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Fuzzy speed regulation for induction motor associated with field-oriented control

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Abstract. *This paper presents a study of an application of speed control by the fuzzy logic of a three-phase induction motor. The indirect field oriented control is treated in digital simulation to compare the performances of the adjustment by a conventional controller PI and by a fuzzy controller. The obtained results put in evidence the effectiveness and the superiority of the fuzzy approach for the behaviors in speed tracking and regulation, and also show a better robustness beside the parametric variations of the motor.*

Keywords. *Induction motor, Fuzzy logic, Speed control, FOC, Proportional integral, Robustness.*

1. Introduction

The variable speed systems took these last years a great importance in the industry and in the research, and require multidisciplinary knowledge in the field of the electric genius. The recent developments in these disciplines permitted to develop systems of very high performance [1].

The induction motor being considered since its discovery as the actuator privileged in the applications of the constant speed, but it offers several advantages comparatively to direct current motor, such as its simplicity of design, the absence of the collector-brooms system, a weight and a small inertia.
It is also appreciated for its reliability and its robustness. On the other hand, in spite of the simplicity of its mechanical structure, its mathematical model is very complex (multivariable and non linear) and does not have allowed during a long time the

development of adequate commands. The difficulty in its command results from the complex coupling between the input variables, the output variables and the internal variables of the motor, such as the torque, the speed or the position.
The enormous technological progress permitted to resolve this problem and to develop commands appropriated for this motor, such as the scalar drive, the field oriented control or the direct torque control.

In the domain of the dynamic system control, today based to the numeric techniques exclusively, news effective approaches found applications, and so new algorithms of control have can implanted thanks to the big powers of calculation, today available. So for some years and thanks to these progresses, news approach has been introduced, such as the artificial intelligence with the fuzzy logic, the neural networks and the genetic algorithms. Although presents in the other domains, these sophisticated approaches only found lately applications in the drive and the electric machine control.

This paper presents the speed control of a three-phase induction motor by the fuzzy logic. The drive of this type of motor by the fuzzy controllers seems an interesting alternative in comparison with the classic controllers of type PI (proportional and integral) extensively employed in the industry. Indeed, this last one does not permit to treat correctly the problem owed to the parametric variations of the process to control.

This inconvenience can be resolved by the use of an adaptive controller based on the fuzzy logic. Furthermore, the fact to surmount the nonlinearities of the motor and to exempt of a mathematical modeling rigorous and arduous is certain advantages [2].

2. Description of the process

In the objective to define a mathematical model of the motor, let's consider the following simplifying hypotheses:

- the motor is symmetrical construction,
- its magnetic circuit is not saturated,
- the magnetic and mechanical power losses are neglected,
- the spatial distribution of the magnetic field in the air-gap is sinusoidal,
- the effects of notches and skin are neglected.

We can describe the model of the motor in the reference frame of Park by the following non linear differential equations [3]:

$$\frac{di_{Sd}}{dt}=-\left(\frac{1}{\sigma.T_S}+\frac{1}{T_R}.\frac{1-\sigma}{\sigma}\right).i_{Sd}+\omega_S.i_{Sq}+\left(\frac{1-\sigma}{\sigma}.\frac{1}{M_{SR}.T_R}\right).\varphi_{Rd}+\left(\frac{1-\sigma}{\sigma}.\frac{1}{M_{SR}}.\omega_R\right).\varphi_{Rq}+\frac{1}{\sigma.L_S}.v_{Sd} \quad (1)$$

$$\frac{di_{Sq}}{dt}=-\omega_S.i_{Sd}-\left(\frac{1}{\sigma.T_S}+\frac{1}{T_R}.\frac{1-\sigma}{\sigma}\right).i_{Sq}+\left(-\frac{1-\sigma}{\sigma}.\frac{1}{M_{SR}}.\omega_R\right).\varphi_{Rd}+\left(\frac{1-\sigma}{\sigma}.\frac{1}{M_{SR}.T_R}\right).\varphi_{Rq}+\frac{1}{\sigma.L_S}.v_{Sq} \quad (2)$$

$$\frac{d\varphi_{Rd}}{dt}=\frac{M_{SR}}{T_R}.i_{Sd}-\frac{1}{T_R}.\varphi_{Rd}+\omega_{gl}.\varphi_{Rq} \quad (3)$$

