



Hardware Implementation of Vector Control of Induction Motor Drive without Speed Encoder Using an Adaptive Luenberger Based MRAS Observer

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Abstract

Vector control of induction motor drives without mechanical speed sensors has the attraction of low cost and high reliability. An adaptive Luenberger style stator flux observers is presented. Therefore, this paper presents a theory of adaptive Luenberger observers and his capability to compensate for stator voltage errors and usefully in electrical drivers systems without sensorless.

Keywords

Sensorless control; Induction motor drives; Adaptive Luenberger observers; MRAS; Modelling; Vector control.

Introduction

Induction motor drives have been thoroughly studied in the past few decades and many vector control strategies have been proposed, ranging from low cost to high performance applications. In order to increase the reliability and reduce the cost of the drive, a great effort has been made to eliminate the shaft speed sensor in most high performance induction motor drive applications [1]. Speed estimation is an issue of particular interest with

induction motor drives where the mechanical speed of the rotor is generally different from the speed of the revolving magnetic field. The advantages of speed sensorless induction motor drives are reduced hardware complexity and lower cost, reduced size of the drive motor, better immunity, elimination of the sensor cable, increased reliability and less maintenance requirements. The induction motor is however relatively difficult to control compared to other types of electrical motors. For high performance control, field oriented control is the most widely used control strategy. This strategy requires information of the flux in motor; however the voltage and current model observers are normally used to obtain this information.

Generally, using the induction motor state equations, the flux and speed can be calculated from the stator voltage and current values. The flux is estimated or observed from the stator voltage equation and the speed is obtained using the estimate flux and the rotor equation.

The main objective of the research presented in this paper was to analyse and evaluate of optimum used flux observer (Adaptive Luenberger) in electrical drivers systems without sensorless. The analysis was done by use of modern control theory and by extensive testing. The testing was done with Matlab/Simulink software implemented in real time hardware model.

Material and Method

Dynamic Model of Induction Motor

The fifth order nonlinear state space model of induction motor is represented in the synchronous reference frame (d-q) by as follows: [2]

$$v_{sd} = (R_s + pL_s)i_{sd} - L_s\omega_e i_{sq} + pL_m i_{rdq} - L_m\omega_e i_{rq} \quad (1)$$

$$v_{sq} = (R_s + pL_s)i_{sq} + L_s\omega_e i_{sd} + pL_m i_{rq} + L_m\omega_e i_{rd} \quad (2)$$

$$0 = (R_r + pL_r)i_{rd} - L_r\omega_{sl} i_{rq} + pL_m i_{sd} - L_m\omega_{sl} i_{sq} \quad (3)$$

$$0 = (R_r + pL_r)i_{rq} + L_r\omega_{sl} i_{rd} + pL_m i_{sq} + L_m\omega_{sl} i_{sd} \quad (4)$$

$$T_{em} = Jp\omega_r + B\omega_r + T_l \quad (5)$$

The electromagnetic torque in terms of d- and q- axes components is given by:

$$T_{em} = \frac{3}{2} p_p L_m (i_{sq} i_{rd} - i_{sd} i_{rq}) \quad (6)$$

Components of rotor flux are:

$$\Psi_{rd} = L_r i_{rd} + L_m i_{sd} \quad (7)$$

$$\Psi_{rq} = L_r i_{rq} + L_m i_{sq} \quad (8)$$

From (7) and (8), d- and q- axes rotor currents are:

$$i_{rd} = \frac{1}{L_r} (\Psi_{rd} - L_m i_{sd}) \quad (9)$$

$$i_{rq} = \frac{1}{L_r} (\Psi_{rq} - L_m i_{sq}) \quad (10)$$

Substituting (7)-(10) into (3) and (4) yields:

$$\frac{d\Psi_{rd}}{dt} + \frac{R_r}{L_r} \Psi_{rd} - \frac{L_m}{L_r} R_r i_{sd} - \omega_{sl} \Psi_{rq} = 0 \quad (11)$$

$$\frac{d\Psi_{rq}}{dt} - \frac{R_r}{L_r} \Psi_{rq} - \frac{L_m}{L_r} R_r i_{sq} - \omega_{sl} \Psi_{rd} = 0 \quad (12)$$

Control Design

If the vector control is established such that q-axis rotor flux is set zero, and d-axis rotor flux is maintained constant then equations (11), (12), (9), (10), and (6) becomes:

$$\Psi_{rd} = L_m i_{sd} \quad (13)$$

$$\omega_{sl} = \frac{1}{T_r} \frac{i_{sq}}{i_{sd}} \quad (14)$$

$$i_{rd} = 0 \quad (15)$$

$$i_{rq} = -\frac{L_m}{L_r} i_{sq} \quad (16)$$

$$T_{em} = \frac{3}{2} p_p \frac{L_m}{L_r} \Psi_{rd} i_{rq} \quad (17)$$

Hence, only q- axis stator current controls the electromagnetic torque [3]. Substituting (6) and rearrangement of (1) and (2), yields:

$$v_{sd} = R_s i_{sq} + \frac{L_s}{L_m} \frac{d\Psi_{rd}}{dt} - L_m \sigma \frac{di_{rd}}{dt} - \omega_e \frac{L_m}{L_r} \Psi_{rq} - \omega_e \sigma L_s i_{sq} \quad (18)$$

$$v_{sq} = R_s i_{sq} + L_s \sigma \frac{di_{sq}}{dt} + \frac{L_m^2}{L_r} \frac{di_{rq}}{dt} + \omega_e L_m i_{rd} + \omega_e L_s i_{sd} + L_m \frac{di_{rq}}{dt} \quad (19)$$

Proposed Control Scheme

The stator command currents are obtained using equation (13) and the PI control loop for speed error as follows [4, 5]:

$$i_{sd}^* = \frac{\Psi_{rd}^*}{L_m} \quad (20)$$

$$i_{sq}^* = K_p (\omega_r^* - \hat{\omega}_r) + K_i \int (\omega_r^* - \hat{\omega}_r) dt \quad (21)$$

where: K_p , K_i are respectively the proportional and integral arbitrary positive gains.

