Reduced-order observer for real-time implementation speed sensorless control of induction using RT-LAB software

Mansour Bechar¹, Abdeldjebar Hazzab², Mohamed habbab³, Pierre Sicard⁴
¹,²,³ Laboratory of Research Control, Analysis and Optimization of Electro-Energetic Systems, University of Tahri Mohammed, Algeria
⁴ Groupe de Recherche en Electronique Industrielle (GREI) Université du Québec à Trois-Rivières, Canada

Article Info

ABSTRACT

In this paper, Reduced-Order Observer For Real-Time Implementation Speed Sensorless Control of Induction Using RT-LAB Software is presented. Speed estimation is performed through a reduced-order observer. The stability of the proposed observer is proved based on Lyapunov’s theorem. The model is initially built offline using Matlab/Simulink and implemented in real-time environment using RT-LAB package and an OP5600 digital simulator. RT-LAB configuration has two main subsystems master and console subsystems. These two subsystems were coordinated to achieve the real-time simulation. In order to verify the feasibility and effectiveness of proposed method, experimental results are presented over a wide speed range, including zero speed.

Keywords:
Induction motor
OP5600 digital simulator
Real-time sensorless control
Reduced-order observer
RT-LAB Software

Corresponding Author:
Mansour Bechar,
Laboratoire de Recherche Commande, Analyse et Optimization des Systèmes Electro-énergétiques,
Université Tahri Mohamed de Bechar, BP 417, Bechar (08000), ALGERIA
Email: mansourbechar@gmail.com

1. INTRODUCTION

In power electronics control of AC machine drives many methods employed of control in various high performance industrial applications [1]. This has been conventionally achieved by using DC motors with their simple control structure. AC machines are generally inexpensive, compact and robust with low maintenance requirements compared to DC machines but require complex control [2].

High performance scalar control of induction motor control require speed or position information for its operation. Generally speed or position transducers provide this information. However these mechanical sensors are costly and fragile. On the other hand, sensorless drives operating without speed or position transducers have the advantage of reduced hardware complexity and lower cost, reduced size of the drive machine, elimination of the sensor cable, better noise immunity, increased reliability, and less maintenance requirements [3]. Due to these reasons speed sensorless systems, in which rotor speed measurements are not available, are preferred and find applications in many areas for speed regulation, load torque rejection and speed tracking purposes.

Estimation of unmeasurable state variables is commonly called observation. A device (or a computer program) that estimates or observes the states is called a state-observer or simply an observer. If the state-observer observes all state variables of the system, regardless of whether some state variables are available for direct measurement, it is called a full-order state-observer. An observer that estimates fewer than the dimension of the state-vector is called reduced-order state-observer or simply a reduced-order observer. If the order of the reduced-order state-observer is the minimum possible, the observer is called minimum-order state-observer [4].
Many researchers have focused on the design of sensorless control algorithms for induction motor. Reduced-order observer is used for speed estimation, one of its disadvantages is the sensitivity to parameter variation especially at low speed or under load application. Various methodologies have been exploited for speed estimation: Adaptive Observers [5], Sliding Mode Technique [6], Extended Kalman Filter [7], MRAS observers [8]. Figure 1 shows a chart of the different speed sensorless estimation strategies:

![Chart showing different speed sensorless estimation strategies](image)

The problem of sensorless controlled induction motor related to the stability of the control method. This is usually faced with direct field oriented control and direct torque control strategies, combined with speed-flux observer. The aim of this paper is to test a reduced order observer for speed sensorless control of IM and its stability over a wide speed range. For the detailed stability analysis the reader could refer to [9-12].

In this research paper, reduced-order observer for speed sensorless scalar control of induction motor has been designed and implemented in real-time using RT-LAB package. The proposed observer estimates the rotor speed, the stator currents. For developing the sensorless control algorithm, modeling of induction motor is presented. Lyapunov’s stability criterion is employed to estimate rotor speed. The experimental results show the effectiveness of the proposed sensorless control method based on a reduced-order observer.

