

Online Speed and Stator Resistance Estimation via an MRAS-Sliding Mode Observer for Induction Motors

F. Mehazzem^{1,2}, A. Reama³, A. Cela³, and H. Benalla²

¹Sciences and technology Department, Oum El Bouaghi University, Algeria,
e-mail: fateh_me@yahoo.fr

²Laboratoire Electrotechnique de Constantine, Université Mentouri-Constantine, Algérie
e-mail: benalladz@yahoo.fr

³Université Paris-Est, ESIEE Paris, Embedded Systems Department,
Cité Descartes –BP 99- 2, Bd Blaise Pascal – 93162 Noisy-Le-Grand Cedex, France
e-mail : a.reama@esiee.fr

Abstract- This paper deals with parallel speed and stator resistance estimation for sensorless induction motors drives purpose. For that, a novel MRAS structure is proposed. It is based mainly on the use of a very robust sliding mode flux observer as reference model, which gives robustness to the whole parameters estimation operation. Unlike to classical MRAS structure, based on the use of pure integrators, which have initial value and drift problems.

By using the proposed MRAS-Sliding mode observer, the system has a better performance and robustness. The effectiveness of this proposed estimation structure is verified by experiment under critical disturbance conditions.

Index Terms— Induction motor, MRAS, Parallel speed and stator resistance estimation, Sliding mode flux observer.

I. INTRODUCTION

It is well known that control laws quality for controlling the induction motor requires a good knowledge of state variables required and the parameters involved in the model. Access to these quantities requires the state measured by sensors whose accuracy is crucial for the performance level required by some industrial applications. The cost of these sensors and their lack of precision, make this task very difficult. To solve these problems, it is essential to use software sensors through the design of observers and estimators.

In induction machine control, the problem of observation arises especially for rotor flux that is not states accessible to the extent and speed rotor through a mechanical sensorless control.

For parametric variations, the rotor and stator resistances are the parameters of the machine the most critical, because their influence is crucial as it is for the control or observation. These parameters can vary up to 100% of their nominal values, due to temperature variation.

Several types of observers and estimators exist in the literature. Among the techniques used may be mentioned: high gain observer [1], the observer of Luenberger [2], the techniques of extended Kalman filter (EKF) [3], adaptive

observers [4], techniques based on adaptive systems reference model (MRAS) [5], and techniques based on sliding mode [6]. Each of these techniques has advantages and disadvantages. The techniques that have attracted the most attention in the literature are: the extended Kalman filter, which is based on solving the Riccati equation from the linearized mathematical model of the machine, and takes into account the variations parametric and noise measurements. This technique has been used both to observe the flux and speed [7] for parameter estimation [8]. This technique has the advantage of the robustness and drawback of the intensity calculations and the need for proper initialization.

The second attractive technique is based on an MRAS structure in which an error vector is formed from the outputs of two independent models. This error is brought to zero by adjusting the variable estimated through an adaptation mechanism. This variable influences one model and not the other. The influenced model is called adjustable model and the other is called the reference model. MRAS structure differs from another by the choice of the output variable of the two models, as well as the choice of the adaptation mechanism. The most common choice of the output variable of the two models is the rotor flux. The MRAS structure based on such a choice has the advantage of estimating the angle of the rotor flux, which can be used as part of a field oriented control. The disadvantage of such a structure is the sensitivity at low speeds, variation of the stator resistance and the drift of the integrator. Other choices of the output variable have been proposed and are based on the electromotive force (EMF) or reactive power [9,10]. Unfortunately, these techniques have not led to satisfactory solutions for the structures based on those choices are always problems at low speed.

The MRAS structure approach has been used both to estimate the speed in a sensorless control and for parameter estimation in real time [11]. It has advantage of having a direct physical interpretation, because of its easy implementation.