$$\frac{d\varphi_{Rq}}{dt}=\frac{M_{SR}}{T_R}.i_{Sq}-\omega_{gl}.\varphi_{Rd}-\frac{1}{T_R}.\varphi_{Rq} \tag{4}$$

$$J.\frac{d\Omega_R}{dt}=p.\frac{M_{SR}}{L_R}.\left(\varphi_{Rd}.i_{Sq}-\varphi_{Rq}.i_{Sd}\right)-\Gamma_R \tag{5}$$

$$\sigma=1-\frac{{M_{SR}}^2}{L_S.L_R} \tag{6}$$

We consider a voltage control of the induction motor with indirect field oriented control. The rectifier transforms the three-phase alternating voltages of the network to a direct voltage; the inverter converts this voltage to a three-phase voltage system with variable amplitude and frequency. We chose for the converter a pulse width modulation (PWM) of sine triangle type.

The indirect field oriented control is currently considered as the technique most used in the domain of variable speed for the induction motor. This control has for objective to drive the induction motor like a DC motor with separated excitation, and its principle consists in cancelling the quadratic component φ_{Rq} of the field to only preserve the direct component φ_{Rd}:

$$\varphi_{Rq}=0 \qquad \Rightarrow \qquad \varphi_R=\varphi_{Rd} \tag{7}$$

It permits to drive the field via the current i_{Sd} and the torque via the current i_{Sq}. It is necessary to determine the amplitude and the position of rotoric field.

The indirect vector control does not require the exact knowledge of the module of rotoric field, and therefore it needs neither its direct measure (sensor), nor his estimate (dynamic model).
In the case of an indirect field oriented control the module is obtained by a block of field weakening given by the following non linear relation [4]:

$$\varphi_{Rd}{}^*=\begin{cases}\varphi_R & \text{if} \quad |\Omega|\le\Omega_N\\ \varphi_{RN}\cdot\dfrac{\Omega_N}{|\Omega|} & \text{if} \quad |\Omega|\succ\Omega_N\end{cases} \tag{8}$$

If the module's real field rotoric is not exploited, his position should be known at any moment to make the change of coordinates. The position is determined by integration of the stator pulsation, it even reconstituted by the speed of the motor and the rotor pulsation [1]:

$$\theta_S=\int\omega_S.dt=\int\left(p.\Omega+\frac{M_{SR}\cdot i_{Sq}}{T_R.\varphi_{Rq}}\right).dt \tag{9}$$

The fig.1 represents the global structure of the process to be controlled.

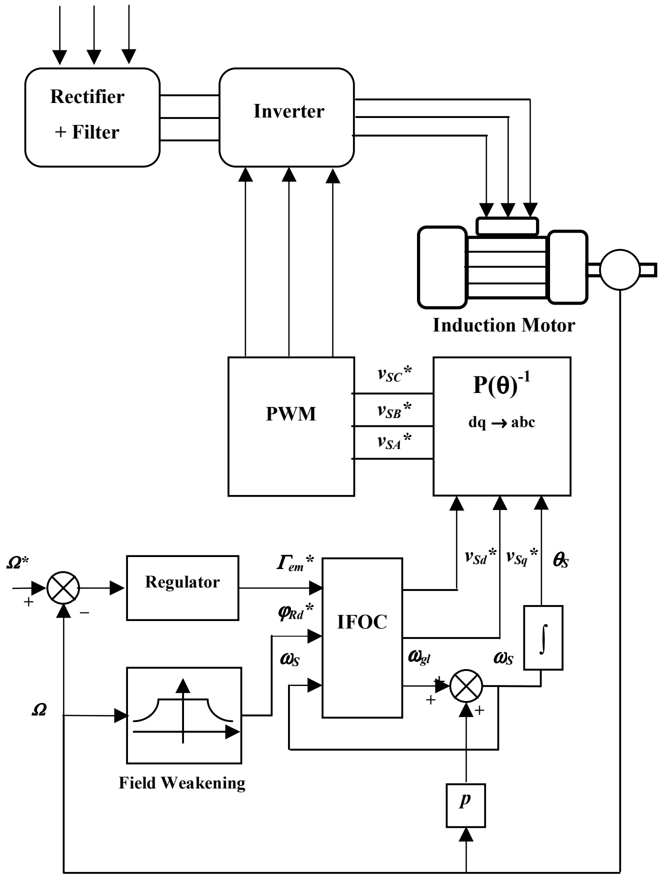


Fig.1. Structure of the process to be controlled

3. Control by the fuzzy logic

The control by fuzzy logic permits to obtain a law of drive, often very effective, without having a precise model of the process, from a linguistic description of the behavior of the system [2]. Its approach is different the one of the automatic classic, in the sense that it does not treat mathematical relations well defined, but it exploits the knowledge of an expert. These are expressed by means of conduct rules based on a symbolic vocabulary and manipulate inferences with several rules using the fuzzy operators AND, OR, THEN, applied to linguistic variables.