2. INDUCTION MOTOR MODEL

The dynamic model of induction motor in stationary reference frame $\alpha$, $\beta$ may be written as given [13-15]:

\[
\begin{align*}
\frac{di_{sa}}{dt} &= -\frac{1}{\sigma L_s} \left( R_s \left( \frac{L_m}{L_r} \right)^2 + \frac{L_m R_r}{\sigma L_s L_r} \right) i_{sa} + \frac{L_m R_r}{\sigma L_s L_r} \varphi_{ra} + \frac{L_m}{\sigma L_s L_r} \omega r \varphi_{rb} + \frac{1}{\sigma L_s} V_s a
\end{align*}
\]

\[
\begin{align*}
\frac{di_{sb}}{dt} &= -\frac{1}{\sigma L_s} \left( R_s \left( \frac{L_m}{L_r} \right)^2 + \frac{L_m R_r}{\sigma L_s L_r} \right) i_{sb} - \frac{L_m}{\sigma L_s L_r} \omega r \varphi_{ra} + \frac{L_m R_r}{\sigma L_s L_r} \varphi_{rb} + \frac{1}{\sigma L_s} V_s b
\end{align*}
\]

\[
\begin{align*}
\frac{d\varphi_{ra}}{dt} &= \frac{L_m R_r}{L_r} i_{sa} - \frac{R_r}{L_r} \varphi_a - \omega r \varphi_{rb}
\end{align*}
\]

\[
\begin{align*}
\frac{d\varphi_{rb}}{dt} &= \frac{L_m R_r}{L_r} i_{sb} + \omega r \varphi_{ra} - \frac{R_r}{L_r} \varphi_b
\end{align*}
\]

where:
L_m, L_s, L_r are magnetizing, rotor self-leakage and stator self-leakage inductances, R_s, R_r are rotor and stator resistances, σ is leakage coefficient\(\sigma = 1 - \frac{L_m}{L_r L_s}\).

The electromagnetic torque can be expressed by:

\[
T_e = \frac{3}{2} P L_m (\varphi_m i_{\beta} - \varphi_0 i_{\alpha})
\]

(2)

3. DESIGN OF REDUCED-ORDER OBSERVER

In this paper the rotor speed and the stator currents \(i_s , i_{\beta}\) were estimated using reduced-order observer, the state equation of the induction machine is given as follows:

\[
\dot{X} = AX + BU + K(Y - \hat{Y})
\]

(3)

\[
A = \begin{bmatrix} -1 & -\dot{w} \\ \dot{w} & -\frac{1}{Tr} \end{bmatrix}; \quad B = \begin{bmatrix} \frac{L_m}{Tr} & 0 \\ 0 & \frac{L_m}{Tr} \end{bmatrix}; \quad K = \begin{bmatrix} k1 & k2 \\ -k2 & k1 \end{bmatrix}
\]

where \(A\) is the estimated value and \(K\) is the observer gain matrix with:

\[
\dot{X} = \begin{bmatrix} \dot{\phi}_{r\alpha} \\ \dot{\phi}_{r\beta} \end{bmatrix}, \quad Y = \begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix}, \quad U = \begin{bmatrix} V_{s\alpha} \\ V_{s\beta} \end{bmatrix}, \quad \dot{Y} = \begin{bmatrix} \dot{i}_{s\alpha} \\ \dot{i}_{s\beta} \end{bmatrix}
\]

The estimation error can be expressed as follows:

\[
\dot{e} = (A + KB)e + \Delta A \begin{bmatrix} \dot{\phi}_{r\alpha} \\ \dot{\phi}_{r\beta} \end{bmatrix}^T
\]

(4)

\[
e = \begin{bmatrix} e_{\phi_{r\alpha}} \\ e_{\phi_{r\beta}} \end{bmatrix}^T
\]

where

\[
\Delta A = \dot{A} - A
\]

The following Lyapunov function is defined:

\[
V = e^T \cdot e + l(\dot{w} - w)^2
\]

(5)

where \(l\) is a positive constant.

The observer gain matrix \(K\) is chosen such that the derivative of a positive definite Lyapunov function \(V\) becomes negative definite as explained in [16].

The rotor speed of induction motor can be estimated by PI controller:

\[
\dot{w} = \left( Kp + \frac{Ki}{s} \right) \cdot \left( e_{\phi_{r\beta}} \dot{\phi}_{r\alpha} - e_{\phi_{r\alpha}} \dot{\phi}_{r\beta} \right)
\]

(6)

where \(Kp\) and \(Ki\) are the proportional and integral constants, respectively. The block diagram of speed estimation of induction motor can be considered as shown in Figure 2.
4. SCALAR CONTROL SCHEME

Due to its simplicity, scalar control is one of the most commonly used methods in industry machine drives. However, its dynamic performance is limited, even in closed loop, particularly when operating in regions of low speed [17].

