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Original Article

Sliding mode sensorless control of an asynchronous motor based on an MRAS-type observer

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ABSTRACT

This work deals with the problem of speed control of a sensorless asynchronous motor. Conventional control laws by PI or PID for example, although still widely used, may prove to be insufficient or unsuitable. We then develop control laws by state feedback, their use nevertheless requires the measurement of the state vector. However, in many cases, sensors for measuring all the physical quantities are not available, essentially for cost reasons. An observer, which is a mathematical object, makes it possible to reconstruct this state vector from the only physical measurements available. In this context, we will propose the use of the sliding mode technique, which is a recursive control method and represents a tool for the study of dynamic stability. We will then approach the observers and in particular those resulting from the theory of the reference model (MRAS). In this proposed work, we are interested in the study of the asynchronous motor by the application of the sliding mode which is a relatively recent technique for nonlinear systems. It is combined with the vector control principle with oriented rotor flux to design robust machine control laws. The motor state quantities are estimated by the MRAS algorithm. A comparison of the performances is established to come out with general conclusions and in particular with regard to the use of the observer to estimate the quantities of state of the engine to control it later by this technique.

1. Introduction

In recent years, the development of power electronics and technological developments have widened the field of application of alternating current machines. Indeed, the asynchronous motor (MAS) known for its robustness, cost and reliability, is the subject of several researches. However, it is traditionally used in industrial applications which do not require high performance, this is due to its strong non-linearity and the coupling between the stator quantities and the rotor quantities.

On the other hand, the DC motor with separate excitation has a natural decoupling between the flux and the torque. These two quantities can be controlled independently by the field current and the induced current. It is for this reason and thanks to its simplicity of control that it is widely used in the field of variable speed applications. Nowadays and given the interest in these actuators, synthesized control techniques are more and more complex because they must meet increasingly stringent requirements.

Indeed, any control developed must, on the one hand, aim to simplify the mathematical model of the asynchronous motor while ensuring the decoupling between these two main dynamics (speed and flux), and on the other hand, a certain robustness with respect to the variation of the parameters, the uncertainty linked to the measurements and/or estimates (observations) of the state variables.

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It was only at the beginning of the seventies that this ambition which consists in facilitating the control of the asynchronous motor became achievable, and this with the proposal of the vector control introduced by "BLASCHKE", based on a change of coordinates which makes it possible to reduce the complexity of the dynamic model of the motor and to ensure decoupling in steady state of the two main quantities (torque, flux). In the case where the flux is kept constant, the motor thus acquires a behavior similar to that of the DC machine, the decoupling properties of which are achieved naturally by means of the brush-collector assembly.

Conventional control laws, by PI or PID for example, although still widely used, may prove to be insufficient or unsuitable. Control laws are then developed by state feedback, their use nevertheless requires the measurement of the state vector. However, in many cases, sensors for measuring all the physical quantities are not available, essentially for cost reasons. An observer, which is a mathematical tool, makes it possible to reconstitute this state vector from the only physical measurements available. In this context, we will propose the use of the sliding mode technique, which is a recursive control method and represents a tool for the study of dynamic stability. We will then discuss the observers and in particular those from the MRAS theory.

In this work, we are interested in the study of the control of the asynchronous motor by the application of the sliding mode which is a relatively recent technique for the nonlinear systems [1]. It is combined with the principle of oriented rotor flux vector control to design the machine control laws. The state quantities of the MAS necessary for its control are supposed to be measured by sensors in the first place, then, estimated by an observer of the MRAS type. A performance comparison is established to come out with general conclusions and in particular with regard to the use of the MRAS technique to estimate the state quantities of the machine to control it.

2. Asynchronous motor model

The process to be controlled consists of a squirrel-cage asynchronous motor voltage-controlled by a two-level inverter driven by a sine-delta PWM.

We consider for the motor, a sinusoidal distribution of the magnetomotive forces, the linearity of the magnetic circuit, the absence of magnetic and mechanical losses, as well as the effects of notches and skin.

We then express its dynamic model in the Park frame by a system of differential equations [2]:

$$\frac{di_{sd}}{dt} = -\left(\frac{R_s}{\sigma.L_s} + \frac{1-\sigma}{\sigma.T_r}\right).i_{sd} + \omega_s.i_{sq} + \frac{L_m}{\sigma.L_s.L_r.T_r}\varphi_{rd} + \frac{L_m}{\sigma.L_s.L_r}\varphi_{rq} + \frac{1}{\sigma.L_s}.v_{sd} \tag{1}$$

$$\frac{di_{sq}}{dt} = -\omega_s.i_{sd} - \left(\frac{R_s}{\sigma.L_s} + \frac{1-\sigma}{\sigma.T_r}\right).i_{sq} - \frac{L_m}{\sigma.L_s.L_r}.\omega_r.\varphi_{rd} + \frac{L_m}{\sigma.L_s.L_r.T_r}.\varphi_{rq} + \frac{1}{\sigma.L_s}.v_{sq} \tag{2}$$

$$\frac{d\varphi_{rd}}{dt} = \frac{L_m}{T_r}.i_{sd} - \frac{1}{T_r}.\varphi_{rd} + (\omega_s - \omega_r).\varphi_{rq} \tag{3}$$

$$\frac{d\varphi_{rd}}{dt} = \frac{L_m}{T_r}.i_{sq} - (\omega_s - \omega_r).\varphi_{rd} - \frac{1}{T_r}.\varphi_{rq} \tag{4}$$

$$\frac{d\omega_r}{dt} = \frac{np^2.L_m}{J.L_r}.(\varphi_{rd}.i_{sq} - \varphi_{rd}.i_{sq}) - \frac{np}{J}.T_L - \frac{f_v}{J}.\omega_r \tag{5}$$

3. Sliding mode control strategy

3.1 Architecture of the proposed speed control strategy

In this part, we propose to eliminate the conventional PI regulators in the diagram of the vector control of the machine given by figure 1 and to replace them by control laws by Sliding Mode.