The structure of a fuzzy logic controller is shown in figure 2.

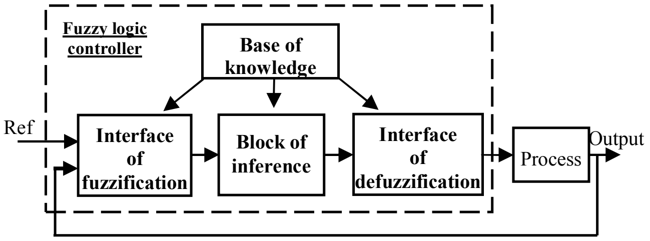


Fig.2. Structure of the fuzzy logic control

The structure shows four functions, each one materialized by a block [5]:

- The interface of fuzzification consists of the fuzzy quantification of the real values of a variable, and thus transforms the not fuzzy variables resulting from the input to fuzzy subsets.
- The base of knowledge contains the definitions of the fuzzy subsets, their membership functions, their universes of discourse and the whole of the rules of inference.
- The block of inference is the heart of a fuzzy logic controller, and possesses the capacity to feign the human decisions and to deduct the fuzzy actions of command by means of the fuzzy implication and the rules of inference. From the rules of inference and the fuzzy subsets corresponding to the input, the block of inference calculates the fuzzy subset concerning the command.
- The interface of défuzzification consists in a transformation the fuzzy subset of exit in a not fuzzy value permitting to drive the process. This operation permits to deduct a precise numerical value of the controller's exit from the fuzzy resultant conclusion stemming from the operation of inference.

The observation of the process shows that the significant sizes for the controller are the error of speed and the variation of this error. The inputs of the fuzzy controller will be these two sizes noted E and dE, and for the exit it is the custom to choose the increment of the drive signal $di_{sq}*$ to apply to the process. This one corresponds to the quadratic statoric of the reference current $isq*$.

The controller introduced in this study for the speed control is the type of Mamdani.

The configuration of the fuzzy controller (FLC) is illustrated in the figure 3 [6].

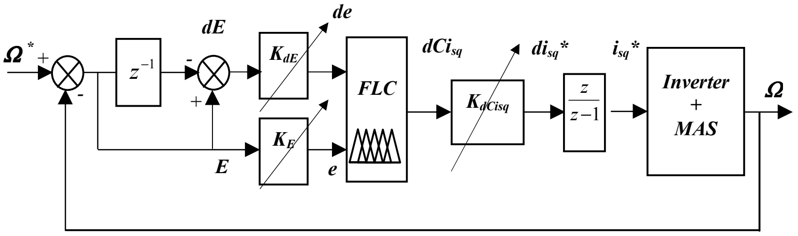


Fig.3. Structure of fuzzy logic controller

The inputs of the fuzzy controller are determined at the moment k in the following way:

$$E(k) = \Omega^{*}(\mathrm{k}) - \Omega(k) \qquad dE(k) = E(k) - \mathrm{E}(k-1) \tag{10}$$

and the drive signal is determined by:

$$i_{Sq}*(k) = i_{Sq}*(k-1) + di_{Sq}*(k) \tag{11}$$

Every period of sampling the fuzzy controller delivers an order $i_{Sq}*(k)$ which corresponds to its two inputs: speed error *E(k)* and speed error changing *dE(k)*.

The whole of the inferences rules expressed in the linguistic form represent the strategy of the desired drive [7]. In the case of the partition of the universe of discourse in five fuzzy subsets, we get a maximal number of twenty five possible combinations and thus the same number of rules.

Table 1, called matrix of inference gives the rules defines to obtain the desired behavior of the commanded process.

Table 1. Matrix of inference

		dE				
		N	N	Z	P	PB
E	N	N	N	N	N	ZE
	NS	N	N	N	Z	PS
	ZE	N	N	Z	P	PB
	PS	N	Z	P	P	PB
	PB	Z	P	P	P	PB

A partition of the universe of discourse in five subsets is envisaged for the synthesized fuzzy controller. After several tests of simulations we notice that to obtain an increase of the robustness and to minimize the dependence of the process to parameter variation, it's better to choose a bigger density of membership functions around the zero value [2]. We adopted of the membership functions to triangular and trapezoidal forms.

