Libyan Journal for Engineering Research (LyJER) *Volume (1) № (2) September 2017*
ISSN 2522-6967

Dynamic Performance of a Sensorless Speed Control for Induction Motor Drives based on Model Reference Adaptive System

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ABSTRACT

Sensorless vector control is greatly used and applied in induction machine drives instead of vector and scalar control for their reliability and robustness, and very low maintenance cost. The estimation of the rotor speed in MRAS-based technique obtained by comparing the output of the adjustable and adaptive models instead of using costly speed sensor gives the sensorless vector control great fortune. MRAS-based techniques are one of the best methods to estimate the rotor position and speed for its performance and stability. In this paper, MRAS-based technique used to estimate rotor speed based on rotor flux estimation, the estimated speed in MRAS used as a feedback for the vector control system. Modeling and simulation of the induction machine and the vector control drives implemented in MATLAB/SIMULINK. Simulation results of the proposed MRAS rotor speed technique are presented. The results show stability and accuracy for the proposed technique.

Keywords: *Induction Machine, Field-Oriented Control, Vector Control, Six-Switch Three-Phase Inverter (SSTPI), Sensorless Control.*

1. Introduction

In many applications that consist of electromechanical systems, the control of speed, torque, and position is significantly important, such as mechanical robots, elevators, and automated factories. The main purpose of any machine control system is to extract and endurance the energy in an efficient way and in wide speed range control. The controlling of wind energy systems through advanced drives are also needed for maximum power point tracking in variable wind speed and contrastive forecasting. In the near future with the increase of dispatchable energy sources, the need for production maximum torque per ampere is a quite crucial matter [1].

With the development in vector control method, the induction machines become a preferable replacement for DC machines. Even though induction machine categorized by their reliability and robust and simplicity in construction, the control and estimation in induction machine is more difficult than in DC drives. The complex dynamic behavior and the complicated calculations required to estimate the speed of induction machine increase the cost due to the use of more advanced microprocessors [2].

Despite the development of vector control method to estimate and control the rotational speed of the induction machine by mean of microprocessors, introducing shaft speed sensor also decrease the reliability and dependability of the induction machine. Therefore, orientation to sensorless ac drive solutions has become the most prospective method to overcome the issues comes from introducing shaft speed sensor in the induction machine. The most promising approach is the Model Reference Adaptive System (MRAS), due to their simplicity [3].

The research and developments in speed sensorless control of induction motor drives (IM) have been continued in the past decades. The MRAS-based technique is one of the most attractive techniques for sensorless control of IM in literature reviews [4, 5, 6]. The MRAS speed technique is based on the comparison between the output of the reference model and the output of adjustable model until the error vanishes between the two models [7, 8].

The integration of pure voltage signal is the common problem encountered the application of MRAS technique to induction machine drives. Reference [9] suggest modifying the pure integration in voltage model to the low pass filter. Reference [10] propose adding linear transfer function as a high pass filter in both the reference and the adjustable models. Reference [11] suggest proposing a robust flux observer to improve the response of the low pass filter represented by [9]. The sensitivity of the model-based technique to motor parameter variation could influence its performance. Many papers provide experimental and simulation comparison between various technique, especially in the low-speed region.

This paper mainly concentrates and focus on the comparison between the performance of well-known indirect field Oriented control (IFOC) of IM which implies using speed sensor against the model reference adaptive system (MRAS).

2. Vector Control

Vector control of induction machine drives based on measuring the rotor speed from the feedback of the controller and compared with a reference speed, the resultant error between the commanded speed and the actual speed of the motor is the value given to the controller to regulate the motor speed.

The torque reference extracted from the controller used to calculate the d-q stator reference currents, then the reference currents resultant from the controller converted to abc components to compare with the actual stator currents of the motor to produce the error needed to regulate the speed in the current regulator. The rotor angle θ is also calculated from the rotor speed to convert the d-q stator currents to abc components. The d-axis current is used to obtain the rotor flux. The resulting abc currents used to generate Pulse-Width modulation (PWM) switching signals. The PWM switching signals govern the inverters to obtain the desired the stator voltages. Those switching pulses control the motor speed, electromagnetic torque, stator and rotor currents.

The operation of the vector control requires the use of the speed sensor in the induction machine. The measured speed from the sensor is the feedback to the controller, which used to compare it with the reference speed to produce the error needed for the current regulator. The resultant error produces the stator currents responsible for switching signals of the Three-phase inverters. Introducing shaft encoder in the induction machine could decrease the reliability of the equipment and increase the cost of the induction machine. Issues come from integrating speed sensor in the induction machine arouse the orientation to the sensorless control of induction machine.

2.1. Indirect Field Oriented control theory

To apply Rotor Field Oriented technique, the rotor flux vector is forced to be aligned with d-axis of the synchronous rotating reference frame. As a result, the quadrature component of the rotor flux in the synchronous rotating reference frame is also forced to be zero. Hence $\lambda_{qr}^{e} = 0$, The q -axis current command can be calculated

$$I_{qs}^{e^*} = (-L_r/L_m) I_{qr}^{e^*} \quad (1)$$

Moreover, the torque command as a function of $I_{qs}^{e^*}$ can be found as:

$$T_e^* = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}(I_{qs}^{e^*}\lambda_{dr}^{e^*}) \quad (2)$$

In addition, the following relation gives the slip frequency:

$$\omega_{sl}^* = \frac{L_m I_{qs}^{e^*}}{\tau_r^* \lambda_{dr}^{e^*}} \quad (3)$$

A relation between the rotor flux and the flux current command can be found from:

$$R_r I_{dr}^{e^*} + \lambda_{dr}^{e^*} = 0 \quad (4)$$

Moreover, $I_{dr}^{e^*}$ is given by:

$$I_{dr}^{e^*} = \frac{\lambda_{dr}^{e^*} - L_m I_{ds}^{e^*}}{L_r} \quad (5)$$

They are used in slip angle calculation, which is added to the measured rotor angle to get the estimated rotor flux - vector space angle (indirect RFO method). This angle is called the synchronous command angle θ_e^* and is used to transform the stator and/or rotor currents, voltages and fluxes from the stationary reference frame to the synchronous reference frame(SYRF) and vice-versa.