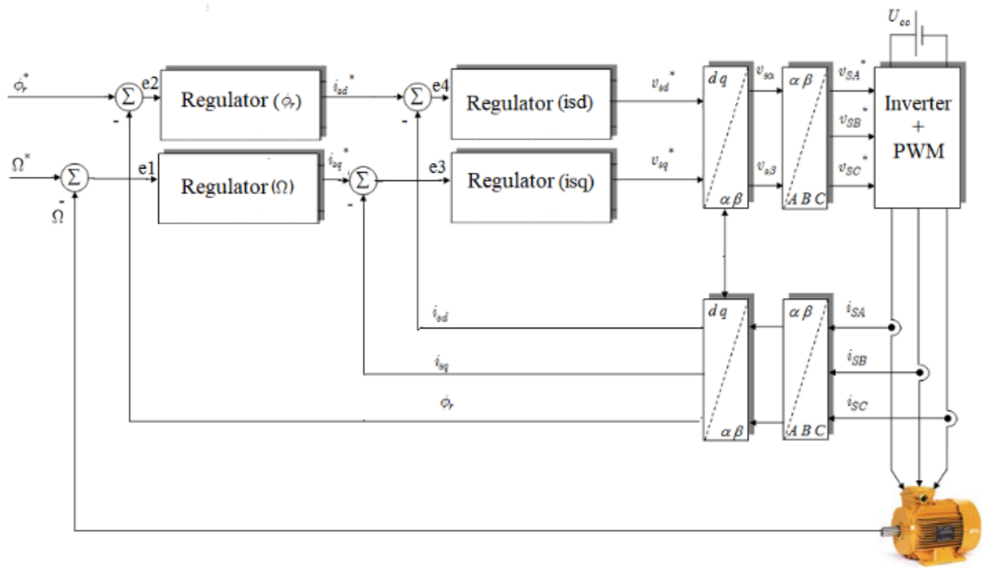


Fig 1. Illustrates all possible transitions of valleys: L-Γ,

The relative degree of the two surfaces is taken equal to two in order to show commands V_{sq} and V_{sd} in its derivatives. The two surfaces are given by :

$$\begin{cases} S_{C1} = S_{C1}(\omega) = \lambda_\omega(\omega^* - \omega) + \dfrac{d}{dt}(\omega^* - \omega) \\ S_{C2} = S_{C2}(\varphi_r) = \lambda_\omega(\varphi_r^* - \varphi_r) + \dfrac{d}{dt}(\varphi_r^* - \varphi_r) \end{cases} \quad (6)$$

Where ω^* and φ^* are the reference velocity and the reference flux, with :

$\lambda_\omega > 0$ et $\lambda_\varphi > 0$.

To determine the control laws which bring the sliding surfaces, equation (6), towards zero in a finite time, we consider the dynamics of , $S_C = (S_{C1}, S_{C2})^T$ given by:

$$\dot{S}_C = F + D\,V_s$$

$$F = \begin{bmatrix} \left(\ddot{\omega}^* + \lambda_\omega \dot{\omega}^* + \dfrac{P}{J}\dot{C}_r\right) + \left(-\lambda_\omega + \dfrac{f}{J}\right) f_1 - k_C\left(i_{sq} f_2 + \varphi_r f_4\right) \\ \left(\ddot{\varphi}_r^* + \lambda_\varphi \dot{\varphi}_r^*\right) + \left(-\lambda_\varphi + \dfrac{1}{T_r}\right) f_2 - \dfrac{L_m}{T_r} f_3 \end{bmatrix}$$

$$F = -\frac{1}{\sigma L_s}\begin{bmatrix} k_C\varphi_r & 0 \\ 0 & L_m/T_r \end{bmatrix},\ V_s = \begin{bmatrix} V_{sq} \\ V_{sd} \end{bmatrix}$$

• During the sliding mode, the derivatives are null, that is to say:

$$\dot{S}_C = 0 = F + D\,V_{s,eq} \quad (7)$$

from which we derive the following equivalent commands:

$$\begin{bmatrix} V_{sq,\,eq} \\ V_{sd,\,eq} \end{bmatrix} = -D^{-1}F$$

(8)

• During convergence mode, we have:

$$\begin{bmatrix} V_{sq} \\ V_{sd} \end{bmatrix} = \begin{bmatrix} V_{sq,\,eq} \\ V_{sd,\,eq} \end{bmatrix} + \begin{bmatrix} V_{sq,\,n} \\ V_{sd,\,n} \end{bmatrix}$$

If Lyapunov's stability theory is used to ensure the attractiveness and invariance of SC, the following condition must be satisfied:

$$S_C \cdot \dot{S}_C < 0$$

The general structure of the Sliding Mode control of the MAS with oriented rotor flux, is presented in figure 2. The blocks calculating $(i_{sd})_{ref}$ and $(i_{sq})_{ref}$ representing the fictitious controls, respectively provide the reference currents obtained from the flux errors rotor and speed. The calculation of the control voltages V_{sd} and V_{sq} is based on the error between the reference and real currents [1].

