# Simulation and Implementation of Sensorless Control Using Estimators in Electric Drives with High Dynamic

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Abstract - In this article we'll tackle the control of electric drive with high dynamic, with rapid changes in torque and speed, where the control strategy is FOC (Field Oriented Control). In the surface mining industry, from which the electric drive application for this article is selected, the general trend is toward using asynchronous motors with shortcircuit rotor, due to the advantages of this motor both in terms of design and operation. In order to achieve the variable speed, must be used the static frequency converters. Simulations were carried out using a converter with FOC control strategy and a 45kW motor. The simulations also followed the direction from simple to complex in order to emphasize both qualitative and quantitative elements with respect to the overall dynamic behavior. Simulations were carried out both in the case where the overall structure contains an encoder for speed information, and where the sensorless approach is used the implementation of an estimator is strictly necessary. Such cases were dealt with where speed is measured directly with an encoder, compared with the case of sensorless control, where speed is estimated using a **Model References Adaptive Control Estimator. Simulations** were carried out in MATLAB/Simulink environment, highlighting the control structures and comparative results achieved for a drive application commonly used in surface mining industry. Following these directions a functional application was implemented and tested.

**Keywords:** *sensorless control; electric drives; controller; estimator.* 

## I. INTRODUCTION

The development of electric drive systems was characterized in recent years by a special dynamic, linked both with technological advancements in the manufacture of semiconductor switching elements and new topologies of electric drive. Electric drives represent complex equipment designed to ensure optimal power supply and command of actuators during the operating processes [1-6].

To study the behavior of the system of frequency converter plus motor prior to the actual construction of the converter, a series of numerical simulations have been carried out using MATLAB/Simulink environment [7-9].

Trial and error type iterations are necessary to avoid the rough design errors, but also to identify a series of complex effects and phenomena, even if in the simulated environment, which should converge towards a positive purposefulness of the whole project. We are showing the control of electric drive with high dynamic, with rapid changes in torque and speed, where the control strategy is FOC. Such cases were dealt with where speed is measured directly with an encoder, compared with the case of sensorless control, where speed is estimated using an Estimator. Simulations were carried out in MATLAB/Simulink environment, highlighting the control structures, the tuning parameters and comparative results achieved for a drive application commonly used in surface mining industry.

The technical data of the electric drive system which includes static frequency converter designed with superior technical features providing speed regulation between zero and the rating value for asynchronous motors with short-circuit rotor, are as follows: supply voltage:  $3 \times 400$  Vac/50 Hz; rated output power: 45 kW; peak output:  $1.5 \times PN/2$  minutes; operating temperature:  $-25^{\circ}C$  to  $45^{\circ}C$ ; stator resistance:  $0.041 \ \Omega$ ; rotor resistance:  $0.050 \ \Omega$ ; stator/rotor inductance:  $0.8 \ mH$ ; mutual inductance:  $20.7 \ mH$ .

Sensorless control has a lot of advantages in terms of hardware technology, as well as performance, but the price is an additional encumbrance on the control system. Therefore, the main function of the control subsystem is prediction of speed. Fortunately, achievements in control theory, such as Kalman or Luenberger estimators, have largely contributed to solving this problem. This emphasizes the importance of continuous migration of new approaches and achievements in control theory to the field of electric drives [10].

In this article we will focus on a different type of estimator than the ones mentioned above, namely a MRAC-Model References Adaptive Control type estimator [11]. Although it doesn't have the advantage of the Kalman type estimator (which provides a good prediction even for additional uncertainty added to the measured values), this estimator has the advantage of simplicity in terms of its structure, because obviously beside the simulations which ensure a good design, it also performs the implementation of algorithms for measurement, control and prediction in a DSP, where the number of variables and performed operations must be optimized.

The structure of the paper is as follows. In second section will briefly present the basics of Field Oriented Control for the induction motor. The simulations performed with the same parameterization sets of the controllers and the references for speed and torque are presented in Section 2 and 3 for a good comparison between the cases of control with encoder and sensorless. Section 4 show the practical implementation of the control structures from previous sections, and the experimental setup and results are presented. Finally, some conclusions will be issued and will be pointed out some ideas for continuation of work.