The speed and the current loops are considered to be fast enough to assume that the actual stator currents are equal to their command inputs ($i_{sd}=i_{sd}^*$ and $i_{sq}=i_{sq}^*$). The command voltages are generated as follows:

$$v_{sd}^* = K_{p1} (i_{sd}^* - i_{sd}) + K_{i1} \int (i_{sd}^* - i_{sd}) dt \quad (22)$$

$$v_{sq}^* = K_{p2} (i_{sq}^* - i_{sq}) + K_{i2} \int (i_{sq}^* - i_{sq}) dt \quad (23)$$

For the field oriented control, the following PI gains of the speed adaptive scheme are selected: $K_p=3$, $K_i=1800$.

Model Reference Adaptive Systems (MRAS)

The basic concept of MRAS is the presence of a reference model which determines the desired states and an adaptive (adjustable) model which generates the estimated values of the states (figure 1).

The error between these states is fed to an adaptation mechanism to generate an estimated value of the rotor speed which is used to adjust the adaptive model. This process continues till the error between two outputs tends to zero [6, 7]. Basic equations of rotor flux based-MRAS can be written as:

$$\Psi_r = \left(\frac{L_r}{L_m} \right) \left[\int (v_s - R_s i_s) dt - L_s i_s \right] \quad (24)$$

$$\hat{\Psi}_r = \left(\frac{1}{T_r} \right) \int (L_m i_s - \hat{\Psi}_r - \hat{\omega} T_r \hat{\Psi}_r) dt \quad (25)$$

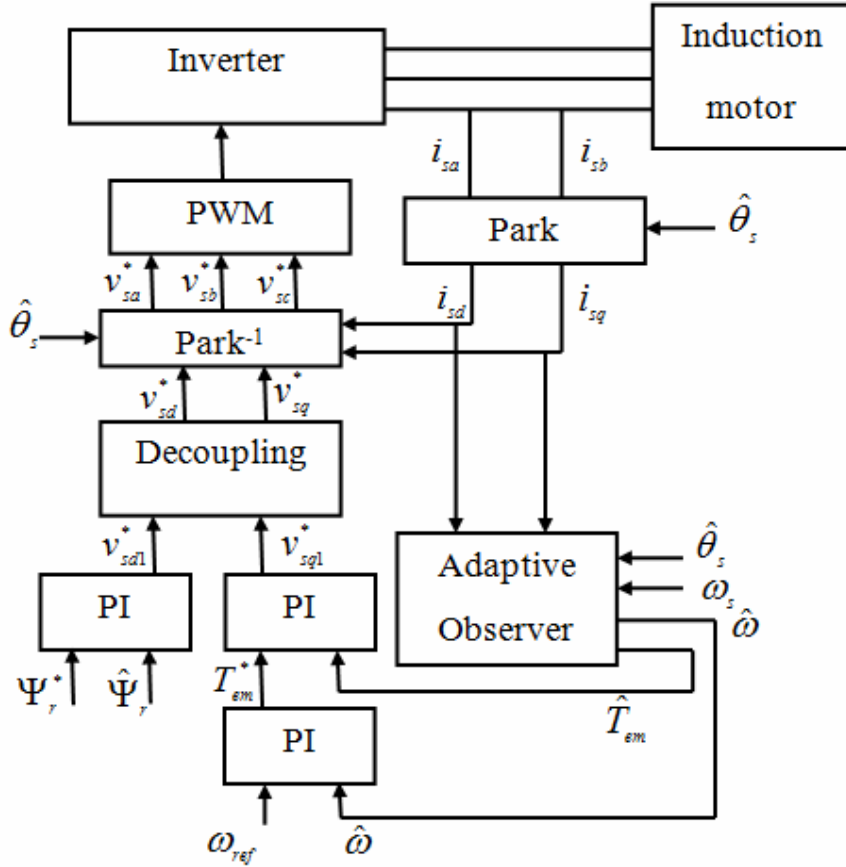


Figure 1. Integration of adaptive observer and vector control

The reference model (24) is based on stator equations and is therefore independent of the motor speed, while the adaptive model (25) is speed-dependant since it is derived from the rotor equation in the stationary reference frame. To obtain a stable nonlinear feedback system, a speed tuning signal (ε_ω) and a PI controller are used in the adaptation mechanism to generate the estimated speed. The speed tuning signal and the estimated speed expressions can be written as [8]:

$$\varepsilon_\omega = \Psi_{rq} \hat{\Psi}_{rd} - \Psi_{rd} \hat{\Psi}_{rq} \quad (26)$$

$$\hat{\omega} = \left\{ K_p + \frac{K_i}{s} \right\} \varepsilon_{\omega} \quad (27)$$

where: K_p , K_i are the proportional and integral constants, respectively.

Adaptive Luenberger Observer

Luenberger Observer is a deterministic observer with applied to state estimation of linear time invariant system, the model of induction motor can described by:

$$\begin{aligned} \dot{x}(t) &= A.x(t) + B.u(t) \\ y(t) &= C.x(t) \end{aligned} \quad (28)$$

The Luenberger observer is then described by:

$$\begin{aligned} \hat{\dot{x}}(t) &= A.x(t) + B.u(t) + L(y(t) - C.\hat{y}(t)) \\ \hat{y}(t) &= C.\hat{x}(t) \end{aligned} \quad (29)$$

where L is the observer gain matrix to avoid the use of an expensive speed sensor we estimate the speed using an adaptive observer based on the MRAS [9].

$$\text{where: } A = \begin{bmatrix} -\gamma I & \delta \left(\frac{I}{T_r} - \omega_r J \right) \\ \left(\frac{L_m}{T_r} \right) I & - \left(\frac{1}{T_r} - \omega_r J \right) \end{bmatrix}, B = \begin{bmatrix} \left(\frac{1}{\sigma L_s} \right) I \\ 0 \end{bmatrix}, C = [I \ 0], I = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \text{ and } J = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}.$$

Description of Laboratory Setup

The experimental system consists of two motors, one of which is the driving motor, and the other serves as the load. The inverters of both motors are controlled by the PC, providing a possibility for full control for experimental purposes of both the driving motor and the load motor. The interfacing is made via a dSPACE1104 control board. The Matlab/Simulink control model can be converted and downloaded to the DSP1104, and then it can work independently of the Matlab/Simulink environment. During the real-time operation of the control algorithm, the supervision and capturing of the important data can be done by the Control Desk software provided with the DSP board. The nominal motor parameters are showing in Table 1 and figure 2 shows real-time experimental setup.