The blocks (dq-αβ) ensure the transition from the system of rotating axes (d-q) to the stationary system (α, β) and vice versa whose relations are given by these equations.

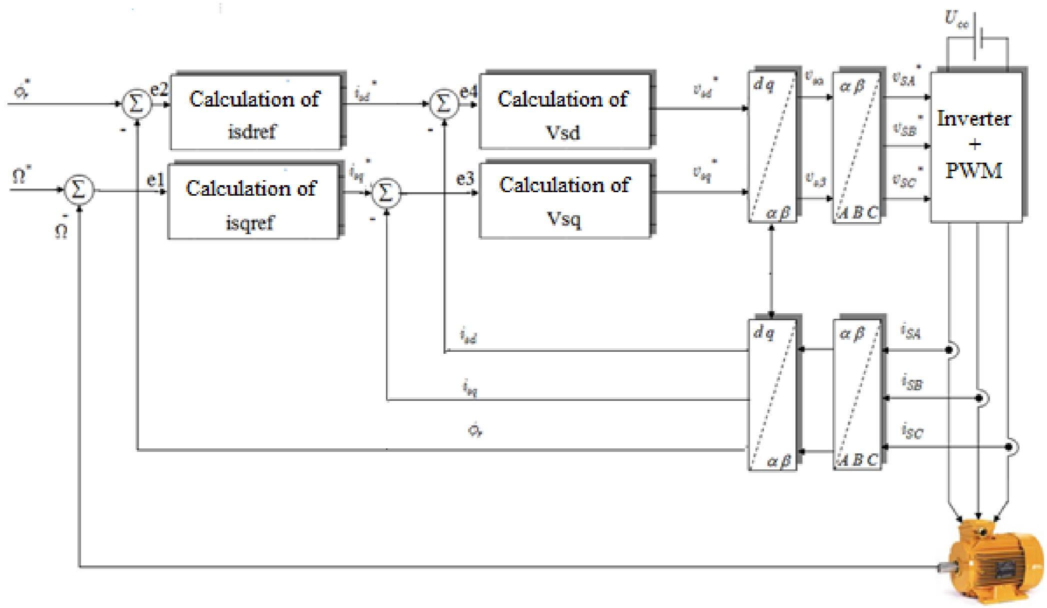


Fig 2. General structure of the sliding mode control of the asynchronous machine

4. Sensorless control based on the MRAS observer

2.1 MRAS Speed Observer Architecture

The MRAS technique (Adaptive Reference Model System) is developed to minimize the error between a real quantity and an estimated quantity. It is based on the comparison of the outputs of two structures:

• The first, which does not introduce the quantity to be estimated, is called the reference model.

• The second structure is the adjustable model depending on the estimated quantity.

The error between the two models drives an adaptation mechanism (algorithm) that generates the estimated speed, which is used in the adjustable model.

For MAS, whose first study of the MRAS technique goes back to Schauder (1992), the two basic models are the stator model (voltage model) and the rotor model (current model), figure 3, [1], [3], [4].

Rotation speed (rad/s) Observation error (rad/s)

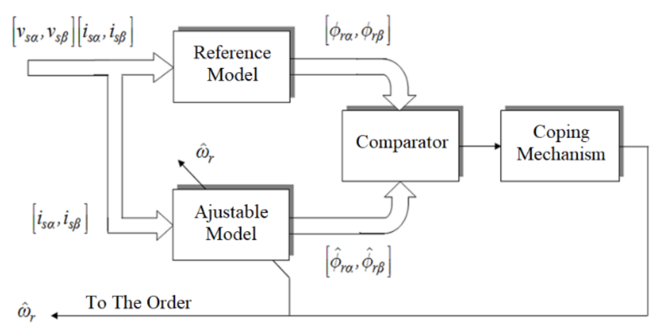


Fig. 3. Structure of an MRAS observer for rotor speed estimation [5].

From the stator and rotor equations, we have [6], [7], [8]: The reference model equations given by:

$$\begin{cases} \frac{d\Phi_{r\alpha}}{dt} = \frac{L_r}{M}\left(V_{s\alpha} - R_s i_{s\alpha} - \sigma L_s \frac{di_{s\alpha}}{dt}\right) \\ \frac{d\Phi_{r\beta}}{dt} = \frac{L_r}{M}\left(V_{s\beta} - R_s i_{s\beta} - \sigma L_s \frac{di_{s\beta}}{dt}\right) \end{cases} \quad (9)$$

Hence the equations of the adjustable model :

$$\begin{cases} \frac{d\widehat{\Phi}_{r\alpha}}{dt} = -\frac{1}{T_r}\widehat{\Phi}_{r\alpha} - P\widehat{\Omega}\widehat{\Phi}_{r\beta} + \frac{M}{T_r} i_{s\alpha} \\ \frac{d\widehat{\Phi}_{r\beta}}{dt} = -\frac{1}{T_r}\widehat{\Phi}_{r\beta} + P\widehat{\Omega} + \frac{M}{T_r} i_{s\beta} \end{cases} \quad (10)$$

The adaptation algorithm is chosen to converge the adjustable model towards the reference model, thus minimizing the error and ensuring model stability. The algorithm parameters are defined according to the criterion of Popov's hyperstability [1].