### II. CONTROL OF ELECTRIC MOTORS DRIVES

In the following simulations with the encoder version, the behavior of the converter unit plus motor will be analyzed, in terms of the following quantities: stator current, rotor speed, torque and voltage in the intermediate circuit.

The varying parameters were: for the speed regulator Kp and Ki, for the flux controller Kp and Ki, speed ramps and the hysteresis band for the current regulator.

The classic form in s domain of a PI controller is:

$$H(s) = K_R (1 + \frac{1}{T_i s}),$$
(1)

then we have the equivalence with the Simulink implementation:

$$K_p = K_R, K_i = \frac{K_R}{T_i}$$
(2)

The PI controllers tuning was carried out using the parameters and discrete models presented in Simulink [1].

The model Simulink is show in Fig. 1, parameterization of the motor is shown in Fig. 2, the parameterization of the rectifier, inverter, intermediate filter and braking chopper is shown in Fig. 3. The chosen vector control mode is of FOC type, and the parameterization of speed regulators, flow controllers, current regulators, acceleration/braking ramp, filters and limitations is shown in Fig. 4.Fig. 5 show the general control diagrams of speed controllers, current and flux controllers, the transform of coordinates and calculation of the rotor position for FOC control strategy implemented in Simulink.

The value of the speed ramp for actual application is 150rpm/s and the hysteresis band of current controller is between 5 and 20A.



Fig. 1. Simulink block diagram for model.



Fig. 2. Parameters of motor.



Fig. 3. Parameters of Rectifier, DC Bus and Inverter.

Speed controller     Speed ramps (rpm/s)     Acceleration:     150	Deceleration: 150	Speed cutoff frequency (Hz): 1000	Speed controller sampling time (s): 100e-6	Machine flux (Wb) Initial: 0.73
Pi regulator Proportional gain: I 300 2	ntegral gain: 2000	Torque output limits Negative: -400	s (N-m) Positive: 400	Nominal: 0.73
Field oriented control Flux controller Proportional gain: 100	Integral g 30	ain:	output limits (Wb) Negative: -2	Positive: 2
Lowpass filter cutoff frequency (Hz): 16	Sampling tin 20e-6	C ne (s): hys	urrent controller steresis band (A): 10	Maximum switching frequency (Hz): 20000

Fig. 4. Adjustable parameters of the controllers.



Fig. 5. Field Oriented Control block diagram.

The output of speed controllers supply the torque  $(T^*)$  and flux (Phi\*) references for inner loop control. Following [1] and Fig. 5 for usual electrical parameters given above we can write the equations and transfer functions for calculate the Id, Iq and the intermediate value of flux used at each iteration by de FOC strategy control.

$$I_q^* = \frac{2}{3} \cdot \frac{1}{p} \cdot \frac{L_r}{L_m} \cdot \frac{T_e}{Phi} = 0.346 \cdot \frac{T_e}{Phi}, \qquad (3)$$

$$I_d^* = \frac{Phi^*}{L_m} = \frac{Phi^*}{20.7} \,, \tag{4}$$

$$\frac{Phi(s)}{I_d(s)} = \frac{L_m}{1+T_r} = \frac{20.7}{1+0.43s},$$
(5)

where the symbol \* mean that the value is calculated and will be used to the next iteration. In this way we can write the equations for each block from Fig. 5.

The simulation results for the parameterization sets of the controllers and the references for speed and torque from below are given in Fig. 6-10.

Set no.1: Speed controller: Kp=30, Ki=20; Flux controller: Kp=100, Ki=3, hysteresis band of current controller=10A; the speed reference is given by the sequence:  $[0 0.5 2]s \rightarrow [0 150 700]$ rpm; the torque reference is given by the sequence:  $[0 0.5 3]s \rightarrow [10 100 200]$ Nm.

