

# Hardware Co-Simulation of an Adaptive Field Oriented Control of Induction Motor

Nadir Kabache\*, Samir Moulahoum\*\* and Hamza Houassine\*\*\*

**Abstract** – The reconfigurability of FPGA devices allows designers to evaluate, test and validate a new control algorithm; a new component or prototypes without damaged the real system with the so-called hardware co-simulation. The present paper uses the Xilinx System Generator (XSG) environment to establish and validate a new nonlinear estimator for the rotor time constant inverse that will be exploited to improve the indirect rotor field control of induction motor.

**Keywords:** Induction motor; IRFOC; FPGA; Xilinx system Generator; Hardware co-simulation

## 2. Introduction

Generally a control system consists of a plant and a controller where the plant is an entity controlled by the controller. In many applications, the sequential operating mode disadvantages the use of microprocessors or microcontrollers due to the number of machine cycles needed to execute controller program instructions [1]-[3]. Therefore, over the past decades both the parallel processing and the increased number of gates have led to a rapid increase in the popularity of Field programmable Gate Array (FPGA) in embedded systems against microprocessors, microcontrollers or DSP [2].

For the prototyping of FPGA, traditional design tools require the use of Hardware Description Languages (HDLs), which are complicated and not very popular in standard control system design tools where the MATLAB/Simulink environment is the most used. Fortunately, the coming of the XSG toolbox for Simulink has made it possible to simulate the hardware within the graphical environment of Simulink, and also generate Hardware Description Language (HDL) code needed for the implementation in FPGA [2]-[6].

The present paper investigate the use of the XSG environment to establish and validate a new nonlinear

estimator for the rotor time constant inverse that will be exploited to improve the indirect rotor field control of induction motor. As it is well known, with the field oriented control [7] and [8], in particularly the IRFOC, the induction motor became the most favored in constant or variable speed drives [8]. The drawback of this control scheme is the sensitivity to rotor time constant which varies with heating and, therefore, affects considerably the motor performances. To overcome this drawback, many approaches have been presented in literature for the estimation of this parameter, among them, those found in [9]-[13]. However, some approaches requires a massive mathematical calculation, some approaches lost their performances at low speed, and some other don't have a practical narrow.

The suggested estimator uses the model reference adaptive system's principle (MRAS). It is based on a comparison between the measured stator currents and their estimated values obtained through the motor model. The dynamics of errors between estimated and measured states are exploited to generate an online adaptive law for the estimator. For the hardware test, The Xilinx System Generator gives bridge between the high-level abstract version of the estimator and its implementation on a Xilinx FPGA target. Firstly, the estimator is described mathematically by using Xilinx toolboxes in Simulink, then optimized with system generator timing analysis and finally translated into a hardware implementation. For this last step there are two parts, the estimator part which is loaded in the FPGA device and the plant part which is described in Simulink environment, the plant includes the induction motor model with the IRFOC.

\* Dept. of Electrical Engineering, University of Medea, Algeria (nadir.kabahe@gmail.com, Kabache.nadir@univ-medea.dz)

\*\* Dept. of Electrical Engineering, University of Medea, Algeria (samir.moulahoum@gmail.com )

\*\*\* Dept. of Electrical Engineering and computer sciences, University of Medea, Algeria (hamza\_houassine@yahoo.fr )

## 2. Rotor time constant inverse estimator

The basic of field oriented control is so familiar that it has been treated too much in the literature. The field orientation's concept implies that the direct axis of rotating reference frame should be pointed toward the rotor flux vector [7] and [8]. Consequently, the direct component of stator current vector controls the rotor flux level whereas the transverse component controls the developed electromagnetic torque. Two schemes of rotor field oriented control are available. In the first scheme, the flux is controlled through a feedback and an appropriate controller, consequently the knowledge of flux vector is required by using a sensor or an observer. These later must furnish sufficient information from which the module of rotor flux and its position are extracted. However, in the second scheme, none information about the rotor flux is required as it is controlled in a feed forward manner. This makes the indirect scheme more attractive but its main disadvantage is the effect of rotor time constant variation. This problem has been the subject of many researches, including the present paper that attempts to provide a new approach to estimate this parameter.