The essence of control to maintain a constant scalar Voltage/Frequency ration (V/f) in order to maintain the magnetic flux in air-gap constant at maximum value. If the voltage does not have a proper relationship with the frequency. The machine can operate in the saturation or field weakening region [18]. The electromagnetic flux produced can be calculated by using the relationship between the voltage and electromagnetic flux, expressed as:

$$V_s = \alpha_s \phi_s$$  \hspace{1cm} (8)

Hence the relationship voltage and frequency, by maintaining the constant stator flux. The principal scheme of speed sensorless control of induction motor based on a reduced-order observer is shown in Figure 3.
5. DESCRIPTION OF REAL-TIME SIMULATION AND SETUP LABORATORY

The simulation of sensorless control algorithm is executed on OP5600 real-time digital simulator using one of a dual quad-core computer. Table 1, Summarizes the characteristics of the RT-LAB system used in this research paper.

| Items       | Quantity | Description                           |
|-------------|----------|---------------------------------------|
| Operating system | 1        | Redhat                               |
| Chassis     | 1        | OP5600 Chassis (OP5142)               |
| CPU         | 1        | 1*(4 cores 2.4 GHZ)                  |
| Memory      | 1        | 4GB                                  |
| Motherboard | 1        | X8DTL-1-O                            |
| OP5340 Ain  | 1        | 16Ch                                 |
| OP5330 Aout | 1        | 16Ch                                 |
| OP5353 Din  | 1        | 32Ch                                 |
| OP5354 Dout | 1        | 32Ch                                 |

RT-LAB simulator also is equipped with Xilinx Spartan 3 programmable FPGA card. The FPGA card can be programmed with Xilinx system generator blockset for Simulink enabling implementation of complex sensor models like resolvers or even complex motor drives [20, 21].

The development process of the integrated Simulink model include following steps:
- Construct block diagram models of the integrated sensorless control algorithm utilize Matlab/Simulink, and then verify feasibility of the algorithm through offline simulation.
- Covert Simulink models into RT-LAB compatible models, based on RT-LAB model design specification.
- Use (RTW) and model separation to generate real-time C code, and uploaded the C code into OP5600 digital simulator to perform real-time simulation.
- Executing the model by launching the real-time Simulation on all the nodes (parallel execution).

The RT-LAB platform is composed of one host PC and one real-time target computer as shown in Figure 4. The network connection TCP/IP protocol is used for communication between computers; the host PC controls simulation through RT-LAB console subsystem. The master subsystem model of sensorless control algorithm is converted into C code using Matlab real-time Workshop (RTW) facility, this generated C code is downloaded to target computer via Ethernet link [22]. Subsystem console runs in the host PC used to display the real-time sensorless control algorithm results.

![Figure 4. Structure of the RT-LAB simulator with the attached real-plant.](image)

The experimental setup of the real-time sensorless control of induction motor based on a reduced order observer is shown in Figure 5. The experimental test has been carried out to verify the effectiveness of the proposed reduced order observer, a 3-ph induction motor fed by a three phase Drivelab Board inverter is chosen. The switching frequency was set at 19kHz, while the time-step was fixed to 100μs.
6. EXPERIMENTAL RESULTS

The real-time implementation of reduced-order observer results have been obtained by using GW-
Instek numerical oscilloscope which was linked with the real-time analog outputs interfaces. Figure 6(a) depicts the actual motor speed and the estimated speed, while Figure 6(b) shows the zoomed version of Figure 6(a).

It can be noticed that the estimated speed follows the real speed at different points of speed range (2388, 2866, 3344, 1910rpm) the estimation error converges to zero. It’s clear that the drive system works at a wide range of speeds, to reveal the effectiveness of the proposed reduced order observer four steps change applied to speed reference, the model was compiled and executed with sampling time of 50 µs on OP5600 real-time digital simulator, the operation with change in reference speed is the main focus of this paper and the great challenge for estimation algorithms designed for the speed-sensorless control of induction motors. Figure 6(a) indicates the good tracking characteristics and more effectiveness, the estimated speed always followed the reference. The step change of the reference speed doesn’t affect the performance of the system. The advantage of this work in that the reduced order observer is simple to implement in real-time and doesn’t contain complex calculations and has good performances compared to another full order observers that requires more calculation time and not easy to implement those full order observer in real-time.