The sliding mode technique has also an extensive development in recent years. This approach is based on a

discontinuous control to force the system state to reach a sliding surface in a first step, and then drag it to the surface to an equilibrium point in a second step. This technique has the advantage of being very robust against uncertainties and disturbances, and the disadvantage of high-frequency called "chattering." To reduce the effect of this drawback, several versions of higher-order sliding mode have been proposed [12]. This technique has been used both to observe the flux, speed and for parameter estimation [13].

In this paper, we have integrated a robust sliding mode observer in an MRAS structure. The use of this robust flux observer based on the principle of sliding mode allowed us to design new MRAS structure for a simultaneous estimation of speed and stator resistance.

The rest of this paper is organized as follows: in section II, we present the sliding mode flux observer, which will be used later in section IV, in section III, we present the classical MRAS observer, in section IV the RF-MRAS sliding mode observer is presented, in section V the Load torque observer is detailed and in section VI the experimental results are discussed.

II. SLIDING MODE FLUX OBSERVER

The proposed observer is based on a current model [14, 15]. This observer has advantage of not requiring speed and rotor time constant as inputs, unlike other flux observers. Therefore, any variation of these quantities will no effect on current and flux estimation. In addition, the use of sliding mode method for the design of this observer guarantees both robustness with respect to various disturbances, and good dynamic performance over all speed range. The equations of the stator currents and rotor flux can be written in the fixed reference as:

$$\begin{aligned} \dot{i}_{s\alpha} &= \frac{1}{\sigma L_s} \frac{L_m}{L_r} \frac{1}{T_r} \phi_{r\alpha} + \frac{1}{\sigma L_s} \frac{L_m}{L_r} \omega \phi_{r\beta} - \frac{1}{\sigma L_s} \left(R_s + \frac{L_m^2}{L_r T_r} \right) i_{s\alpha} + \frac{1}{\sigma L_s} u_{s\alpha}, \\ \dot{i}_{s\beta} &= \frac{1}{\sigma L_s} \frac{L_m}{L_r} \frac{1}{T_r} \phi_{r\beta} - \frac{1}{\sigma L_s} \frac{L_m}{L_r} \omega \phi_{r\alpha} - \frac{1}{\sigma L_s} \left(R_s + \frac{L_m^2}{L_r T_r} \right) i_{s\beta} + \frac{1}{\sigma L_s} u_{s\beta}, \\ \dot{\phi}_{r\alpha} &= -\frac{1}{T_r} \phi_{r\alpha} - \omega \phi_{r\beta} + \frac{L_m}{T_r} i_{s\alpha}, \\ \dot{\phi}_{r\beta} &= -\frac{1}{T_r} \phi_{r\beta} + \omega \phi_{r\alpha} + \frac{L_m}{T_r} i_{s\beta}, \end{aligned} \quad (1)$$

These equations can be represented in matrix form by

$$\begin{bmatrix} \dot{i}_{s\alpha} \\ \dot{i}_{s\beta} \end{bmatrix} = k_1 \left(\begin{bmatrix} \eta & \omega \\ -\omega & \eta \end{bmatrix} \begin{bmatrix} \phi_{r\alpha} \\ \phi_{r\beta} \end{bmatrix} - \eta L_m \begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix} \right) - k_2 \begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix} + k_3 \begin{bmatrix} u_{s\alpha} \\ u_{s\beta} \end{bmatrix}, \quad (2)$$

$$\begin{bmatrix} \dot{\phi}_{r\alpha} \\ \dot{\phi}_{r\beta} \end{bmatrix} = - \left(\begin{bmatrix} \eta & \omega \\ -\omega & \eta \end{bmatrix} \begin{bmatrix} \phi_{r\alpha} \\ \phi_{r\beta} \end{bmatrix} - \eta L_m \begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix} \right) \quad (3)$$

