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# SENSORLESS VECTOR CONTROL OF PM SYNCHRONOUS MOTORS USING ADAPTIVE STATE OBSERVERS WITH DISTURBANCE TORQUE ESTIMATION

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*In this paper, a novel sensorless nonlinear speed control for a permanent magnet synchronous motor (PMSM) driving an unknown load torque is developed and integrated with the vector control scheme. An extended nonlinear state observer with parameter adaptive scheme is used to estimate the states of the motor and disturbance torque avoiding the use of mechanical sensors. The parameter identified adaptively is stator resistance which varies with motor temperature and frequency. Furthermore, to improve the performance of the speed controller the load inertia is identified by the periodic test signal. The proposed sensorless makes the drive system accurate, robust and insensitive to parameter variation. The steady state and dynamic performances of the proposed sensorless drive using digital simulation results are demonstrated.*

## 1. INTRODUCTION

Permanent magnet synchronous motors (PMSM) are used in various industrial applications of electromechanical systems due to their high power density, large torque to inertia ratio, high efficiency and good controllability over a wide rang of speeds. Fast and accurate response, quick recovery of speed from any disturbances and insensitivity to parameter variations are some of the main criteria of high performance drive systems used in robotics, rolling mills, machine tools, etc. In these applications, equivalent performance characteristics of a separately excited dc motor can be obtained from the PMSM if the closed loop vector control scheme is employed [1]. The PMSM drive system involving the vector control scheme not only decouples the torque and flux which provides faster response but also makes the control task easy. The speed controller used in PMSM drive system plays an important role to meet the other required criteria of the high performance drive. It should enable the drive to follow any reference speed taking into account the effects of load impact, saturation and parameter variations. Conventional controllers such as proportional integral (PI) or proportional integral differential (PID) have been widely used in both dc and ac motor controls. But these types of controllers are difficult to design if an accurate system model is not available. Moreover, unknown load dynamics and other factors such as noise, temperature, saturation, etc. affect the performance of these controllers for wide range of speed operations [2].

Coupling the load to the motor shaft may cause variations of the inertia and viscous friction coefficient besides the load variation. In [3], a speed control method for a PMSM using the input-output linearization has been proposed. In this scheme, an integral controller has been introduced to improve the robustness against the inaccurate speed measurement. However, other motor parameter variations have not been considered. Even though a steady-state response can be improved by introducing the integral controller, it can not give a good transient response under the parameter mismatch.

The performance of adjustable speed drives containing PMSM can be improved implementing nonlinear control strategies. Among others, feedback linearization has emerged as a very useful control law for electrical drives [4]. The implementation of feedback linearization, as well as the other strategies, requires an optical/mechanical sensor to obtain position and speed as part of the state to be fed back. However, mechanical sensors can be avoided when sensorless control strategies are designed. In such cases rotor position and speed must be estimated and these estimated values are used to compute the control law.

State observers can be used to estimate the rotor position and speed of PMSM. Several approaches to obtain PMSM state observers have been proposed, such as nonlinear full order observers based on linearization, extended Kalman filter (EKF), viz nonlinear observers, nonlinear reduced order observers [5]. In [5], [6] and [7] observer-based speed controllers have been proposed. In these papers certain assumptions have to be introduced to design the observer-based controller. In [6], a known load torque has been considered, while in [7] the value of inductance is assumed to be zero to design the controller. In [5], the authors assume that machine speed is approximately constant during a short time interval. Nevertheless, when higher performance is required the mismatches caused by an unknown load torque, a nonzero inductance and variable speed have to be compensated. Recently, an adaptive input-output linearization technique [8] and a sliding mode control technique [9] have been reported for the speed control of the PMSM. Although good performance can be obtained, the controller design are quite complex.

In this paper, a novel sensorless nonlinear speed control for a PMSM drive with vector control scheme is presented. The states of the motor and disturbance load torque are estimated via an extended nonlinear observer with parameter adaptive scheme avoiding the use of mechanical sensors. The adaptive state observer uses a mechanical model to improve the behavior during speed transients. The parameters identified adaptively are stator resistance which varies with motor temperature and frequency and load inertia. The use of the adaptive state observer makes the drive system robust, accurate and insensitive to parameter variations. The steady state and dynamic performance of the proposed sensorless drive system are evaluated by digital simulations. Simulation results are presented to demonstrate smooth steady state operation and exhibits good dynamic performance of the drive system during disturbance of load torque.

## 2. DYNAMIC MODEL OF PMSM

A PMSM consists of permanent magnets mounted on the rotor surface and three phase stator winding that are sinusoidally distributed and displayed by 120°. The dynamic model of a surface mounted PMSM in the stationary reference frame (α-β axes) can be described by the following equations [5] and [6],

$$p\theta_r = \omega_r \tag{1}$$

$$pi_{\alpha s} = -\frac{R_s}{L_s} i_{\alpha s} + \frac{\lambda_m}{L_s}\omega_r \sin\theta_r + \frac{V_{\alpha s}}{L_s} \tag{2}$$

$$pi_{\beta s} = -\frac{R_s}{L_s} i_{\beta s} - \frac{\lambda_m}{L_s}\omega_r \cos\theta_r + \frac{V_{\beta s}}{L_s} \tag{3}$$

The developed electromagnetic torque can be expressed as:

$$T_e = \frac{3}{2} p\lambda_m (i_{\beta s}\cos\theta_r - i_{\alpha s}\sin\theta_r) \tag{4}$$

and the motor dynamics can be represented by

$$T_e = Jp\omega_r + B\omega_r - T_d \tag{5}$$

The model voltages and currents are related to the actual physical quantities by a simple linear transformation given by:

$$V_{\alpha s} = \frac{2}{3}(V_{as} - \frac{V_{bs}}{2} - \frac{V_{cs}}{2}) \tag{6}$$

$$V_{\beta s} = \frac{1}{\sqrt{3}}(V_{bs} - V_{cs}) \tag{7}$$

$$i_{\alpha s} = \frac{2}{3}(i_{as} - \frac{i_{\beta s}}{2} - \frac{i_{cs}}{2}) \tag{8}$$

$$i_{\beta s} = \frac{1}{\sqrt{3}}(i_{bs} - i_{cs}) \tag{9}$$

## 3. VECTOR CONTROL OF PMSM DRIVE

A vector control strategy is formulated in the synchronously rotating reference frame. The stator voltages and currents in the stationary reference frame are projected on to those in a frame that is synchronous with the rotor, via transformation [10]

$$\begin{bmatrix} V_{ds} \\ V_{qs} \end{bmatrix} = \begin{bmatrix} \cos\theta_r & \sin\theta_r \\ -\sin\theta_r & \cos\theta_r \end{bmatrix} \begin{bmatrix} V_{\alpha s} \\ V_{\beta s} \end{bmatrix} \tag{10}$$

$$\begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} = \begin{bmatrix} \cos\theta_r & \sin\theta_r \\ -\sin\theta_r & \cos\theta_r \end{bmatrix} \begin{bmatrix} i_{\alpha s} \\ i_{\beta s} \end{bmatrix} \tag{11}$$

The model of PMSM (1)-(4) in the synchronous rotating reference frame becomes

$$p\theta_r = \omega_r \tag{12}$$

$$pi_{ds} = -\frac{R_s}{L_s} i_{ds} + \omega_r i_{qs} + \frac{V_{ds}}{L_s} \tag{13}$$

$$pi_{qs} = -\frac{R_s}{L_s} i_{qs} - \omega_r i_{ds} - \frac{\lambda_m \omega_r}{L_s} + \frac{V_{qs}}{L_s} \tag{14}$$

Note that the electromagnetic torque can be expressed as:

$$T_e = \frac{3}{2} P(i_{qs}\lambda_{ds} - i_{ds}\lambda_{qs}) \tag{15}$$

The stator flux components $(\lambda_{ds}, \lambda_{qs})$ are in the form

$$\lambda_{ds} = L_s i_{ds} + \lambda_m \qquad , \tag{16}$$

$$\lambda_{qs} = L_s i_{qs} \tag{17}$$

An efficient control strategy of the vector control technique is to make the d-axis current $i_d$ zero so that the direct axis stator flux linkage $\lambda_{ds}$ becomes dependent only on the flux linkage by the permanent magnet rotor $\lambda_m$. With this control strategy, the machine model becomes simpler and can be described by the following equations

$$pi_{qs} = -\frac{R_s}{L_s} i_{qs} - \frac{\lambda_m \omega_r}{L_s} + \frac{V_{qs}}{L_s} \tag{19}$$

$$p\omega_r = \frac{T_e}{J} - \frac{B\omega_r}{J} - \frac{T_d}{J} \tag{20}$$

and the electromagnetic torque is proportional to the q-axis stator current as given by

$$T_e = K_T i_{qs} \tag{21}$$

Where $K_T = \frac{3}{2} P\lambda_m$

Equation (21) is similar to the torque equation of a separately excited dc motor, where $i_{qs}$ corresponds to the armature current of a dc motor. Hence, a precise torque control of the PMSM is achieved by controlling the q-axis stator current component $i_{qs}$.