The transfer function of PI is given by:

$$G_s = \frac{k_{ps}[1+\tau_{cs}S]}{\tau_{cs}S} \quad (6)$$

The torque command, as the output of PI speed controller, can be written as a function of the input as:

$$T_e^* = \frac{k_{ps}[1+\tau_{cs}S]}{\tau_{cs}S}(\omega_r^* - \omega_r) \quad (7)$$

The q - axis current command can be found as:

$$I_{qs}^{e^*} = \frac{1}{k_t}\frac{(\omega_r - \omega_r^*)}{\lambda_{dr}^{e^*}}\frac{k_{ps}[1+\tau_{cs}S]}{\tau_{cs}S} \quad (8)$$

The indirect current command $I_{ds}^{e^*}$, is set by the rotor flux level $\lambda_{ds}^{e^*}$, and is written as:

$$I_{ds}^{e^*} = (\frac{1}{L_m})(\lambda_{ds}^{e^*} + I_{ds}^{e^*}) \quad (9)$$

Note that the value of $I_{ds}^{e^*}$ is constant below the base speed and should be reduced in an inverse relation with the speed to achieve the field weakening. If the flux command level is kept constant, the relation between $I_{ds}^{e^*}$ and $\lambda_{ds}^{e^*}$ is simplified as:

$$I_{ds}^{e^*} = (1/L_m)\lambda_{ds}^{e^*} \quad (10)$$

As $\lambda_{ds}^{e^*}$ is the rotor flux, the $I_{ds}^{e^*}$ represents the rotor field producing component. After that the reference $I_{qs}^{e^*}$ and $I_{ds}^{e^*}$ are transformed to $I_{qs}^{s^*}$ and I_{ds}^{*s} in stationary reference frame and then to abc current commands using inverse park's transformation [2].

The current controller has been implemented in the rotor flux reference frame using PI regulators, the influence of parameters variations at low speed has been considered in this study. The parameters of the PI controller are tabulated in Appendix B.

3. Sensorless control of IM drives

Implementation of indirect field oriented control method of induction machines drives introduce speed sensor, which is necessary for the measurement of the motor speed. The speed measured by the sensor is used as a feedback for the controller to compare it against the reference speed desired. However, installation of shaft speed encoder in the induction machine require space on the machine shaft; moreover, it reduces the motor reliability and increases the cost of the equipment. It is possible to renounce the shaft speed encoder if the speed of the motor could be estimated by using the machine parameters, such as terminal voltage and currents. Most of the identification methods depend on the machine model. In order to obtain the stator flux vector, integration of the voltage vector in the stator voltage equation is required. Fore though, great importance to acquire accurate machine model for stable performance is required.

The estimation of rotor speed become difficult and complex in the low-speed operation mode. since the machine inductance affects the estimation of the rotor flux. For that, the accuracy of the sensorless speed estimation depends on the accuracy in calculating machine model parameters. Therefore, the performance of Sensorless vector control techniques become poor in the low-speed range.

As mentioned early, the estimation of motor speed is used in the closed loop control as a feedback signal for speed regulation. The MRAS-based method is the most attractive method among the sensorless vector control of induction machine drives and has a great potential. In our study, the performance of MRAS is compared and evaluated against the vector control technique.

3.1. Proposed Model reference adaptive system MRAS

The adaptive control methods have considered as a potential solution when high performance required for different and wide operation modes, especially when dynamic characteristics of the model is complex or even unknown. The Model Reference Adaptive System (MRAS) provide reliable and stable performance, the presence of reference adaptive model specifies the desired performance. The adaptive model use stator voltages and currents to compare the output of the adaptive model with the reference model. The rotor speed estimated based on the error from both models. A number of papers discussed MRAS technique [12-14]. The general scheme of MRAS field-oriented IM drives is shown in Figure1.

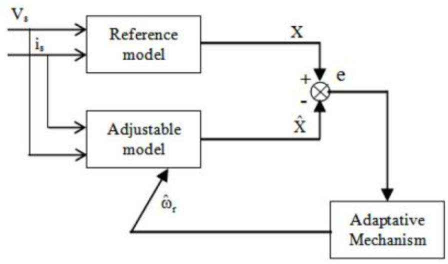

Fig. 1: Block diagram for MRAS control

The stator current is represented as:

$$i_{ds} = \frac{1}{L_m}[\lambda_{dr} + T_r\lambda_{qr}\omega_r + T_r p\lambda_{dr}] \quad (11)$$

$$i_{qs} = \frac{1}{L_m}[\lambda_{qr} - T_r\lambda_{qr}\omega_r + T_r p\lambda_{qr}] \quad (12)$$

Using the above equations, and estimated instead of measured speed, the stator current is estimated as:

$$\hat{\imath}_{ds} = \frac{1}{L_m}[\lambda_{dr} + T_r\lambda_{qr}\widehat{\omega}_r + T_r p\lambda_{dr}] \quad (13)$$

$$\hat{\imath}_{qs} = \frac{1}{L_m}[\lambda_{qr} - T_r\lambda_{qr}\widehat{\omega}_r + T_r p\lambda_{qr}] \quad (14)$$

ISSN 2522-6967

The difference in the stator current is obtained as:

$$(i_{ds}-\hat{\imath}_{ds})=\frac{T_r}{L_m}\lambda_{qr}[\omega_r-\widehat{\omega}_r] \quad (15)$$

$$(\hat{\imath}_{qs}-i_{qs})=\frac{T_r}{L_m}\lambda_{qr}[\omega_r-\widehat{\omega}_r] \quad (16)$$

Multiplying by the rotor flux and adding them together:

$$(i_{ds}-\hat{\imath}_{ds})\lambda_{qr}=\frac{T_r}{L_m}\lambda_{qr}{}^2[\omega_r-\widehat{\omega}_r] \quad (17)$$

$$(\hat{\imath}_{qs}-i_{qs})\lambda_{qr}=\frac{T_r}{L_m}\lambda_{qr}{}^2[\omega_r-\widehat{\omega}_r] \quad (18)$$

By summing the above two equations

$$(i_{ds}-\hat{\imath}_{ds})\lambda_{qr}+(\hat{\imath}_{qs}-i_{qs})\lambda_{qr}=\frac{T_r}{L_m}(\lambda_{qr}{}^2+\lambda_{dr}{}^2)[\omega_r-\widehat{\omega}_r] \quad (19)$$

Hence, the error of the rotor speed is obtained as follows:

$$\omega_r-\widehat{\omega}_r=\left[(i_{ds}-\hat{\imath}_{ds})\lambda_{qr}-(\hat{\imath}_{qs}-i_{qs})\lambda_{dr}\ \right]/K \quad (20)$$

The right-hand term seems as the term of speed calculation from the adaptive observer, so the speed can be calculated from the following equation:

$$\widehat{\omega}_r=[(K_p(i_{ds}-\hat{\imath}_{ds})\lambda_{qr})-(K_I\int(i_{ds}-\hat{\imath}_{ds})\lambda_{qr}-(\hat{\imath}_{qs}-i_{qs})\lambda_{dr}\ \ )] \quad (21)$$

The vector signals can be estimated if the speed and the stator current signals are known, the above equations provide information on the speed and current components. Those equations are firstly suggested by Blaschke and called Blaschke equations, which are creating the adaptive model [1]. The aim in MRAS-based method is to match the output of both the reference model which not consist the estimated rotor speed ω_r with the output of the adjustable model which consist the rotor speed estimated from the motor. If all the parameters of the motor are known, then the output of the both models should be matched.

