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OPTIMAL CONTROL OF INDUCTION MOTOR

Abstract. *An adaptive optimal controller for the induction motor is proposed. Our aims are to have an adaptive controller that can stabilize of work the induction motor with good performances and that can minimize the consumed energy. In order to achieve this goal, steepest gradient descent with constant and variable steps is adopted. The variable steps are obtained via a simple fuzzy system with just two rules.*

Keywords*: induction motor, adaptive optimal controller, minimize the consumed energy, fuzzy logic.*

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ОПТИМАЛЬНОЕ УПРАВЛЕНИЕ АСИНХРОННЫМ ДВИГАТЕЛЕМ

Аннотация. *Предлагается оптимальный адаптивный регулятор для асинхронного двигателя. Его цель – стабилизация работы асинхронного двигателя и обеспечение хороших показателей качества и минимального потребления энергии. Для достижения этой цели принят наискорейший градиентный спуск с постоянным и переменным шагом. Переменные шаги получены с помощью нечеткой логики и двух правил.*

Ключевые слова*: асинхронный двигатель, оптимальный адаптивный регулятор, минимальное потребление энергии, нечеткая логика.*

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ОПТИМАЛЬНЕ КЕРУВАННЯ АСИНХРОННИМ ДВИГУНОМ

Анотація. *Пропонується оптимальний адаптивний регулятор для асинхронного двигуна. Його мета – стабилизація роботи асинхроного двигуна і забезпечення необхідних показників якості і мінімального використання енергії. Для досягнення цієї мети взято щонайшвидший градієнтний спуск з постійним та змінним кроком. Змінні кроки отримані за допомогою нечіткої логіки і двох правил.*

Ключові слова*: асинхронний двигун, оптимальний адаптивний регулятор, мінімальне споживання енергії, нечітка логіка.*

Introduction

Adaptive control of induction motors is one of most recent strategies applied in electrical drives field. In the few last decades, induction motors have gained a great interest due to their characteristics (weak inertia, no mechanical switching, etc.) and seem to be very useful in high speed driving [1].Induction motors have a complex model that is a high order nonlinear model with coupled parts and time-varying parameters. Therefore, the classical strategies of control were not effectively sufficient.

Adaptive control is one alternative of control that deals with time-varying parameters. It can adjust the controller parameters at every time taking in consideration the varying parameters of the system to be controlled. Several techniques were developed for adaptive control of the induction motor.

In [2], we find a systematic design of adaptive control for feedback linearizable systems. An application to the induction motor is given in [3].

There are several approaches for adaptive control (direct, indirect, self tuning, model reference tracking, and so on …). In indirect schemes, the parameters of the controller are adjusted after the identification of the parameters of the model proposed to represent the system. In the direct scheme, we don't need to identify the parameters of the model. The control parameters are obtained directly by optimizing (minimizing or maximizing) a certain objective functions (the criterion) [4].

In addition to the least squares algorithm, the steepest gradient descent algorithm is used for deriving the parameters of the controller. In gradient descent method we have to choose a good value for the step. High step values imply oscillations and/or divergence of the algorithm, whereas, low ones slow down the convergence speed to the optimal values of the parameters of the controller. A good idea is to use a variable step for gradient descent algorithm.

Another field is the optimisation of energy consumed by the system [5]. In electrical drives, we can reach this objective by various techniques. One can use optimal control strategies to minimise the consumed energy (minimal energy control), or maximize the generated torque [6].

Combinations between adaptive and optimal control strategies have been proposed. Adaptive optimal control strategies of induction motors in electrical drives have to ensure both speed control and minimal used energy. The minimal energy is constrained by the system under control and the used adaptive controller [6].

In this paper, we propose a direct adaptive optimal controller for the induction motor. The steepest gradient descent is used to determine the controller parameters. Theses parameters have certain significances and we can choose them to be variable or constant (for some of them). For the varying parameters, the gradient descent derives their values that minimise the objective function (criterion). Some steps in the gradient descent are chosen to be variable to deal with certain problems, whereas the others are taken to be constant.