## 4. NONLINEAR STATE OBSERVER

An extended nonlinear state observer is used to estimate the PMSM states and the unknown load torque disturbance. The observer states copies the PMSM model adding a correction term that works as a driving input and the unknown load torque disturbance. A new state is added to track a slowly varying load torque [11]. The torque due to viscosity is incorporated to the disturbance torque $T_d$, so the $B\omega_r$ term does not appear explicitly in the observer. Even though, the disturbance torque $T_d$ is not a constant parameter under the mechanical parameter variations from their nominal values. If the sampling interval is sufficiently fast as compared with the time, the variation in viscous friction coefficient, inertia and hence of the unknown disturbance $T_d$ can be assumed to be constant during each sampling interval as [10] and [11].

$$pT_d = 0 \tag{22}$$

In order to satisfy convergence conditions, stability, the correction term and the adaptation law are derived using Lyapunovs theorem [9].

The extended observer is given as follows:

$$\begin{bmatrix} p\hat{\theta}_r \\ p\hat{\omega}_r \\ p\hat{i}_{\alpha s} \\ p\hat{i}_{\beta s} \\ p\hat{T}_d \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & -\frac{3}{2}\frac{P\lambda_m}{J}\sin\hat{\theta}_r & \frac{3}{2}\frac{P\lambda_m}{J}\cos\hat{\theta}_r & -\frac{1}{J} \\ 0 & \frac{\lambda_m}{L_s}\sin\hat{\theta}_r & -\frac{R_s}{L_s} & 0 & 0 \\ 0 & -\frac{\lambda_m}{L_s}\cos\hat{\theta}_r & 0 & -\frac{R_s}{L_s} & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \hat{\theta}_r \\ \hat{\omega}_r \\ \hat{i}_{\alpha s} \\ \hat{i}_{\beta s} \\ \hat{T}_d \end{bmatrix} \tag{23}$$

$$+ \begin{bmatrix} \frac{1}{L_s} \\ \frac{1}{L_s} \end{bmatrix} \begin{bmatrix} V_{\alpha s} \\ V_{\beta s} \end{bmatrix} + GG \begin{bmatrix} \hat{i}_{\alpha s} - \hat{i}_{\alpha s} \\ \hat{i}_{\beta s} - \hat{i}_{\beta s} \end{bmatrix}$$

$$= Ax + BV_s + GG(\hat{i}_s - i_s)$$

$$i_s = Cx$$

With

$$GG = \begin{bmatrix} \Gamma G \\ k(\sin\hat{\theta}_r - \cos\hat{\theta}_r) \end{bmatrix}, \qquad G = \begin{bmatrix} g_1 & g_2 & g_3 & g_4 \\ -g_2 & g_1 & -g_4 & g_3 \end{bmatrix}^T,$$

$$\Gamma = \begin{bmatrix} \frac{L_s}{\lambda_m}\frac{\cos\hat{\theta}_r}{\hat{\omega}_r} & \frac{L_s}{\lambda_m}\frac{\sin\hat{\theta}_r}{\hat{\omega}_r} & 0 & 0 \\ \frac{L_s}{\lambda_m}\frac{\sin\hat{\theta}_r}{\hat{\omega}_r} & -\frac{L_s}{\lambda_m}\frac{\cos\hat{\theta}_r}{\hat{\omega}_r} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \text{ and } C = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

where $\hat{\theta}_r, \hat{\omega}_r, \hat{i}_{\alpha s}, \hat{i}_{\beta s}$ are the estimated states and $\hat{T}_d$ is the estimated load torque disturbance. In the observer driving gain (*GG*), *G* is a constant gain matrix and *k* is the proportional constant value.

# 5. NONLINEAR STATE OBSERVER WITH PARAMETER ADAPTATION

## 5.a. Adaptive Adjustment Scheme for Stator Resistance Estimation

The stator resistance changes with motor temperature during the operation of the machine. The drive performance deteriorates and the estimated states of the observer become unstable if the stator resistance value used in the observer differs from that of the actual machine. Therefore, compensation for the influence of the stator resistance variation is necessary especially at low speed [12]. An adaptive adjustment scheme for stator resistance estimation in addition to state observer described by equation (23) is proposed to overcome the problem mentioned above.
The parameter update law is proposed as follows:

$$\Delta\hat{R}_s = -\lambda(e_{i_{\alpha s}}\hat{i}_{\alpha s} + e_{i_{\beta s}}\hat{i}_{\beta s}) \qquad (24)$$

and $\hat{R}_s = R_{sn} + \Delta\hat{R}_s$ (25)

where $e_{i_{\alpha s}} = i_{\alpha s} - \hat{i}_{\alpha s}$ , $e_{i_{\beta s}} = i_{\beta s} - \hat{i}_{\beta s}$ and $\lambda$ is an arbitrary positive gain

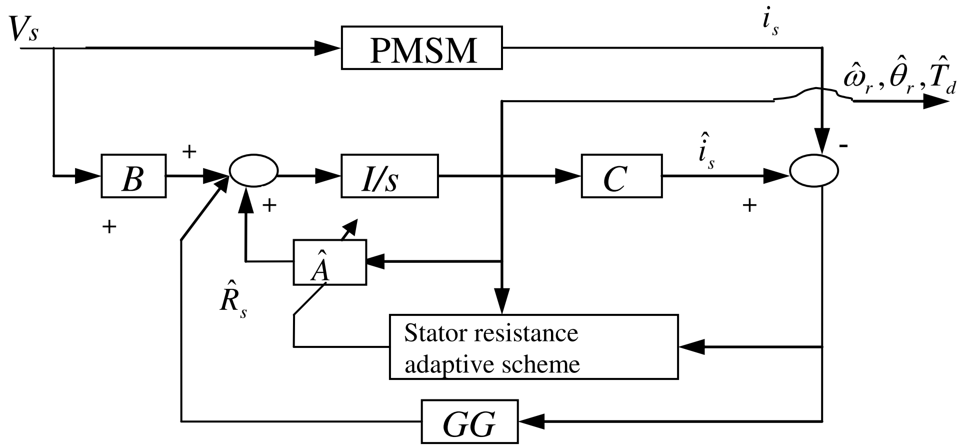


Figure 1: Shows a block diagram of the proposed state observer with stator resistance estimation adjustment

## 5.b. Adaptive Adjustment Scheme for Load Inertia Estimation

The instantaneous speed controller and the nonlinear state observer have the nominal inertia value $J_n$ of the PMSM. Theoretically, it is possible to design the speed controller even if the load inertia is unknown. In the real system implementation the mechanical time constant of the observer should be small. However, it is difficult to realize the small time constant on demand due to noise in the mechanical system. Consequently, the overall speed control performance of the drive system must be controlled by the estimation of the mechanical system inertia (rotor inertia of the machine and its attached load). The estimated states of the nonlinear observer are influenced if the load inertia value differs from its nominal value.

The inertia of the mechanical load condition is estimated in this paper using the periodic test signal according to the relationship of the mathematical orthogonality of the disturbance between the periodic signal and its derivative.

For the purpose of this estimation, the disturbance load torque observer corresponding to nominal inertia value $\hat{T}_{dn}$ can be modified as:

$$\hat{T}_{dn}(t) = -J_n p\omega_r(t) - B\omega_r(t) + T_e(t) \tag{26}$$

$$pi_{qs} = -\gamma i_{qs}(t) + \gamma \frac{T_e(t)}{K_T} \tag{27}$$

Where $\gamma$ is the observer pole ( $\gamma$ >0)

The load inertia variation is caused by the variation of machine load condition or an estimated error of load inertia and it is expressed as:

$$\Delta J = J - J_n$$

From equations (26) and (27) above, the derivative of the estimated disturbance torque is derived as:

$$p\hat{T}_d(t) = -\gamma\hat{T}_d(t) - \gamma(\Delta Jp\omega_r(t) + \Delta B\omega_r(t) - T_c) = 0 \tag{28}$$

where $T_c$ is the constant load torque

Using equations (26)-(28) the estimated disturbance load torque for any load condition can be obtained as:

$$\hat{T}_d(t) = -\Delta Jp\omega_r(t) - \Delta B\omega_r(t) + K_T i_{qs} \tag{29}$$

The angular speed of the PMSM drive system imposed by the periodic speed command, the can be expressed as:

$$\lim_{t \to \infty}\left[\omega_r(t) - \omega_r(t-T)\right] = 0$$

The inner product of arbitrary signals can be confined as follows:

$$\left(\phi_a, \phi_b\right) = \int_{(k-1)T}^{kT} \phi_a(t)\phi_b(t)dt \tag{30}$$

From equation (30), the inner products of $\omega_r p\omega_r$ and $i_{qs} p\omega_r$ can be written as follows:

$$\lim_{k \to \infty} \int_{(k-1)T}^{kT} \omega_r(t) p\omega_r(t)dt = 0$$

$$\lim_{k \to \infty} \int_{(k-1)T}^{kT} i_{qs}(t) p\omega_r(t)dt = 0$$

From above relations, the convergence of the estimated load inertia can be evaluated as follows:

$$\int_{(k-1)T}^{kT} \hat{T}_d(t)p\omega_r(t)dt = -\Delta J \int_{(k-1)T}^{kT} \left(p\omega_r(t)\right)^2 dt - \Delta B \int_{(k-1)T}^{kT} \omega_r(t)p\omega_r(t)dt + K_T \int_{(k-1)T}^{kT} i_{qs}(t)p\omega_r(t)dt$$

$$\int_{(k-1)T}^{kT} \hat{T}_d(t)p\omega_r(t)dt = -J \int_{(k-1)T}^{kT} \left(p\omega_r(t)\right)^2 dt$$

$$k \to \infty \qquad\qquad k \to \infty$$

$$\hat{J} = -\lim_{k \to \infty} \frac{\int_{(k-1)T}^{k} \hat{T}_d p\hat{\omega}_r(t)dt}{\int_{(k-1)T}^{k} \left(p\hat{\omega}_r(t)\right)^2 dt} \tag{31}$$

Consequently, the estimated load inertia $\hat{J}$ value converges to the actual one due to the existence relationship of the orthogonality between the periodic forward-reverse speed command and its derivative.