![Experimental setup of RT-LAB platform at CAOSEE Laboratory.](image)

Figure 6. Speed curves, (a) The reference, actual and estimated speed with estimation error, (b) Zoomed version of (a)
As shown in Figure 8 the estimated stator current components converge to the real stator current components with small phase shift, it’s clear that the waveforms of currents are sinusoid.

From the above experimental results we concluded that that the sensorless control scheme associated with reduced-order observer has a fast response time and good estimation accuracy over a wide speed range.

7. CONCLUSION

In this paper, a reduced-order observer for speed sensorless scalar control of induction motor is presented and implemented in real-time. The drive system with the proposed observer is built offline using Matlab/Simulink blocksets and executed in real-time using RT-LAB package and an OP5600 target. Digital simulations and experimental setup have been carried out in order to validate the proposed sensorless diagram. The experimental results show that the drive system works at a wide range of speeds, this indicates the good accuracy and robustness of the designed observer.

APPENDIX INDUCTION MOTOR PARAMETERS

The parameters of the three-phase Induction motor, employed for real-time implementation, in SI units are: 120W, 133Hz, P=2, Rs=1.05 ohm, Rr=1.705 ohm, Ls=0.02939 H, Lr=0.02939 H, Lm=0.02526 H, J=0.00037 Kg.m^2, fr=0.00006 SI.
REFERENCES

[1] A. Gouichiche, M. S. Boucherit, A. Safa, Y. Messlem, “Sensorless Sliding Mode Vector Control of Induction Motor Drives” International Journal of Power Electronics and Drive Systems (IJPEDS), Vol. 2, No. 3, 2012.

[2] J. W. Finch and D. Giaouris, “Controlled AC Electrical Drives,” IEEE Transactions on Industrial Electronics, vol. 55, no 1, pp. 1-11, Feb. 2008.

[3] Joachim Holtz, “Sensorless Control of Induction Motor Drives,” proceedings of the IEEE, vol. 90, no. 8, august 2002.

[4] Bilal Akin, “State Estimation Techniques for Speed Sensorless Field Oriented Control of Induction Motors,” thesis, The Middle East Technical University, August 2003.

[5] H. Kubota and K. Matsuse, “Speed sensorless field-oriented control of induction motor with rotor resistance adaptation,” IEEE Trans. Ind. Appl., vol. 30, no. 5, pp. 1219 –1224, Sep. 1994.

[6] T. Chen, J. Chang, and K. Tsai, “Integral-variable-structure-control-based adaptive speed estimator and resistance identifier for induction motor,” Int. J. Control, vol. 69, no. 1, pp. 31–47, 1998.

[7] Y. Kim, S. Sul, and M. Park, “Speed sensorless vector control of induction motor using extended Kalman filter,” IEEE Trans. Ind. Appl., vol. 30, no. 5, pp. 1225–1233, Sep. 1994.

[8] C. Schauder, “Adaptive speed identification for vector control of induction motors without rotational transducers,” IEEE Trans. Ind. Appl., vol. 28, no. 5, pp. 1054–1061, Sep./Oct. 1992.

[9] Y. Beddiaf, F. Zidani, L. Chrifi-Aloui, “Modified speed sensorless indirect field-oriented control of induction motor drive,” Int. J. Modelling. Identification and Control, vol. 25, no. 4, pp. 273–286, 2016.

[10] M. Montanari, Sergei M. Peresada, “Speed sensorless control of induction motors based on a reduced-order adaptive observer,” IEEE Trans. Control Systems Technology., vol. 15, no. 6, pp. 1049–1064, Nov. 2007.

[11] S. Alizea Davari, D. Arab Khaburi, F. Wang, R. M. Kennel, “Using full order and reduced order observers for robust sensorless predictive control of induction motors,” IEEE Trans. Power Electronics., vol. 27, no. 7, pp. 3424–3433, July. 2012.

[12] A. A. Z. Diab, V. N. Anosov, “Implementation of full order observer for speed sensorless vector control of induction motor drive,” 15th International Conference on Micro/Nanotechnologies and Electron Devices EDM, pp. 347–352, 2014.

[13] G. Tarchala, T. Orlowska-Kowalska, “Sliding mode speed observer for the induction motor drive with different function approximation forms and gain adaptation,” Przegl. Elektrotechniczny, vol. 89, pp. 1-6, 2013.