Table 1. Motor Parameters

Stator Resistance	$R_s = 22\Omega$
Rotor Resistance	$R_r = 18.165\Omega$
Stator/rotor Inductances	$L_s = L_r = 0.8264\text{H}$
Mutual Inductance	$L_m = 0.7844\text{H}$
Moment of inertia	$J = 0.0251\text{Kg.m}^2$
Viscous friction	$f = 0.000166\text{N.m.s / rad}$
Number of Pole pairs	$p = 2$

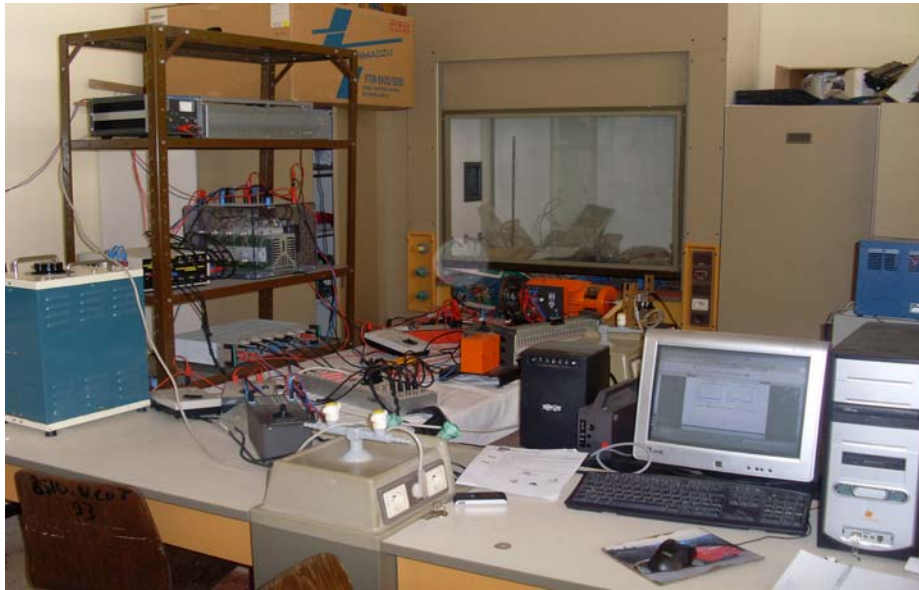
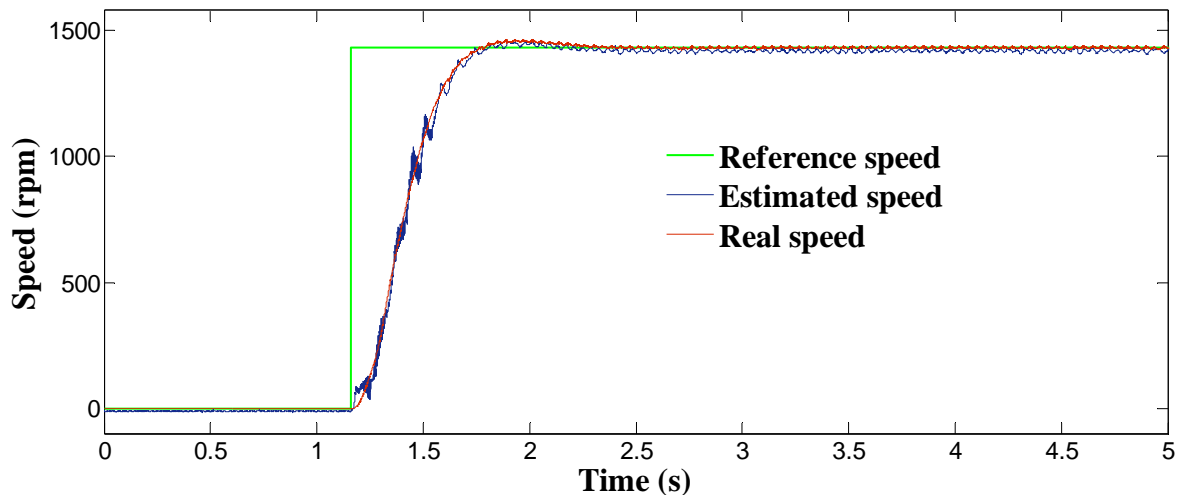


