SUST Journal of Engineering and Computer Science (JECS), Vol. 16, No. 3, 2015

Speed Sensorless Vector Control of Induction Motors Using Rotor Flux based Model Reference Adaptive System

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Received: 20.07.2014
Accepted: 24.11.2014

ABSTRACT - Vector Control (VC) schemes are increasingly used in Induction Motor (IM) drive systems to obtain high performance. However, in order to implement the vector control technique, the induction motor speed information is required. Different speed sensors are used to detect the speed. But in most applications, speed sensors have several problems. These problems are eliminated by speed estimation by using different speed estimation algorithms. Out of which, Model Reference Adaptive System (MRAS) techniques are one of the popular methods to estimate the rotor speed due to its good performance and simplicity. In this paper, the induction motor with Rotor Flux based Model Reference Adaptive System (RF-MRAS) rotor speed estimator is designed and validated through MATLAB/SIMULINK software package. The results of simulations show that the performance of the speed estimation is very good under different operation conditions.

Keywords: *Induction Motor, Vector Control, Sensorless, Speed Estimation, Model Reference Adaptive System, Rotor Flux based Model Reference Adaptive System.*

المستخلص– تستخدم مخططات التحكم المتجهى بشكل متزايد فى أنظمة القيادة للمحرك الحثى للحصول على الأداء العالى. و رغم ذلك من أجل تنفيذ تقنية المتحكم المتجهى, مطلوب معرفة سرعة المحرك الحثى. تستخدم مجسات مختلفة لقياس السرعة. و لكن فى معظم التطبيقات، مجسات السرعة لديها العديد من المشاكل. يتم التقليل من هذه المشاكل عن طريق تقدير السرعة بإستخدام خوارزميات مختلفة لتقدير السرعة. منها، تقنيات نظام النموذج المرجعى التكيفى (MRAS) التى تعتبر واحدة من الطرق الشائعة لتقدير السرعة نظراً لأدائها الجيد والبساطة. فى هذه الورقة، تم تصميم المحرك الحثى مع فيض العضو الدوار بناءاًعلى نظام النموذج المرجعي التكيفى (RF-MRAS) لتقدير السرعة, وتم التحقق منها من خلال حزمة برنامج MATLAB/SIMULINK. نتائج المحاكاة تبين أن أداء السرعة المقدرة جيدة جدا تحت ظروف التشغيل المختلفة.

INTRODUCTION

The induction motor has been gradually replacing the Direct Current (DC) motor in many applications due to its reliability, ruggedness and relatively low cost. Unfortunately, they have nonlinear dynamics, and for variable speed applications, they require advanced control schemes [1-3]. Fortunately, however, using power electronics and fast Digital Signal Processors (DSP), the implementation of such advanced control techniques is now becoming practical. One of these techniques is the well known Field Oriented Control (FOC) or vector control. Field oriented control or vector control originated from the works of Blaschke and Hasse has become an industry standard for controlling induction motors in high performance drive applications [4, 5]. By providing decoupling of torque and flux control demands, the vector control can navigate induction motor similar to a separately excited DC motor without sacrificing the quality of the dynamic performance [6-8].

Traditionally, there have been two conventional methods thought which vector control is achieved: Direct Vector Control (DVC) and Indirect Vector Control (IVC). Both direct vector control and indirect vector control, has been successfully established in theory and practice. Indirect vector controlled induction motor drives are increasingly used in high performance systems due to their relative simple configuration compared to direct vector control scheme which requires flux and torque estimators. However, the majority of these control strategies requires a perfect knowledge of the motor speed or position of its shaft, hence the use of sensor dedicated to measure these variables. The sensors include the search coils, coil taps, or Hall Effect sensors. The use of this sensor, nevertheless, implies more electronics, higher cost, lower reliability, and difficulty in mounting in some cases such as motor drives in harsh environment and high speed drives, increase in weight, increase in size, and increase in electrical susceptibility [9-12].

To overcome these problems, in recent years, the elimination of these sensors has been considered as an attractive prospect. Therefore, many studies and intensive works have focused on research techniques avoiding the utilization of speed sensor, while maintaining a high level of performance. Indeed these techniques, called sensorless, are a challenge both technically and economically because they provide many advantages the most important being a lower cost, more compact drive system, less maintenance requirements, reducing measurement noise, elimination of the sensor cable, and increased reliability [13-16].