After some analysis of the induction motor model, we proposed a structure for the controller ensuring the decoupling between electrical, electromagnetic and mechanical parts. The study of each part separately is conducted in order to have some static controllers (with non adaptable parameters).

These controllers are not sufficient to control the induction motor. So, we propose to add some parts with adaptable parameters to the controllers. The added parts have to be adjusted by the adaptive laws. Certain parts deals with the optimisation of the consumed energy minimization and the others ensure good tracking of desired speed, desired currents and desired torque.

Desired torque and currents are considered to be optimal, because they are obtained from the adjusted parameters given by the adaptive laws. Another part can generate a certain estimation of the resistive torque. In fact, for this part, there is no distinction between inertial torque and resistive torque. So we must be careful in the choice of the step for the gradient descent concerning this part.

Also, we will use fuzzy logic [7] to generate variable steps for the gradient descent algorithm in order to meet good performances in low and high speed driving.

Some tests are conducted by simulation in order to validate our approach. And the effect of several parameters is given in this paper.

Induction motor modelling

The induction motor has two parts: stator (fixed) and rotor (mobile). Modelling the motor consists of deriving the equations relating inputs (voltages), outputs (speed, currents, fluxes …), and the parameters of the motor and extern disturbances (perturbations).

Model of the induction motor in Park frame

We consider the model in Park frame given by the equations (1). This model consists of three coupled subsystems (stator, rotor, mechanical).

$$\begin{cases} \dot{I}_{sd} = -\gamma I_{sd} + \omega_s I_{sq} + \frac{k}{T_r}\Phi_{rd} + pk\Omega\Phi_{rq} + \frac{1}{\sigma L_s}u_{sd} \\ \dot{I}_{sq} = -\gamma I_{sq} - \omega_s I_{sd} + \frac{k}{T_r}\Phi_{rq} - pk\Omega\Phi_{rd} + \frac{1}{\sigma L_s}u_{sq} \\ \dot{\Phi}_{rd} = \frac{M}{T_r}I_{sd} - \frac{1}{T_r}\Phi_{rd} - (\omega_s - p\Omega)\Phi_{rq} \\ \dot{\Phi}_{rq} = \frac{M}{T_r}I_{sq} - \frac{1}{T_r}\Phi_{rq} - (\omega_s - p\Omega)\Phi_{rd} \\ \dot{\Omega} = \frac{pM}{JL_r}(\Phi_{rd}I_{sq} - \Phi_{rq}I_{sd}) - \frac{f}{J}\Omega - \frac{1}{J}C_r \end{cases}, \quad (1)$$

with

$$\sigma = 1 - \frac{M^2}{L_r L_s}, \gamma = \frac{R_s + \frac{R_r M^2}{L_r^2}}{\sigma L_s},$$

$$k = \frac{M}{\sigma L_r L_s} \text{ and } T_r = \frac{L_r}{R_r}.$$

The electromagnetic torque is given by (2)

$$C_{em} = \frac{pM}{L_r}\left(\Phi_{rd}I_{sq} - \Phi_{rq}I_{sd}\right). \quad (2)$$

As we can see, the fluxes contribute to have the electromagnetic torque. But theses fluxes are not measurable (but we still can estimate them).

Model decomposition

In order to develop our approach, the model of the induction motor is decomposed in three parts:

– the first is the electrical one, it deals with the currents I_{sd} and I_{sq},

– the second deals with the electromagnetic torque C_{em},

– the third one concern the mechanical part of the machine with the speed Ω as an output.