Figure 2. Real-time experimental setup

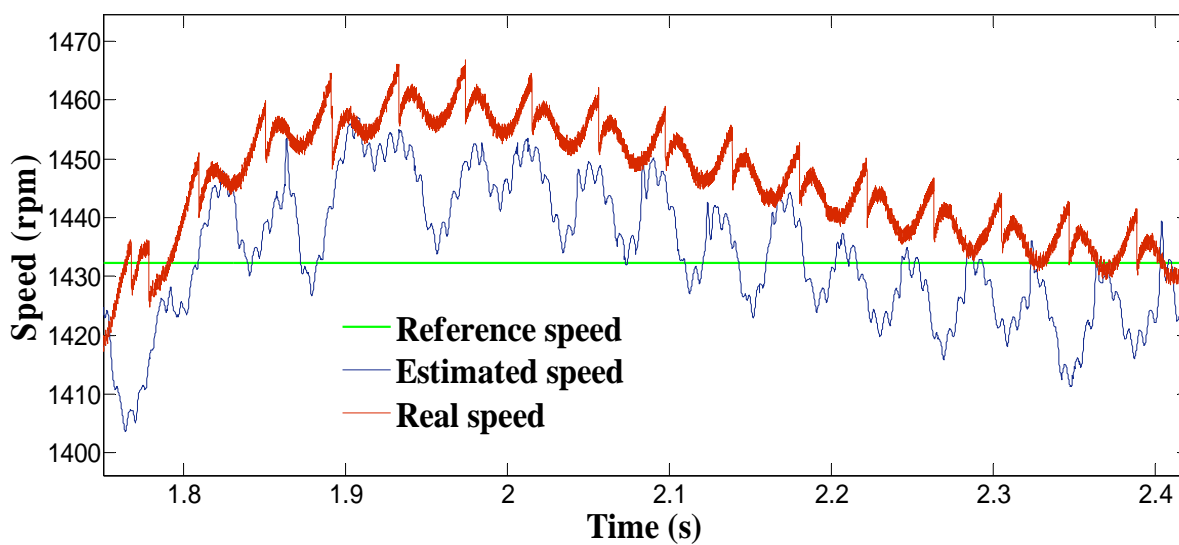
Results and Discussion

Scenario 1: Free acceleration characteristics

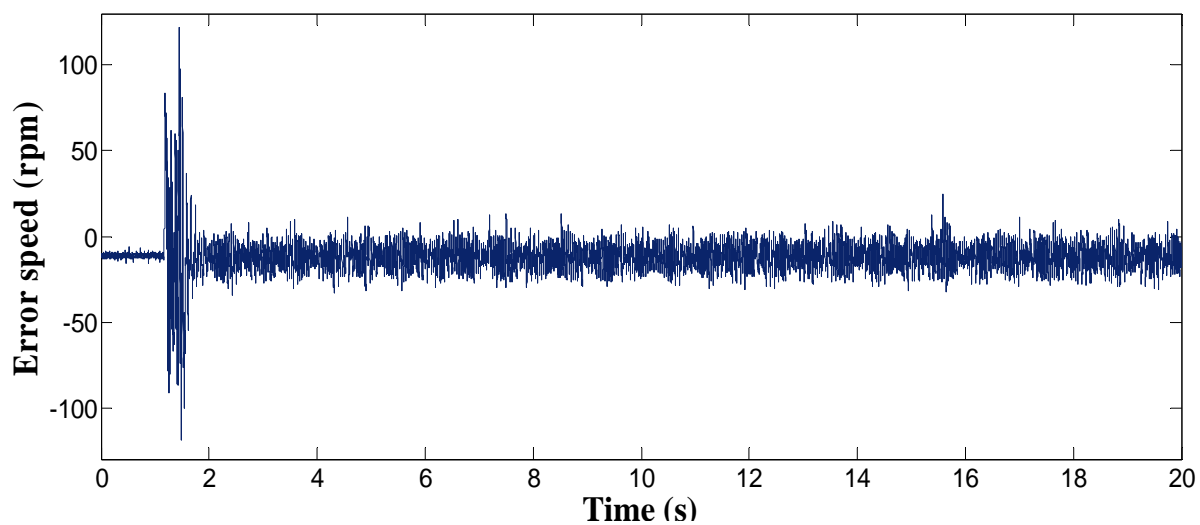
The motor was allowed to accelerate from zero speed to rated speed at no-load. The steady-state was reached at 1.8 seconds. The waveform of estimated speed show faster response as compared to its actual counterpart. It can be seen that there is a very good accordance between real and estimated speed without any steady state error (figure 3).



(a) The reference, actual and estimated speed



(b) Zoom of speed

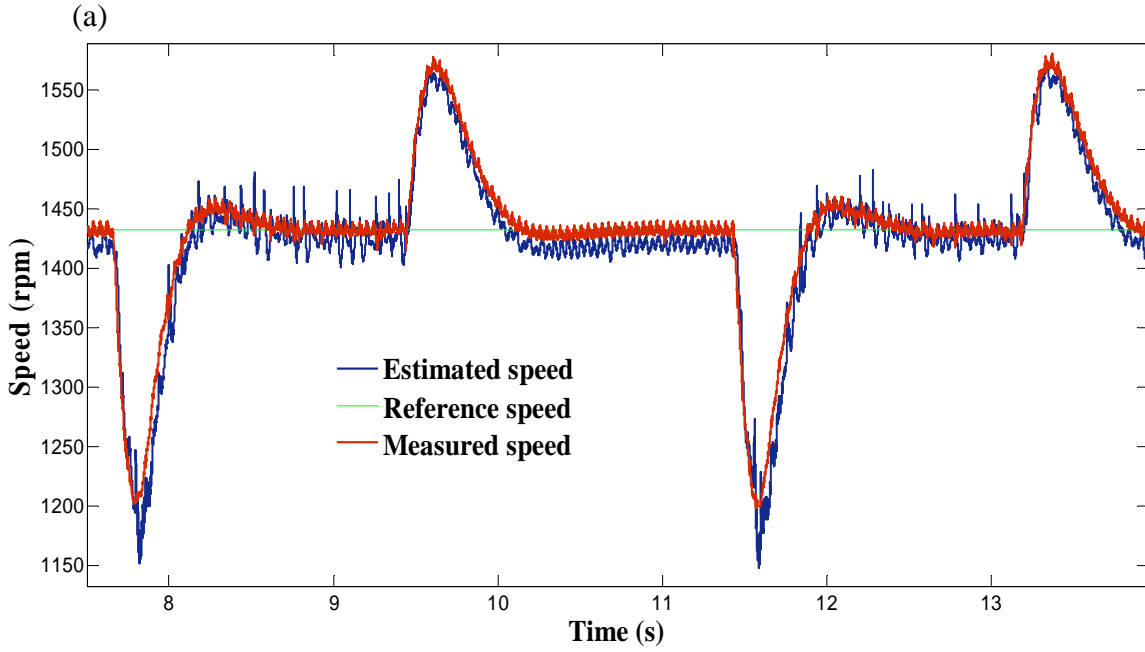
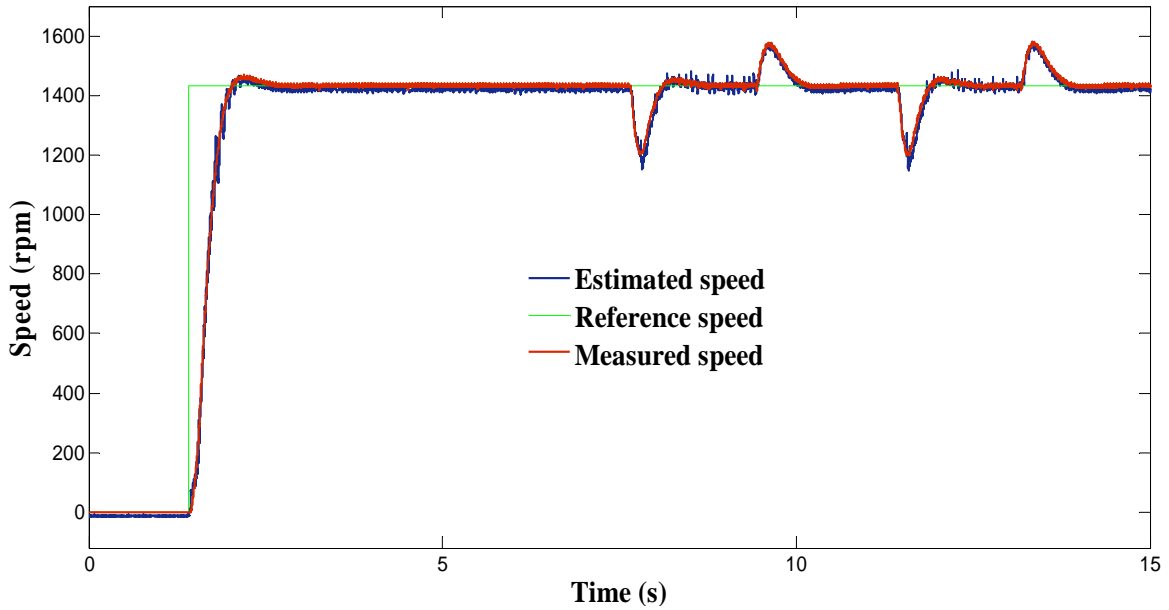