Speed sensorless field oriented control methods of induction motor using speed estimation to replace speed sensor has been developed since 1980. Various techniques for speed estimation have been suggested such as MRAS, Luenberger Observer (LO), Kalman Filters (KF), Artificial Intelligence Techniques (AI), and Sliding Mode Observers (SMO). In theses techniques, speed is estimated using stator voltages and currents of the induction motor and this speed is used to compare the commanded one [17-22]. Among different rotor speed estimation techniques, model reference adaptive systems schemes are the most common strategies employed due to their relative simplicity and low computational effort. Various model reference adaptive system schemes have been introduced in the literature based on rotor flux, back electromotive force, and reactive power. However, rotor flux based model reference adaptive system is the most popularly used conventional speed estimation scheme for sensorless induction motor drives [23-27]. In this paper, the indirect vector control scheme using the rotor flux based model reference adaptive system designed and simulated using MATLAB/SIMULINK software package. A general scheme of the structure applied in this paper in order to estimate the speed of the induction motor as shown in Figure 1[24].

INDCTION MOTOR MODEL

Under the assumptions of linearity of the magnetic circuit, equal mutual inductances, and neglecting iron losses, a three-phase induction motor model in the fixed stator d-q reference frame can be described as a fifth order nonlinear differential equations with four electrical variables (stator currents (i_{ds}, i_{qs}) and rotor fluxes (ψ_{dr}, ψ_{qr})), and one mechanical variable (rotor speed ω_r) [28].

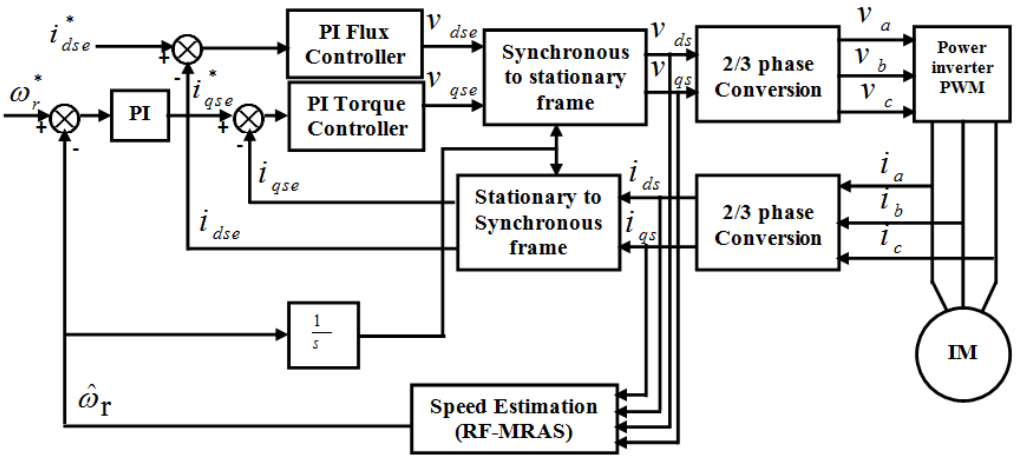

Figure 1: Speed sensorless block diagram of indirect vector controlled induction motor with RF-MRAS

$$\begin{bmatrix} \frac{di_{ds}}{dt} \\ \frac{di_{qs}}{dt} \\ \frac{d\psi_{dr}}{dt} \\ \frac{d\psi_{qr}}{dt} \\ \frac{d\omega_r}{dt} \end{bmatrix} = f(x) + \begin{bmatrix} \frac{1}{L_a} & 0 \\ 0 & \frac{1}{L_a} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} v_{ds} \\ v_{qs} \end{bmatrix} \tag{1}$$

where:

$$f(x) = \begin{bmatrix} -\alpha\, i_{ds} + \beta\, \psi_{dr} + \omega_r\, \gamma\, \psi_{qr} \\ -\alpha\, i_{qs} + \beta\, \psi_{qr} - \omega_r\, \gamma\, \psi_{dr} \\ \delta\, i_{ds} - T_{ri}\, \psi_{dr} - \omega_r\, \psi_{qr} \\ \delta\, i_{qs} - T_{ri}\, \psi_{qr} + \omega_r\, \psi_{dr} \\ \frac{P}{2}\left(\frac{3PL_m\left(\psi_{dr} i_{qs} - \psi_{qr} i_{ds}\right)}{4L_r J} - \frac{T_L}{J} \right) \end{bmatrix}$$

$$\alpha = \frac{R_s}{L_a} + \frac{R_r L_m^2}{L_r^2 L_a}; \quad \beta = \frac{R_r L_m}{L_r^2 L_a}$$

$$\gamma = \frac{L_m}{L_r L_a}$$

$$L_a = L_s - \frac{L_m^2}{L_r}$$

$$\delta = \frac{L_m}{T_r}; \ T_{ri} = \frac{1}{T_r}; \ T_r = \frac{L_r}{R_r} \tag{2}$$

where L_s is the stator inductance, L_r is the rotor inductance, L_m is the mutual inductance, L_a is the redefined leakage inductance. R_s and R_r are stator and rotor inductance resistances, respectively. J is the moment of inertia of the motor, T_L is the torque of external load disturbance, P is the number of pole, and T_r is the time constant of the rotor dynamics. From Equation (1) the rotor speed is a nonlinear output with respect to the state variables of the dynamical model. Therefore, it is difficult to control the rotor speed directly from control inputs v_{ds} and v_{qs}.

SPEED ESTIMATION USING RF-MRAS

Several schemes have been proposed for speed a sensorless vector controlled induction motor, which implies the estimation of the speed from the only measurements of the stator currents and voltages. MRAS technique offer simpler implementation and require less computational effort compared to other methods and therefore the most popular strategies used for sensorless control. This technique is based on the comparison between the outputs of two estimators. The outputs of two estimators may be the rotor flux, back emf, or motor reactive power. However, RF-MRAS first introduced by Schauder is the most popular MRAS strategy [23-27]. The schematic representation of RF-MRAS is shown in Figure 2 [24].

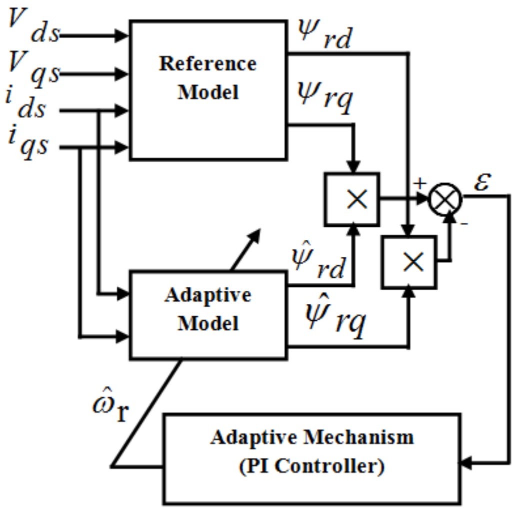

Figure 2: Block diagram of RF-MRAS

In the RF-MRAS speed estimator, the state variable used is the rotor flux. Two models are used in the RF-MRAS approach. The model that does not involve the quantity to be estimated (the rotor speed) is considered as the reference model or the voltage model. The model which involves the quantity to be estimated is considered as the adaptive model or the adjustable model or current model. The output of the adaptive model is compared with that of the reference model, and the difference (error) is used to drive a suitable adaptive mechanism whose output is the quantity to be estimated (the rotor speed). This is used to adjust the adaptive model. This process continues till the error between two outputs tends to zero. The adaptive mechanism can be a Proportional-Integral (PI) controller, as used in this paper, or any other tool such as neural networks, fuzzy systems, or some other options. The adaptive mechanism should be designed to assure the stability of the control system. The reference model, usually expressed by the voltage model, represents the stator equation. It generates the reference value of the rotor flux components in the stationary reference frame from the monitored stator voltage and current components. The reference rotor flux components obtained from the reference model are given by [24]:

$$\frac{\psi_{rd}}{dt} = \frac{L_r}{L_m}(v_{ds} - R_s i_{ds} - \sigma L_s \frac{di_{ds}}{dt})$$
$$\frac{\psi_{rq}}{dt} = \frac{L_r}{L_m}(v_{qs} - R_s i_{qs} - \sigma L_s \frac{di_{qs}}{dt}) \quad (3)$$