Model decomposition

1. Electrical subsystems for I_{sd} and I_{sq}.

By putting

$$\frac{1}{\sigma L_s}u_{sd1}=\omega_s I_{sq}+\frac{k}{T_r}\Phi_{rd}+pk\Omega\Phi_{rq}+\frac{1}{\sigma L_s}u_{sd}$$
$$\frac{1}{\sigma L_s}u_{sq1}=-\omega_s I_{sd}+\frac{k}{T_r}\Phi_{rq}-pk\Omega\Phi_{rd}+\frac{1}{\sigma L_s}u_{sq} \quad (3)$$

one can have the decoupled models with inputs u_{sd1} and u_{sq1} and outputs I_{sd} and I_{sq}

$$\dot{I}_{sd}=-\gamma I_{sd}+\frac{1}{\sigma L_s}u_{sd1}$$
$$\dot{I}_{sq}=-\gamma I_{sq}+\frac{1}{\sigma L_s}u_{sq1} \quad (4)$$

2. Ectromagnetic part

It concerns the electromagnetic torque given by the equation (2).

3. Mechanical subsystem

It is given by the equation below

$$\dot{\Omega}=\frac{1}{J}C_{em}-\frac{f}{J}\Omega-\frac{1}{J}C_r. \quad (5)$$

Where the torque C_{em} is the main input and Ω the output and C_r is the resistive torque (perturbation).

Controller synthesis

We propose to separate the controller into two sub-controllers: non-adaptive and adaptive.

Non-adaptive sub-controller: (controllers for decoupled subsystems)

1. PI controllers for both electrical subsystems (fig.1)

Both subsystems of the electrical part have the same transfer function

$$G_{ei}(s)=\frac{1}{\sigma L_s(s+\gamma)}, \ i=1,2 . \quad (6)$$

We just need to study this transfer function and find a simple PI controller that is sufficient to just stabilise it. The PI controllers are taken to be as:

$$R_{ei}(s)=K_{pei}+\frac{K_{iei}}{s}, \ i=1,2, \quad (7)$$

with $K_{pei}=1$ and $K_{iei}=50$, i=1,2 .

2. PID controller for mechanical subsystem (fig.2)

The transfer function of the mechanical part is given by (we put here $C_r=0$)

$$G_2(s)=\frac{1}{(Js+f)}. \quad (8)$$

A simple PID controller can stabilise this subsystem. We take:

$$R_m(s)=K_{pm}+\frac{K_{im}}{s}+K_{dm}s , \quad (9)$$

with $K_{pm}=0.3$, $K_{im}=0.05$ and $K_{dm}=0.01$.

Adaptive sub-controller (fig.3)

The controllers derived above can stabilize the decoupled sub-systems, but they fail in the control of the induction motor due to the coupling effects. So we need some enhancements to deal with this problem. We propose to take some additional adaptive sub-controllers in order to cope with the coupling effects.

1. Controller structure: guide lines

From equations (1), one can propose to take

$$u_{sd}=u_{sd1}-\sigma L_s\omega_s I_{sq}-\frac{k}{T_r}\sigma L_s\Phi_{rd}-\sigma L_s pk\Omega\Phi_{rq}$$
$$u_{sq}=u_{sq1}+\sigma L_s\omega_s I_{sd}-\frac{k}{T_r}\sigma L_s\Phi_{rq}+\sigma L_s pk\Omega\Phi_{rd} \quad (10)$$

The signals u_{sd1} and u_{sq1} are given by the PI controllers R_{e1} and R_{e2} respectively, but the fluxes are not known (we can use estimators or observers).

In our work, we will not use estimators or observers, but just propose to take:

$$u_{sd}=u_{sd1}-\sigma L_s\omega_s I_{sq}+k_2+k_1(\Omega^*-\Omega)$$
$$u_{sq}=u_{sq1}+\sigma L_s\omega_s I_{sd}+k_4+k_3(\Omega^*-\Omega) \quad (11)$$

The parameters k_i, i = 1,2,3,4 are to be calculated by the adaptation laws.

The PID controller R_m generates the control signal τ.