The error between the states of the two models can be represented in matrix form as follows:

$$\begin{bmatrix} \varepsilon_{\alpha} \\ \varepsilon_{\beta} \end{bmatrix} = \begin{bmatrix} \Phi_{r\alpha} - \hat{\Phi}_{r\alpha} \\ \Phi_{r\beta} - \hat{\Phi}_{r\beta} \end{bmatrix} \quad (11)$$

The purpose of this device is to generate the value of the supposed speed, to be reintroduced into the adjustable model in order to cancel the error between the two flow estimation models. It must therefore converge this error asymptotically to zero, providing a fast response and guaranteeing the stability of the system. Schauder studies the stability of this algorithm by applying the so-called hyperstability criterion [5].
Finally, the estimated speed can be expressed by a law of the proportional and integral type given by the following relationship:

$$\hat{\omega}_r = k_p\, e_{\Phi r} + k_i \int e_{\Phi r}\, dt \quad (12)$$

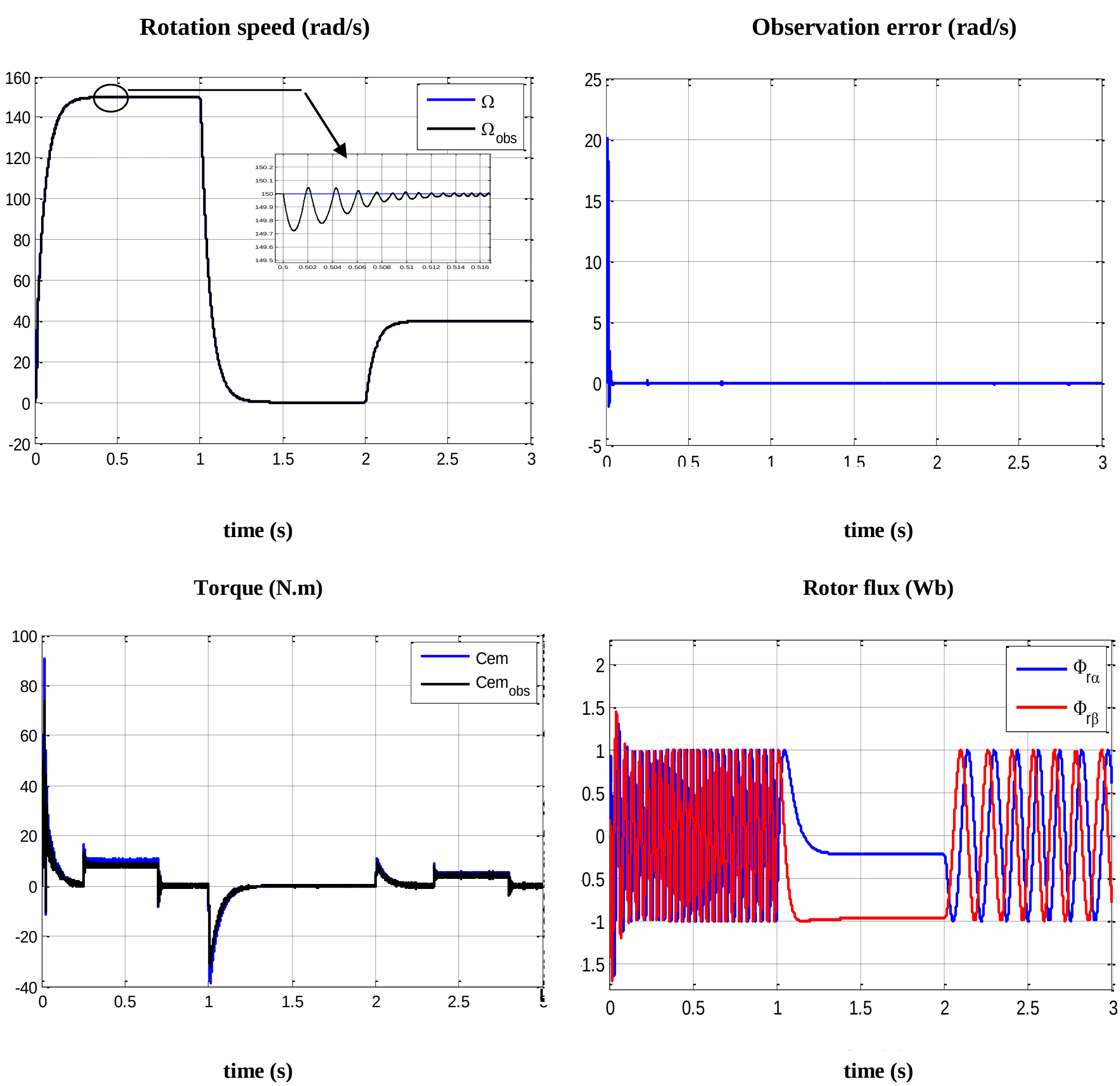


Fig 4. Performance of sliding mode control without speed sensor – Test with nominal parameters.

In order to test the performance and robustness of the Backstepping control without speed sensor, a series of numerical simulations is carried out to validate the performance of the proposed control technique:

No-load starting with application of a speed reference of 150 rad/s, application and elimination of a load torque of 10 N.m at times t= 0.25s and t=0.7s respectively and a torque of 5 N.m at times t = 2.35s and t= 2.8s respectively.

Figure 4 represents the simulation results of the sliding mode control without speed sensor based on the MRAS technique, the study of the results clearly shows that this type of control gives very satisfactory performance, the speed observed follows the evolution of the real speed with practically zero overshoot, the decoupling is maintained as well as the current is admissible with a minimal observation error.