Indeed, according to field oriented control principle, the equations of the control scheme in the rotating frame are as follow [8]:

$$\begin{aligned}
 \phi_q^* &= 0 \\
 i_d^* &= \phi_d^* / l_m \\
 i_q^* &= (l_r / p l_m) \cdot (T_e^* / \phi_r^*) \\
 \omega_{sl} &= \alpha \cdot i_q^* / i_d^* \\
 \omega_{syn} &= p \Omega_r + \omega_{sl}
 \end{aligned} \quad (1)$$

where:

- $(i_d^*, i_q^*), (\phi_d^*, \phi_q^*)$ : Are the reference values of stator currents  $(i_d, i_q)$  and rotor flux  $(\phi_d, \phi_q)$  in the rotating frame.
- $\Omega_r, \omega_{syn}, \omega_{sl}, T_e^*$ : Are respectively, motor speed, synchronous speed, sleep speed and reference torque.
- $l_r, l_s, l_m, P$ : Are respectively rotor, stator and magnetizing inductance and number of pair poles.
- $\alpha = 1/T_r$ : Is the rotor time constant inverse

If the rotor time constant is well known, the IRFOC can insure a good decoupling between the flux and the motor torque, therefore high dynamic performances speed – torque control is expected to be achieved. Unfortunately, the motor heating behavior leads to an important change in rotor time constant. Therefore, the control scheme will be considerably affected and needs to be equipped of estimation means for this parameter.

The estimator suggested here is derived from some adaptive nonlinear theories [14] and it is based on the Model reference adaptive system (MRAS) where the errors between estimated and measured stator currents are used for adaptation.

Before we proceed to develop the proposed estimator, considering the following assumptions:

- Stator currents and rotor speed are available for measurement;
- Stator time constant is considered as known parameter;
- Rotor time constant is considered as uncertain parameter however its initial value obtained from off-line standard tests (Dc test, no-load test, locked-rotor test) is supposed to be known.

According to the above assumptions, we can write:

$$\bar{\alpha} = \alpha_n + \bar{\Delta}_\alpha \quad (2)$$

where:

- $\bar{\alpha}, \alpha_n$ : Are respectively the real (ideal) and the initial value of rotor time constant inverse.
- $\bar{\Delta}_\alpha$ : is the ideal value of the unknown variation in rotor time constant inverse (to be estimated).

Now, if the variation in the rotor time constant inverse is well known (true value), we can suppose that the values of measured stator currents can be expressed in the rotating frame, according to the above assumptions, as follow [12]:

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = -A \begin{bmatrix} i_d \\ i_q \end{bmatrix} + B \begin{bmatrix} \bar{\phi}_d \\ \bar{\phi}_q \end{bmatrix} + P \bar{\Delta}_\alpha + \frac{1}{\sigma l_s} \begin{bmatrix} V_d \\ V_q \end{bmatrix} \quad (3)$$

Where the true values of the rotor flux are given as:

$$\begin{cases} \dot{\hat{\phi}}_d = \bar{\alpha}(l_m I_d - \hat{\phi}_d) + \omega_{sl} \hat{\phi}_q \\ \dot{\hat{\phi}}_q = \bar{\alpha}(l_m i_q - \hat{\phi}_q) - \omega_{sl} \hat{\phi}_d \end{cases} \quad (4)$$

where  $(V_d, V_q)$  are the stator voltages,  $\bar{X}$  is the true value of  $X$ ,  $\sigma = 1 - l_m^2 / l_s l_r$  and:

$$A = \begin{bmatrix} \frac{1-\sigma}{\sigma} \alpha_n + \frac{1}{\sigma T_s} & -\omega_{syn} \\ \omega_{syn} & \frac{1-\sigma}{\sigma} \alpha_n + \frac{1}{\sigma T_s} \end{bmatrix} \quad (5)$$

$$B = \begin{bmatrix} \frac{1-\sigma}{\sigma l_m} \alpha_n & \frac{1-\sigma}{\sigma l_m} \omega_r \\ -\frac{1-\sigma}{\sigma l_m l_r} \omega_r & \frac{1-\sigma}{\sigma l_m} \alpha_n \end{bmatrix} \quad (6)$$

$$P = \begin{bmatrix} \frac{1-\sigma}{\sigma l_m} (\bar{\phi}_d - l_m i_d) \\ \frac{1-\sigma}{\sigma l_m} (\bar{\phi}_q - l_m i_q) \end{bmatrix} \quad (7)$$