The Adjustable model, usually represented by the current model, describes the rotor equation where the rotor flux components are expressed in terms of stator current components and the rotor speed. The rotor flux components obtained from the adaptive model are given by [24]:

$$\frac{\hat{\psi}_{rd}}{dt} = \frac{L_m}{T_r} i_{ds} - \frac{1}{T_r}\hat{\psi}_{rd} - \hat{\omega}_r \hat{\psi}_{rq}$$
$$\frac{\hat{\psi}_{rq}}{dt} = \frac{L_m}{T_r} i_{qs} - \frac{1}{T_r}\hat{\psi}_{rq} - \hat{\omega}_r \hat{\psi}_{rd} \quad (4)$$

Finally, the adaptation scheme generates the value of the estimated speed to be used in such a way as to minimize the error between the reference and estimated fluxes. In the RF-MRAS scheme, this is performed by defining a speed tuning signal ε to be minmized by a PI controller which generates the estimated speed which is fed back to the adaptive model. The expressions for the speed tuning signal and the estimated speed can be given as [24]:

$$\varepsilon = \psi_{rq}\hat{\psi}_{rd} - \psi_{rd}\hat{\psi}_{rq} \quad (5)$$

$$\hat{\omega}_r = (K_P + \frac{K_I}{p})\,\varepsilon \quad (6)$$

where K_P and K_I are the proportional and integral constants respectively and "^" signifies the estimated value.

RESULTS AND DISCUSSION

In this section, simulation results are presented to evaluate the effectiveness of the proposed control scheme for different operating conditions such as low speed operation, high speed operation, variable speed command, and inversion of the speed. The software environment used for the simulation is MATLAB/SIMULINK software package. The parameters and data of the IM used for simulation procedure are listed in Table1 [28].

Table I: Parameters and data of the IM

Parameters	Values
Number of phases	3
Connection	star
Rated power	2.24 KW
Line voltage	230V rms
Line current	9 A rms
Rated speed	1430 rpm
Rated torque	14.96 Nm
Rotor resistance, R_r	0.72 Ω
Stator resistance, R_s	0.55 Ω
Rotor inductance, L_r	0.068 H
Stator inductance, L_s	0.068 H
Magnetizing inductance, L_m	0.063 H
Moment of inertia, J	0.05 $kg.m^2$
Viscous friction coefficient, B	0.002 Nms^{-1}

The MATLAB/SIMULINK block diagram of speed sensorless control of Indirect Vector Controlled Induction Motor (IVCIM) using RF-MRAS is shown in Figure 3.

Low speed operation

Figure 4 shows the behavior of induction motor speed estimation where the induction motor rotates at a constant low speed (50rad/sec) at noload. The simulation is performed for 10 seconds. It is seen that the actual (real) speed and estimated speed can track the trajectory of the reference speed very well with a little overshoot which is reasonable and no steady state error. Figure 5 shows the speed error or estimated error (calculated from the difference between the real speed and the estimated speed). The peak speed error between estimated and actual speeds is within the range +5rad/sec and -1rad/sec.