The generation of the electromagnetic torque passes by both electrical and electromagnetic parts. So we need the electromagnetic torque to behave as the signal given below (desired electromagnetic torque):

$$C_{em}^{*} = \tau + k_9 + k_{10}\left(\Omega^{*} - \Omega\right). \qquad (12)$$

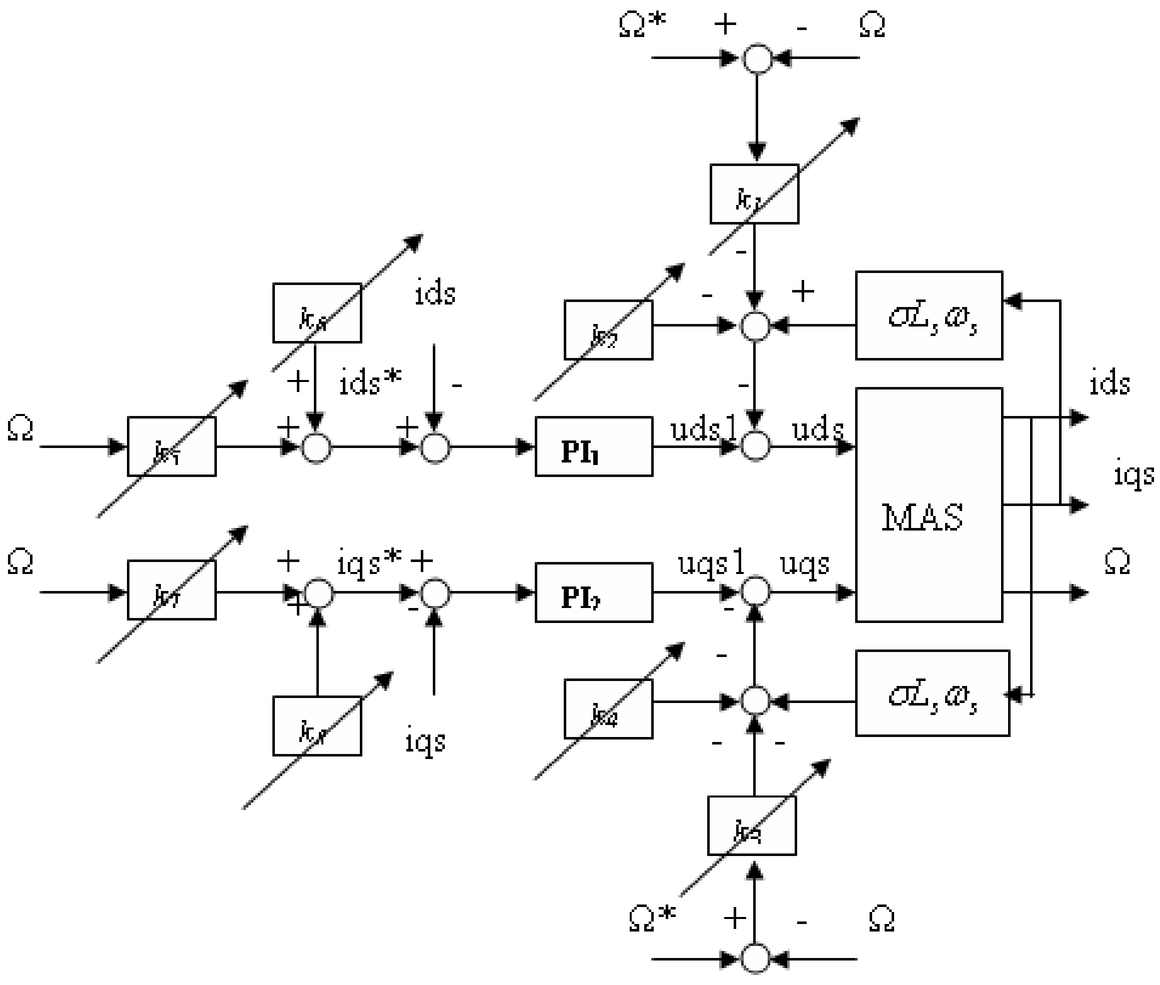

Fig. 1. Structure of the proposed adaptive and optimal controller (for electrical subsystems)