However, this true value exists but it is unknown, we have only its estimation. Therefore, using the estimated parameter the stator currents and rotor flux can be estimated through the motor model (3) and (4) as follows:

$$\begin{cases} \frac{d}{dt} \begin{bmatrix} \hat{i}_d \\ \hat{i}_q \end{bmatrix} = -A \begin{bmatrix} \hat{i}_d \\ \hat{i}_q \end{bmatrix} + B \begin{bmatrix} \hat{\phi}_d \\ \hat{\phi}_q \end{bmatrix} \\ \quad + \hat{A}_\alpha \hat{\Delta}_\alpha + \frac{1}{\sigma l_s} \begin{bmatrix} V_d \\ V_q \end{bmatrix} \\ \hat{\phi}_d = \hat{\alpha}(l_m I_d - \hat{\phi}_d) + \hat{\omega}_{sl} \hat{\phi}_q \\ \hat{\phi}_q = \hat{\alpha}(l_m i_q - \hat{\phi}_q) - \hat{\omega}_{sl} \hat{\phi}_d \end{cases} \quad (8)$$

Where the estimate value of the sleep speed is given by:

$$\hat{\omega}_{sl} = \left( \hat{i}_q^* / \hat{i}_d^* \right) \hat{\alpha} \quad (9)$$

and,

$$\hat{P} = \begin{bmatrix} \frac{1-\sigma}{\sigma l_m} (\hat{\phi}_d - l_m \hat{i}_d) \\ \frac{1-\sigma}{\sigma l_m} (\hat{\phi}_q - l_m \hat{i}_q) \end{bmatrix} \quad (10)$$

As indicated below, for the adaptation of the proposed estimator, the dynamic of the stator currents is used. Indeed, the error between the estimated currents (8) and those measured (3) is exploited to obtain an adaptive law for the estimator. Therefore, by using (3) and (8), the dynamic of stator current estimate error can be given as:

$$\frac{d}{dt} \begin{bmatrix} \tilde{i}_d \\ \tilde{i}_q \end{bmatrix} = -\tilde{A} \begin{bmatrix} \tilde{i}_d \\ \tilde{i}_q \end{bmatrix} + \tilde{B} \begin{bmatrix} \tilde{\phi}_d \\ \tilde{\phi}_q \end{bmatrix} + \tilde{P} \tilde{\Delta}_\alpha \quad (11)$$

where,

$$\tilde{\Delta}_\alpha = \bar{\Delta}_\alpha - \hat{\Delta}_\alpha, \quad \begin{bmatrix} \tilde{i}_d \\ \tilde{i}_q \end{bmatrix} = \begin{bmatrix} i_d - \hat{i}_d \\ i_q - \hat{i}_q \end{bmatrix}$$

And,

$$\tilde{A} = \begin{bmatrix} \frac{1-\sigma}{\sigma} \bar{\alpha} + \frac{1}{\sigma T_s} & -\omega_{syn} \\ \omega_{syn} & \frac{1-\sigma}{\sigma} \bar{\alpha} + \frac{1}{\sigma T_s} \end{bmatrix} \quad (12)$$

$$\tilde{B} = \begin{bmatrix} \frac{1-\sigma}{\sigma l_m} \tilde{\alpha} & \frac{1-\sigma}{\sigma l_m} \omega_r \\ -\frac{1-\sigma}{\sigma l_m l_r} \omega_r & \frac{1-\sigma}{\sigma l_m} \tilde{\alpha} \end{bmatrix} \quad (13)$$

Based on the dynamics of the stator currents estimate errors (11), the estimation of the rotor time constant inverse variation can be given as follow [14]:

$$\begin{aligned} \dot{\hat{\Delta}}_\alpha &= -K_1 \cdot \hat{P} \cdot \begin{bmatrix} \tilde{i}_d \\ \tilde{i}_q \end{bmatrix} - K_2 \left[ \begin{bmatrix} \tilde{i}_d \\ \tilde{i}_q \end{bmatrix} \right] \hat{\Delta}_\alpha \\ &= -K_1 \frac{1-\sigma}{\sigma l_m} \left\{ (\hat{\phi}_d - l_m \hat{i}_d) \tilde{i}_d + (\hat{\phi}_q - l_m \hat{i}_q) \tilde{i}_q \right\} \\ &\quad - K_2 \left( |\tilde{i}_d| + |\tilde{i}_q| \right) \hat{\Delta}_\alpha \end{aligned} \quad (14)$$

With  $K_1$  and  $K_2$  are appropriate positive constants used to improve the estimator behavior.