We use the following designations for membership functions:

- NB: Negative Big,
- NS: Negative Small,
- ZE: Zero Equal.
- PB: Positive Big,
- PS: Negative Small,

These choices are described in figure 4.

For the digital treatment of the inferences, we opted for choices requiring volumes and reduced time of calculations:

- for the logic AND: → method of the “mini”,
- for the logic OR: → method of the “max”,
- for the inference rules:
  implication → method of the “mini”, aggregation → method of the “max”.

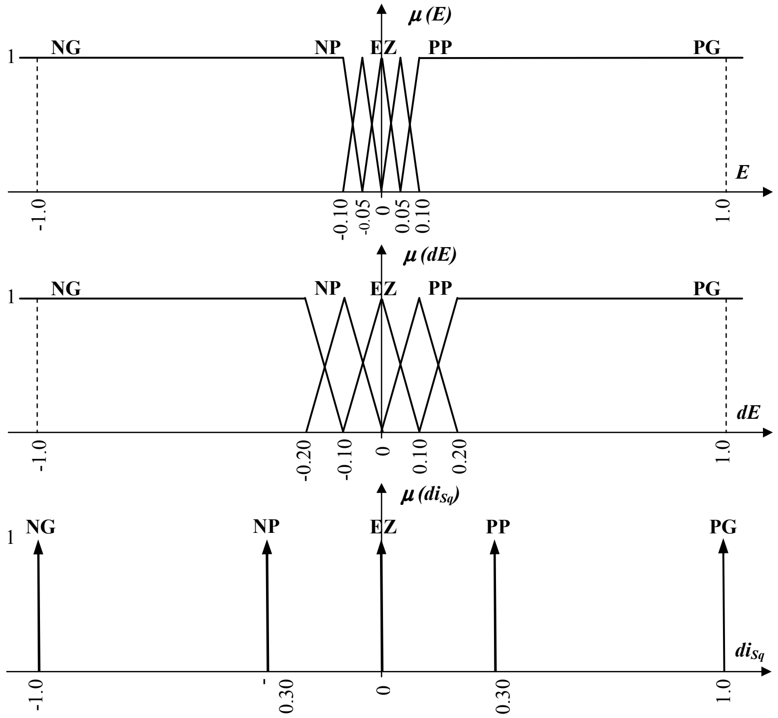


Fig.4. Shapes of membership functions

The figure 5 gives a 3D representation in coordinates normalized of the function characterizing the considered fuzzy controller and clearly illustrates its not- linearity:

$$dCi_{Sq} = F\left(e(k) - de(k)\right) \tag{12}$$

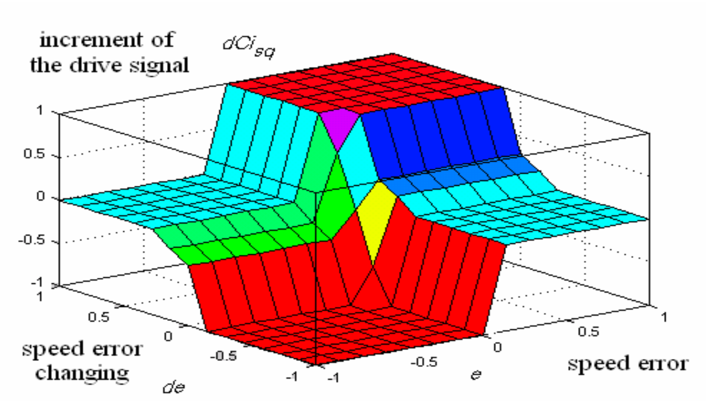


Fig.5. Characteristic surface of the considered fuzzy controller

4. Simulation results

In the objective to evaluate the performances of the linguistic approach two categories of tests have been realized. In the first category the goal is to compare the behavior of a classic controller of PI type and the one of the studied fuzzy logic controller previously with different conditions of working in order to test them in regulation and in tracking. In the second category, we planned to check robustness of the two controller types facing variations of rotoric resistance and the inertia of the motor.

Simulations have been realized under the *MATLAB/SIMULINK* environment; the main features of the motor used are indicated in the Table 2.