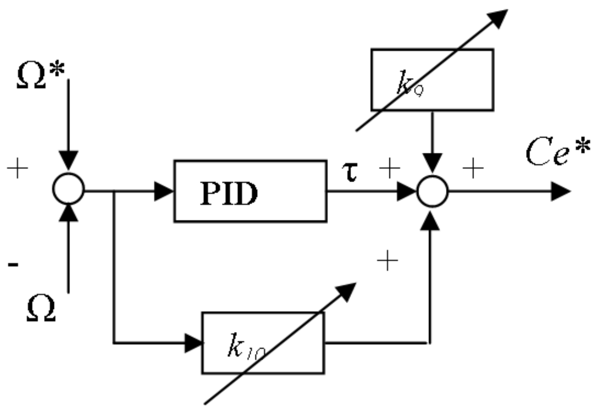

Fig. 2. Structure of the proposed adaptive and optimal controller (for mechanical subsystem)

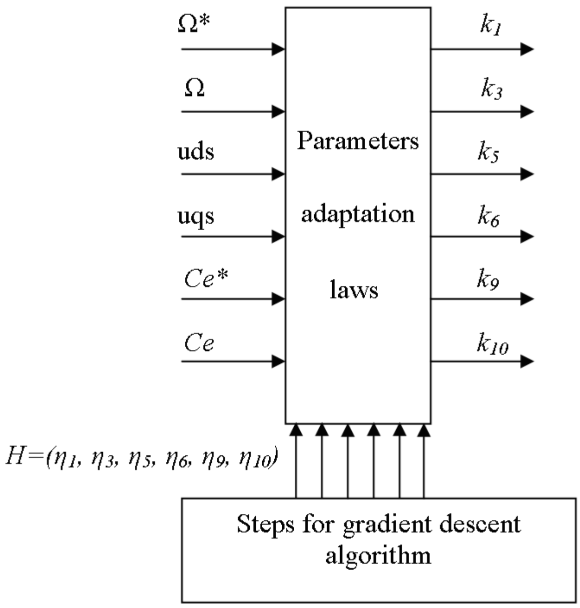

Fig. 3. Structure of the proposed adaptive and optimal controller (parameters adaptation bloc)

The parameters k_9 and $k_{10}$are obtained by adaptation laws.

In the steady state, the currents I_{sd} and I_{sq} will behave as the desired currents I^*_{sd} and I^*_{sq}. These ones are given by adaptive expressions:

$$\begin{aligned} I^*_{sd} &= k_5\Omega + k_6 \\ I^*_{sq} &= k_7\Omega + k_8 \end{aligned} . \quad (13)$$

The parameters k_i, i = 5,6,7,8 are obtained by adaptation laws.

Now, let's take a look to the electromagnetic torque expression given by equation (2). This equation suggest to take

$$C^*_{em} = \alpha I^*_{sq} + \beta I^*_{sd}, \quad (14)$$

with α and β some parameters we don't need to know their values. Equation (14) is used in deriving the adaptation laws.

2. Controller structure: adaptive controller

The equations (11), (12) and (13) form the adaptive sub-controller of the induction motor.

Equation (11) ensures the optimisation of the consumed energy; the equation (12) deals with inertial and resistive torques and the equation (13) have to take coupling effects in consideration in order to have good tracking of the desired references (speed, currents and torque).

The parameter k_{10} in equation (12) is an adaptive adjustment of the proportional gain for the PID controller R_m.

3. Gradient descent algorithm

Given the criterion J, the parameters k are adjusted by the adaptation law:

$$\dot{k} = -\eta \frac{\partial J}{\partial k}, \quad (15)$$

where η is the gradient step.

The step can be constant or variable. It plays a great role in the convergence of the gradient descent algorithm. For low values of η, the convergence will be too slow and for high values, we risk to have instability of the algorithm.

4. Adaptive laws derivation

The criterion to be minimized is given by:

$$J = \frac{1}{2}\left(\Omega^* - \Omega\right)^2 + \frac{1}{2}\left(C^*_{em} - C_{em}\right)^2 + \frac{1}{2}\left(u^2_{sd} + u^2_{sq}\right), \quad (16)$$

with some considerations in our work, we have chosen to put $k_2 = 0$, $k_4 = 0$ (for simplicity, we consider them as some offsets to be taken equal to zero), $k_7 = 0$, $k_8 = 0$ (so $I^*_{sq} = 0$, which correspond to the oriented flux control), and $k_{10} = 0.07$ (as static adjustment of the proportional gain K_{pm} of the PID controller R_m). In another work, we will take them to be adapatable.