With

$$k_1 = \frac{k_3 L_m}{L_r}, \quad k_2 = \frac{R_s}{\sigma L_s}, \quad k_3 = \frac{1}{\sigma L_s}, \quad \sigma = 1 - \frac{L_m^2}{L_s L_r}, \quad \eta = \frac{1}{T_r} = \frac{R_r}{L_r},$$

We define the matrix S by

$$S = \left(\begin{bmatrix} \eta & \omega \\ -\omega & \eta \end{bmatrix} \begin{bmatrix} \phi_{r\alpha} \\ \phi_{r\beta} \end{bmatrix} - \eta L_m \begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix} \right) \quad (4)$$

We can note that the matrix S appears simultaneously in the equations of currents and flux. This implies that design of current and the flux observer can be based on replacing the common term, which is the matrix S by the proposed sliding mode functions $\psi_{r\alpha\beta}$

$$\begin{bmatrix} \psi_{r\alpha} \\ \psi_{r\beta} \end{bmatrix} = \hat{S} = \left(\begin{bmatrix} \eta & \hat{\omega} \\ -\hat{\omega} & \eta \end{bmatrix} \begin{bmatrix} \hat{\phi}_{r\alpha} \\ \hat{\phi}_{r\beta} \end{bmatrix} - \eta L_m \begin{bmatrix} \hat{i}_{s\alpha} \\ \hat{i}_{s\beta} \end{bmatrix} \right) \quad (5)$$

Current and flux observers became

$$\begin{bmatrix} \dot{\hat{i}}_{s\alpha} \\ \dot{\hat{i}}_{s\beta} \end{bmatrix} = k_1 \begin{bmatrix} \psi_{r\alpha} \\ \psi_{r\beta} \end{bmatrix} - k_2 \begin{bmatrix} \hat{i}_{s\alpha} \\ \hat{i}_{s\beta} \end{bmatrix} + k_3 \begin{bmatrix} u_{s\alpha} \\ u_{s\beta} \end{bmatrix} \quad (6)$$

$$\begin{bmatrix} \dot{\hat{\phi}}_{r\alpha} \\ \dot{\hat{\phi}}_{r\beta} \end{bmatrix} = - \begin{bmatrix} \psi_{r\alpha} \\ \psi_{r\beta} \end{bmatrix} \quad (7)$$

Where

$$\psi_{r\alpha} = -u_0 \text{sign}(S_{s\alpha}), \quad \psi_{r\beta} = -u_0 \text{sign}(S_{s\beta}), \quad (8)$$

And

$$\begin{aligned} S_{s\alpha} &= \bar{i}_{s\alpha} = \hat{i}_{s\alpha} - i_{s\alpha} \\ S_{s\beta} &= \bar{i}_{s\beta} = \hat{i}_{s\beta} - i_{s\beta} \end{aligned} \quad (9)$$

$\hat{i}_{s\alpha}, \hat{i}_{s\beta}$ and $i_{s\alpha}, i_{s\beta}$ are respectively, observed and measured components of stator current.

When the estimated current converges to the measured current, the flux estimation is a simple integration of sliding mode functions without having to know either the speed or the rotor time constant.

Selection of u_0 in (8) will ensure convergence of the observation of the current by the Lyapunov stability analysis.

It should be noted that we have assumed that the equivalent control of sliding mode observer is obtained by a simple low-pass filtering of the discontinuous control.

$$\psi_{r\alpha\beta}^{eq} = \frac{1}{\mu p + 1} \psi_{r\alpha\beta} \quad (10)$$

μ is time constant of the low-pass filter

Now the rotor flux can be estimated by

$$\begin{bmatrix} \dot{\hat{\phi}}_{r\alpha} \\ \dot{\hat{\phi}}_{r\beta} \end{bmatrix} = - \begin{bmatrix} \psi_{r\alpha}^{eq} \\ \psi_{r\beta}^{eq} \end{bmatrix} \quad (11)$$