The difference between the two models produce an error in the rotor flux reference, which is used to generate the desired speed ω_r. The error generated used as a feedback to the proportional-integral controller in tuning the motor speed. The stability and the accuracy of the dynamic performance depend and affected by the algorithm used in the MRAS-based method. In the most algorithms proposed, the PI controller gives satisfactory results. The accuracy of the algorithm used depend also on tuning the PI controller parameters.

4. Software Implementation

MATLAB/Simulink has been chosen to simulate the IM drives. The main advantages of MATLAB/Simulink are its easy implementation of any control algorithm, including linear control, fuzzy logic, neural networks and others. The graphical tools are comprehensive and very easy to use. There are some disadvantages, however, with Simulink. Incorporating models for real power semiconductors is not yet possible and the complexity of the blocks increase with the number of semiconductors used in the circuit. Therefore, the Power System Blockset (PSB) [15-16] was also used. The PSB is a special toolbox in Simulink, which simulate the power circuit by interconnecting the differential components comprising the real circuit. Compared to Simulink, PSB is simpler as it takes advantage of all MATLAB–Simulink capabilities. It has certain special blocks for simulating ac/dc motors. However, one can easily encounter some convergences problems with the PSB if the parameters are not set properly. Setting values for the blocks in PSB can become a very tricky part of the simulation. In this paper, most of the blocks shown were developed using Simulink, but certain blocks, such as the IGBT model, were taken directly from the PSB libraries.

5. Results

The aim of this study is to compare sensor and sensorless vector control schemes for induction machine drives. The steady state error and the dynamic response during speed step change and the resultant torque of each method can be interpreted as an indication of the accuracy and the reliability of each method. In addition, the sensorless algorithm proposed had been examined during the low-speed performance. Also, the applicability of each method to be implemented in the industrial applications also has been studied.

The study aims to evaluate the control characteristics of speed sensor and sensorless vector control schemes and observe the influence of each method strategy on the motor drives performance.

The evaluation of the system performance through simulation require exact modeling for all the elements of the system to measure the complexity of the proposed method on the dynamic response of the induction machine. To achieve that the simulation carried out by MATLAB/SIMULINK power system Blockset, the advantage of using power system Blockset is to simulate the power circuit with the control system proposed in the same diagram by choosing the proper fixed step integration algorithm. The calculation mechanism in both control systems is the same in both indirect field oriented control and model reference adaptive system. The major difference between the two methods is in the speed estimation, in the field oriented control method the speed is directly measured through shaft encoder speed sensor, while in model reference adaptive system the rotor speed estimated through the motor parameters. The studied system contains a 1 hp, 380 V induction motor fed by three-phase inverters, the parameters of the induction motor are tabulated in Appendix A.

6. Simulation results for the proposed drive system

For studying the response properties of multi-loop control of induction motor drive, a series of simulation have been carried out. In this simulation, the drive response of the control system, for the following cases were studied; at 150, 100 and 75 (rad/sec) speed references at full load.

6.1. Drive response at 150(rad/sec) speed reference

The induction motor drives response at 150(rad/sec) reference speed is used to evaluate the performance in terms of steady state errors and stability. The motor is subjected to full load conditions to evaluate the performance. Fig. 2 shows the estimated rotor speed response with its command speed of 150 rad/sec. It can be seen that the rotor speed is accelerated smoothly to follow its reference value. Fig. 3 shows the simulated (real) rotor speed response. It can be seen that the response of simulated and estimated rotor speed are very close. Fig. 4 shows motor developed torque. Fig. 5 and 6 show the q–axis and d–axis stator current components respectively. The d-axis current component is kept constant; this confirms the correct orientation. Also, the q-axis current profile is close to the motor developed torque, this means that the motor torque is a function of q-axis current. Fig. 7 shows the motor phase current.

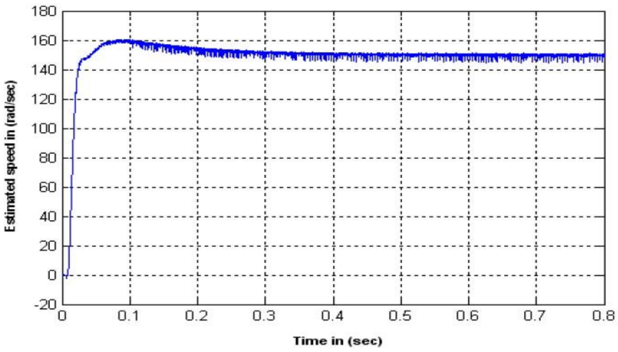

Fig. 2: Estimated Speed via MRAS.

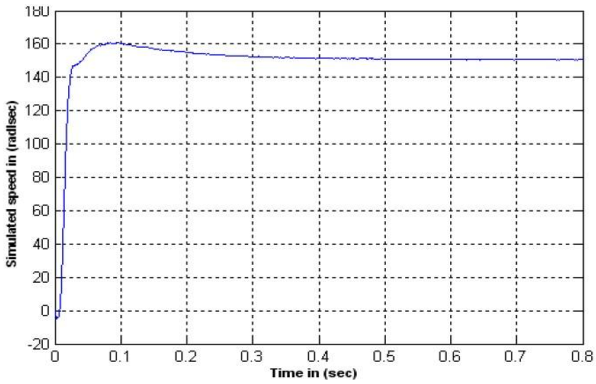

Fig. 3: Estimated Speed via IFOC.

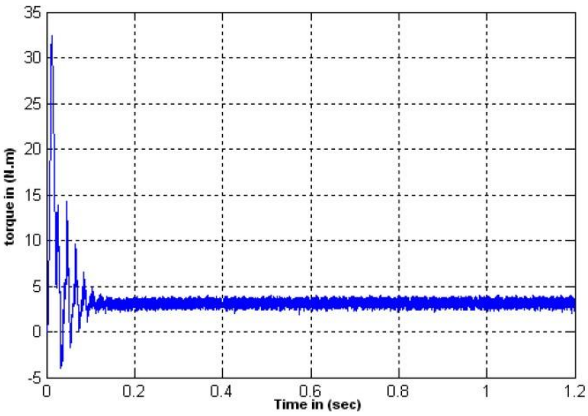

Fig. 4: Motor Developed Torque.

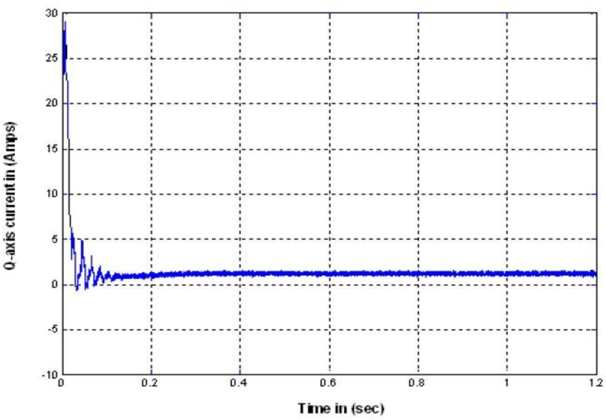

Fig. 5: Q-Axis Current.