Set no.2: Speed controller: Kp=300, Ki=2000; Flux controller: Kp=100, Ki=30, hysteresis band of current controller=10A; the speed reference is given by the sequence:  $[0 \ 0.5 \ 2]s \rightarrow [0 \ 150 \ 700]$ rpm; the torque reference is given by the sequence:  $[0 \ 0.5 \ 3]s \rightarrow [10 \ 100 \ 200]$ Nm.

Set no.3: Speed controller: Kp=300, Ki=2000; Flux controller: Kp=100, Ki=30, hysteresis band of current controller=10A; the speed reference is given by the sequence:  $[0\ 0.5\ 2]s \rightarrow [0\ 150\ 700]$ rpm; the torque reference is given by the sequence:  $[0\ 0.5\ 3]s \rightarrow [10\ 100\ 200]$ Nm; rotor resistance is doubled: 2x0.05 $\Omega$ .

Set no.4: Speed controller: Kp=300, Ki=2000; Flux controller: Kp=100, Ki=30, hysteresis band of current controller=10A; the speed reference is given by the sequence:  $[0 7]_{s} \rightarrow [800 \ 300]$ rpm; the torque reference is given by the sequence:  $[0 3 7]_{s} \rightarrow [10 \ 300 \ 10]$ Nm.

Set no.5: Speed controller: Kp=300, Ki=2000; Flux controller: Kp=100, Ki=30, hysteresis band of current controller=10A; the speed reference is given by the sequence:  $[0\ 0.5\ 2\ 4\ 7\ 8\ 9]s \rightarrow [0\ 150\ 300\ 500\ 350\ 450\ 700]$ rpm; the torque reference is given by the sequence:  $[0\ 3\ 6\ 9\ 10]s \rightarrow [10\ 100\ 200\ 300\ 100]$ Nm.

IN FOC control strategy (see Fig. 1 and Fig. 5) the flux and current controllers are in inner loop and the speed controller is in outer loop control. Besides the good dynamic performance are achieved (stationary error, settling time, rising time, overshooting and oscillating index), due to proper tuning of the regulators PI using Ziegler-Nichols method and varying the hysteresis band of current controller between 5A and 20A. Using a quality index given by de sum of squared errors between desired speed and measured speed, after a lot of simulations the best tuning is achieved in Fig. 7. The actual parameters of the motor can vary in time from the rated parameters (particularly due to temperature), in such a way that through simulation, it is found that controllers have a good tuning even for a fluctuation of 100% in rotor resistance (see Fig. 8).

In Fig. 9 at second 7, when the torque reference decreases from 300Nm to 10Nm regenerative braking occurs and the voltage in the intermediate circuit increases. In Simulink, in order to analyze this phenomenon we have set the limits of the braking chopper between 750V (Activation Voltage) and 650V (Shutdown Voltage). For actual implementation, instead of the braking chopper, a regenerative inverter will be used.

The simulations for an increasing dynamic of the references torque and speed are presented in Fig. 10.



Fig. 6. The simulation of model for the set no.1 of parameters of the controllers and references.



Fig. 7. The simulation of model for the set no.2 of parameters of the controllers and references.



Fig. 8. The simulation of model for the set no.3 of parameters of the controllers and references.



Fig. 9. The simulation of model for the set no.4 of parameters of the controllers and references.



Fig. 10. The simulation of model for the set no.5 of parameters of the controllers and references.

# III. CONTROL SENSORLESS OF ELECTRIC MOTORS DRIVES

The model Simulink for the sensorless version is shown in Fig. 11, [1]. As opposed to the model in Figure 1, an additional estimator block will be noticed (see Fig. 12), [11].The type of estimator for angular speed is MRAS.

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Fig. 11. Simulink block diagram for sensorless model.



Fig. 12. Speed estimator block diagram.