## Hardware implementation

Before the hardware model is build some steps must be considered. Firstly, the model is build, arranged, simplified and tested in Matlab-Simulink environment (floating point) to help prevent potential timing issues. For this step, the suggested estimator can be divided on three sub-blocks: Stator currents estimation sub-block, rotor flux estimation sub-block and parameter estimation sub-block (Fig.1).

The second step is the use of the XSG blocks provided in the Xilinx toolbox from Simulink library to build the hardware model (fixed point) of the estimator. Each hardware bloc is build and compared with Simulink block to select the appropriate data size allowing the same signal at a convenient precision. For the data size, a compromise must be achieved between a precise computation and the needed amount of inner resources. This step is ended by a timing analysis where the estimator is verified and optimized for the synchronization of the hardware flow at different design stages.

In the third step, after the verification of the design through both simulation and timing analysis, the hardware co-simulation should be executed in order to validate the design performances on the selected board. The co-simulation process uses Xilinx ISE and core generator to synthesize and generate an FPGA programming bit file (bitstream file) from the hardware model. A new JTAG block is generated for the hardware co-simulation; this last replaces the previously built design (Fig.1).

Finally, the generated block is inserted in the design and then a hardware implementation is executed by connecting the board to the PC.

## Results and discussion

To perform a hardware-in-the-loop, the estimator is inserted in the field oriented control scheme which is achieved in Simulink environment. For hardware co-simulation behavior, when a value is presents at one of the JETAG block's input ports, the block sends the corresponding data to the hardware, the estimator output, from the hardware, is read back into the Simulink module using the USB interface, the output port converts the fixed point data type into the Simulink format and fed into the field oriented control block (Fig. 1).

The suggested estimator has been checked under brusque (step) and linear variations of the rotor time constant inverse for several motor operating conditions. The obtained results show that, while introducing the considered variations on estimated parameter, the proposed estimator provides a satisfactory estimation for rotor time constant inverse (Fig. 2) and (Fig. 3). Compared with those obtained from Simulink environment (floating point), the results from hardware co-simulation (fixed point) present some fluctuations, this is due to the choice made for data size where a compromise has been achieved between the precise computation and the minimum of inner resources. Indeed, the fluctuation in estimated parameter has not an important effect on motor dynamic responses where the speed (Fig. 4), the torque and the estimated rotor flux (Fig. 5) are not affected. Moreover, without counting the fluctuation during the brusque changes of operating conditions, the results reported on Fig.6, show the capability of the estimator to keep its performances even for zero speed (Fig. 7).

## Conclusion

In the presented paper, a hardware co-simulation is achieved for a nonlinear estimator suggested to improve the induction motor control by estimating the rotor time constant inverse. In this implementation, the estimator has been accomplished using the Xilinx system generator-Simulink environment. After the verification of the design through both simulation and timing analysis, the XSG generate programming bitstream file from the hardware model. This file is loaded in the FPGA and a hardware-in-the-loop is performed where the induction motor and the IRFOC present the plant. The obtained results prove the ability of the suggested estimator to insure satisfactory performances for the induction motor control in different operating conditions. Therefore, the perspectives can be extended toward the implementation of the whole IRFOC control scheme.

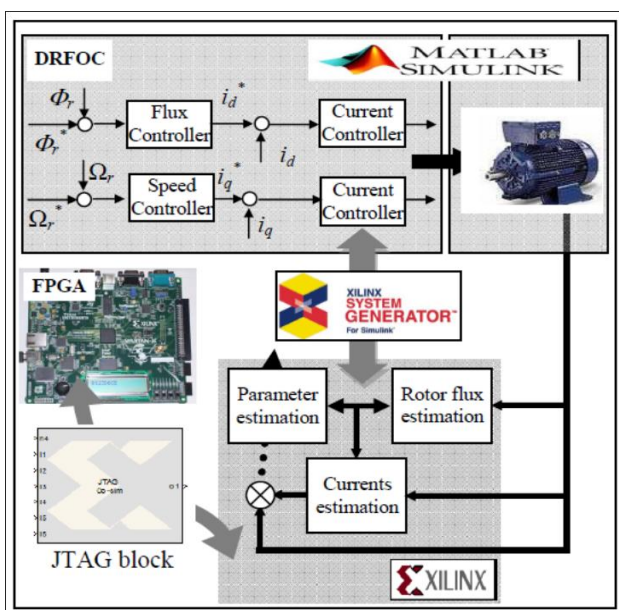


Fig. 1. Architecture of the suggested estimator.