$\omega^*{}_r(t) = \omega^*{}_r(t-T),\ \omega^*{}_r(t) \neq 0$

Figure 2 shows the block diagram of the estimated load inertia variation of the mechanical system described by equation (31)

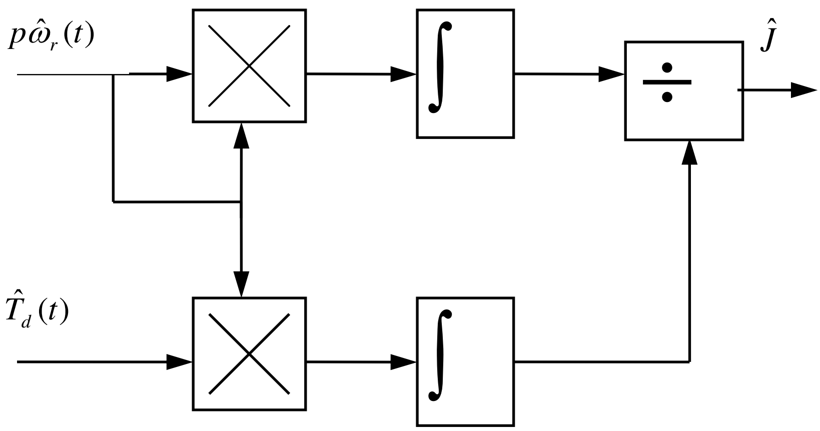


Figure 2: Block diagram of the load inertia estimation

## 6. The Proposed Sensorless Vector Controlled Pmsm Based On State Observer

The proposed nonlinear adaptive state observer is applied to the sensorless vector controlled PMSM drive as shown in Fig. 3. It consists mainly of a loaded PMSM, a hysteresis current controlled PWM (CCPMW) inverter, a vector control scheme followed by vector rotator and phase transform and an outer speed loop. In addition to the machine and inverter the system includes speed controller, an adaptive states observer, an adaptive stator resistance and load inertia estimators. The speed controller generates the torque component current command $i^*_{qs}$ from the speed error between the estimated motor speed and the command speed. The estimated speed is obtained from the nonlinear adaptive states observer. Measurements of two stator phase voltages and currents are transformed to α- and β- components and used in an adaptive states observer. The nonlinear adaptive states observer is used to estimate PMSM states ($\hat{i}_{\alpha s}, \hat{i}_{\beta s}, \hat{\theta}_r$ and $\hat{\omega}_r$) and the unknown load torque disturbance $\hat{T}_d$. This observer with stator resistance and load inertia estimations is used for adapting the parameters of speed controller. The vector rotator and phase transform in Fig. 3 is used for transforming the stator current components command ($i^*_{qs}$ and $i^*_{ds} = 0$) to the three phase stator current commands ($i^*_{as}, i^*_{bs}$ and $i^*_{cs}$) by using the estimated rotor angle position $\hat{\theta}_r$. The hysteresis current control compares the stator current commands to the actual currents of the machine and switches the inverter transistors in such a way that the commanded currents are obtained.

## 6. SIMULATION RESULTS AND DISCUSSION

The proposed observer-based controller with disturbance torque estimation of Fig. 3 is verified by means of simulations. The nominal parameters and specifications of a PMSM used for the simulations are listed in Table I.

Table I: Parameters and data specification of the PM motor used

| | |
|---|---|
| Rated output | 1.5 kW |
| Rated current | 9.3 A |
| Rated speed | 1500 r.p.m |
| Rated torque | 9.6 N.m |
| No. of poles | 6 poles |
| Rotor inertia $J$ | $0.015\, kg.m^2$ |
| Frictional constant | $9.37 \times 10^{-4}\, kg.m^2 / s$ |
| Stator resistance $R_s$ | 0.513 ohm |
| Stator inductance $L_s$ | 8.5 mH |
| Magnet flux linkage | 0.24 web. |
| Inverter input voltage $V_{dc}$ | 290 V |

The transient performance of the conventional (without observer) vector control of the PMSM for step change of load-torque disturbance is investigated.

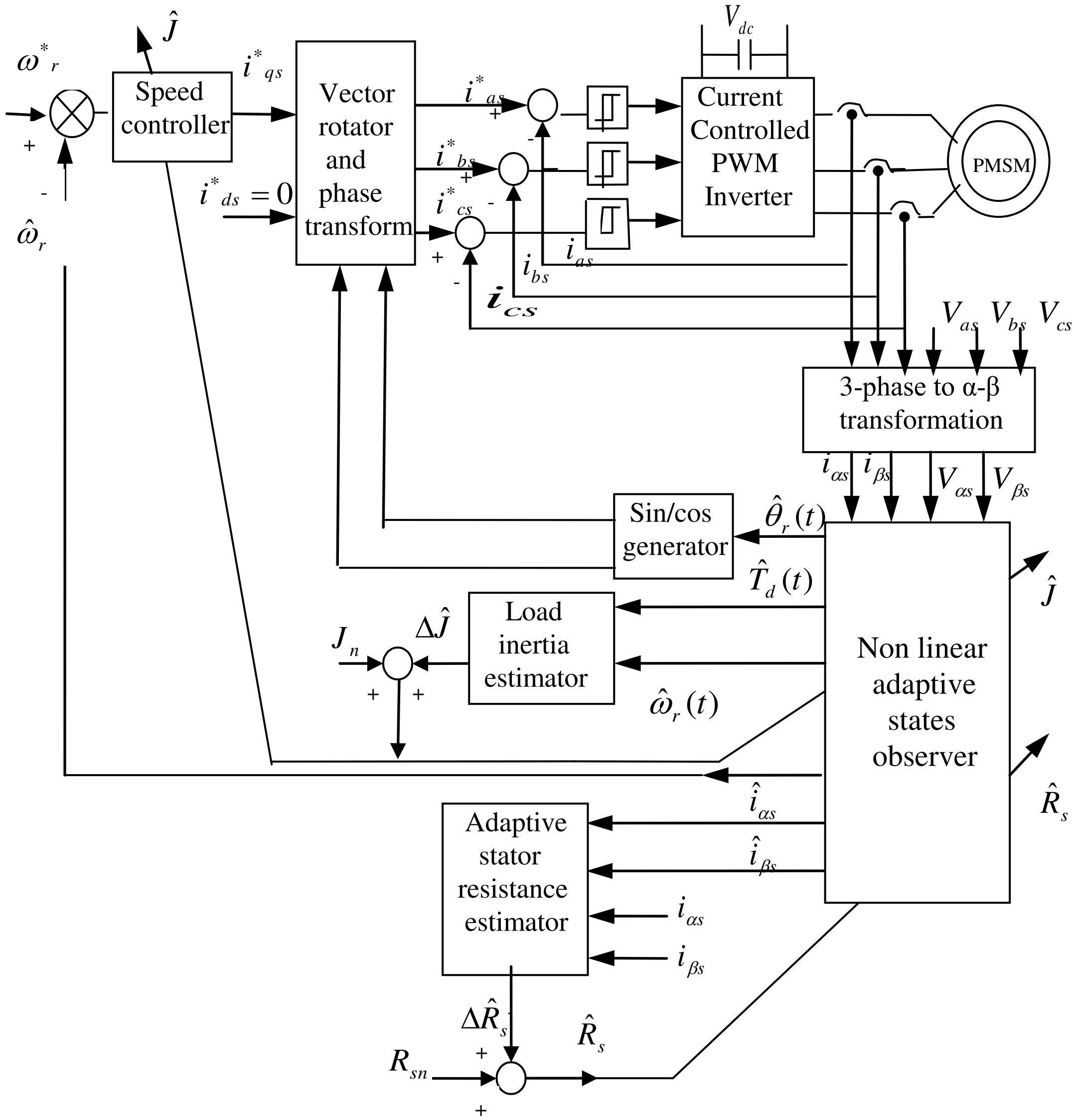


Figure 3: Overall block diagram for the proposed sensorless PMSM drive

Figures 4a, 4b and 4c show the motor speed response, load torque disturbance and d-axis and q-axis current components when the motor is subjected to a load disturbance applied at t=0.5 sec. and removed at t=0.7 second. These figures show that there exist steady-state errors in the speed response and in d-axis and q-axis current components. These performances can be improved by introducing the proposed nonlinear-state observer.