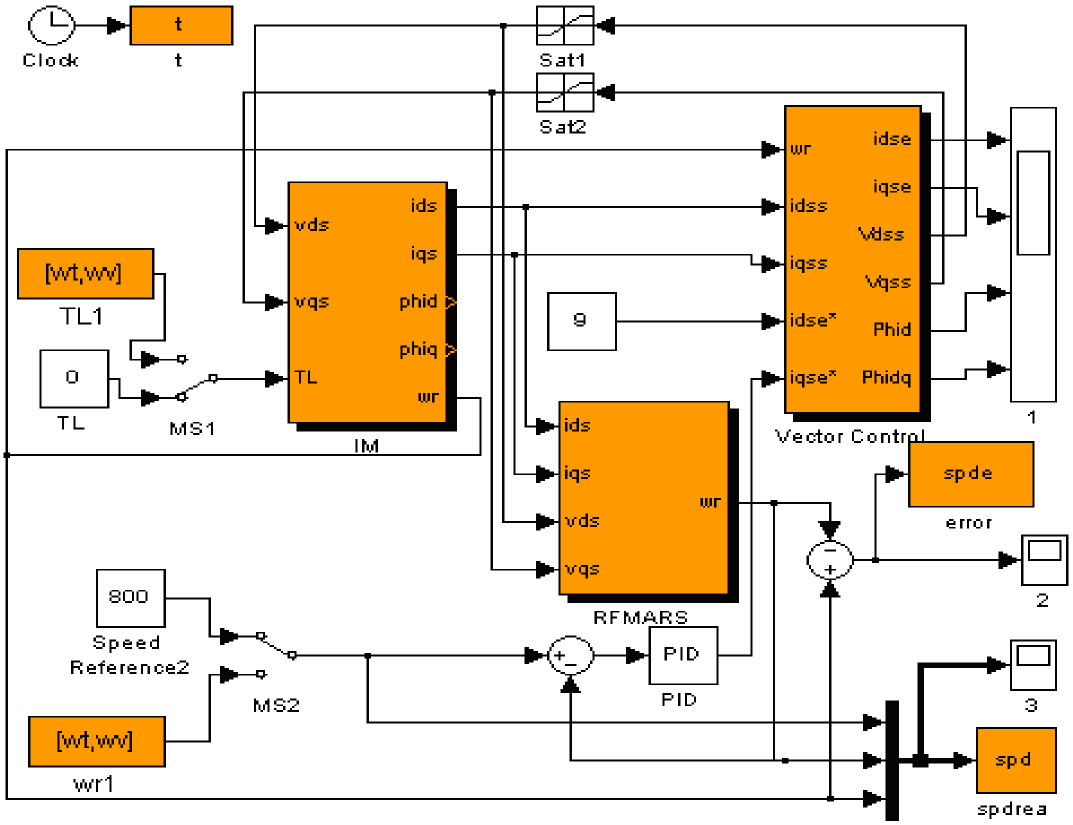

Figure 3: MATLAB/SIMULINK block diagram of sensorless speed control of IVCIM using RF-MRAS

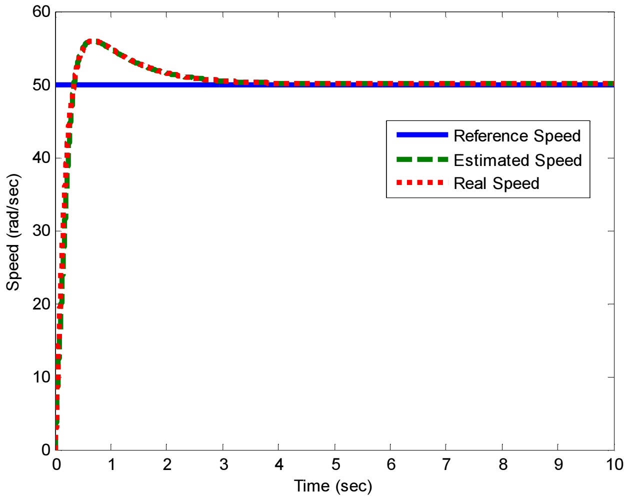

Figure 4: The real and estimated speeds at low speed

High speed operation

In this case, the performance of the proposed speed sensorless control algorithm is tested under high speed operation at noload. The command speed is assumed to be increased from zero to 1000rad/sec under no torque load. The simulation is performed for 5 seconds. The real and estimated speed responses are shown in Figure 6. It can be seen that there is a very good accordance between real speed and estimated speed without any steady state error. Figure 7 is speed error between estimated speed and real speed. The peak speed error between estimated and actual speeds is within the range +0.06rad/sec and -30rad/sec.