So, we need just to adapt parameters k_1, k_3, k_5, k_6 and k_9. The adaptive laws are given by:

$$\dot{k}_i = -\eta_i \frac{\partial J}{\partial k_i}, \; i=1,3,5,6,9 . \quad (17)$$

After some calculations, we have:

$$\begin{aligned} \dot{k}_1 &= -\eta_1 u_{sd}\left(\Omega^* - \Omega\right) \\ \dot{k}_3 &= -\eta_3 u_{sq}\left(\Omega^* - \Omega\right) \\ \dot{k}_5 &= -\eta_5 \Omega\left(C^*_{em} - C_{em}\right) \\ \dot{k}_6 &= -\eta_6\left(C^*_{em} - C_{em}\right) \\ \dot{k}_9 &= \operatorname{sgn}\left(\left(\Omega^* - \Omega\right)\Omega\right)\sqrt{\left|\eta_9\left(\Omega^* - \Omega\right)\Omega\right|}, \end{aligned} \quad (18)$$

with $\eta_1 = 0.0001$ and $\eta_3 = 0.0001$, η_5 and η_6 variables and the step η_9 plays a very interesting role and needs to be adequately chosen.

5. Variable step for gradient descent algorithm

With constant η_5 and η_6, we can't satisfy both the cases of small and high desired speeds. So, we take them variable and equal $\eta_5 = \eta_6$ (for simplicity) fig.4.

To do so, fuzzy logic for variable step generation with just two rules permits to cope with this problem.

We define A as $A = \dfrac{0.01 + \Omega^*}{0.01 + \Omega^{*2}}$, and we propose the fuzzy system with the two rules below:

Rule1: IF Ω^* **is LOW THEN**

$$\eta_5 = A . \quad (19)$$

Rule2: IF Ω^* **is HIGH THEN**

$$\eta_5 = 10A . \quad (20)$$

The desired speed Ω^* takes its values in the range (0, ..., 157 rd/sec).

We define membership functions fig.5 for the linguistic values LOW and HIGH as follows:

$$\mu_{LOW}\left(\Omega^*\right) = e^{-\left(\frac{\log_{10}\left(\left|\Omega^* + 0.001\right|\right)}{\delta}\right)^2} \quad (21)$$

$$\mu_{HIGH}\left(\Omega^*\right) = e^{-\left(\frac{\log_{10}\left(\left|\Omega^* + 0.001\right|\right) - 2}{\delta}\right)^2}, \quad (22)$$

with $\delta = 1$ and the numerical value 0.01 in μ_{LOW} formula is to prevent to have $\log_{10}(0)$.

So, for the steps η_5 and η_6 we can write:

$$\eta_5 = A \cdot \left[\frac{\mu_{LOW}\left(\Omega^*\right) + 10 \cdot \mu_{HIGH}\left(\Omega^*\right)}{\mu_{LOW}\left(\Omega^*\right) + \mu_{HIGH}\left(\Omega^*\right)}\right]$$

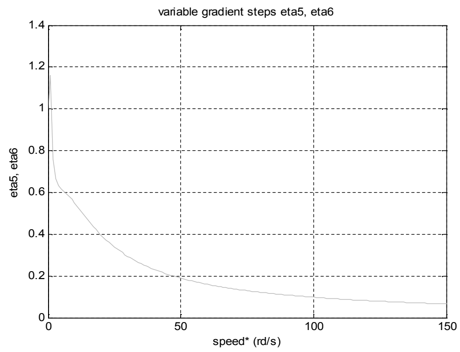

Fig. 4. Membership functions

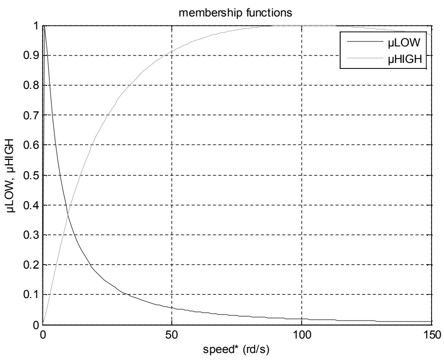

Fig. 5. Step parameters η_5, η_6

6. Remarks on the steps

We have some remarks on the steps:

– If we put $\eta_1 = \eta_3 = 0$, there will be no optimization in the control energy.