Figure 1 illustrates the overall scheme of the observer

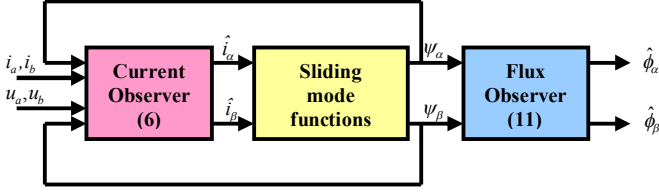


Fig. 1. Overall scheme of sliding mode flux observer

III. CLASSICAL MRAS ESTIMATION

Model reference adaptive system (MRAS) is one of the most popular methods used for observing the parameters and states of the induction machine. Using stator and rotor equations in the fixed frame, we can estimate the rotor flux in two different forms [16]

$$\begin{bmatrix} \dot{\hat{\phi}}_{r\alpha} \\ \dot{\hat{\phi}}_{r\beta} \end{bmatrix} = \frac{L_r}{L_m} \begin{bmatrix} u_{s\alpha} \\ u_{s\beta} \end{bmatrix} - \begin{bmatrix} (R_s + \sigma L_s p) & 0 \\ 0 & (R_s + \sigma L_s p) \end{bmatrix} \begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix} \quad (12)$$

$$\begin{bmatrix} \dot{\hat{\phi}}_{r\alpha} \\ \dot{\hat{\phi}}_{r\beta} \end{bmatrix} = \begin{bmatrix} (-1/T_r) & -\omega \\ \omega & (-1/T_r) \end{bmatrix} \begin{bmatrix} \hat{\phi}_{r\alpha} \\ \hat{\phi}_{r\beta} \end{bmatrix} + \frac{L_m}{T_r} \begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix} \quad (13)$$

The structure of the classical MRAS is based on the use of output error between two independent flux observer models. This error is driven to zero through adjustment of the parameter by an adaptive mechanism.

Implementation method for simultaneous rotor speed and stator resistance estimation is based on hyperstability concept in order to obtain asymptotically stable system.

The adaptation mechanism is based on the assumption of a constant speed rotation since it varies slowly with respect to variations of flux. As stator resistance variation is slow, it is also considered as a constant parameter. The parallel structure of the proposed estimator is shown in Figure 2 [17, 18].

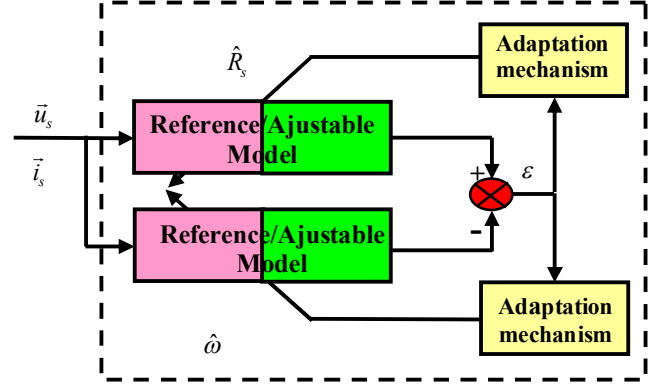


Fig. 2. Parallel speed and stator resistance estimator structure

Reference and adjustable models are represented by equations (12) and (13). In this structure, we note that for speed and stator resistance estimation, the two models switch roles.

The presence of two mechanisms of adaptation led to consider two errors:

$$\begin{aligned} e_\omega &= \hat{\phi}_{rI}^S \times \hat{\phi}_{rV}^S = \hat{\phi}_{\alpha I} \hat{\phi}_{\beta V} - \hat{\phi}_{\beta I} \hat{\phi}_{\alpha V} \\ e_{R_s} &= i_{\alpha s} (\hat{\phi}_{\alpha V} - \hat{\phi}_{\alpha I}) + i_{\beta s} (\hat{\phi}_{\beta V} - \hat{\phi}_{\beta I}) \end{aligned} \quad (14)$$

V, I indices represent variables from voltage and current models respectively.