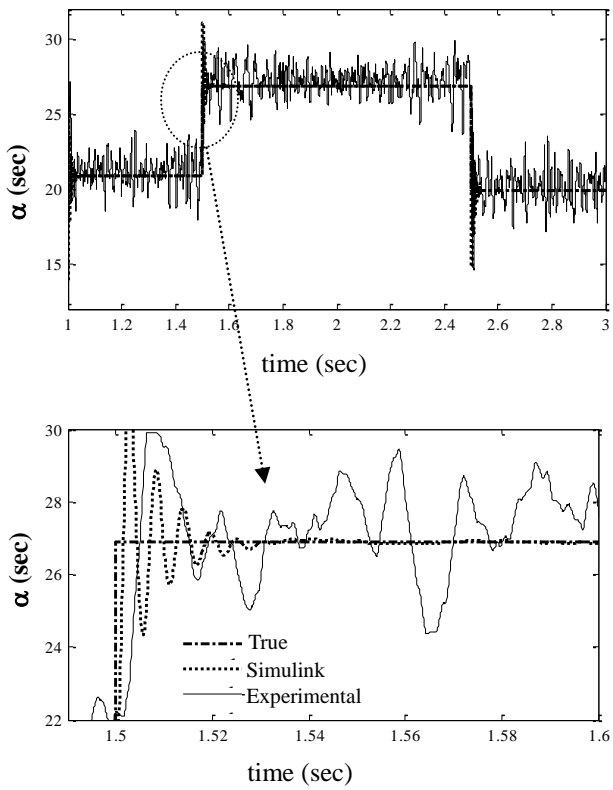


Fig. 2. Estimated parameter for step variations

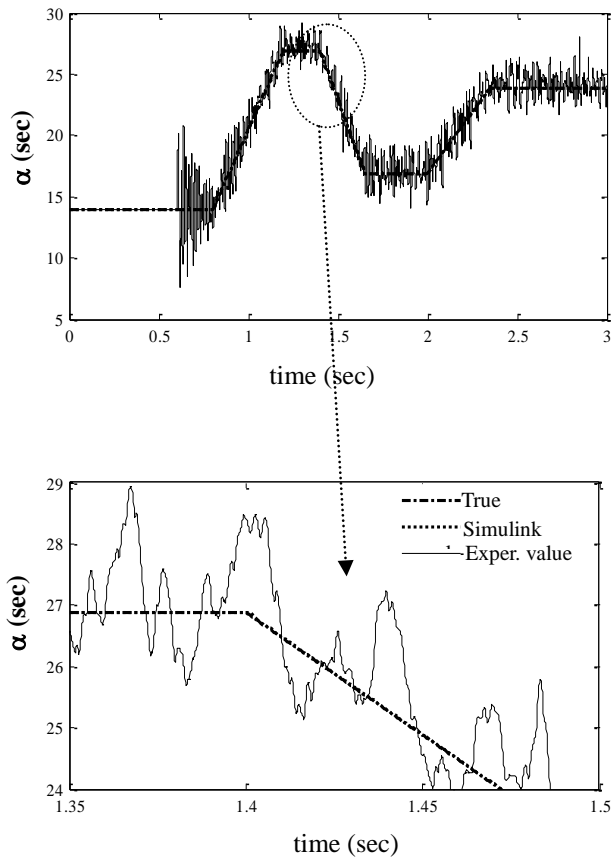


Fig. 3. Estimated parameter for linear variations.