Figure 5a shows that the speed responses can be effectively improved by using this control scheme under load torque variation. This Fig. 5a shows a small dip and overshoot of the estimated motor speed following the application and removal of the load torque. The speed dip and overshoot are determined by the gains of the PI controller of the motor speed loop. Figure 5b indicates a fast and precise transient response of the estimated load torque disturbance is achieved by using the proposed control scheme. The q-axis current component matches the value of load torque disturbance provided that the d-axis current component is kept constant at zero value and the trajectory command can be well tracked during the load disturbance as shown in Fig. 5c.

Figure 6a and 6b show the motor speed and acceleration under the inertia variations. Even though the reference speed can be well tracked under the nominal parameter values, it can be shown that the speed response shows an undesirable transient error under the inertia variations as shown in Fig. 6a. The computed acceleration becomes quite different under the inertia variations from the acceleration under nominal inertia value as shown in Fig. 6b.

In reality, the stator resistance in a practical machine does not change in step manner. In actual operating conditions, the rate of change of temperature is quite slow. A linearly changing stator resistance is modeled when the motor is running at 10 rad./sec. with nominal load torque. Figures 7a, 7b, 7c and 7d show the vector control response when the motor stator resistance increases linearly by 25 % from its nominal value and decreases again to its nominal value as indicated in Fig. 7a.

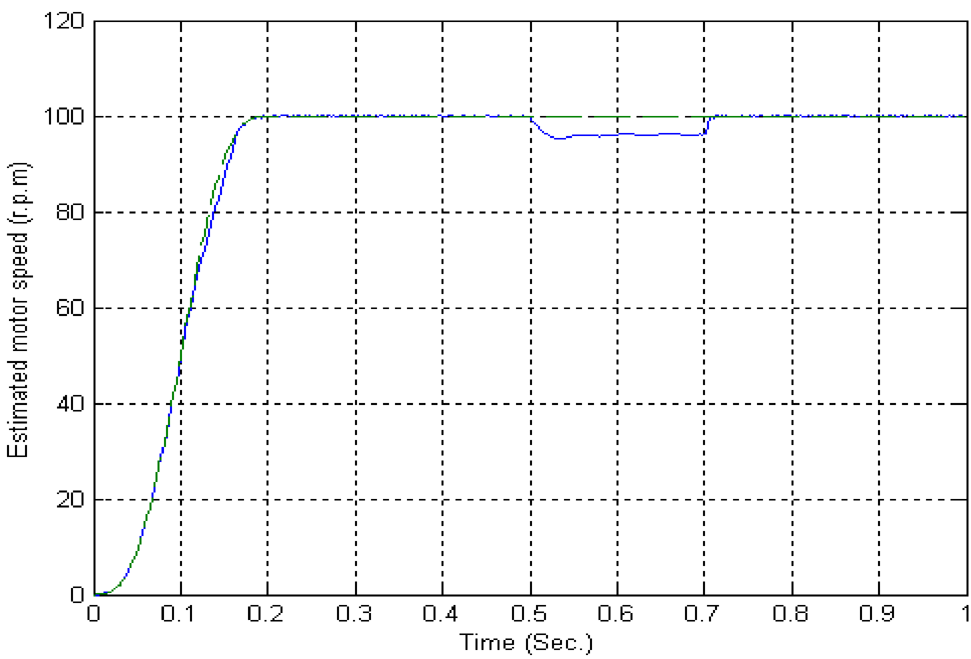


Figure 4a: Speed response under load torque variation without nonlinear state observer

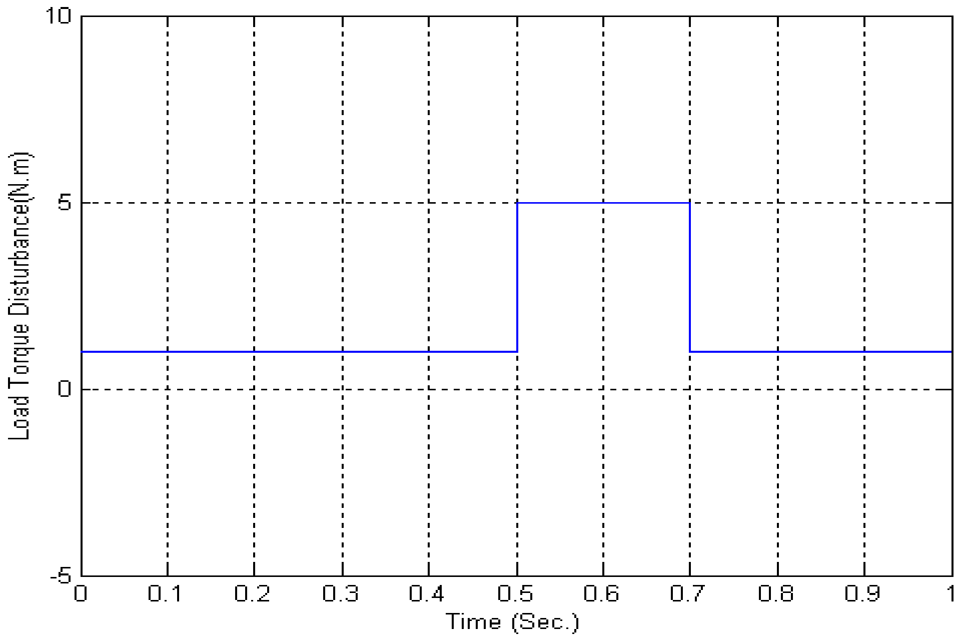


Figure 4b: Load torque variation

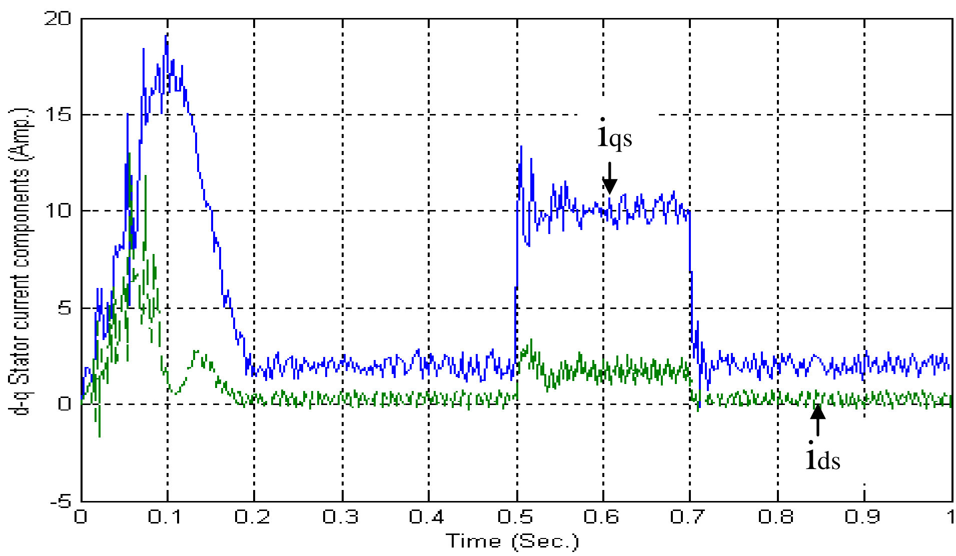


Figure 4c: q-axis current component --- d-axis current component without nonlinear state observer

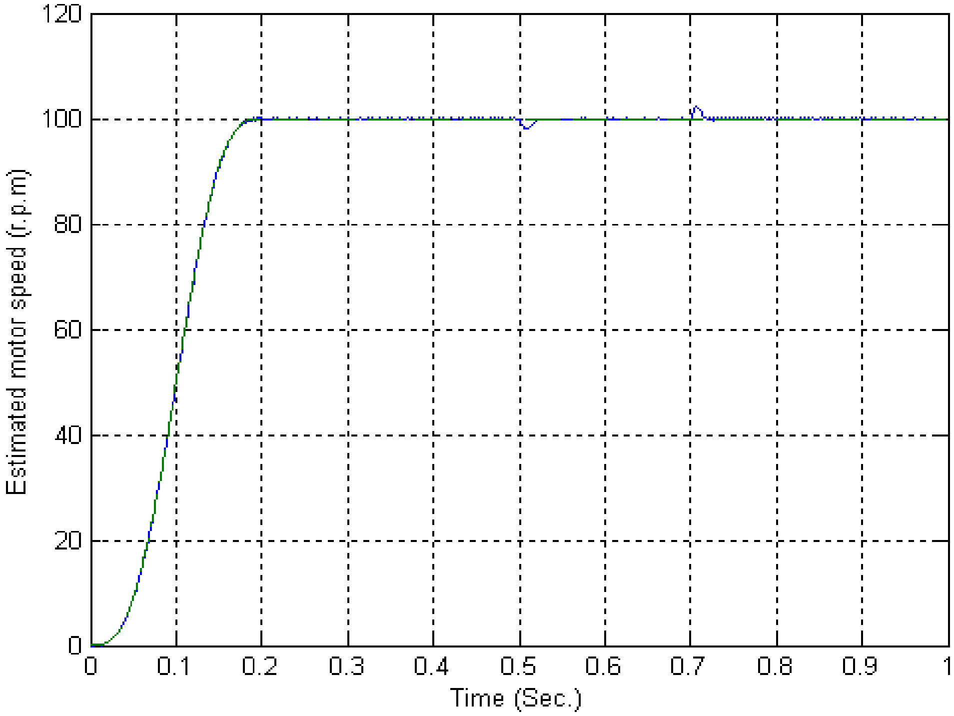


Figure 5a: Speed response under load torque variation with nonlinear state observer