[14] I. Bendaas, F. Naceri, “A new method to minimize the chattering phenomenon in sliding mode control based on intelligent control for induction motor drives,” Serb. J. Electr. Eng, vol 10, pp. 231-246, June. 2013.

[15] M. Habbab, A. Hazzab, P. Sicard, “Real-Time Implementation of Fuzzy Adaptive PI-Sliding Mode Controller for Induction Machine Control”, International Journal of Electrical and Computer Engineering (IJEEC), vol 8, no 5, 2018.

[16] Y. Beddiaf, F. Zidani, Larbi.Chrifi.Alaoui and S. Drid, “Modified Speed Sensorless Indirect Field-Oriented Control of Induction Motor Drive,” International Journal Modelling, Identification and control, vol 25, no 4, pp. 273- 286, 2016.

[17] M. Suetake, I.N. Silva, A. Goedtel, “Embedded dsp-based compact fuzzy system and its application for induction-motor v/f speed control,” IEEE Transactions on Industrial Electronics, vol 58, no. 3, pp. 750-760, 2011.

[18] B.K. Bose, Modern power electronics and AC drives, Prentice-Hall, New Jersey, 2001.

[19] K.Vinoth Kumar, S.Suresh Kumar, Kishore Reddy, “Implementation of Scalar Control Technique in SVPWM Switched Three-level Inverter Fed Induction Motor Using DSP Controller,” International Journal of Power Electronics and Drive System (IJPEDS), vol.1, no.2, pp. 83–93, December 2011.

[20] C. Dufour, J. Bélanger, V. Lapointe, “FPGA-Based Ultra-Low Latency HIL Fault Testing of a Permanent Magnet Motor Drive using RT-LAB-XSG”, Simulation: Transactions of the Society for Modeling and Simulation International, SAGE Publications, vol.84, issue 2/3, February/March 2008, pp. 161-172.

[21] C. Dufour, J. Bélanger, S. Abourida, V. Lapointe, “FPGA-Based Real-Time Simulation of Finite-Element Analysis Permanent Magnet Synchronous Machine Drives”, Proceedings of the 38th Annual IEEE Power Electronics Specialists Conference (PESC’07), Orlando, Florida, USA, June 17-21, 2017.

[22] M. Bechar, A. Hazzab, M. Habbab, “Real-Time Scalar Control of Induction Motor using RT-LAB Software,” The 5th International Conference on Electrical Engineering (ICEE-B), October. 2017.
BIOGRAPHIES OF AUTHORS

Mansour Bechar was born in Bechar, Algeria. He received the M.S. degree in electrical engineering from Tahri Mohammed University in 2015. Where he is currently working toward the Ph.D. degree in electrical engineering. His research interests include power electronics, process control. Observer and estimator design for induction motor drive systems, renewable energy.

Hazzab Abdeldjebar received his State Engineer, M.S., and Ph.D degrees in Electrical Engineering from the Electrical Engineering Institute of The University of Sciences and Technology of Oran (USTO), Algeria in 1995, 1999, and 2006, respectively. He is currently a Professor of Electrical Engineering at the University of Bechar (Algeria), where he has been the Director of the Research Laboratory of Command, Analyses, and Optimization of Electro-Energetic Systems since 2009. His research interests include power quality, modeling, modern controller and observer design for nonlinear systems, control of power electronics and multidrive systems, control of power electronics, multidrive systems and electrical vehicle, and adaptive control and nonlinear systems diagnostic, adaptive control, neural networks and fuzzy logic systems.

Mohamed Habbab was born in 1969 at Relizane-Algeria, received the state engineer degree in electronic engineering in 1994 from the University of Sciences and Technology of Oran (USTO), Algeria the M.Sc. degree from the University of Bechar. He’s currently preparing his Ph.d. degree in electronic engineering.

Pierre Sicard received the bachelor degree in technology of electricity from the Ecole de Technologie Supérieure, Montréal QC, Canada, in 1985, the M.Sc degree in industrial electronics from the University of Québec in Trois-Rivières, Trois-Rivières, QC, Canada, in 1990, and the Ph. D. degree in electrical engineering from Rensselaer Polytechnic Institute, Troy, New York, USA, in 1993. In 1992, he joined the University of Québec in Trois-Rivières as professor in electrical and computer engineering, where he has been director of the Research Group in Industrial Electronics since 2004. His research interests include power quality, modeling, controller and observer design for nonlinear systems, control of power electronics and multidrive systems, passivity-based control, adaptive control, and neural networks.