(c) Error of estimated speed

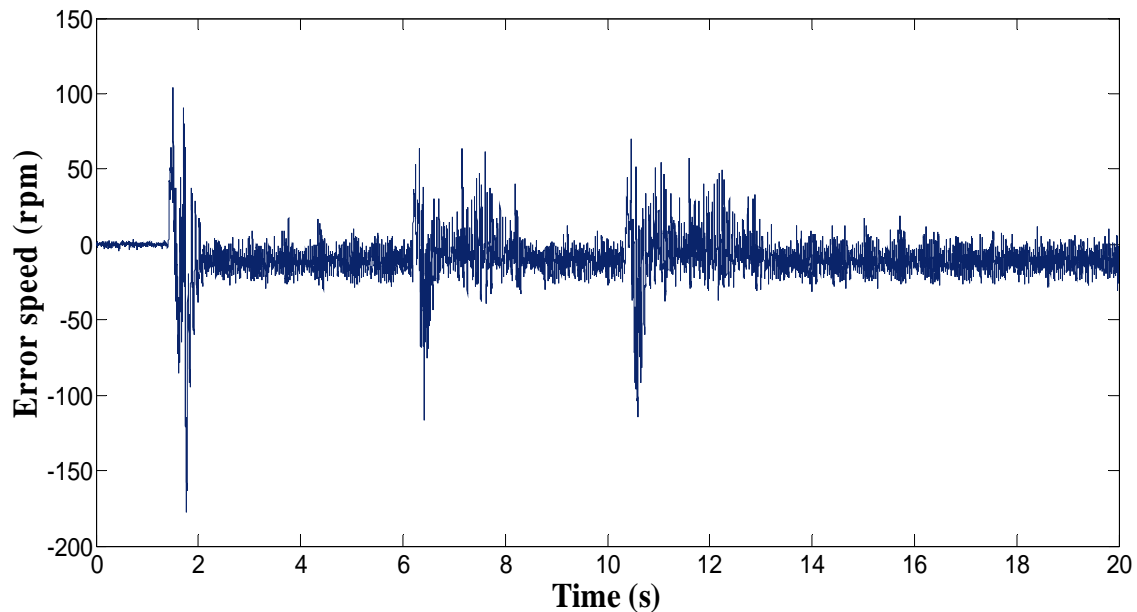
Figure 3. Response of the drive at free acceleration

Scenario 2: Free acceleration characteristics

Figure 4 shows the speed-sensorless control performance where the load was applied and omitted. The estimated speed coincides exactly with the real speed even the load torque application instant. From these results, it is shown that the proposed speed-sensorless control algorithm has good performances.



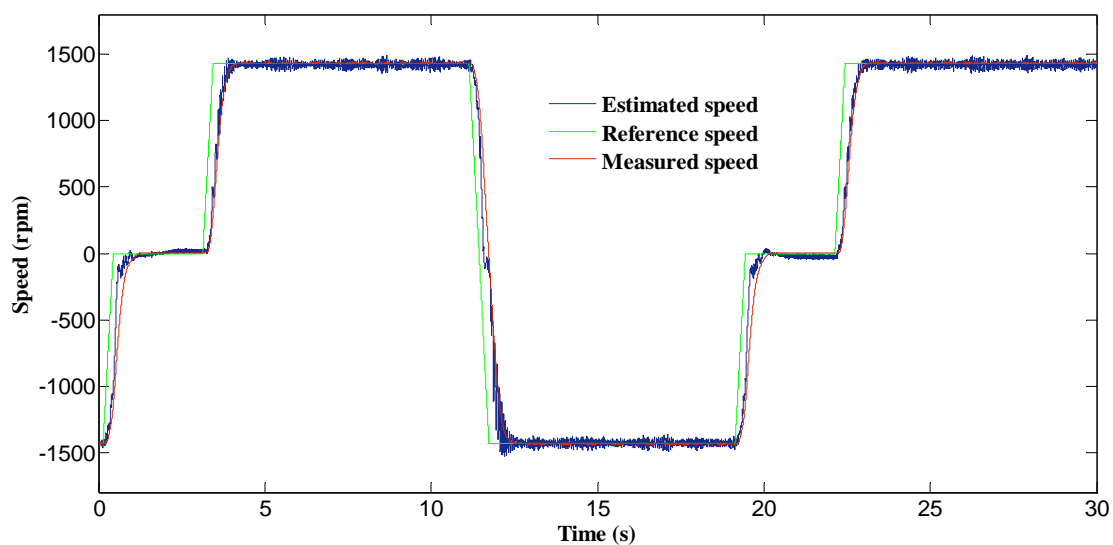
(b)
Figure 4. Response of the drive with a load applied: (a) = The reference, actual and estimated speed; (b) = Zoom of speed