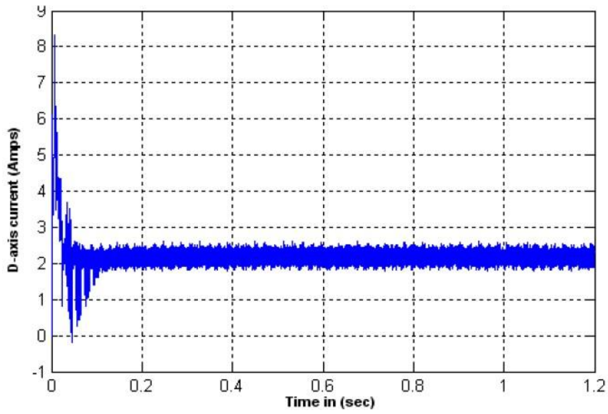

Fig.6: D-Axis Current.

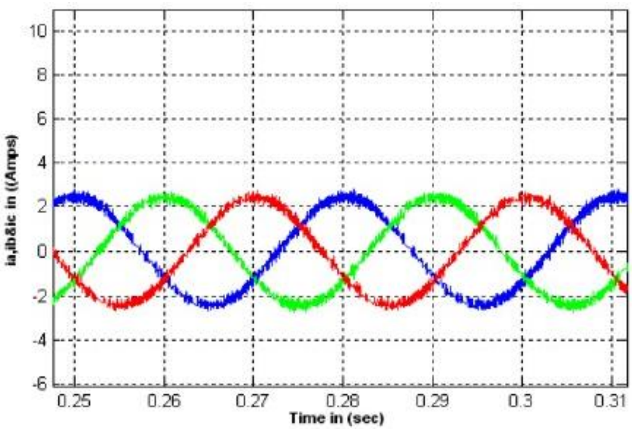

Fig. 7: Three-Phase Motor Current.

6.2. Drive response at 100(rad/sec) speed reference

Another operating point, when the motor subjected to 100(rad/sec) to study the proposed MRAS-based performance. Fig. 8 shows estimated rotor speed. It can be seen the pulsing in speed signal increase compared to 150(rad/sec). This means when speed decreases, the pulsing in the speed signal increase. The estimated speed is similar to simulated speed. Fig. 9 shows the simulated speed. Fig. 10 shows motor developed torque. Fig. 11 and 12 show the q–axis and d–axis stator current components respectively. Fig. 13 shows the motor phase current.

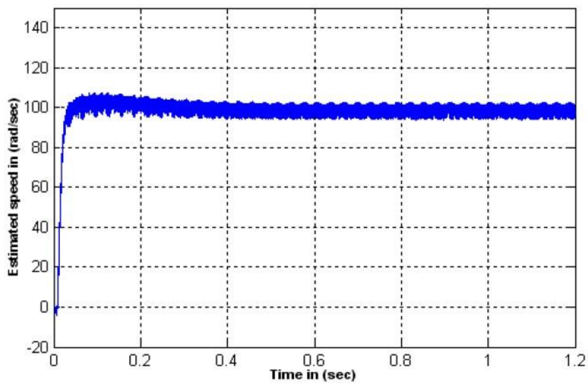

Fig. 8: Estimated Speed via MRAS.

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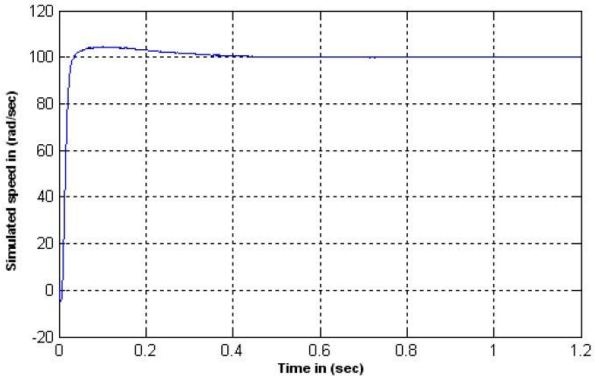

Fig. 9: Estimated Speed via IFOC.

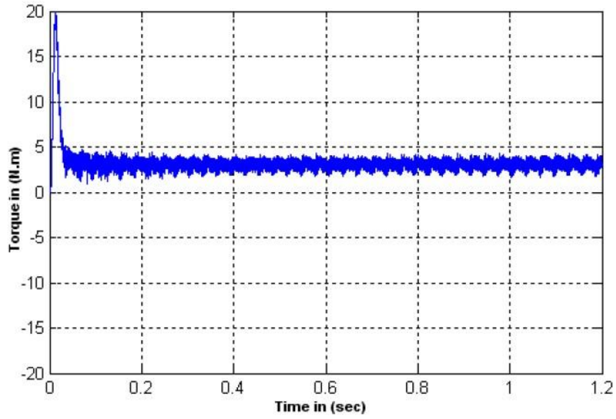

Fig. 10: Motor Developed Torque.

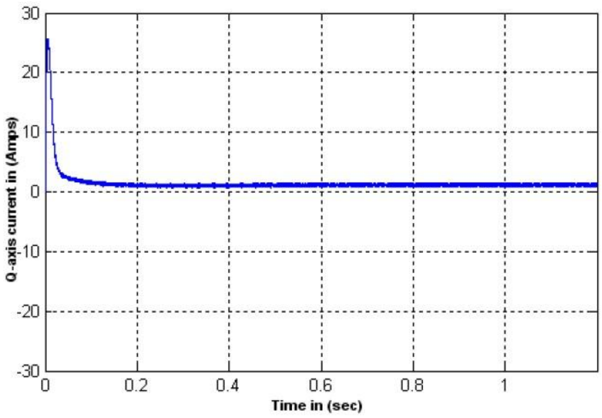

Fig. 11: Q-Axis Current.

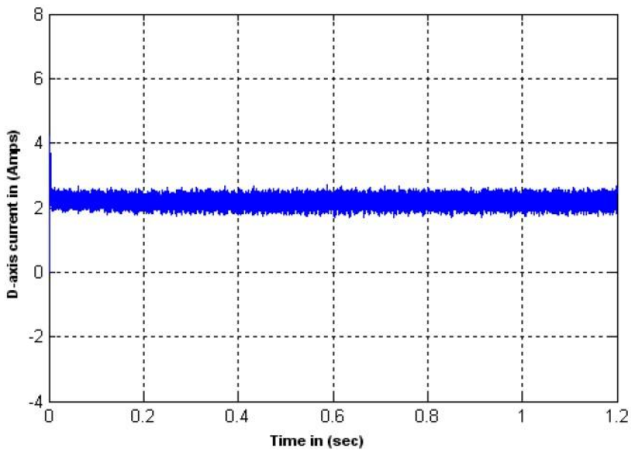

Fig. 12: D-Axis Current.