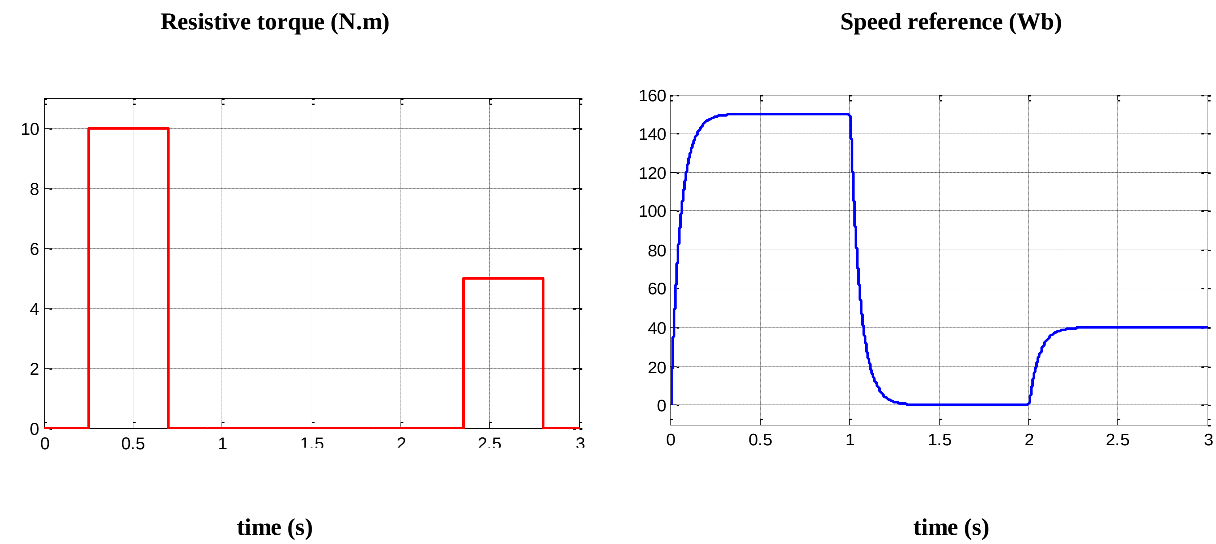
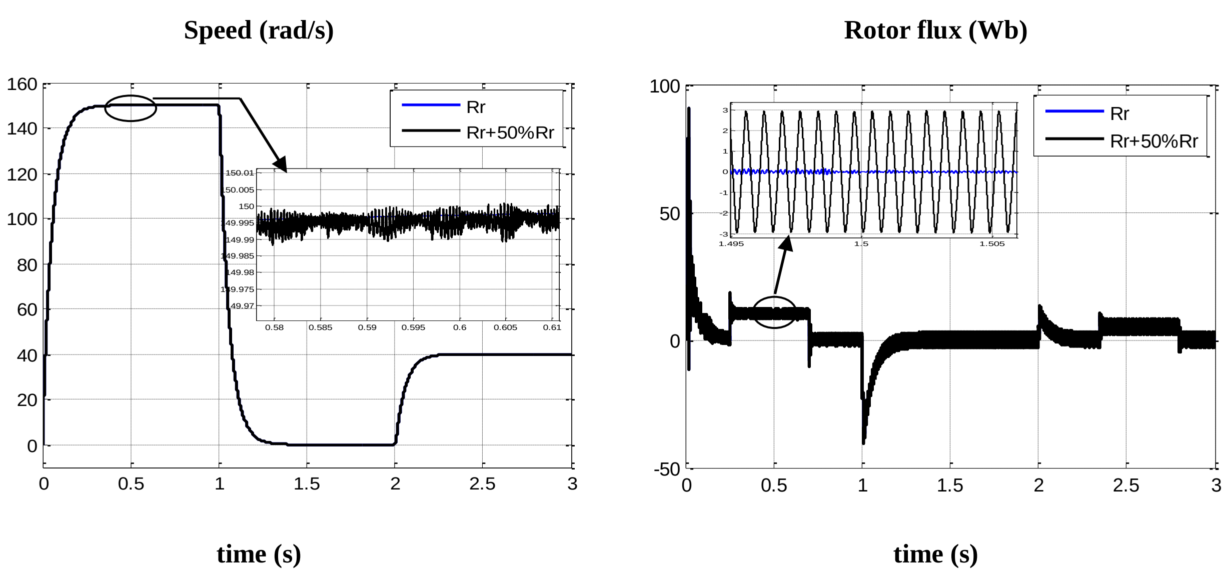