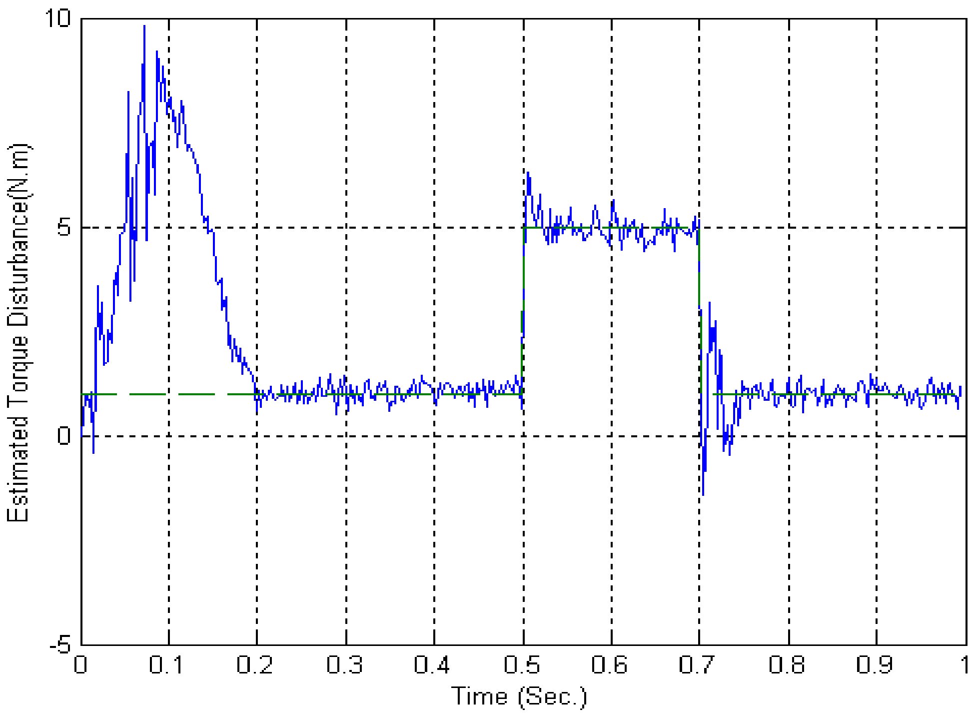


Figure 5b: Estimation performance of the disturbance load torque

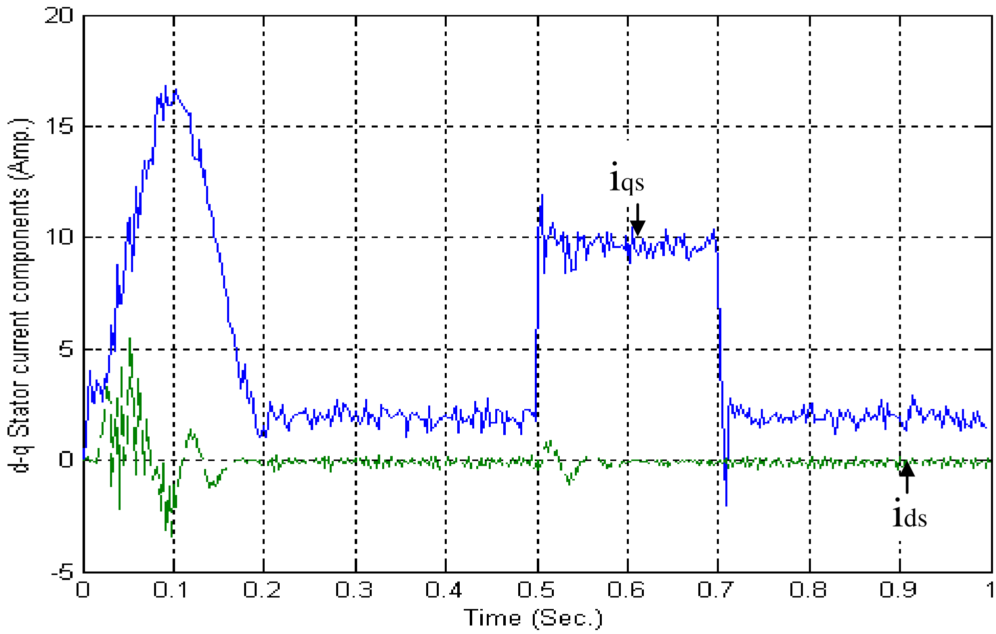


Figure 5c: q-axis current component ---- d-axis current component with nonlinear state observer