IV. RF-MRAS-SLIDING MODE ESTIMATION

New MRAS structure is proposed for speed and stator resistance estimation [19]. The idea is to use the flux observer presented in section I as a reference model with its performance especially in terms of robustness, and recalibrated current and voltage models on this model for simultaneous estimation of speed and stator resistance. The diagram of the structure is shown in Figure 3.

The adaptive mechanism, which is a simple PI controller, relies on an error quantity that represents the difference between the instantaneous positions of the two rotor flux estimates by the two models (reference and adjustable).

Using sliding mode observer, as reference model gives a big advantage to the whole MRAS structure. The parallel rotor speed and stator resistance MRAS estimation scheme, developed in this section, will make use of this advantage to achieve simultaneous estimation of the two quantities. The role of the reference and the adjustable model will be interchanged for this purpose, since the rotor flux estimate of (11) is independent of stator resistance.

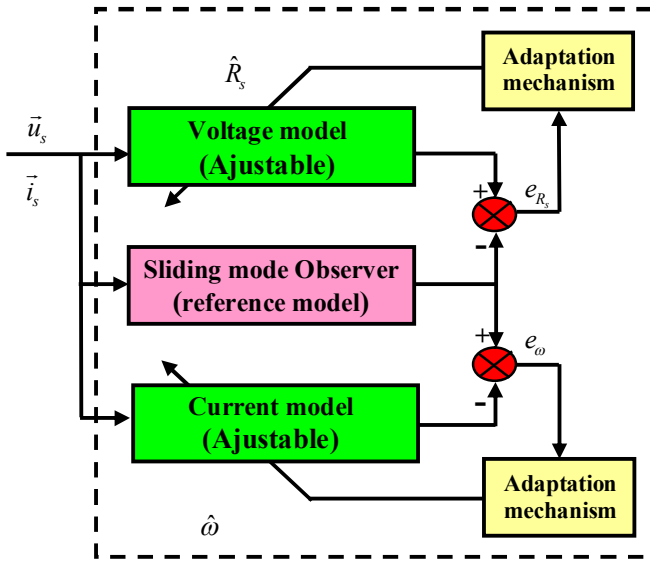


Fig. 3. RF-MRAS observer structure for speed and R_s estimation

The rotor flux oriented control scheme for an induction motor, utilized in the paper in experimental investigation, is illustrated in Fig. 4. It includes, apart from a speed controller, rotor flux and currents controllers as well.

The required feedback quantities for the rotor flux closed loop control are obtained from the reference model (12).

Induction motor data are given in the Appendix. A DSP system, based on DS1104 controller board from dSPACE, is used for experimental investigation. Motor stator currents are measured, while stator voltages are reconstructed from the known PWM pattern and the measured dc voltage.

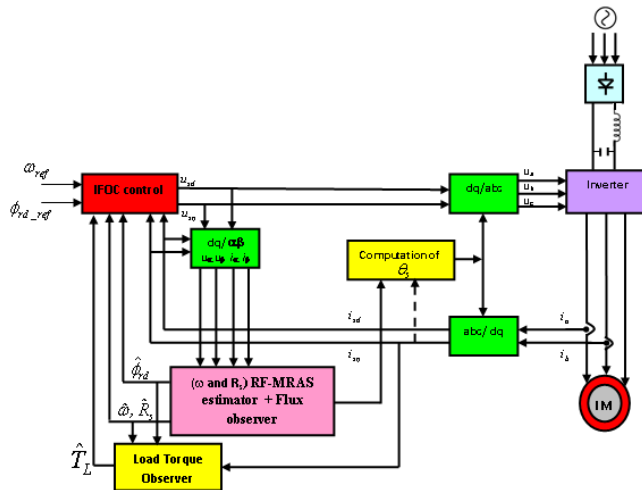


Fig. 4. Rotor flux oriented control scheme

V. LOAD TORQUE OBSERVER

To observe the load torque, we use the observer proposed in [20]

$$\hat{i}_L = \frac{1}{\tau_0} \left(z - \frac{J}{n_p} \omega \right) \quad (15)$$

$$\frac{dz}{dt} = n_p \frac{2}{3} L_m \lambda_{2d} i_{1q} - \hat{i}_L$$

\hat{i}_L is the observed load torque, τ_0 is the observer time constant and z is the observer state.