Variable speed operation

In this case, the performance of the proposed speed sensorless control algorithm is tested under variable speed operation. The simulation is performed for 10 seconds. The speed command is 50rad/sec for the first 2 seconds, followed by 80rad/sec for the next 2 seconds, then 100rad/sec for the next 2 seconds followed by 50rad/sec for the last 4 seconds. The real and estimated speed responses are shown in Figure 8. It can be seen that there is a very good accordance between real speed and estimated speed. Figure 9 is speed error between estimated speed and real speed. The peak speed error between estimated and actual speeds is within the range +4.4rad/sec and -1.98rad/sec.

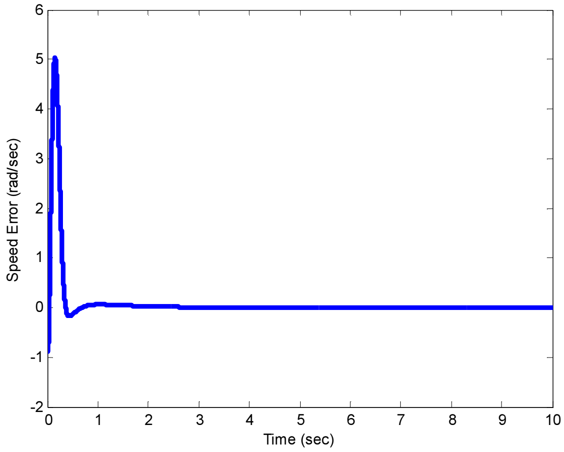

Figure 5: The estimated error at low speed

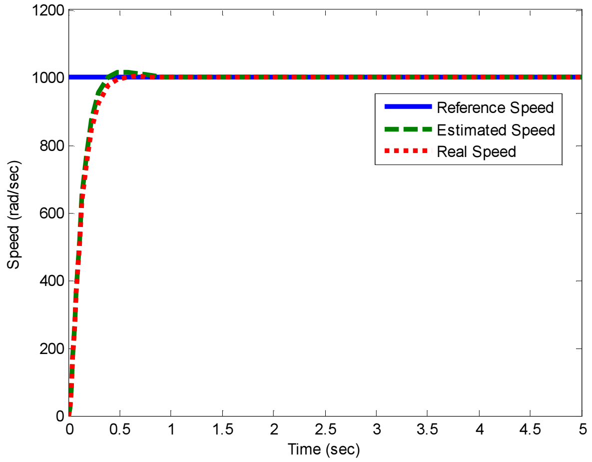

Figure 6: The real and estimated speeds at high speed

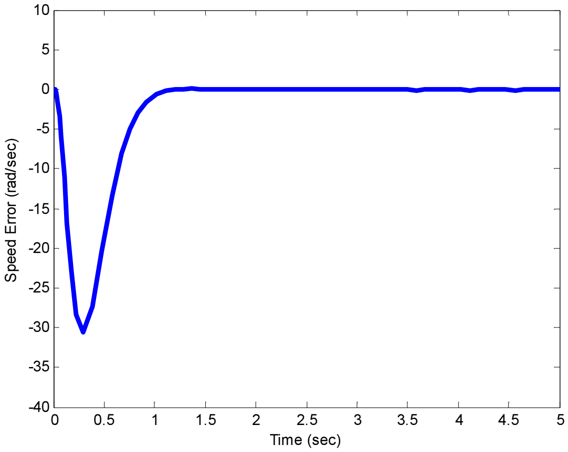

Figure 7: The estimated error at high speed

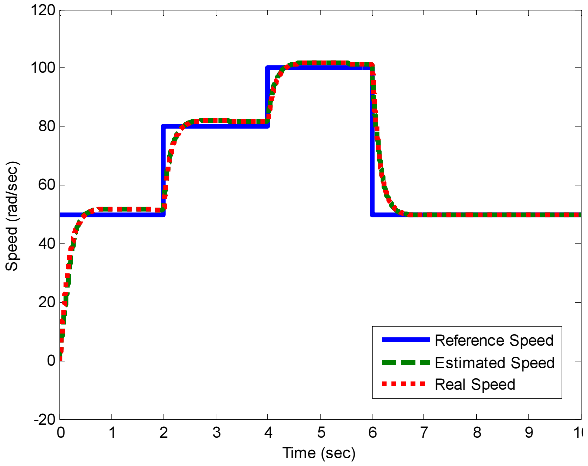

Figure 8: The real and estimated speeds at variable speed

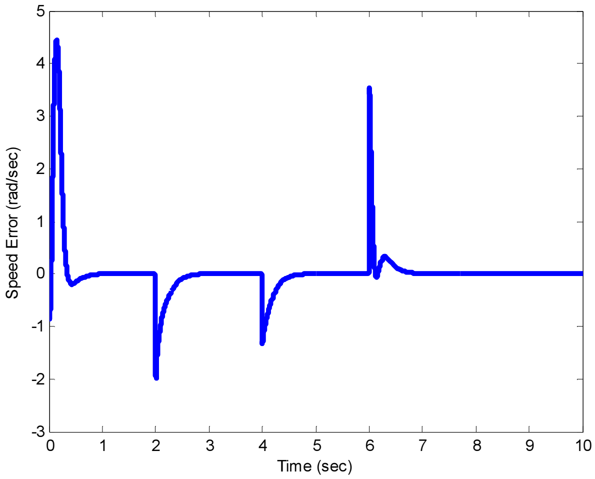

Figure 9: The estimated error at high speed

Inversion of the speed