The equations of Blocks A and B are [11]:

$$\begin{bmatrix} \dot{\psi}_{dr}^{s} \\ \dot{\psi}_{qr}^{s} \end{bmatrix} = \frac{L_{r}}{L_{m}} \left\{ \begin{bmatrix} u_{ds}^{s} \\ u_{qs}^{s} \end{bmatrix} - \begin{bmatrix} R_{s} + \sigma L_{s}S & 0 \\ 0 & R_{s} + \sigma L_{s}S \end{bmatrix} \begin{bmatrix} i_{ds}^{s} \\ i_{qs}^{s} \end{bmatrix} \right\}, (6)$$
$$\begin{bmatrix} \dot{\psi}_{dr}^{s} \\ \dot{\psi}_{qr}^{s} \end{bmatrix} = \begin{bmatrix} -1 \\ T_{r} & -\omega_{r} \\ \omega_{r} & -\frac{1}{T_{r}} \end{bmatrix} \begin{bmatrix} \psi_{dr}^{s} \\ \psi_{qr}^{s} \end{bmatrix} + \frac{L_{m}}{T_{r}} \begin{bmatrix} i_{ds}^{s} \\ i_{qs}^{s} \end{bmatrix}, (7)$$

For the speed Estimator implemented in Simulink, let note  $\sigma = 1 - \frac{L_m^2}{L_r L_s}$  and starting with equations [11,12] we obtain:

$$\frac{d}{dt}\left(\Psi_{dr}^{s}\right) = \frac{L_{r}}{L_{m}} v_{ds}^{s} - \frac{L_{r}}{L_{m}} \left(R_{s} + \sigma L_{s}s\right) i_{ds}^{s}, \qquad (8)$$

$$\frac{d}{dt}\left(\Psi_{qr}^{s}\right) = \frac{L_{r}}{L_{m}}v_{qs}^{s} - \frac{L_{r}}{L_{m}}\left(R_{s} + \sigma L_{s}s\right)j_{qs}^{s},\qquad(9)$$

and using that  $\theta = \tan^{-1} \frac{\Psi_{qr}^s}{\Psi_{qd}^s}$ , after calculus we obtain:

$$\omega_r = \frac{1}{\hat{\Psi}_r^2} \left[ \left( \Psi_{dr}^s \dot{\Psi}_{qr}^s - \Psi_{qr}^s \dot{\Psi}_{dr}^s \right) - \frac{L_m}{T_r} \left( \Psi_{dr}^s \dot{i}_{qs}^s - \Psi_{qr}^s \dot{i}_{ds}^s \right) \right]. (10)$$

The encoder is thus eliminated, and the angular speed is estimated from current and voltage measurements. Using Popov hyperstability criterion, in order to achieve the overall asymptotic stability, an estimator will be achieved as follows [11]:

$$\hat{\omega}_r = \xi \left( K_p + \frac{K_i}{s} \right), \tag{11}$$

$$\xi = \hat{\Psi}_{dr}^s \Psi_{qr}^s - \Psi_{dr}^s \hat{\Psi}_{qr}^s \,. \tag{12}$$

In the following simulations without encoder version, the behavior of the converter unit plus motor will be analyzed, in terms of the following quantities: stator current, rotor speed, torque and voltage in the intermediate circuit.

The varying parameters were: for the speed regulator Kp and Ki, for the flux controller Kp and Ki, speed ramps and the hysteresis band for the current regulator. In addition with the encoder case, the estimator which is implemented around a PI controller will also have tuning parameters Kp and Ki.

The simulation results for the parameterization sets of the controllers and the references for speed and torque from below are given in Fig. 13-17.

Set no.1: Speed controller: Kp=300, Ki=2000; Flux controller: Kp=100, Ki=30, hysteresis band of current controller=10A; speed estimator controller: Kp=500, Ki=5000; the speed reference is given by the sequence:  $[0 0.5 2]s \rightarrow [0 150 700]$ rpm; the torque reference is given by the sequence:  $[0 0.5 3]s \rightarrow [10 100 200]$ Nm.

Set no.2: Speed controller: Kp=30, Ki=20; Flux controller: Kp=100, Ki=3, hysteresis band of current controller=10A; speed estimator controller: Kp=500, Ki=5000; the speed reference is given by the sequence:  $[0 \ 0.5 \ 2]s \rightarrow [0 \ 150 \ 700]$ rpm; the torque reference is given by the sequence:  $[0 \ 0.5 \ 3]s \rightarrow [10 \ 100 \ 200]$ Nm.