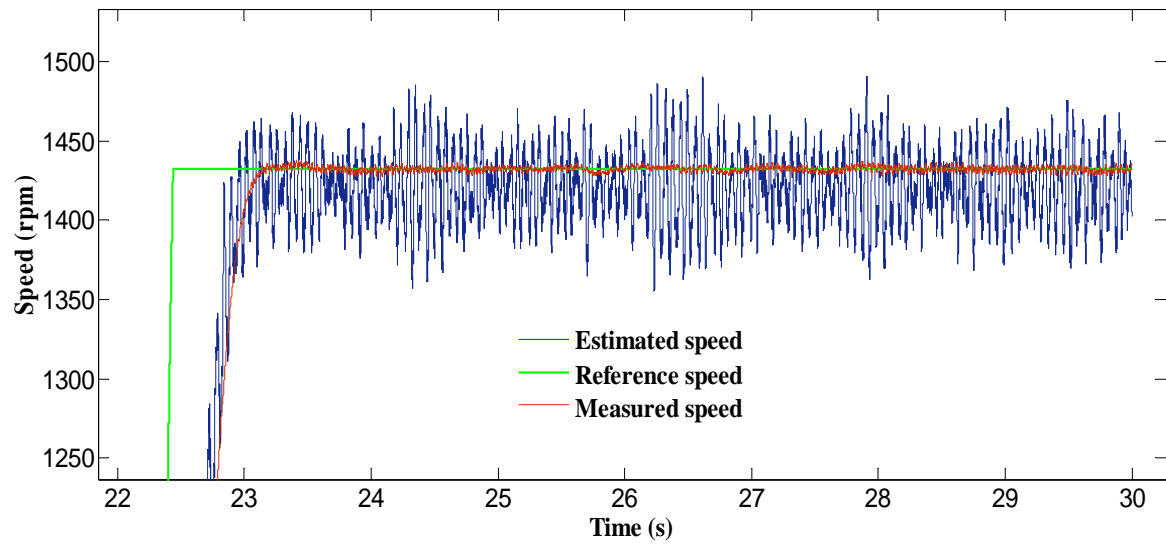
(c) **Figure 4.** Response of the drive with a load applied: (c) = Error of estimated speed

Scenario 3: Inversion of the speed

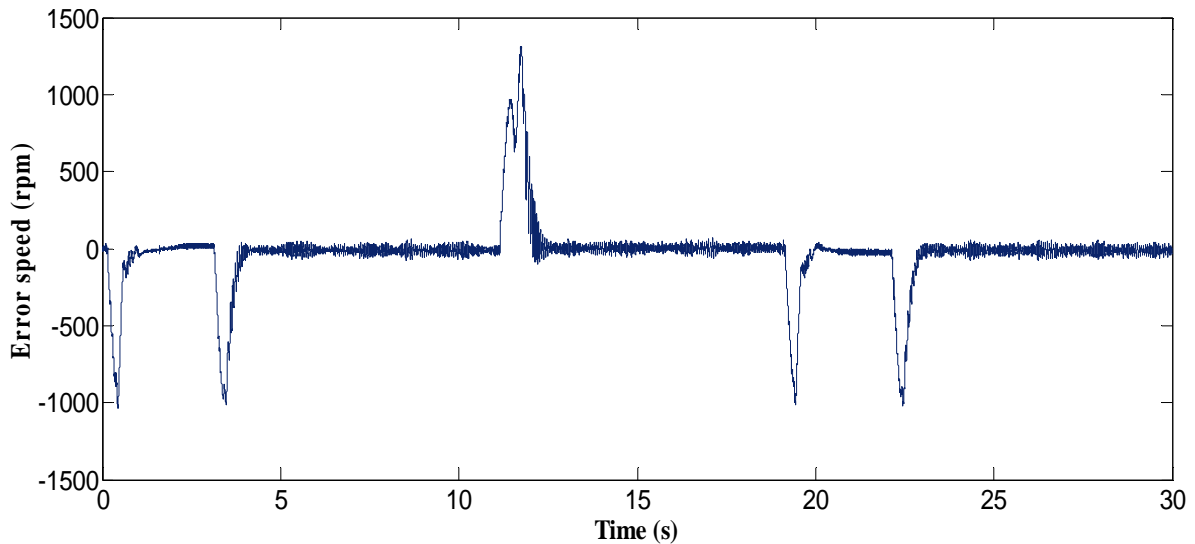
A step change in speed reference from +1490 rpm to -100% is applied at 11 sec. This step change is equivalent to 100% speed change. The response is shown in figure 5. The phase sequence reverses to rotate the motor in reverse direction. The drive reaches steady-state for this change very short time. This proves that the speed estimation is stable even at very low and zero speeds.



(a) **Figure 5.** Response of the drive at speed reversal with no load condition: (a) = The reference, actual and estimated speed



(b)

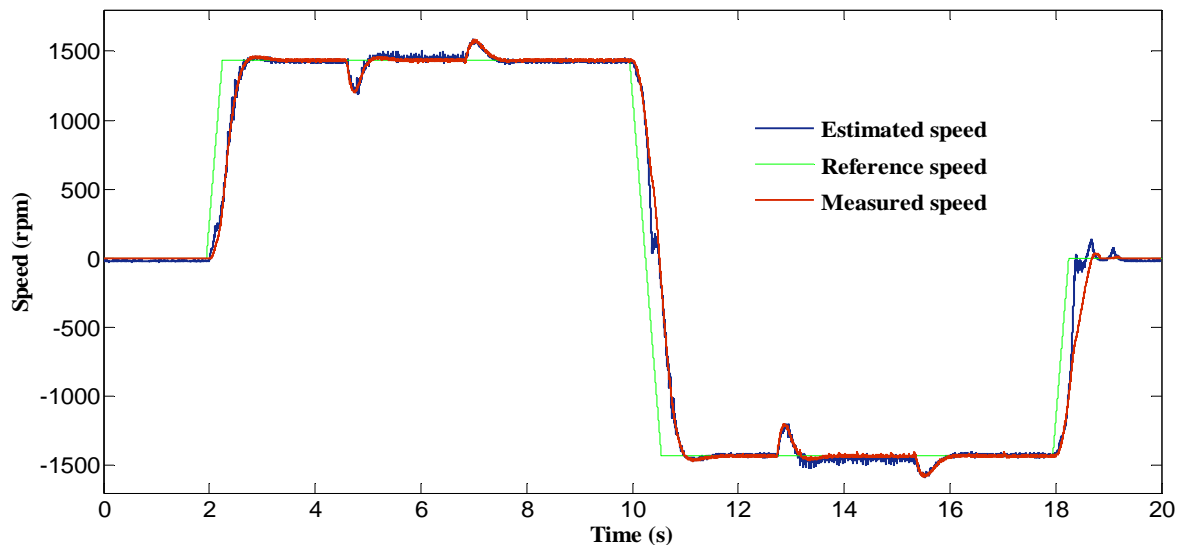


(c)