Fig. 5. Speed setpoint profile and mechanical load



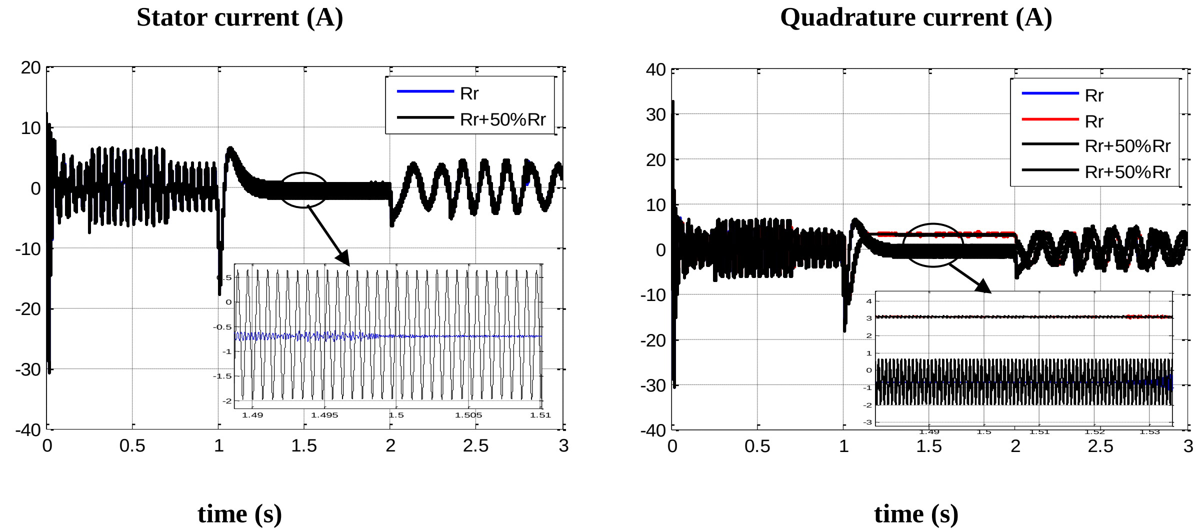
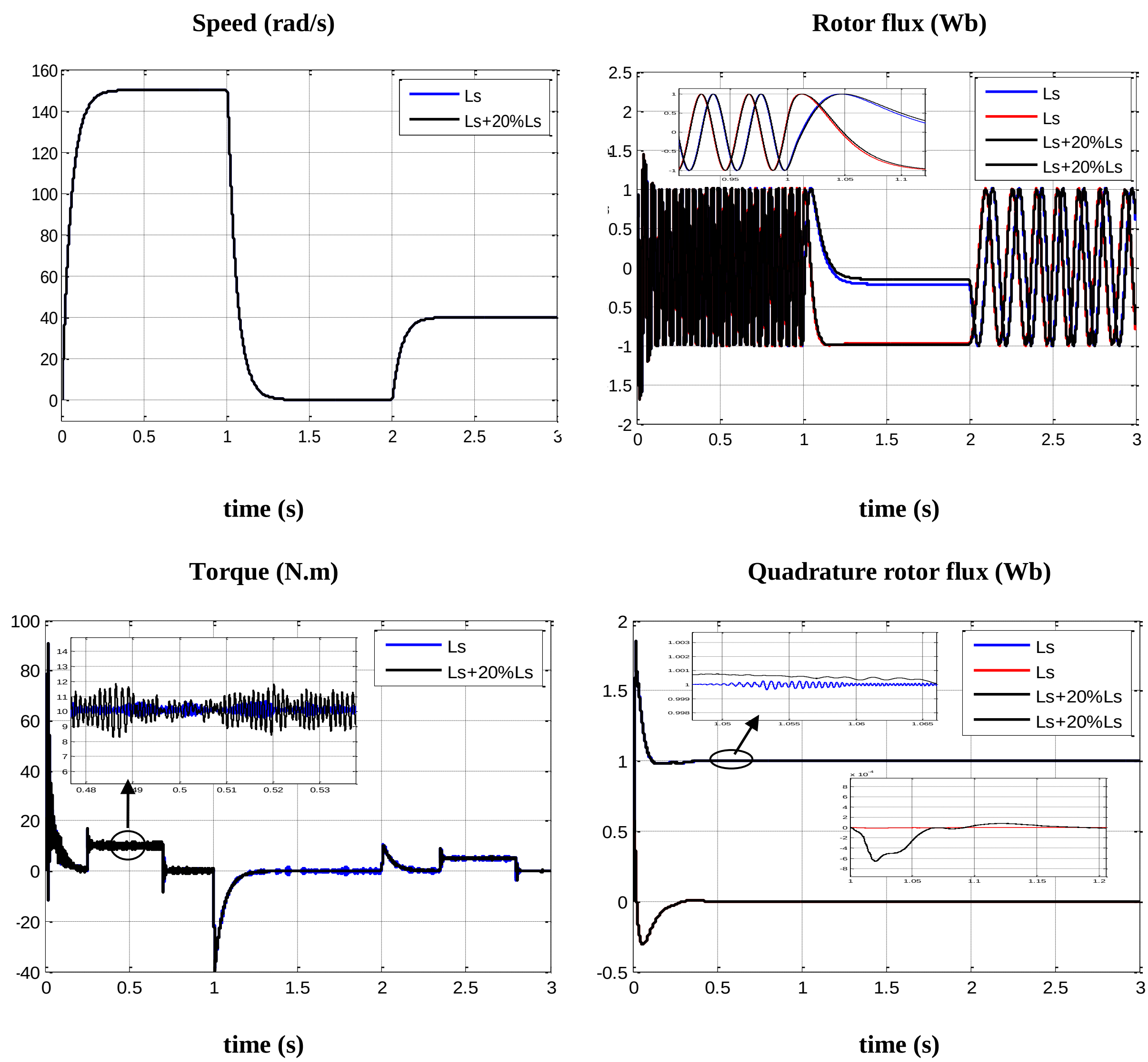


Fig 6. Performance de la commande par mode glissant sans capteur de vitesse – Essai avec variation de 50%Rr