Figure 10 presents the simulation result obtained for speed inverting from 80rad/s to -80rad/s under no torque load. The simulation is performed for 10 seconds. Estimated speed, actual speed, and reference speed are shown in this figure. This figure indicates that the estimated speed tracks its real speed very closely in both the forward and reverse directions, and it is possible to verify the excellent behaviour of the proposed speed sensorless control algorithm. In fact, the waveforms depicted through this figure, prove the feasibility of the proposed speed sensorless control scheme. Figure 11 shows the speed error or estimated error. The peak speed error between estimated and actual speeds is within the range +5rad/sec and -0.8rad/sec.

CONCLUSIONS

This paper addresses the problems of rotor speed estimation in sensorless indirect vector controlled induction motor drive based RF-MRAS scheme. The effectiveness of the proposed method was confirmed through MATLAB/SIMULINK simulation results in different induction motor operating conditions. Simulation results obtained show that sensorless speed control strategy based on RF-MRAS approach can be applied successfully in induction motor drives.

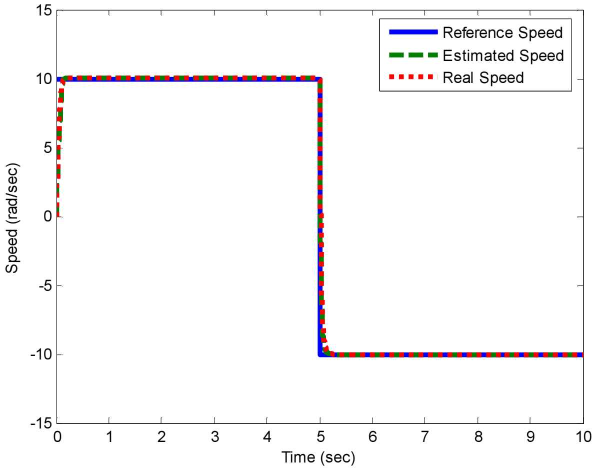

Figure 10: The real and estimated speeds with reversing speed reference

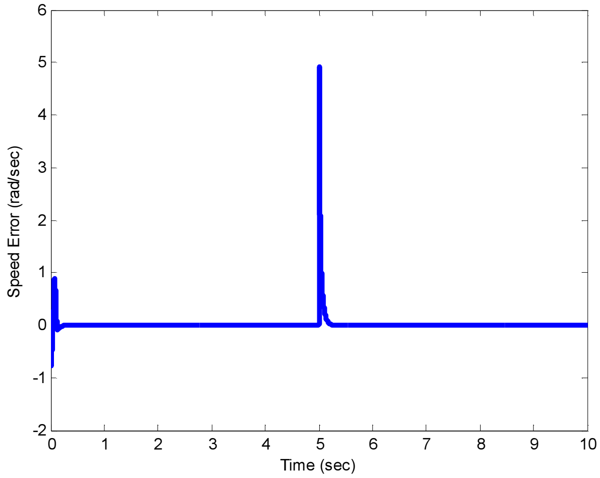

Figure 11: The estimated error

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