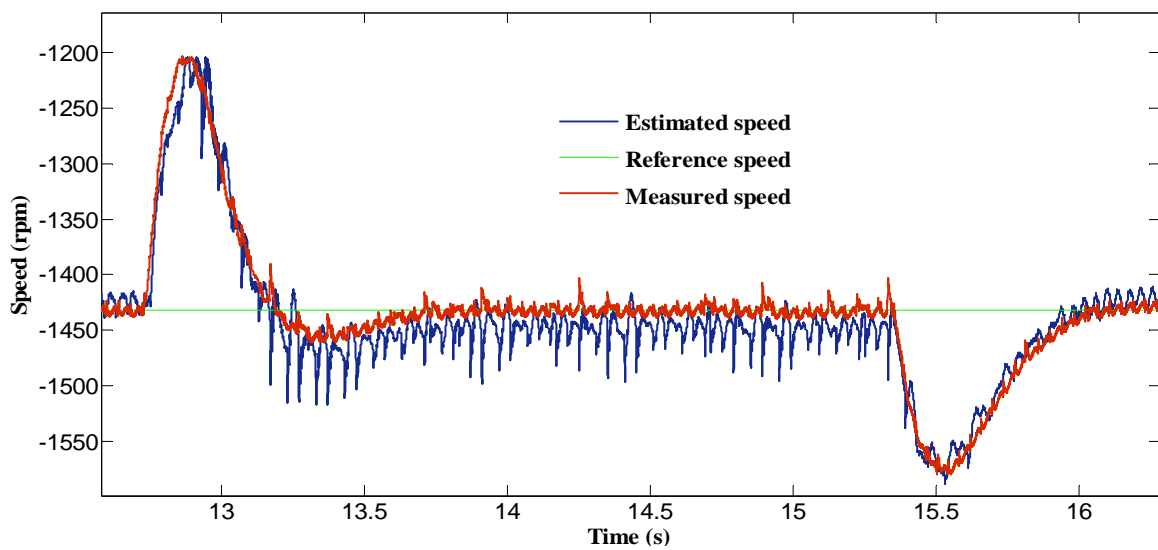
Figure 5. Response of the drive at speed reversal with no load condition: (b) = Zoom of speed; (c) = Error of estimated speed

Scenario 4 Inversion of the speed under load change

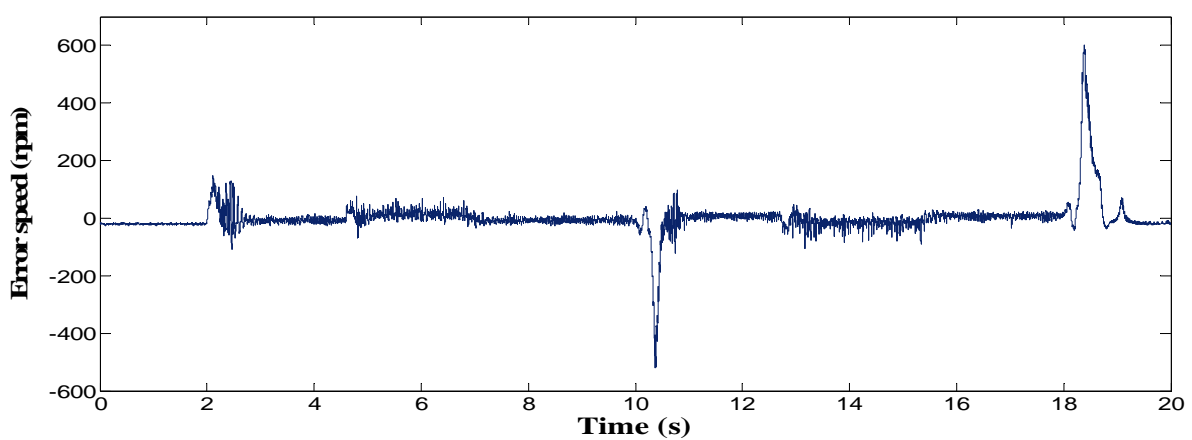
In this scenario, the controller was tested under the speed dependent load produced by the synchronous machine. The reversal speed response of the motor is shown in figure 6 at high speeds under different levels of load torque. This figure indicates that the estimated value also tracks its true value very closely in both the forward and reverse directions, and it is possible to verify the excellent behaviour of the proposed algorithm. In fact, the waveforms depicted through this figure, prove the feasibility of the proposed scheme.