Table 2. Main features of the motor used

Rated voltage	U_N	220 / 380	V
Rated power	P_N	1.5	kW
Pole pairs	p	2	
Rated speed	n_N	1420	tr/mn
Rated load torque	Γ_N	10	N.m
Rated current Δ/Y	I_N	6.4 / 3.7	A
Statoric resistance	R_S	4.85	Ω
Rotoric resistance	R_R	3.805	Ω
Statoric inductance	L_S	0.274	H
Rotoric inductance	L_R	0.274	H
Mutual inductance	M_{SR}	0.258	H
Rotor inertia	J	0.031	kg.m^2
Rubbing parameter	f	0.00114	N.s/rad

The speed reference is imposed in trapezoidal form and is filtered to protect of the states transient and to impose a model of pursuit of first order. The transfer function of the filter was chooses such as:

$$G(s) = \frac{1}{0.08.s + 1} \tag{13}$$

The starting of the motor is realized without load torque with an order of 100 rad/s, followed an inversion of the rotation at t=2s, then of an annulment of speed to t=3s.

The external disturbances are introduced by the nominal load (10 N.m) applied suddenly applied abruptly then suppressed at the times t=0. 7s and t=1. 3s. Finally the motor being to the stop is subject to the half-nominal load at t=3 5 s.

To compare behaviors of controllers the parameters of adjustment were chooses to have response times identical ($tr_{5\%} = 0.24s$), in the case of a step speed reference and without couple of load applied to the motor.

4.1. Regulation test

This test has for object the study of controller behaviors considered in pursuit and in regulation. The gotten results are represented respectively on figures 6 and 7, for the classic control and for the fuzzy logic.

Figure 8 and 9 shows enlarging of the answers of speed to the beginning of the starting and during the application of disturbances.

Indeed in spite of the fact that classic control is recognized for its reaction speed to starting obtained by its proportional action, the fuzzy controller surpasses it during this phase with the choices and the adjustments selected.

The pursuit is executed with a light error, before joining the speed of reference. The studied process provides with the fuzzy controller is very little sensitive to the presence of disturbances and reject these last very quickly at the time of their apparition.

4.2. Robustness tests

The objective of these tests is to compare the performances of the controllers for parametric variations of the sizes of the motor resulting from drift or a bad identification.

We considered the nominal sizes of the rotoric resistance and the rotor inertia ($R_R=R_{RN}$ and $J=J_N$), then the same sizes with the respective increases of 50% and 20% ($R_R=1.5*R_{RN}$ and $J=1.2*J_N$).

Figs 10 to 13 give, for the two controllers, the evolution of the speed error and the quadratic component of rotoric field for the variations of quoted parameters.

The gotten results permit us to affirm that:

- The most appreciable changes are those observed during the variations of rotoric resistance, this is in conformity with the fact that the field oriented control is especially sensitive to the variations of this resistance.
- The observation of behavior changes respective for controllers PI and fuzzy logic shows that these are less important for the fuzzy controller and that in spite of the variations, its behavior in regulation and in pursuit remains remarkable.
- For the fuzzy adjustment, the error of pursuit remains very weak and the disturbances are rejected very quickly.

We observe, in the two cases of drive, the sensitivity of the indirect vector control to variations of the rotoric resistance.

We can affirm that the fuzzy controller is more robust than the PI controller; however it is interesting to note that the imposed variations remain weak and probable in reality.

Nevertheless, for other simulations with more important variations, the performances of this controller deteriorate. Variations of quadratic rotoric field show that its orientation is affected during the transient states, and can be damaged even strongly for important variations of parameters, what can lead to the loss of the control.