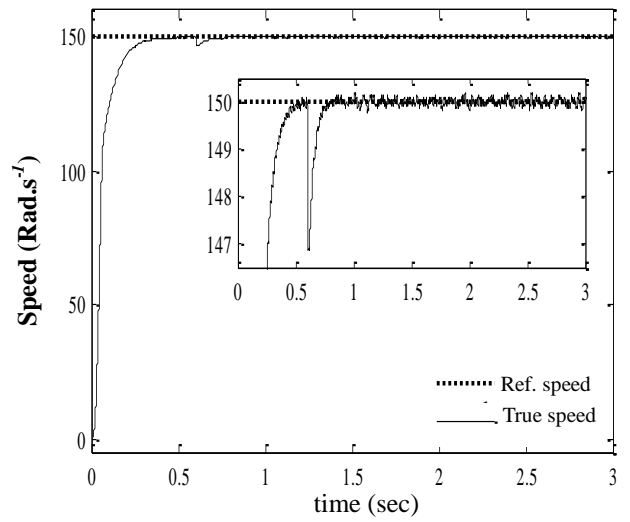


Fig. 4. Evolution of rotor speed.

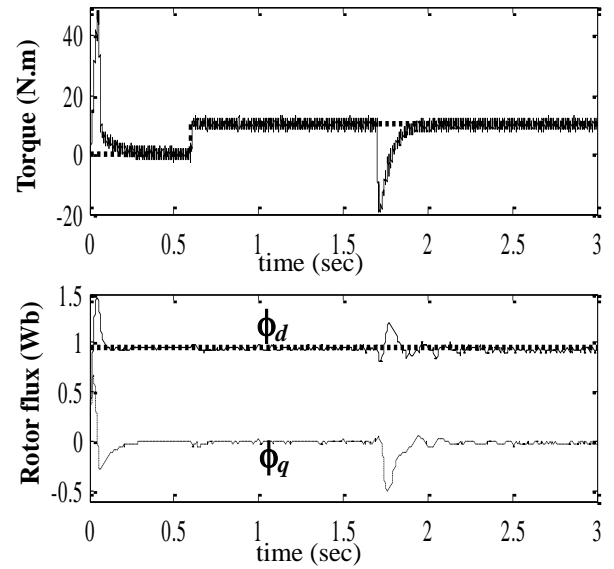


Fig. 5. Evolution of the torque and estimated rotor flux

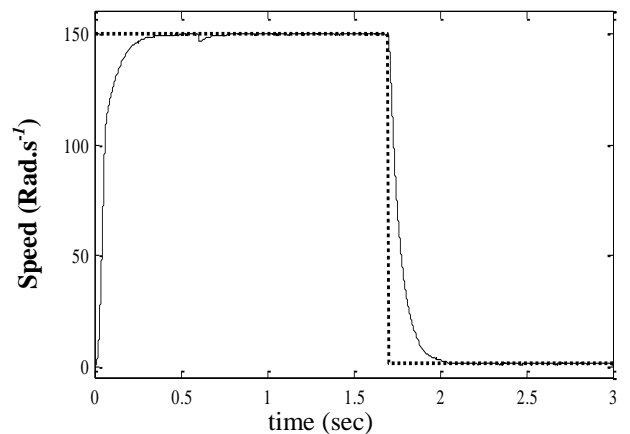


Fig. 6. Rotor speed evolution for zero reference value.

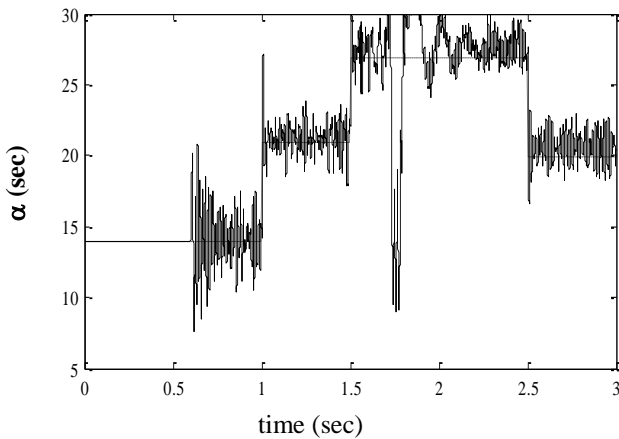


Fig. 7. Estimated rotor time constant inverse at zero speed.