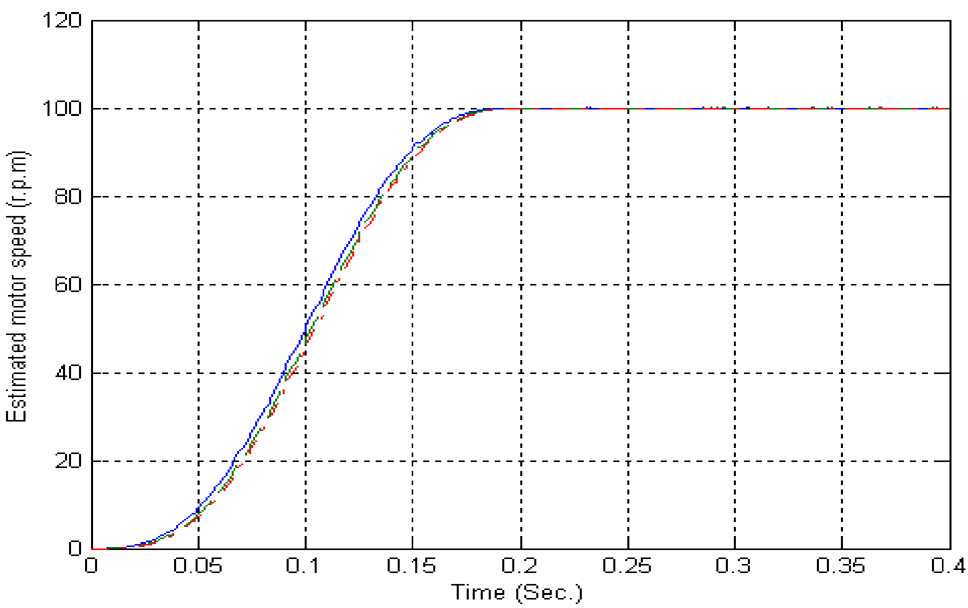


Figure 6a: Speed responses under the load inertia variations

speed command - - - speed with *J=2Jn* -.-.- speed with *J=3Jn*

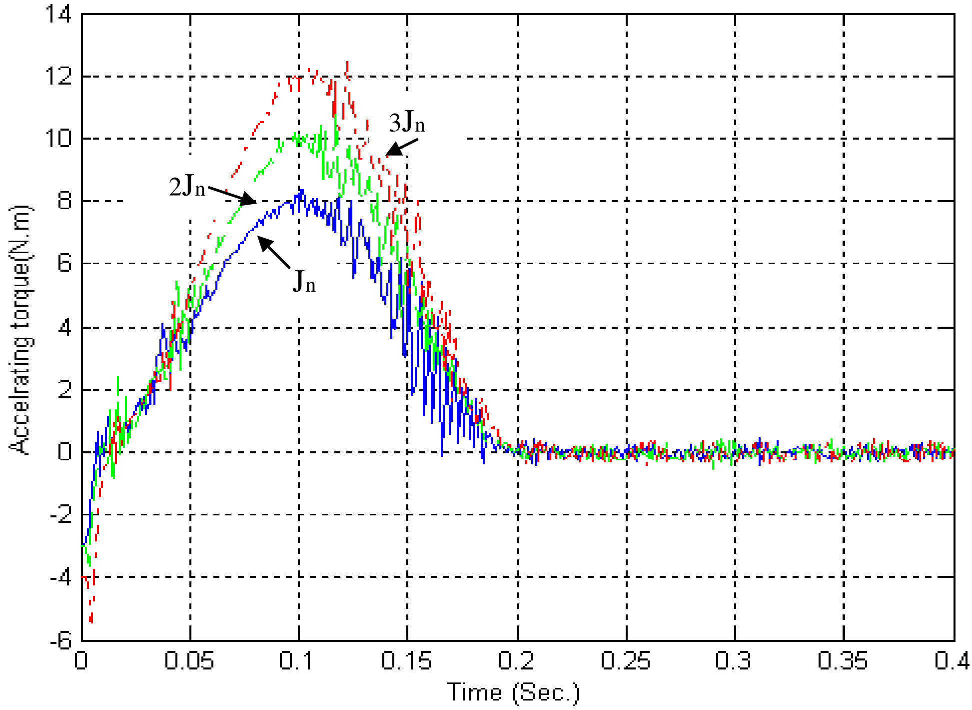


Figure 6b: Computed acceleration responses under the load inertia variations

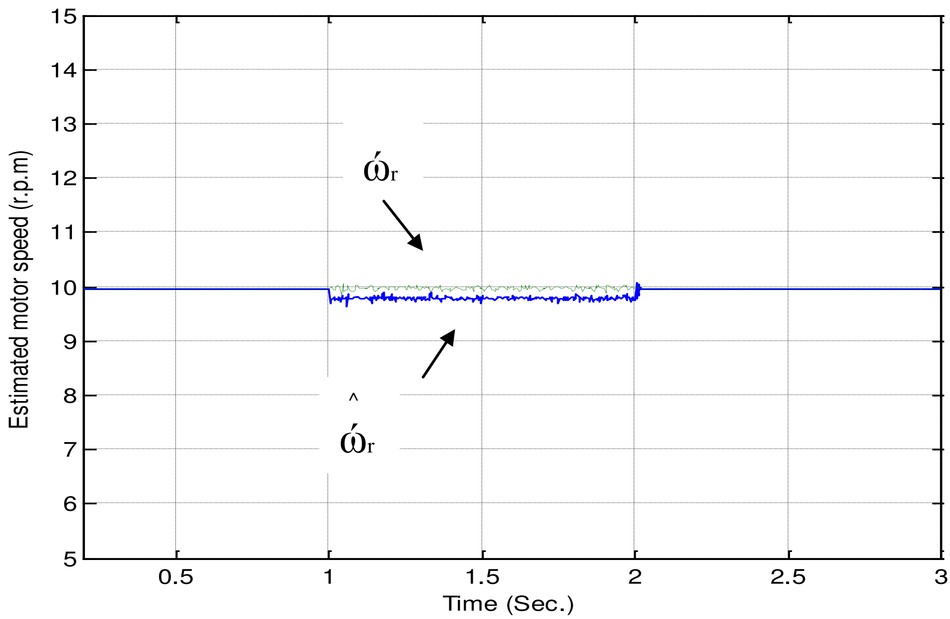


Figure 7a: Actual and estimated motor speed

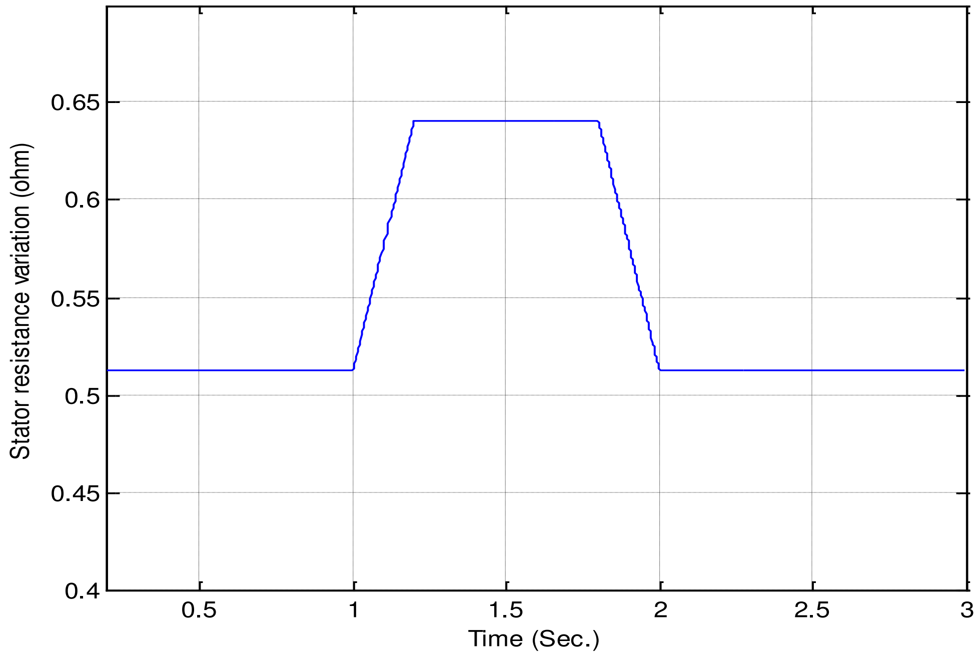


Figure 7b: Linear variation of stator resistance

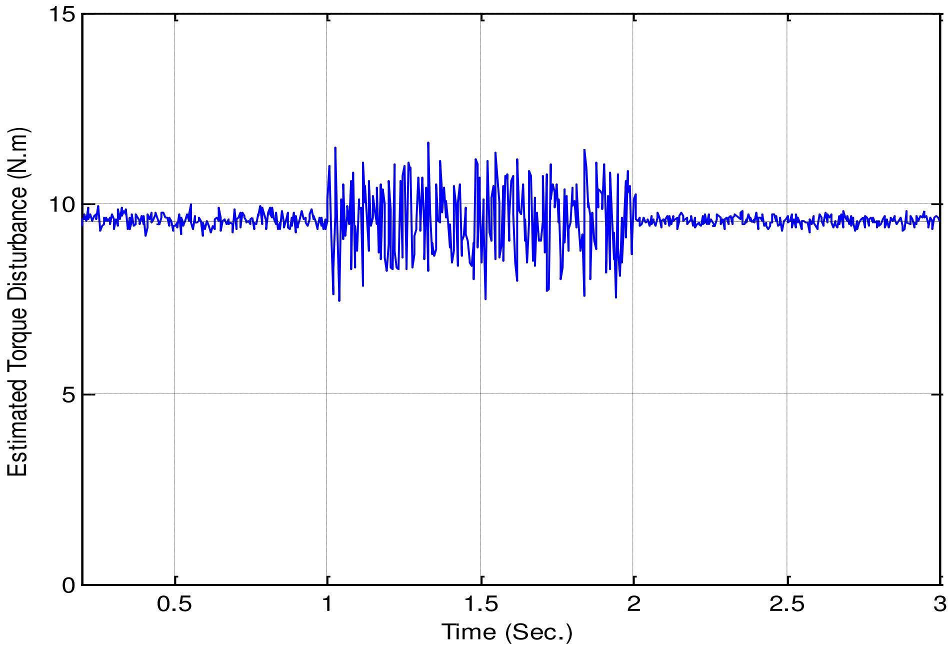


Figure 7c: Estimated torque disturbance

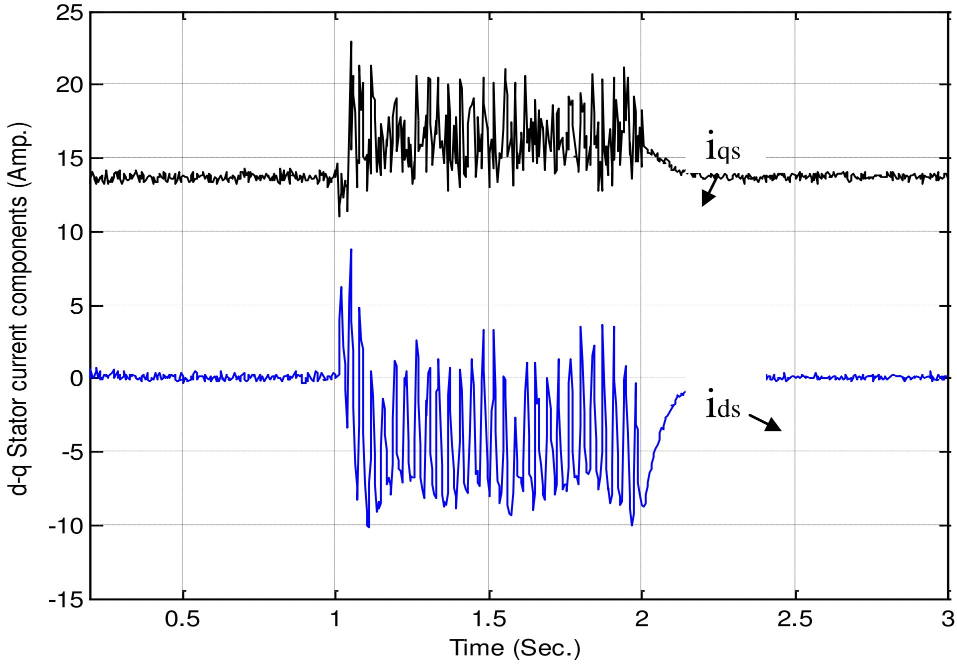


Figure 7d: d-q stator current components

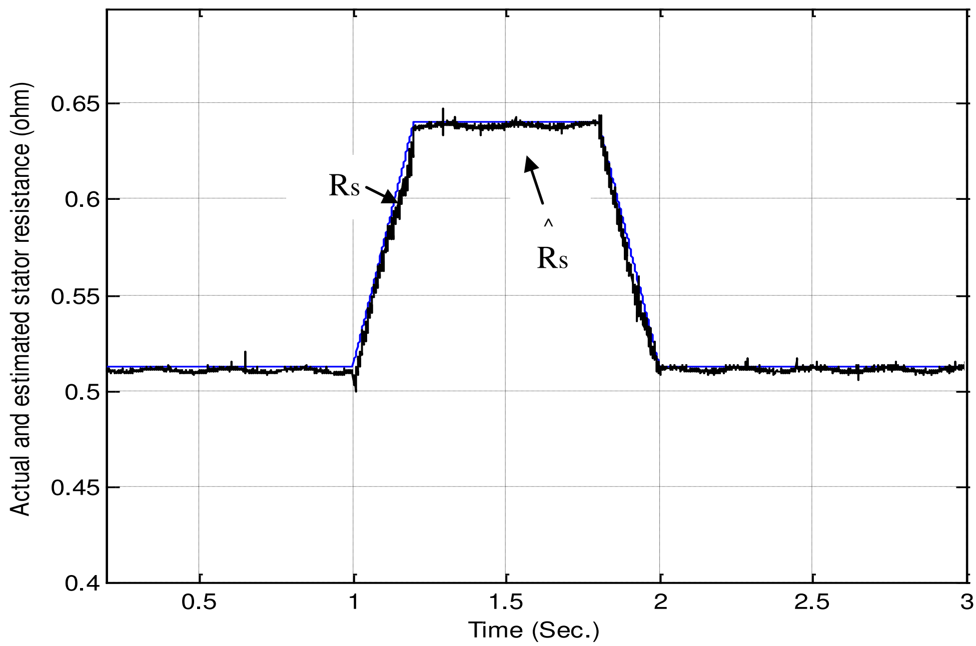


Figure 8a: Actual and estimated stator resistance

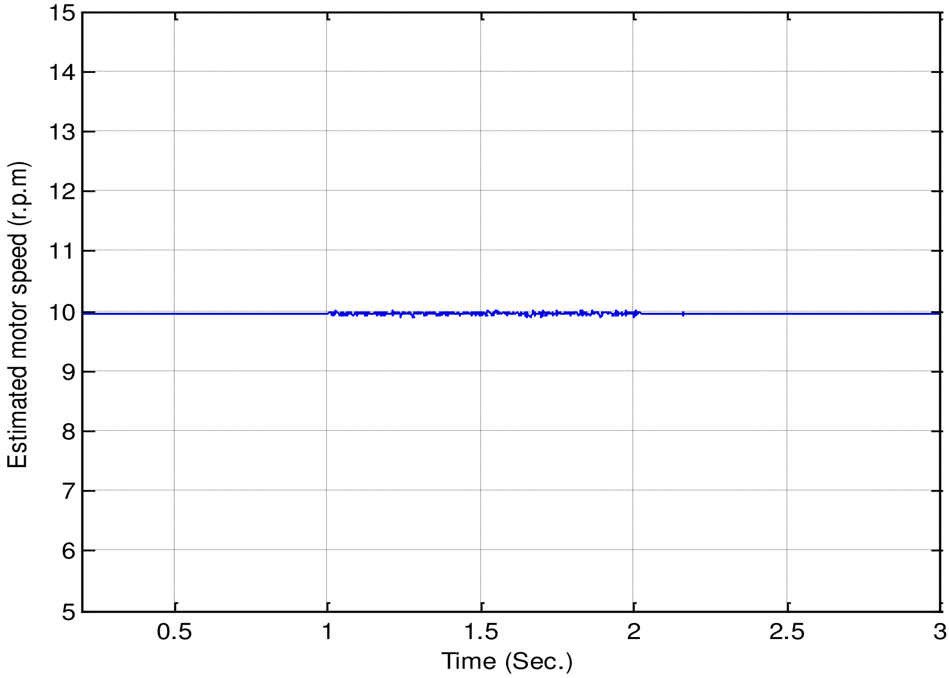


Figure 8b: Actual and estimated motor speed with stator resistance estimator

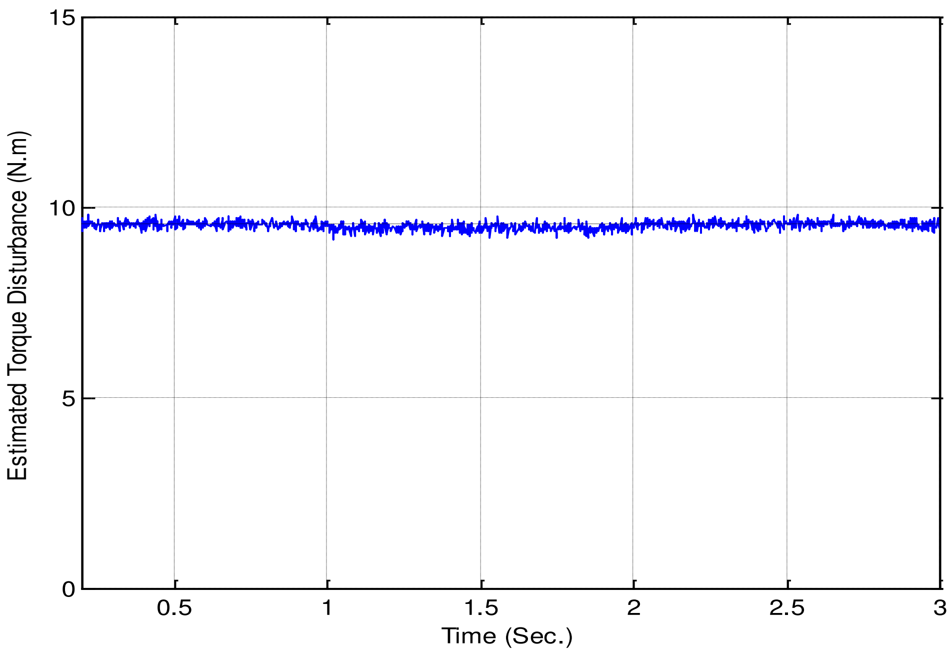


Figure 8c: Estimated torque disturbance with stator resistance estimator

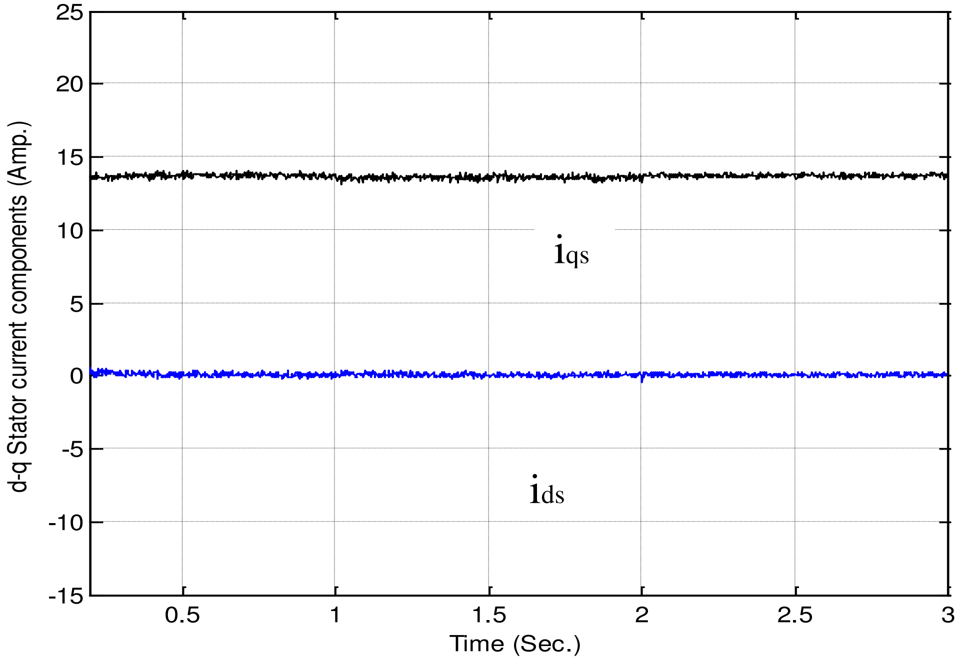


Figure 8d: d-q stator current components with stator resistance estimator

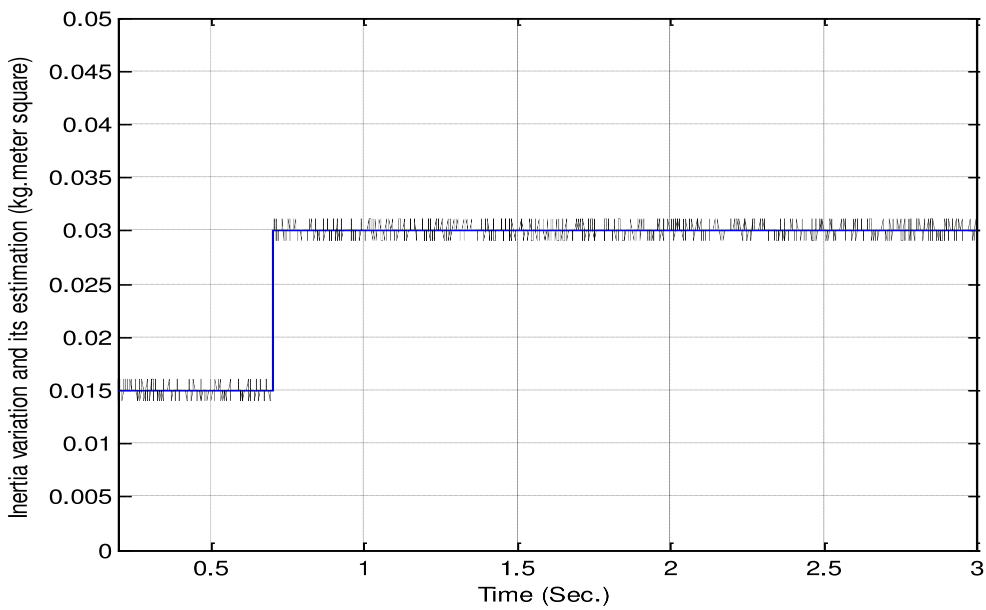


Figure 9a: Inertia variation and its estimation

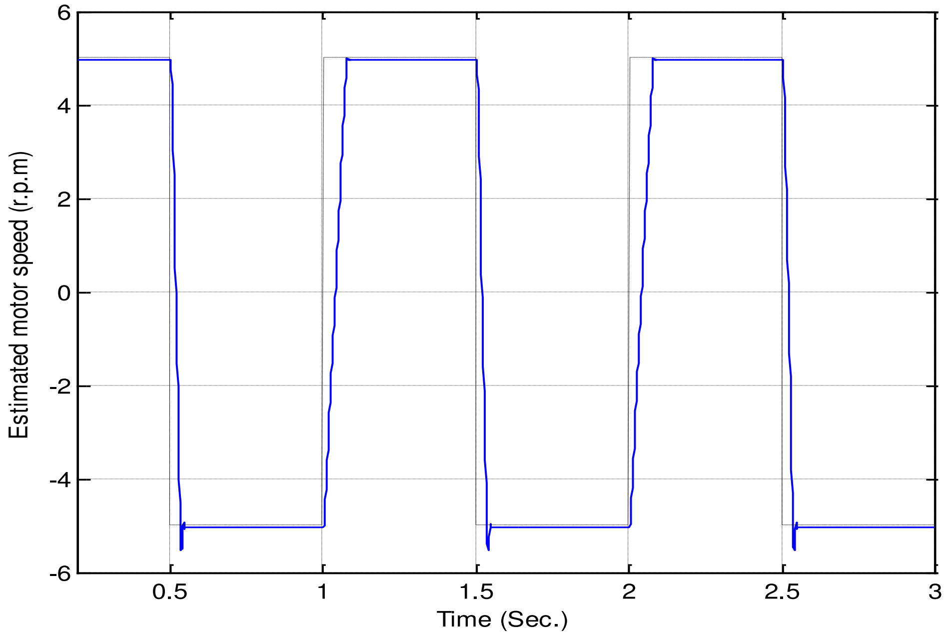


Figure 9b: Estimated speed response and its reference

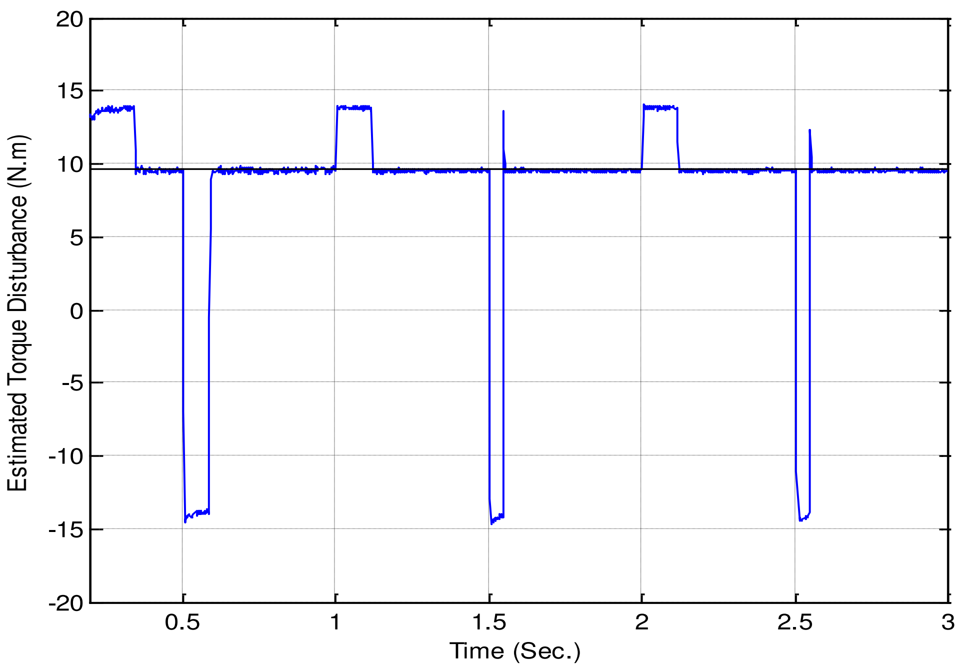


Figure 9c: Estimated disturbance torque

From figures 7b, 7c and 7d, it is seen that the estimated speed, torque disturbance and d-q axes stator current components are oscillating and deviate from their reference values during the stator resistance variation. These deviations and oscillations may cause the vector control drive system to become unstable.

The estimated stator resistance is able to track bi-directional change in stator resistance adequately as shown in Fig. 8a. The estimation error in the steady-state is found to be less than $\pm 3\%$. Also, the estimator is able to track this difference and converge to the correct stator resistance. With stator resistance estimator, the estimated speed, torque and the d-q axes stator current components are kept constant and matched with their references as shown in figures 8b, 8c and 8d.