6.3. Drive response at 75 (rad/sec) speed reference

Another operating point, when the motor subjected to 75 (rad/sec) reference speed to study the proposed MRAS-based performance. Fig. 14 shows the estimated rotor speed response with its command speed of 75 rad/sec. It can be seen the pulsing in speed signal increases when speed decreases to 75(rad/sec). This problem existed in all methods of speed sensorless, because it is difficult to estimate the flux in low and zero speed. Fig. 15 shows the simulated (real) rotor speed response. It can be seen that the response of simulated and estimated is very close. Fig. 16 shows motor developed torque. Fig. 17 and 18 show the q–axis and d–axis stator current components respectively. Fig. 19 shows the motor phase current.

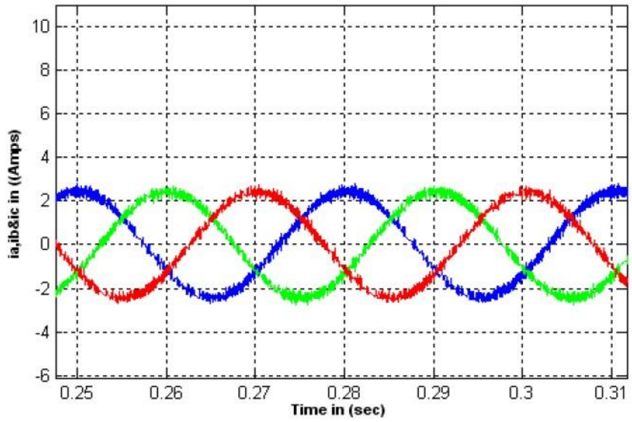

Fig. 13: Three-Phase Motor Current.

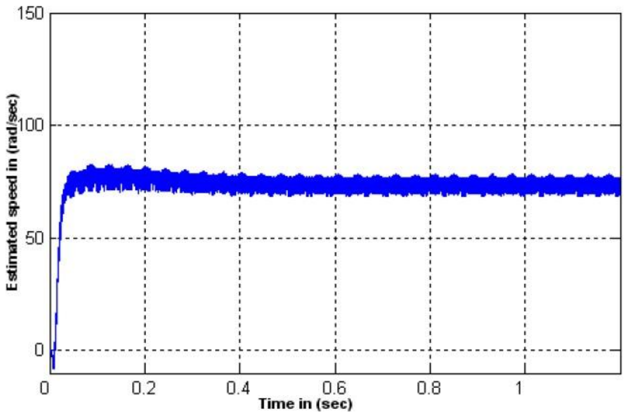

Fig. 14: Estimated Speed via MRAS.

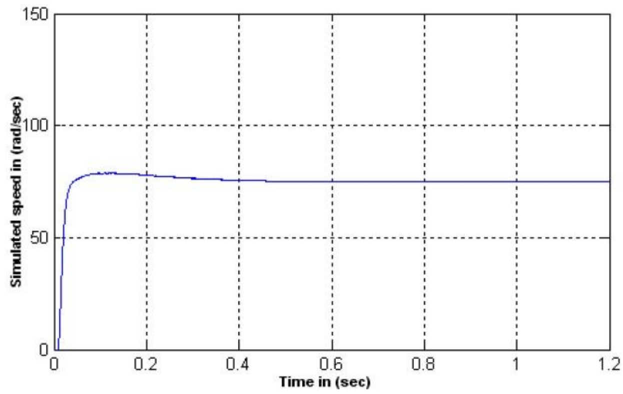

Fig. 15: Estimated Speed via IFOC.

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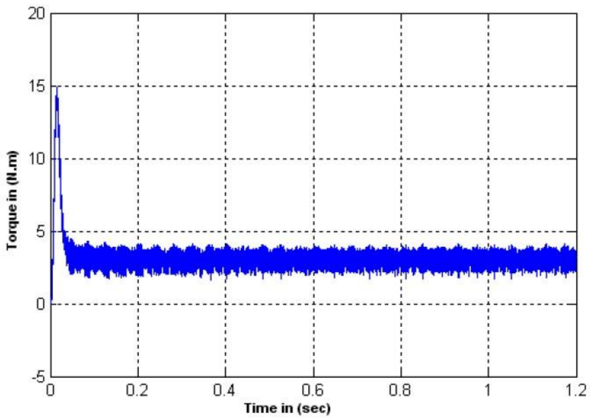

Fig. 16: Motor Developed Torque.

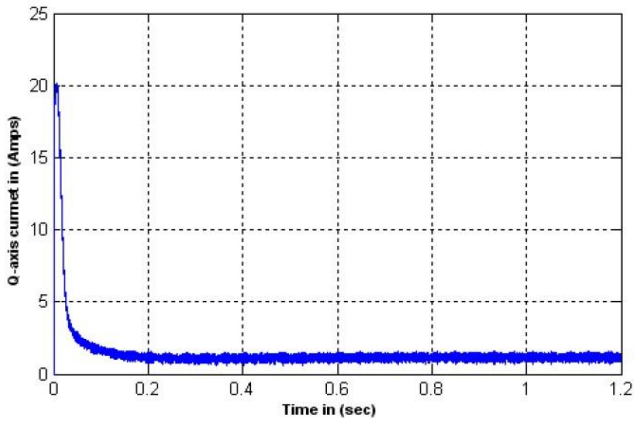

Fig. 17: Q-Axis Current.

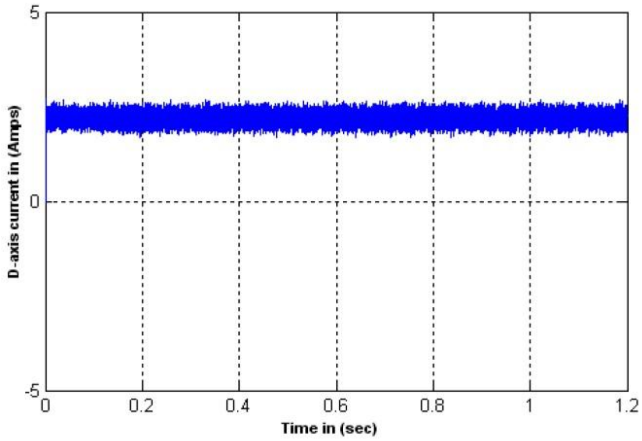

Fig. 18: D-Axis Current.

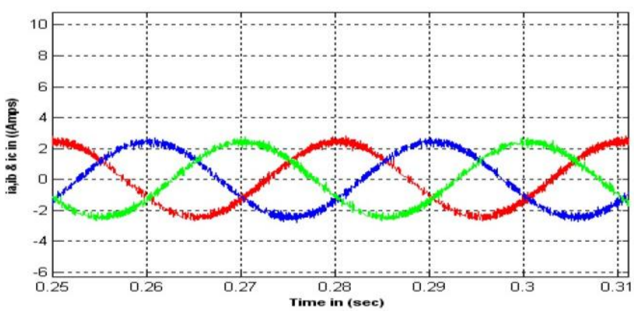

Fig. 19: Three-Phase Motor Current.