Set no.3: Speed controller: Kp=30, Ki=20; Flux controller: Kp=100, Ki=3, hysteresis band of current controller=10A; speed estimator controller: Kp=500, Ki=5000; the speed reference is given by the sequence:  $[0 \ 0.5 \ 2]s \rightarrow$  $[0 \ 150 \ 700]$ rpm; the torque reference is given by the sequence:  $[0 \ 0.5 \ 3]s \rightarrow [10 \ 100 \ 200]$ Nm; rotor resistance is doubled:  $2x0.05\Omega$ .

Set no.4: Speed controller: Kp=30, Ki=20; Flux controller: Kp=100, Ki=3, hysteresis band of current controller=10A; speed estimator controller: Kp=500, Ki=5000; the speed reference is given by the sequence:  $[0 \ 7]s \rightarrow [800 \ 300]$ rpm; the torque reference is given by the sequence:  $[0 \ 3 \ 7]s \rightarrow [10 \ 300 \ 10]$ Nm.

Set no.5: Speed controller: Kp=30, Ki=20; Flux controller: Kp=100, Ki=3, hysteresis band of current controller=10A; speed estimator controller: Kp=500, Ki=5000; the speed reference is given by the sequence:  $[0\ 0.5\ 2\ 4\ 7\ 8\ 9]s \rightarrow [0\ 150\ 300\ 500\ 350\ 450\ 700]$ rpm; the torque reference is given by the sequence:  $[0\ 3\ 6\ 9\ 10]s \rightarrow [10\ 100\ 200\ 300\ 100]$ Nm.

Because the speed estimator must operate faster than the outer control loops, maintaining the tuning parameters for the speed regulator like in the case with the encoder will result in an insufficient response like the one in Fig. 13. Therefore, by considerably lowering the tuning values for the speed regulator (so that they will be much smaller than the values of the controller from the estimator), the optimum tuning is achieved in Fig. 14 and it is found that controllers have a good tuning even for a fluctuation of 100% in rotor resistance (see Fig. 15). In Fig. 16 occur the regenerative braking and the simulations for an increasing dynamic of the references torque and speed are presented in Fig. 17.

Besides the good dynamic performance are achieved due to proper tuning of the controllers, even in sensorless case. Both in simulations and in implementation in DSP, a special attention is given to the phenomenon of saturation of component blocks. For the control loops, limiting and anti wind-up components will be implemented in the PI controllers.



Fig. 13. The simulation of sensorless model for the set no.1 of parameters of the controllers and references.



Fig. 14. The simulation of sensorless model for the set no.2 of parameters of the controllers and references.



Fig. 15. The simulation of sensorless model for the set no.3 of parameters of the controllers and references.



Fig. 16. The simulation of sensorless model for the set no.4 of parameters of the controllers and references.



Fig. 17. The simulation of sensorless model for the set no.5 of parameters of the controllers and references.

#### IV. HARDWARE AND SOFTWARE IMPLEMENTATION

For hardware implementation of Command and Control Unit we used the DSP dsPIC33EP810MU810 Microchip. This DSP have Harvard Architecture, 70 MIPS, Acc 40bits, PWM hardware blocks, USB, SPI and ECAN interfaces.

For the three-phase diode rectifier block we used DD160N 160A / 2200V modules from Infineon and for three-phase inverter block we used LNC2W562M modules from Infineon. The current transducers are HAT 500-S from LEM with IPN = 500A, IPM=  $\pm 1500A$  and Ua =  $\pm 15V$ . The voltage transducers are LV 25-P-1000 from LEM with UPN = 10...500V and IPN = 10mA.

The block diagram of hardware implementation is presented in Fig. 18 and contain the blocks: 1- c.c. circuit, 2three-phase main inverter, 3- synchronization block, 4-PWM block, 5- induction motor, 6- output filter, 7- PWM block for recovery inverter, 8- three-phase recovery inverter, 9- estimation block, 10- voltage controller, 11- flux controller, 12- speed controller, 13- current controller, 14data bus. The blocks 9 to 13 are implemented software in main DSP.

An image of cabinet of hardware structure for driving application is presented in Fig. 19.