VI. EXPERIMENTAL RESULTS

In order to validate our MRAS structures for simultaneous speed and stator resistance estimation, we have used an experimental setup, consisting of a 3Kw wound rotor induction machine. Rheostat-phase is connected to the stator in order to allow us a voluntary change in the value of the stator resistance during operation of the induction motor.

The block schematic of the experimental setup is shown in Fig. 5. Experimental setup consists of a wound rotor induction motor of rating: Star/Delta 380V/220V AC, 8.9 A/ 15.5 A, 4 kW, p.f. 0.82, 1440 r.p.m, 50 Hz and is coupled with a powder brake. The rotor shaft of the induction motor is fitted with an optical position encoder with 1024 lines per rotation for measuring angular position and speed. The induction motor receives power from an SVPWM inverter of 1000 V, 30 A rating. The dSPACE interface generates the SVPWM pulses for the inverter and takes the signals of the measured currents for phase "a" and "b" through ADCs and angular position signals through encoder. It takes also the speed command from the dSPACE "controldesk" and generates the voltage command for the SVPWM inverter. The signal for angular positions are sampled for every 750 microsecond interval and the current signals are sampled for every 200 microsecond interval. The computation for control algorithm is done within a time step of 200 microseconds. The inverter switching frequency is kept at 10 kHz using the slave DSP. The control and estimation algorithms need as inputs (1) the stator currents and (2) the encoder position. For that filters are used:

- Digital low pass filter is used for filtering encoder position signal.
- Digital synchronous resonating filter [21] is used for reducing high-frequency noise in the stator current signals arising out of SVPWM and electrical grid.

A sudden change in stator resistance was caused during motor operation to test the performance of the two methods described above.

APPENDIX

INDUCTION MOTOR DATA

Stator resistance	1.34 ohms;
Rotor resistance	1.18 ohms;
Mutual inductance	0.17 H;
Rotor inductance	0.18 H;
Stator inductance	0.18 H;
Number of pole pairs	2
Motor load inertia	0.0153 kgm ² ;