6.4. Drive response at step change

The motor response due to a step change in the command speed is used to evaluate the performance in terms of steady state errors and stability. The motor is subjected to step increase and decrease in the reference speed under loading condition to evaluate its performance. Fig. 20shows the estimated speed;it is set initially at 100(rad/sec) at full load condition. After 0.4 second it increased to 150(rad/sec) and returned to 100(rad/sec) after 0.4 second. Fig. 21 shows the simulated speed, it can be seen that the response of simulated and estimated speed are very close. Fig. 22 shows the motor estimated developedtorque, which correspondingly increases, and decreases during the step changes in the reference speed due to the dynamic response.Fig. 23 and 24 show the q–axis and d–axis stator current components respectively. Fig. 25 shows the motor phase current.

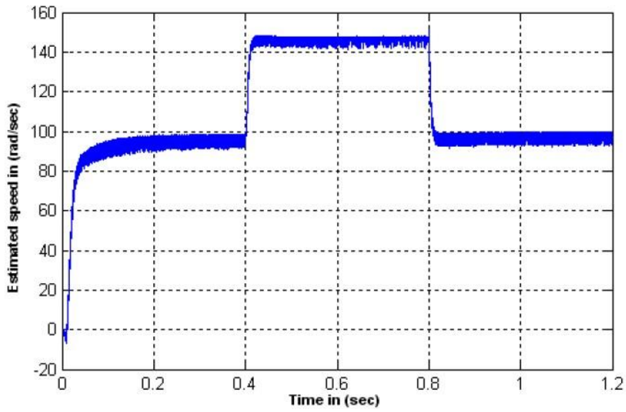

Fig. 20: Estimated Speed via MRAS.

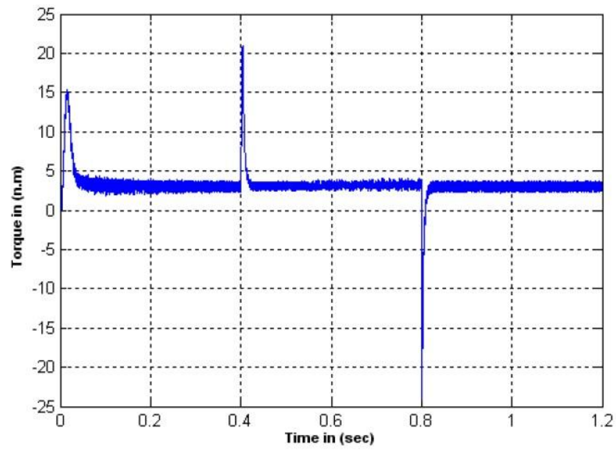

Fig. 21: Estimated Speed via IFOC.

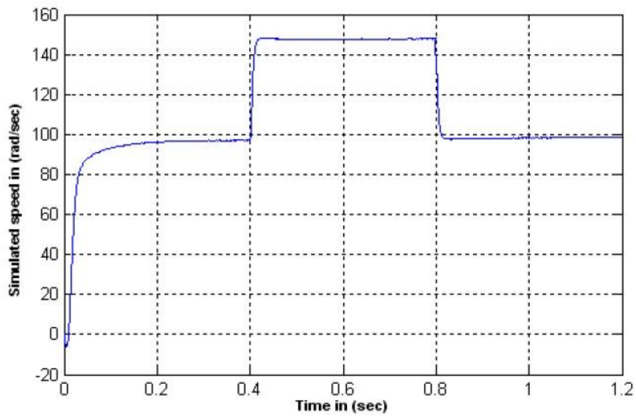

Fig. 22: Motor Developed Torque.

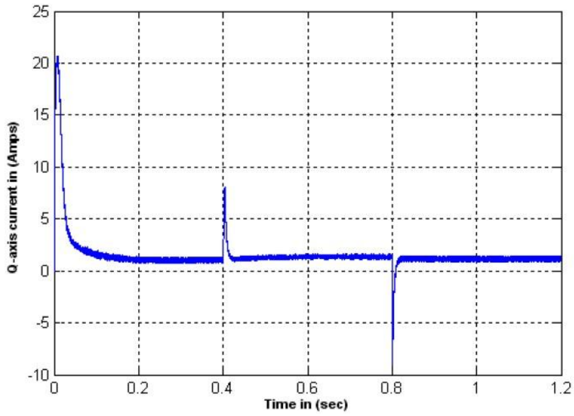

Fig. 23: Q-Axis Current.

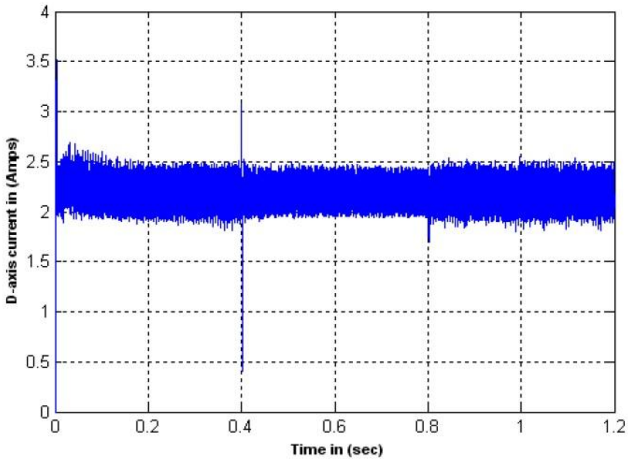

Fig. 24: D-Axis Current.

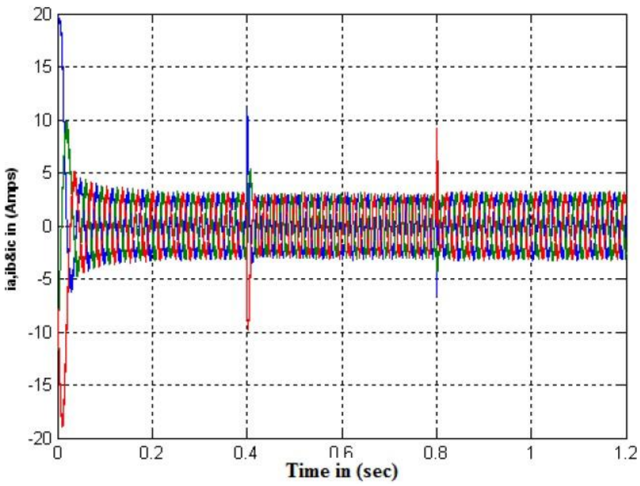

Fig. 25: Three-Phase Motor Current.

6.5. Drive response at Load impact

The motor response due to load impact in the command speed is used to evaluate the performance in terms of steady state errors and stability. The dropped amplitude of the system output such as rotor speed and its recovering time is the important performance specifications. Fig. 26 shows the estimated speed response when a full load impact is applied for 150 rad/sec. The motor started at no load and the full load is applied after 1.5 seconds. After one second, the load released. Fig. 27 shows simulated speed. It can be seen that the response of simulated and estimated speed are very close. Fig. 28 shows the motor estimated developed a torque, which correspondingly increases, and decreases during the step changes in the reference speed due to dynamic response. Fig. 29 and 30 show the q–axis and d–axis stator current components respectively. Fig. 31 shows the motor phase current.