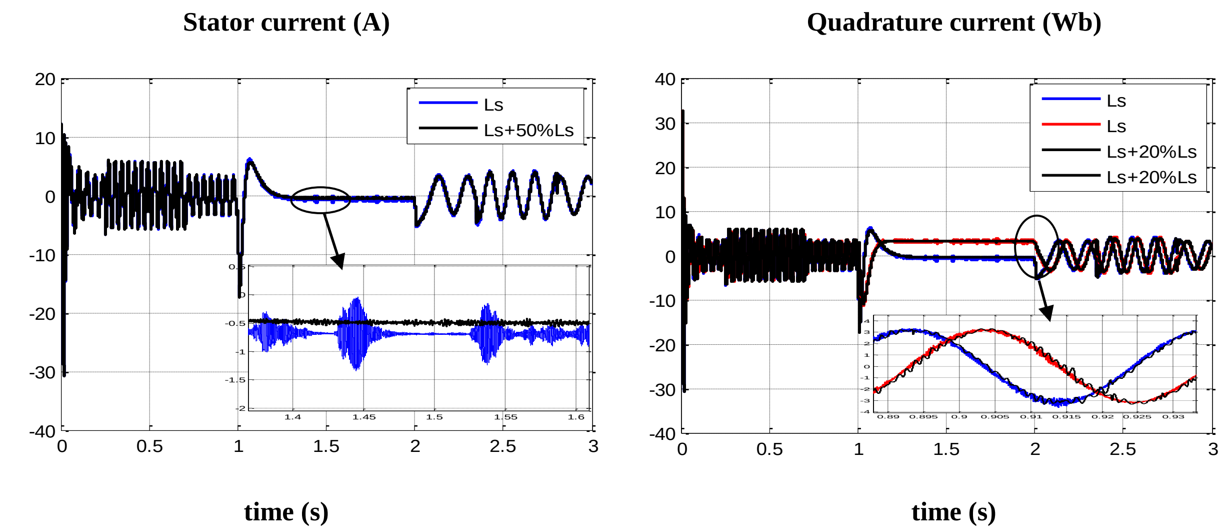


Fig 7. Performance of sliding mode control without speed sensor – Test with variation of 20%Ls