To improve the performance of the speed controller the load inertia is estimated using the periodic test signal. Figure 9a shows the step variation of load inertia from nominal value to its double value ($Jn=2Jn$) at t=0.7 sec.. This figure shows the inertia estimation on the same graph when the test signal of the periodic speed command from forward 5 rad./sec. to reverse 5 rad./sec. and the ripple of the estimated inertia is the estimated error according to the estimated speed error during forward-reveres operation. Figure 9b shows the estimated speed response of the speed step command during the inertia estimation. The disturbance torque for inertia estimation is well achieved as shown in Fig. 9c.

## 7. CONCLUSIONS

An adaptive state observer for a speed sensorless vector controlled PMSM is proposed to estimate the rotor position, speed and disturbance load torque. The adaptive state observer uses a mechanical model to improve the speed estimation during transient. The effect of stator resistance variation on the performance of a proposed sensorless PMSM drive has been presented, followed by an investigation of the adaptive adjustment scheme for stator resistance estimation. Also, the load inertia is identified adaptively by using the periodic test signal to improve the performance of the speed controller. The simulation results show that the proposed sensorless control scheme yields a robust control performance even under the presence of the stator resistance variation and the external disturbances caused by the inertia and load changes.

The main conclusions that can be inferred from the present results are:

1- The estimated speed response with the proposed scheme gives a desired dynamic performance and a zero steady-state error, which is not affected by the load torque disturbance and the variation of the motor parameters.
2- The speed and computed acceleration responses exhibit undesirable transient errors under the load inertia variations.
3- The variation of stator resistance degrades the performance of the sensorless vector controlled PMSM drive by introducing errors in the estimated disturbance load torque, speed and d-axis and q-axis current components.
4- The adaptive stator resistance estimation scheme is capable of tracking the stator resistance variation very well. It is also seen that the compensator can overcome the problem of instability caused by a large mismatch between the value used in the state observer and the actual one.

5- The estimated load inertia tracks well the step variation in the load inertia during forward-reverse speed command. Also, the estimated speed and disturbance load torque are achieved well during the inertia estimation

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# التحكم الاتجاهي لمحرك متزامن ذو مغناطيس دائم بدون مقياس للسرعة وذلك باستخدام ملاحظ ملائم مع التغير المفاجئ للعزم المقيم

– هذا البحث يقدم طريقة جديدة للتحكم اللاخطي لسرعة محرك متزامن و مغناطيسي دائم يقود حمل غير معرف بدون استخدام مقياس للسرعة وتم استكمال ذلك مع نظام التحكم ألاتجاهي.

– تم استخدام ملاحظ لاخطي ذو ثوابت مقيمة بطريقة ملائمة للحصول علي موضع العضو الدوار والسرعة ومركبات تيار العضو الثابت وكذلك التغير المفاجئ في عزوم الحمل لتلاشي استخدام حساسات ميكانيكية.

– تم تقييم مقاومة العضو الثابت التي تتغير مع درجة الحرارة للمحرك وكذلك التردد وذلك باستخدام طريقة التحكم الملائم وأيضا تم تحسين خواص محكم السرعة وذلك بتقييم لقيمة عزم القصور الذاتي للحمل باستخدام إشارة اختبار دورية للسرعة المرغوبة.

– الطريقة المقترحة تجعل نظام المحرك يعمل بدقة ومقاومة ولايتا ثر بالتغير في ثوابت المحرك.

– الخواص الديناميكية والمستقرة للنظام المقترح تم عرضها وتوضيحها وذلك باستخدام النتائج النظرية التي تم الحصول عليها من الحاسب.