### References

- [1] R. Woods, J. Mcallister, G. Lightbody, and Y. Yi, FPGA-based implementation of signal processing systems, Edition John Wiley & Sons, Ltd., Publication, 2008.
- [2] Ö. AKIN, İ. ALAN, "The use of FPGA in field-oriented control of an induction machine," Turk J Elec Eng & Comp Sci, Vol. 18, No. 6, pp. 943-962, 2010.
- [3] S. Simard, R. Beguenane, and J.G. Mailloux, "Performance Evaluation of Rotor Flux-Oriented Control on FPGA for Advanced AC Drives," Journal of Robotics and Mechatronics, vol. 21, No. 1, pp. 113-120, 2009
- [4] V. Gupta, K. Khare, and R.P. Singh, "Efficient FPGA design and implementation of digital PID controllers in Simulink," Int. J. of Recent Trends in Eng., vol 2, No. 6, pp. 147-150, 2009.
- [5] S. Simard, J.G. Mailloux, and R. Beguenane, "Prototyping advanced control systems on FPGA," EURASIP J. on Emb. Sys. vol.2009, pp. 1-12, 2009
- [6] T. Saidani, D. Dia, W. Elhamzi, M. Atri, and R. Tourki, "Hardware Co-simulation For Video Processing Using Xilinx System Generator," Proc. of the World Congress on Eng. (IWCE), London, U.K., July 1 - 3, 2009.
- [7] F. Blaschke, "The principle of Field Orientation as Applied to the New Transvector Closed Loop Control for Rotating Machines," Siemens Review, vol. 39, pp. 217-220, 1972.
- [8] W. Leonhard, Control of Electrical Drives, Springer Verlag, New York., 1990.
- [9] B. Chetate, N. Kabache, A.N. Ladygin, "Adaptive Control in an Asynchronous Electric Drive on the Basis of an Artificial Neural Network with Calculation of the Rotor Flux", Russian Electrical Engineering, vol. 78, pp. 315-321, 2007.
- [10] K. Wang, J. Chiasson, M. Bodson, and L.M. Tolbert, "An Online Rotor Time Constant Estimator for the Induction Machine, IEEE trans. control systems, vol. 15, pp. 339-348, 2007.
- [11] R. Marino, P. Tomei, C. Verrelli, "A Nonlinear Tracking Control for Sensorless Induction Motors," Automatica, vol. 41, pp. 1071-1077, 2005.
- [12] S.H. Jeon, K. K. Oh, and J. Y. Choi, "Flux Observer with Online Tuning of Stator and Rotor Resistances for Induction Motors," IEEE Trans. Industrial Electronics, vol. 49, pp. 653-664, 2002.
- [13] R. Marino, S. Peresada, and P. Tomei, "Global Adaptive Output Feedback Control of Induction Motors with Uncertain Rotor Resistance," IEEE Trans. Automatic Control, vol. 44, pp. 967-983, 1999.
- [14] K. S. Narendra, and A.M. Annaswamy, "A new Adaptive Law for Robust Adaptation Without Persistent Excitation," IEEE Trans. Automatic Control, vol. 32, pp. 134-145, 1987.



**Nadir Kabache** received the Engineer, Magister and Doctorate degrees in Electrical Engineering in 1997, 2001 and 2007 respectively from M'hamed Bouguerra University of Boumerdes. He is currently an associate professor in

Electrical Engineering Department at the University of Medea. His research interests include electric drives, nonlinear control, embedded system, FPGA. He is also the head of the LREA Research Laboratory in the University of Médéa since 2010.



**Samir Moulahoum** was born in Algiers in 1971. He received the Engineer degree in Electrical Machines in 1995 and the Magister degree in Electrical Engineering in 1998 and the Doctorate degree in Power Electronics and Drives in 2006 from University of Sciences and

Technology of Algiers USTHB. He was with GREEN laboratory, UHP University, Nancy, France, as invited researcher for two years. He is actually an associate professor in Department of Electrical Engineering at the University of Medea. His research interests are Power Electronics, Electrical Drives, Power Generation and Power Quality.



**Hamza Houassine** received the Engineer degree in Electrical Engineering in 2001 from Mouloud Mammeri University of Tizi-Ouzou, the Magister degree in élektrotechnical systems in 2004 from polytechnic Military School of Algiers. The Doctorate degree in Electrical

Engineering in 2010 from Mouloud Mammeri University of Tizi-Ouzou. He is currently an associate professor in Electrical Engineering Department at the University of Medea. His research interests include Electric Machines, field analysis, Power systems.