REFERENCES

- [1] G. Kenné, T. Ahmed-Ali, F. Lamnabhi-Lagarrigue, and A. Arzandé, "Time-Varying Parameter Identification of a Class of Nonlinear Systems With Application to Online Rotor Resistance Estimation of Induction Motors", IEEE International Symposium on Industrial Electronics, Vol. 1, pp. 301-306, July 9-13, 2006, Montreal, Quebec, Canada.
- [2] Tae-Sung Kwon, Myoung-Ho Shin, and Dong-Seok Hyun, "Speed Sensorless stator fluxoriented control of induction motor in the field weakening region using Luenberger observer", IEEE transaction on Power Electronics, Vol. 20, Issue. 4, pp. 864- 869, July 2005
- [3] Y.R.Kim, S.K.Sul and M.H.Park, "Speed Sensorless Vector Control of Induction Motor Using Extended Kalman Filter", IEEE transaction on Industry Applications, Vol. 30, Issue. 5, pp. 1225-1233, Oct. 1994.
- [4] R. Marino, P. Tomei, and C.M. Verrelli, "A global tracking control for speed Sensorless induction motors", Automatica, Vol. 40, pp. 1071-1077, January 2004
- [5] P.Vas, "Sensorless Vector and Direct Torque Control", New York, Oxford University Press, 1998.
- [6] Jingchun Li, Longya Xu, and Zheng Zhang, "An adaptive sliding mode observer for induction motor Sensorless speed control", IEEE Transaction on Industry Application, Vol. 41, Issue. 4, pp.1039-1046, July/August 2005.
- [7] K. L. Shi, T.F. Shan, Y.K. Wong, and S.L. Ho, "Speed estimation of an induction motor drive using an optimized extended Kalman filter", IEEE Transactions on Industrial Electronics, Vol. 49, Issue. 1, pp.124-133, February 2002.
- [8] P.Vas, "Parameter Estimation, Condition Monitoring and Diagnosis of Electrical Machines", New York, Oxford University Press, 1993.
- [9] Marwali, M.N, and Keyhani, A, "A comparative study of rotor flux based MRAS and back-EMF based MRAS speed estimators for speed Sensorless vector control of induction machines", Proceeding. IAS Annual Meeting, pp. 160-166, 1997, New Orleans, USA.
- [10] M.S. Nait Said, M.E.H. Benbouzid, " Induction Motors Direct Field Oriented Control with Robust On-Line Tuning of Rotor Resistance", IEEE Transactions on Energy Conversion, Vol. 14, No. 4, December 1999.
- [11] Colin Schauder, "Adaptive Speed Identification for Vector Control of Induction Motor without Rotational Transducers", IEEE Transaction on Industry Application, Vol. 28, no. 5, pp.1054-1061, Oct. 1992.
- [12] T. Floquet, "Contributions à la commande par modes glissants d'ordre supérieur", Thèse de Doctorat, Université des Sciences et Technologie de Lille, Décembre 2000.
- [13] V. Utkin, J. Guldner, and J. Shi, "Sliding Mode Control in Electromechanical Systems", New York, Taylor & Francis, 1999.
- [14] H. Rehman, A. Derdiyok, M. K. Guven, and L. Xu, "A new current model flux observer for wide speed range sensorless control of an induction machine", IEEE Transaction on Power Electronics, Vol. 17, no. 6, pp. 1041-1048, November 2002.
- [15] Habib-ur Rehman, "On The Analysis, Estimation and Control of Field Oriented Induction Motor Drives", Ph.D thesis, The Ohio State University, 2001.
- [16] R. Beguenane, MEH. Benbouzid, M.Tadjine and A.Tayebi, "Speed and Rotor Time Constant Estimation via MRAS Strategy for Induction Motor Drives", IEEE International Electric Machines and Drives Conference Record, pp. TB3/5.1-TB3/5.3, May 18-21, 1997, Milwaukee, WI, USA.
- [17] Veran Vasic, Slobodan N. Vukosavic, and Emil Levi, "A Stator Resistance Estimation Scheme for Speed Sensorless Rotor Flux Oriented Induction Motor Drives", IEEE Transactions on Energy Conversion, Vol. 18, no. 4, December 2003.
- [18] Rachid Beguenane, Mohand A. Ouhrouche, and Andrzej M. Trzynadlowski, "Stator Resistance Tuning in an Adaptive Direct Field-Orientation Induction Motor Drive at Low Speeds", the 30th Annual Conference of the IEEE Industrial Electronics Society, November 2 - 6, 2004, Busan, Korea.
- [19] F. Mehazzem, "Contribution to induction motor control for electric traction", PhD thesis, Department of embedded systems, ESIEE School, Paris Est University, Paris, France, 2010.
- [20] S. Endo, H. Kobayashi, Y. Yoshida, S. Kobayashi, "Robust Digital Tracking Controller Design for High speed Positioning System -New Experimental Results, 3rd International Workshop on Advanced Motion Control, University of California, Berkeley, March 1994, pp. 643-647.
- [21] P. Syam, P. K. Nandy, and A. K. Chattopadhyay, "Improvement in power quality and a simple method of subharmonic suppression for a cycloconverter-fed synchronous motor drive" IEE Proc. B, EPA, Issue -4, pp. 292-303, July 2002.