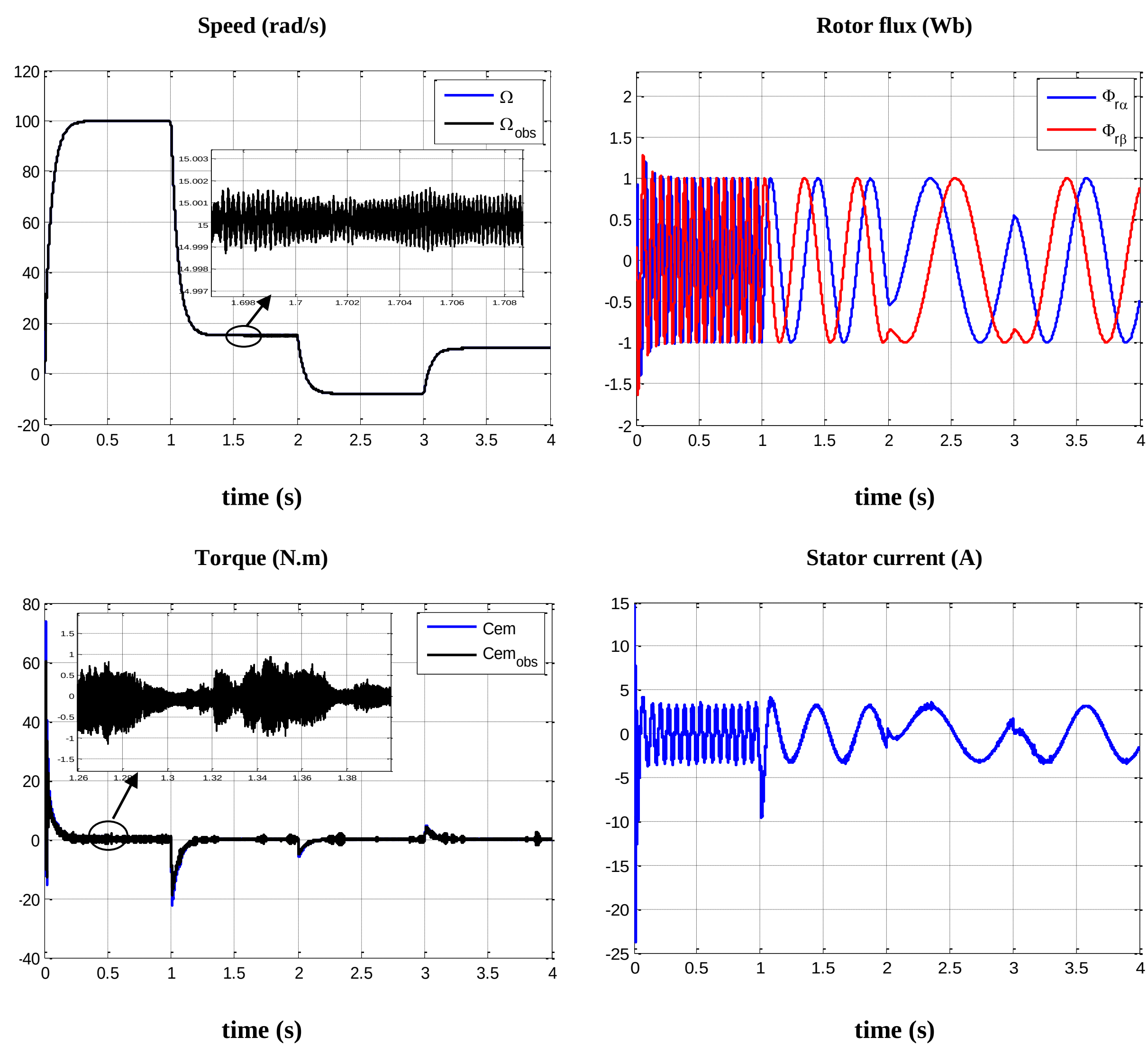


Fig 8. Chase test with different speed ranges

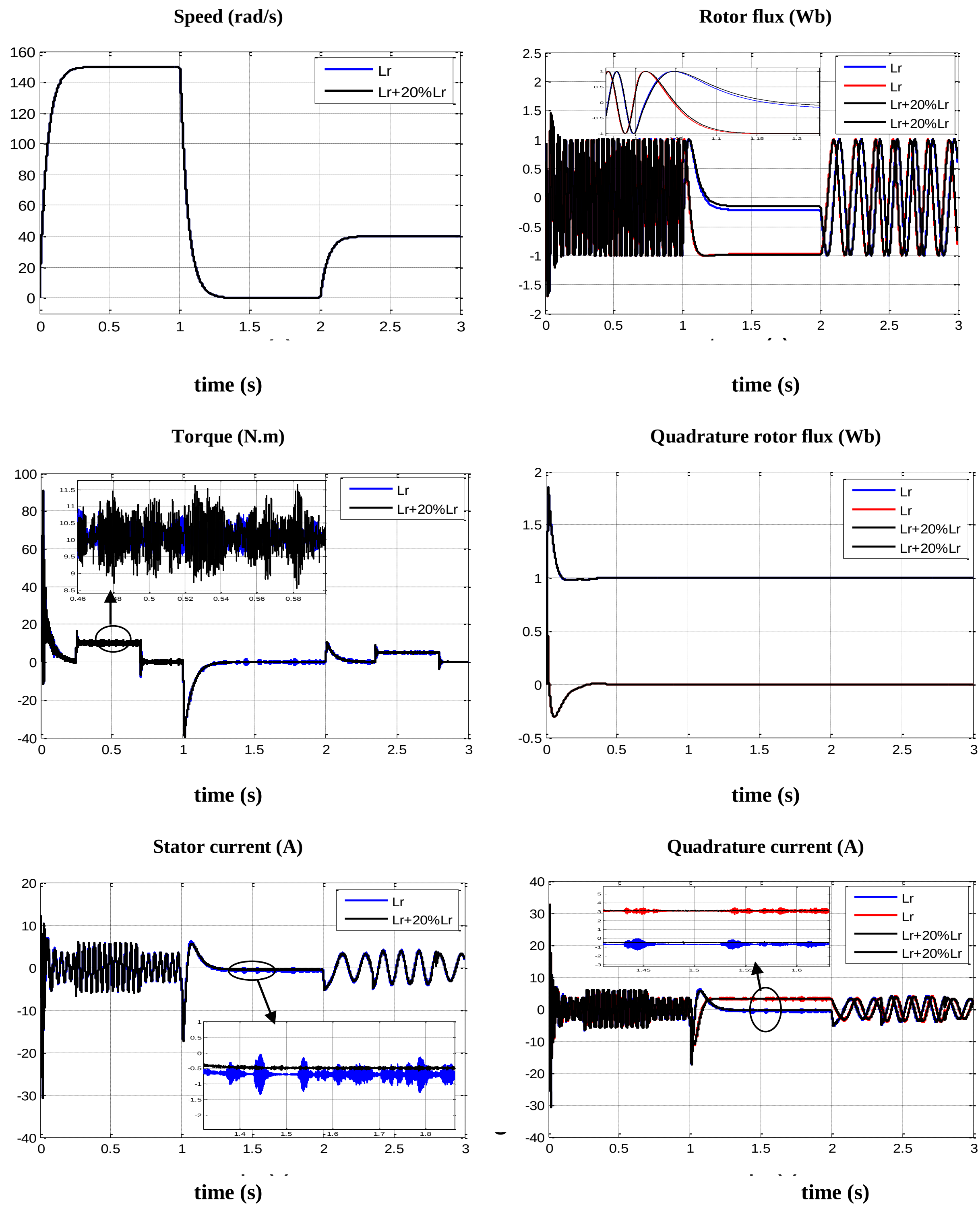


Fig 9. Performance of sliding mode control without speed sensor – Test with variation of 20%Lr

5. Conclusion

According to the simulation results obtained, it can be concluded that the proposed observation technique is valid for the nominal conditions, going even to satisfy the operations at low speed, stopping and even when the machine is loaded. On the other hand, the observer proposed has good robustness with respect to the variation of the load and the continuation, making it possible to achieve good functional performance with a low-cost and low-volume installation, this to give a minimal structure at our command, on the other hand the proposed observer is not robust in front of the parametric variations of the machine. Indeed, sensorless control methods based on the MRAS technique. Generally suffer from a limited convergence domain and a relatively high sensitivity to uncertainties and/or disturbances, but also robustness in the presence of a nonlinear system parameter change during start-up and at low speed . To solve this problem, it is therefore necessary to turn to the so-called model-free methods.

Appendix

Table I. Motor Parameters

Powerful	**1.5 kW**
Tension	220/380 V
Current (Δ/Y)	6.4/3.7 A
Speed	1420 rpm
Nominal torque	10 Nm
Frequency	50bHz
Rs	4.85 Ω
Rr	3.805 Ω
Ls	0.274H
Lr	0.274H
Lm	0.258H
D	0.031 Kg.m²
fr	0.00114 N.m.s/rad
P	2

Conflict of Interest

The authors declare that they have no conflict of interest.

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