(a) The reference, actual and estimated speed



(b) Zoom of speed

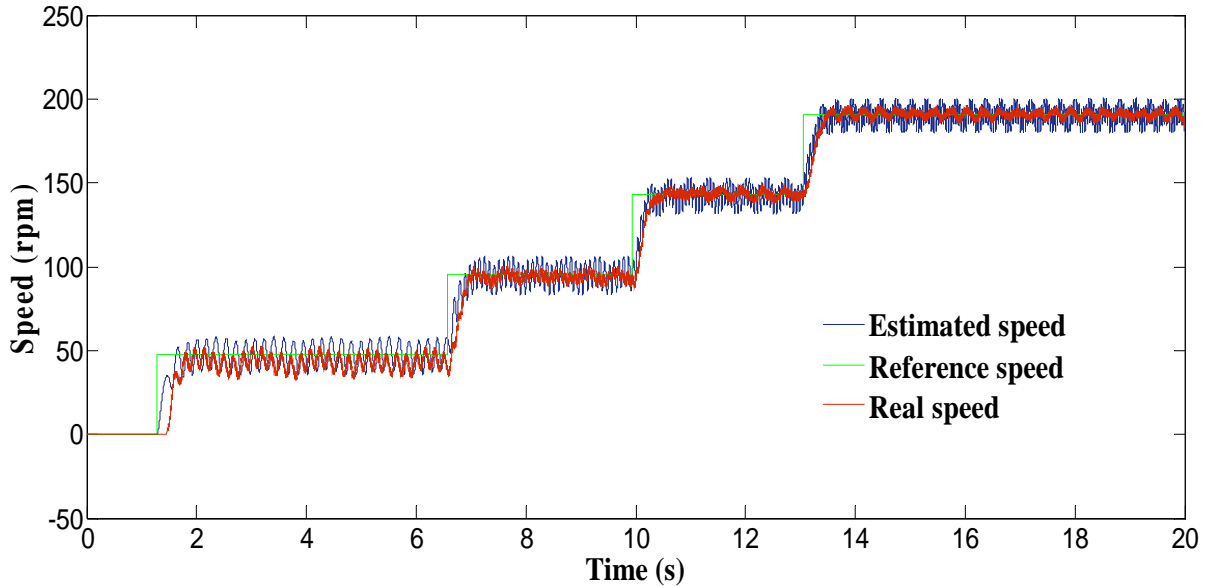


(c) Error of estimated speed

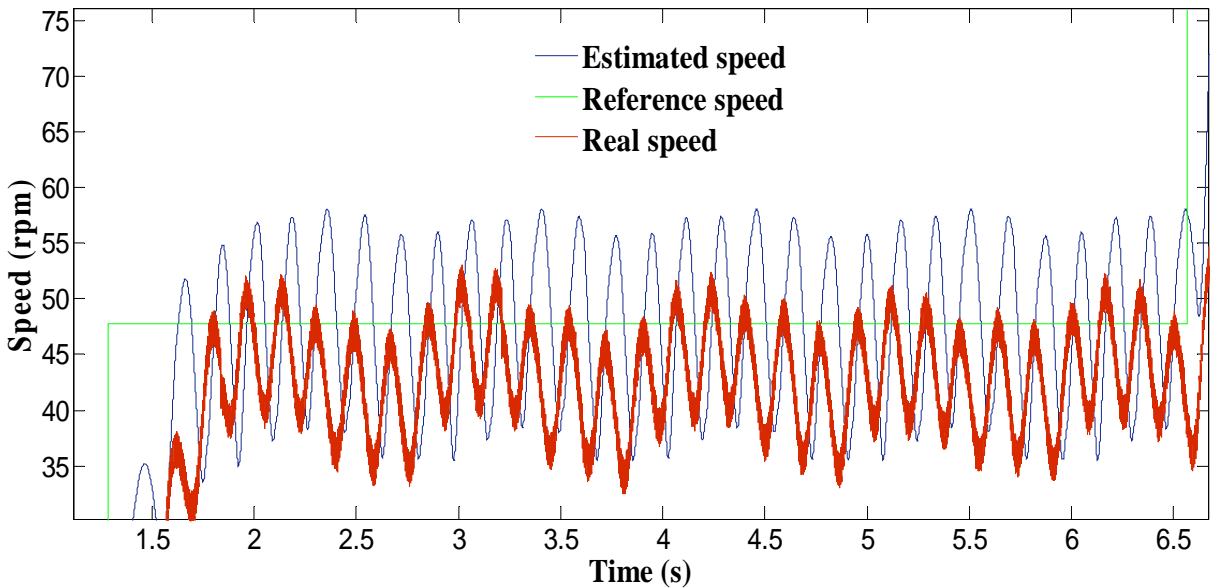
Figure 6. Response of the drive at reversal speed and speed applied a load

Scenario 5: Staircase tracking waveform include low speed region

A reference speed of 50 rpm was initially applied at $t = 1.5$ seconds, increased to 100 rpm, 150 rpm and 200 rpm respectively at $t = 6.5$ seconds, $t=10$ seconds and at $t=13$ seconds (figure 7) (different level of speed including low speed region).

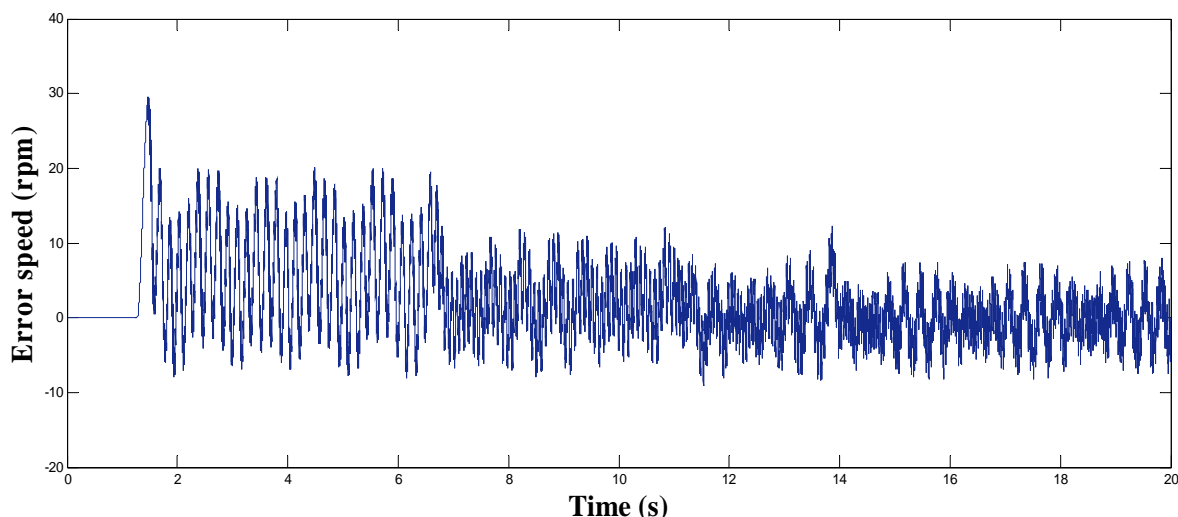


(a)



(b)

Figure 7. Response of the drive at stair speed waveform: (a) = The reference, actual and estimated speed; (b) = Zoom of speed



(c)

Figure 7. Response of the drive at stair speed waveform: (c) = Error of estimated speed

It is seen that the speed responses were smooth in different speed zones. We can see that the speed follow perfectly the speed reference. We note that the performance degrades as approaching the low speed region and fails to provide small oscillations.

Conclusions

Both observers presented in the paper can estimate the speed in an electrical drive system. The values of the on-line speed estimated can be used by the control of the electrical drive systems in speed range. The main features are the following:

- The rotor speed of the motor is estimated by reference model with Luenberger observers.
- To obtain a high-dynamic current sensorless control, a current to voltage feed forward decoupling and a good dynamic correction are obtained.
- Moreover, an accurate dynamic limitation of the real electromagnetic torque is obtained.
- The final algorithm can be implemented with relatively few instructions using the Embedded Matlab function block based on an M-file written in the MATLAB language because it can be supported by RTI (Real Time Interface) with execution times of each algorithm 164.

- Results of the dynamic and steady state behavior of a sensorless speed control of an induction motor are given.
- The experimental results were satisfactory.
- Both at low, at load applied, at high and reversal motor speed the proposed control scheme is working very well and proves a robustness of the proposed control structure in dSPACE environment.
- The described control system is a solution without mechanical sensors for a wide range of applications where good steady state and dynamic properties are required.

At present, sensor-based controls are still widely used in industrial and transportation applications. But in the near future, speed sensorless-based drive systems will become a practical reality and will be used in many industrial applications. Sensorless-based systems will provide higher reliability and operation in adverse environmental conditions at a lower cost.

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