– This algorithm is too sensible to η_1 and η_3 which must be kept small enough to ensure convergence.

– For high constant η_5 and η_6, good performances are attained for low reference speeds and poor performances for high reference speeds.

– For low constant η_5 and η_6, good performances are attained for high reference speeds and poor performances for low reference speeds.

– Variable steps η_5 and η_6 can enhance the results for both high and low reference speeds.

– Low values for η_9 give good time response in starting time but poor rejection of the resistive torque.

– High values for η_9 give good rejection of the resistive torque, but at the starting time the response can be of poor performances.

Simulation results

In order to see the performances of our adaptive and optimal controller, we have conducted some simulation under Matlab/Simulink environment and some results are shown in the figures below. The simulations are done using the Park frame and further simulations using the abc frame and PWM inverter are needed to confirm the validation of the proposed controller.

In fig. 6, we can see the time response of the induction motor to the reference speed Ω*=100 rd/s.

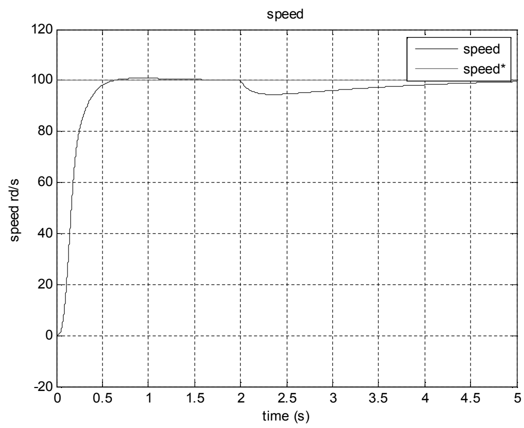

Fig. 6. Speed

As we can see, the output speed reaches the reference speed in approximately 0,5 s and is stable with no oscillations.

The response to a resistive torque applied at time t=2 s takes approximately less than two seconds to be rejected. The rejection of this resistive torque can be enhanced by taking the step η_9 so adequately. But this will compromise the response at the starting time. An overshoot will occur depending on the value of the step η_9. As an alternative, we can take the step η_9 to be variable so that to ensure both performances at starting time (small overshoot of approximately 2 % of the reference speed) and in disturbance rejection. More precisely and with additional simulation we found that with an adequate η_9 the parameter k_9 gives a good estimate of the resistive torque. Also, in starting time, the inertial torque (torque due to inertia) affects the parameter k_9 which changes the response at starting time (the overshoot changes). So the parameter k_9 gives some estimates for both inertial and resistive torques, more precisely it consider the inertial torque as an additional resistive torque.

The fig.7 gives an illustration of the generated electromagnetic torque. As we can see, the tracking of the desired torque is ensured. In starting time, the generated electromagnetic torque reaches the desired torque in less than 0,2 s and the tracking is kept ensured. The tracking is not greatly affected by the resistive torque and here we can't see a difference between the developed electromagnetic torque the resistive torque in the presence of the perturbation (resistive torque).