The software implementation is realized in MPLAB from Microchip. MPLAB is a integrated and development environment IDE, who contain editor, project manager, debugger, profiler and C/C++ optimizer.

The software application supply the following features:

o Sensorless vectorially control of induction motors

o Automatically identification of electrical motor parameters

o Stability and fast response at fast changes of load

o Implementation of PWM Space Vector modulation

o Implementation of PI controllers and estimators

o Implementation of communication with PC host.

The main software blocks are:

o Init- make the configuration of registers and the limits of CAN converters

o Clarke- implement the Clarke transformation

o iClarke- implement the inverse Clarke transformation

o Control- make the configuration of DSP

o eCAN- make the configuration and activate the communication on CAN interface with other DSP

o Ethet- make the configuration on Ethernet

o Park- implement the Park transformation

o iPark- implement the inverse Park transformation

o Measure- implement the read and conversion of digital and analog ports

o PI- make the configuration and implement the software PI controllers

o Estim- implement the software estimators

o SVgen- implement the software PWM Space Vector modulation

o Timer- make the configuration of timers

o Main- implement the main loop.



Fig. 18. Hardware block diagram.



Fig. 19. Picture of electric drives equipment.

Following [13] all the software blocks that make the control of hardware structure are implemented on DSP, resulting a functional application.

The code for software blocks are implemented in MPLAB IDE, like a C language but optimized for DSP, where in a special format data Q15, the execution speed is increased even through the replacement of divide operations (large time consumer) by the shifting bit operations (low time consumer).

When are make the implementation of the equation of speed Estimator in DSP, can appear some little errors due

the data format representation instruction and the algorithm for increasing of accuracy of estimated speed value is presented in [13].

It's worth to say that the software implementation in DSP is not a trivial task and represent the last stage and the validation of the chain: theory, design, simulation and implementation.

Similar results with those of Section III are obtained even in the case of the functional application. In Fig. 20 are presented the signals recorded on the PC host for 1 minute. The signals presented are: speed reference and speed output, output torque, DC bus voltage, output current and voltage filtered.

The reference and output speed (the brown and red line) are overlaid, indicating a very good control and stationary and dynamic performance. The prescribed and actual output frequency (running and slope frequency) are overlapping under acceleration and braking ramps. The controllers follows the prescribed values properly in both cases: increase and decrease the frequency.

Output voltage is directly proportional to engine speed, based on the operation principle of inverter the U/f = constant. Observe correct output voltage variation depending on engine speed. The current through motor is influenced by the functioning regime of drive motor (acceleration or braking) and by the variation of the shaft load (at constant speed). The variation of current is correct and correlated with the engine operating conditions.

DC voltage value from intermediate circuit is the rectified and filtered voltage value of three-phase line voltage and is influenced by the functioning regime of drive motor (motor/generator) and the current through the motor.



Fig. 20. Signals recorded on the PC host from driving application

It is obvious that the tuning of the controllers from the DSP will be slightly different from the one achieved through simulation, since simulations cannot identify every single mode and dynamic from practice, but the qualitative aspect will surely be maintained, and the good results achieved through simulations and the implementation of algorithms in the DSP which follow the direction of the ones in Simulink is a guarantee that the actual model will also function with good results. The practical experiment proved us this fact.

#### V. CONCLUSIONS

In this article was presented the control of electric drive with high dynamic, with rapid changes in torque and speed, where the control strategy is FOC.

Such cases were dealt with where speed is measured directly with an encoder, compared with the case of sensorless control, where speed is estimated using an Estimator and the references for speed and torque are same.

Simulations were carried out in MATLAB/Simulink environment, highlighting the control structures and comparative results achieved for a drive application commonly used in surface mining industry. Following these directions a functional application was implemented.

Due to proper tuning of the controllers the good dynamic performance are achieved, even in sensorless case for a structure of estimator like a MRAC.

The results of the research consist in the implementation of the FOC sensorless control for an industrial drive which will be offered on the market.

In future approaches, based on the results presented in this article, the problem of multi-engine drive will inherently occur, where cases of combined constant or variable speed and torque drive will be analyzed.

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