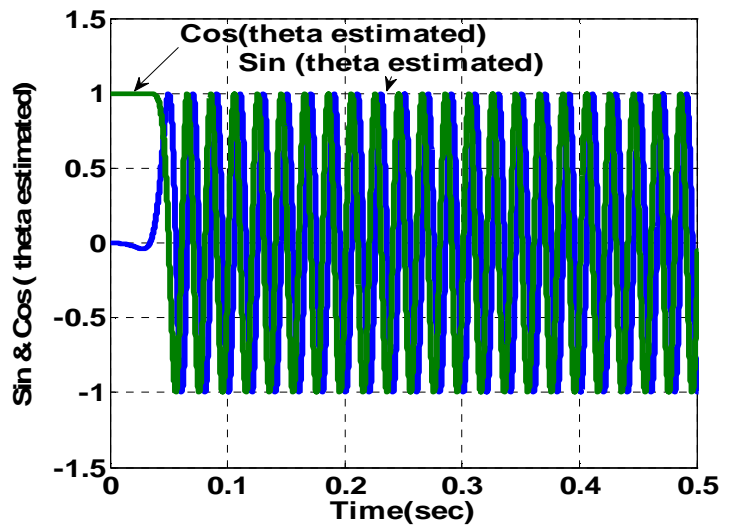
Fig. 9. The Electromagnetic torque T_e

Fig. 12. The Sin & Cos (estimated theta)

Conclusions

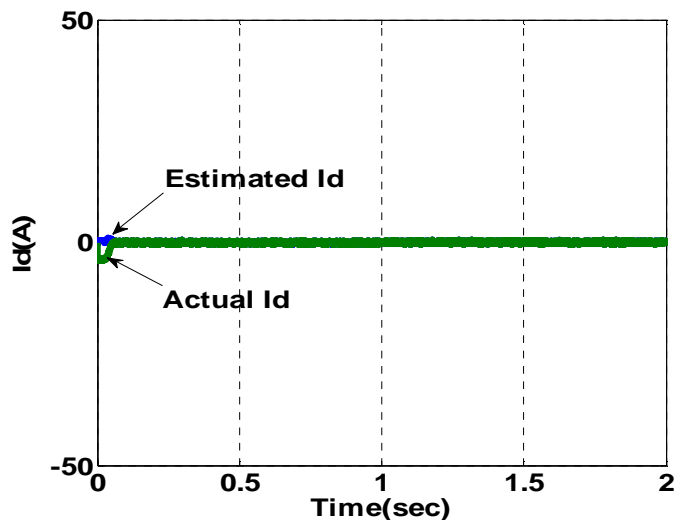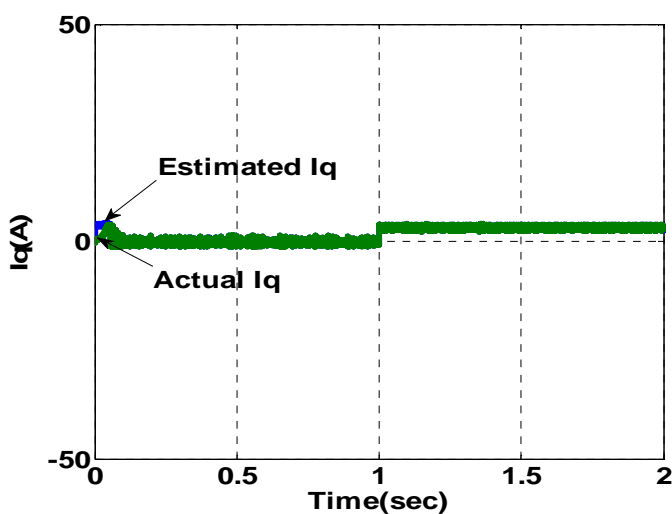This paper presents a sensorless control of PMSM using the SUI PID controller and Luenberger adaptive observer to estimate both rotor angular speed and the rotor position. The efficiency of using luenberger adaptive observer has been studied and indicated on the simulation results in the simulink/ matlab software package.

This technique of estimation for both rotor angular speed and rotor position instead of using mechanical sensors; increases the system reliability and reduces the system cost.

The adaptive with control algorithm for the rotor angular speed associated with the SUI PI speed and current controllers show good performances at starting and at sudden loading condition.

Fig. 10. The actual and estimated d-axis current i_d

APPENDIX

Motor parameter used in the simulation:-

Power	1.7 KW
Frequency	150 Hz
Line Voltage	380 V - Star
Line Current	3.4 A - Star
No. of Pole Pairs	3
Rated angular Speed	314 rad/sec
Stator Resistance	$2\Omega / phase$
d- axis Inductance (L_d)	7.75mH
q- axis Inductance (L_q)	7.75mH
EMF Constant	0.098V/rad/sec

Fig. 11. The actual and estimated q-axis current i_q

Friction Coefficient	0
Moment of inertia coefficient	$0.00037\ Kg.m^2$
Load Torque	1.5 N.m

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