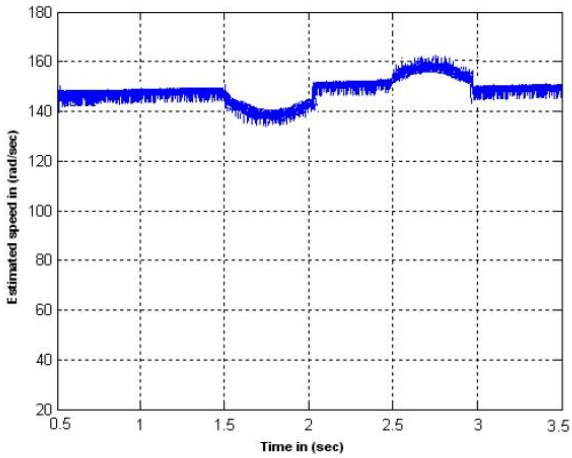

Fig. 26: Estimated Speed via MRAS.

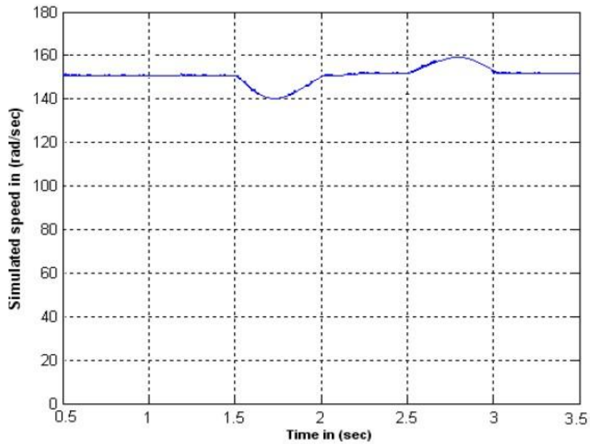

Fig. 27: Estimated Speed via IFOC.

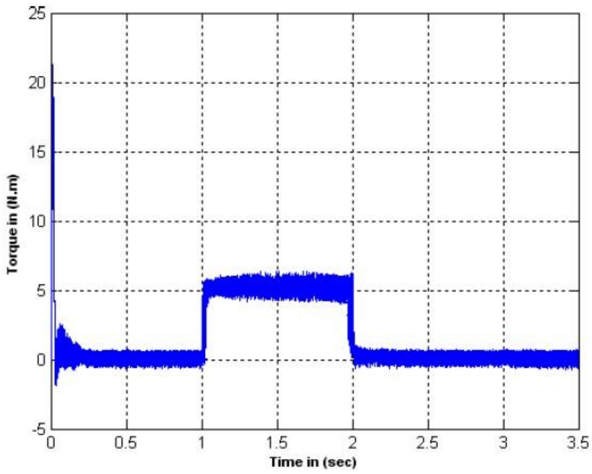

Fig. 28: Motor Developed Torque.

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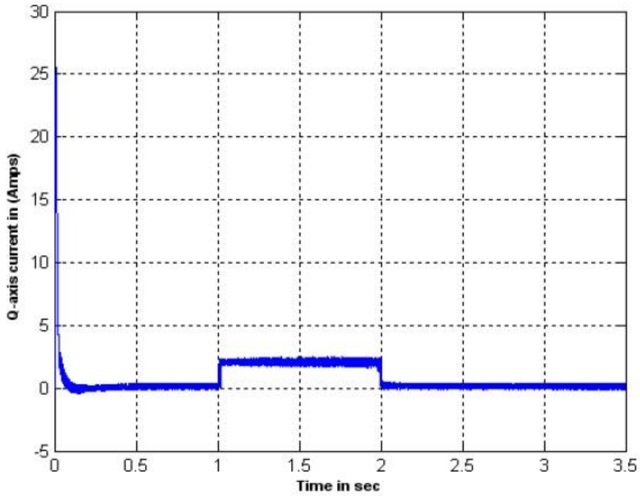

Fig. 29: Q-Axis Current.

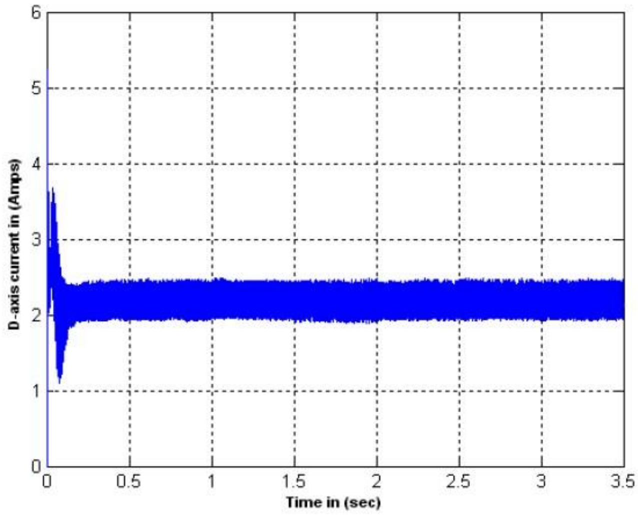

Fig. 30: d-Axis Current.

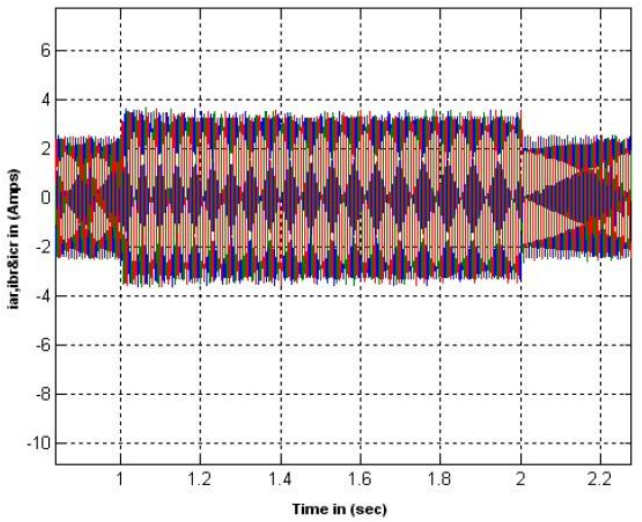

Fig. 31: Motor Developed Torque.

The induction motor can be controlled linearly by applying field orientation control scheme. Multiple loop control method has been investigated by simulation. Series of operating condition used to analysis the drive in the synchronous reference frame have been carried out to verify the control scheme performance.

In addition to the above estimated variables, the rotor speed is estimated in sensorless control. To estimate the rotor speed, some other variables have to be estimated depending on the speed estimation algorithm used. In MRAS, both d- and q-axis components of rotor flux are estimated for reference and adjustable model. These variables are estimated using the stator voltages and currents of the motor to be controlled. The rotor speed depends on the difference between the outputs of the reference model and adjustable model. For MRAS, the problem of choosing the coefficients of the adaptation mechanism as well as loop stability is not straightforward, and it is clear in the oscillation and ripple on the estimated speed obtained by the MRAS-based method.