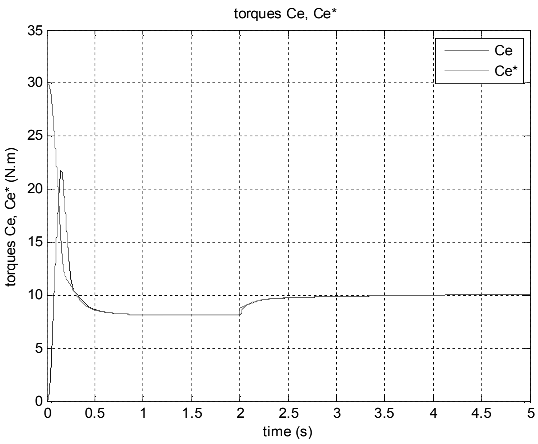

Fig. 7. Torque

The same results are seen for the response of the current Ids (fig. 8). But the current Iqs presents some problems (fig. 9). The fig.10 gives an illustration voltages uds, uqs. Indeed, because of the constancy of the parameters k_7 and k_8 (which are taken to be equal to zero) and because they are not adjusted by the gradient descent algorithm (the steps η_7 and η_8 are equal to zero and here we did not give the adaptation laws for them), the current Iqs takes approximately 0,75 s to reach its desired value Iqs* and oscillations occur when the resistive torque is applied.

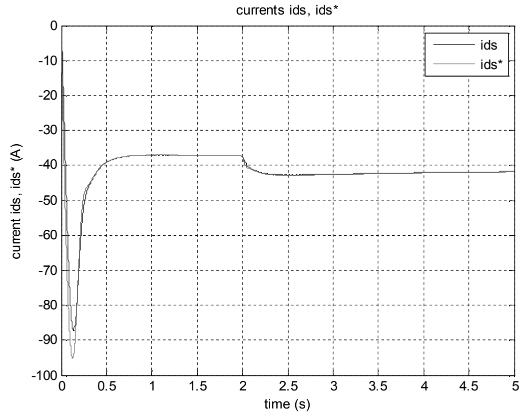

Fig. 8. Currents ids, ids*

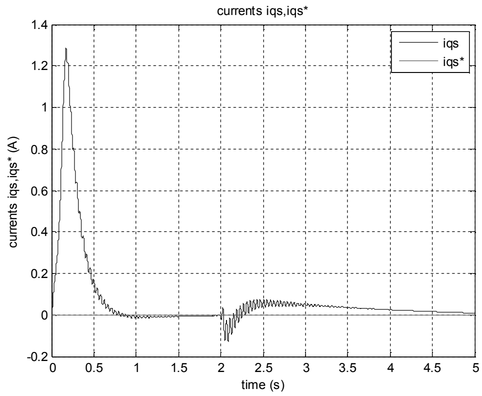

Fig. 9. Currents Iqs, Iqs*

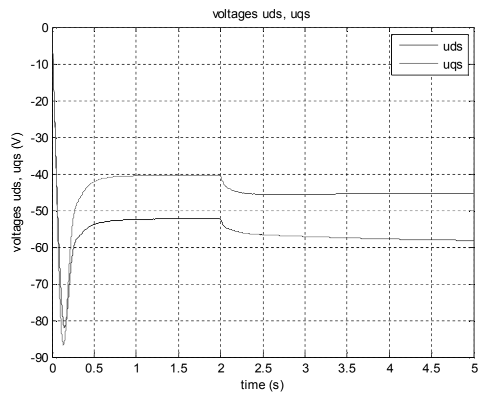

Fig. 10. Voltages uds, uqs

In fact, we developed our work in general manner, and we tested the effect of variable parameters k_7 and k_8 and adjusted them by adaptation laws that are similar to those for k_5 and k_6. Interesting results were obtained and some difficulties occurred.

Moreover, simulation results have shown that the consumed energy is minimized when we use adjusted parameters k_1 and k_3. We have seen in our application a preservation of 5 joules per second than the case without the use of adjusted parameters k_1 and k_3.

Concerning the parameters k_5 and k_6, we have seen that the proposed fuzzy system generates good variable steps η_5 and η_6. the simulation for several values of the desired speed have shown that the time responses have all similar forms. The overshoot is of approximately 0,2 % of the reference speed. This is not the case with constant steps η_5 and η_6.

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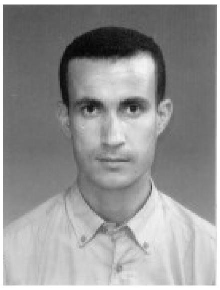

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