7. Conclusion

This study focused on the design, and simulation, of the sensorless drive system for induction motor drives, based on theestimation of the rotor speed, and used as a feedback signal for the drives. Speed sensorless control and vector control techniques for IM drives were simulated. The torque and speed characteristics obtained from those results were compared and investigated. In the different cases and scenarios simulated, it is evident that the proposed sensorless control method work just as well as the vector control method. The difference between the two from the hardware point of view is evident in decreasing the number of sensors (current or speed) that are necessary for vector control methods. Sensors generally make the difference in cost for drive control implementation. Because of this, there is a strong interest in vector-controlled drives without any shaft sensor. The advantage of speed sensorless IM drives are increased reliability (no possibility of tachometer failure), lower cost, and reduced the size of the drive system and elimination of sensor cable. However, there are some limitations in speed estimation with sensorless control methods, speed estimation methods experience problems at low speeds, which are responsible for poor performance, and oscillations in the estimated rotor speed. Also further investigation for the effect of the air gap flux saturation, which is concluded from our model should be considered and manipulated and implemented for further accuracy, Fuzzy logic methods for controlling IM drives, which used instead of conventional PI controller could filter and suppress the oscillations and ripples in the estimation of the rotor speed.

References

[1] B.K. Bose, Modern Power Electronics and AC Drives, Prentice-Hall, Upper Saddle River, 2002.

[2] T. Orlowska-Kowalska, M. Dybkowski, "Stator Current-based MRAS Estimator for a Wide Range Speed-sensorless Induction-Motor Drive", *IEEE Trans. on Industrial Electronics*, vol. 57, no. 4, April 2010

[3] J. W. Finch and D. Giaouris, “Controlled AC electrical drives,” *IEEE Trans. Ind. Electron.*, vol. 55, no. 2, pp. 481–491, Feb. 2008.

[4] V. Verma, M.J.Hossain, T. Saha, C. Chakraborty, “Performance of MRAS Based Speed Estimators for Grid Connected Doubly fed Induction Machines during Voltage Dips,” IEEE 978-1-4673- 2729-9/12, 2012.

[5] Teresa Orlowska- Kowalska, Mateusz Dybkowski, “Stator – Current-Based MRAS Estimator for a Wide Range Speed- Sensorless Induction-Motor Drive,” IEEE Transactions on Industrial Electronics, Vol.57, No.4, pp. 1296-1308, April 2010.

ISSN 2522-6967

[6] Abdelrahaman Yousif EshagLesan, Mamadou Lamine Doumbia, Pierre Sicard, “Comparative Study of Speed Estimation Techniques for Sensorless Vector Control of Induction Machine,” IEEE 978-1-4673-2421-2/12, pp. 4298-4303, 2012.

[7] Ahmad Razani Haron, Nik Rumzi Nik Idris, “Simulation of MRAS-based Speed Sensorless Estimation of Induction Motor Drives using MATLAB/SIMULINK,” First International Power and Energy Conference, Putrajaya, Malaysia, pp. 411-415, 2006.

[8] Lin-Yu Lu, Tzu-Wei Yeh, Chia-Chi Chu, “Back-EMF-Based Model-Reference Adaptive Sensorless Control for Grid- Connected DFIGs,” IEEE 978-1-4799-1303-9/13, 2013.

[9] S. Tamai, H. Sugimoto, M. Yano, Speed sensorless vector control of induction motor with model reference adaptive system, Conf. Record of the 1985 IEEE-IAS Annual Meeting, pp. 613–620.

[10] R.D. Lorenz, Tuning of field oriented induction motor controllers for high-performance applications, IEEE Industry Appl. Soc. Annu. Meet. (1985) 607–612.

[11] H. Tajima, Y. Hori, Speed sensorless field orientation control of the induction machine, IEEE Trans. Industry Appl. 29 (1) (1993) 175–180.

[12] S. M. Krishna and J. L. F. Daya, "Dynamic performance analysis of MRAS based speed estimators for speed sensorless induction motor drives," *2014 International Conference on Advances in Electronics Computers and Communications*, Bangalore, 2014, pp. 1-6.

[13] A. Y. E. Lesan, M. L. Doumbia and P. Sicard, "Comparative study of speed estimation techniques for sensorless vector control of induction machine," *IECON 2012 - 38th Annual Conference on IEEE Industrial Electronics Society*, Montreal, QC, 2012, pp. 4298-4303.

[14] Rajalakshmi, D., et al. "Analysis of Speed Estimation for Sensorless Induction Motor Using Model-Based Artificial Intelligent Estimation Techniques. “Proceedings of the International Conference on Soft Computing Systems. Springer India, 2016.

[15] User’s Manual-Power System Blockset for use with Simulink, The Mathworks Inc., Natick, MA, 2001.

[16] Advanced electric drives: analysis, control, and modeling using MATLAB/Simulink® / Ned Mohan, Copyright © 2014 by John Wiley & Sons, Inc. All rights reserved.

Appendix A: Induction machine data

A 1 HP, 380 V Three-Phase induction machine was used to simulate vector control, MRAS using MATLAB/Simulink with the following data:

Motor Rated Power	1 hp
No. of Poles	4
Motor Inertia	0.02 Kg.m^2
Friction co-efficient	0.0008 Kg.m^2/s
Stator resistance	7.4826 Ohm
Rotor resistance	3.834 Ohm
Stator self-inductance	0.4335 H
Rotor Self-Inductance	0.4335 H
Magnetizing inductance	0.4111 H

Appendix B: Vector Control Parameters

SYMBOL	PARAMETER’S NAME	VALUE	UNIT
λrc	Flux Command	0.9	P.U
P	Speed PI Proportion Gain	0.25	
I	Speed PI Integral Gain	1	

Appendix C:NOMENCLATURE

$I_{qs}^{e^*}$	Quadrature-Axis Component of the Stator Current Command in The Synchronous Reference Frame
L_r	Rotor Self Inductance
L_m	Mutual Inductance
$I_{qr}^{e^*}, I_{dr}^{e^*}$	Quadrature and Direct-Axis Component of the Rotor Current Command in The Synchronous Reference Frame
$\lambda_{dr}^{e^*}$	Direct-Axis Component ofthe Rotor Flux Command in The Synchronous Reference Frame
ω_{sl}^*	Command Slop Angular Speed
R_r	Rotor Resistance
ω_r^*	Rotor Speed Command
i_{ds}	Direct-Axis Component of the Stator Current
λ_{dr}	Direct-Axis Component of the Rotor Current
T_r	Rotor time constant
$\hat{\imath}_{ds}, \hat{\imath}_{qs}$	Direct and Quadratic Axis Estimated Stator Current
$\widehat{\omega}_r, \omega_r$	Actual Rotor and Estimated speed