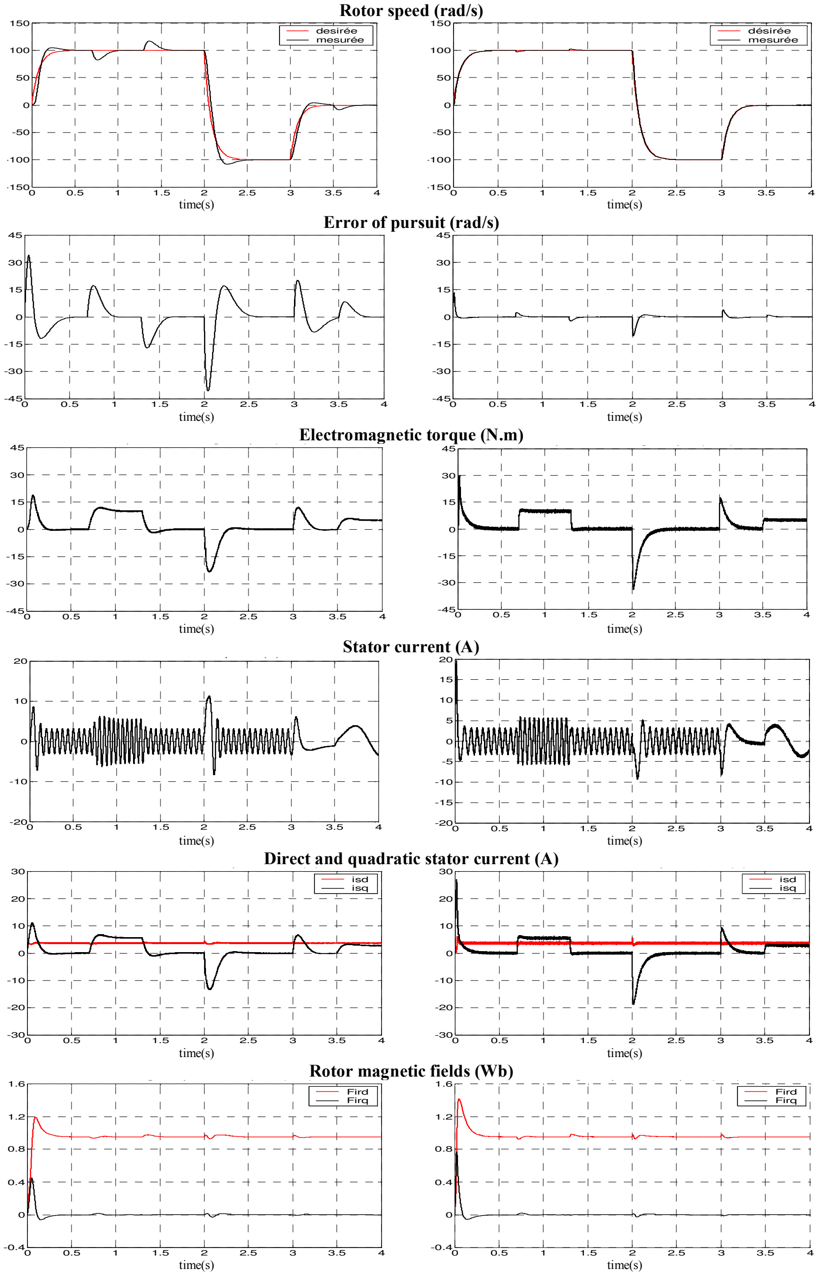


Fig.6. Results of speed control using PI controller

Fig.7. Results of speed control using FLC controller

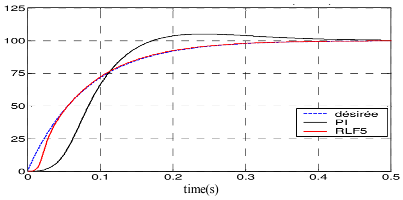


Fig.8. Zoom of the speed answer during the starting

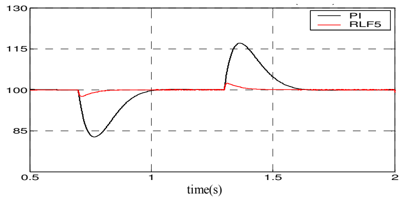
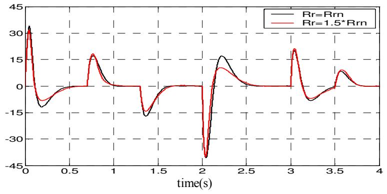
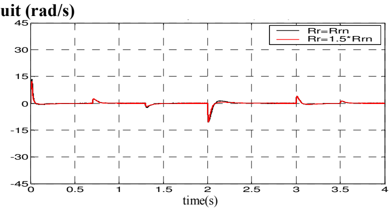


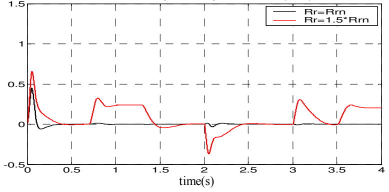
Fig.9. Zoom of the speed answer during the application of the disturbance

Error of pursuit (rad/s)





Quadratic rotor field (Wb)



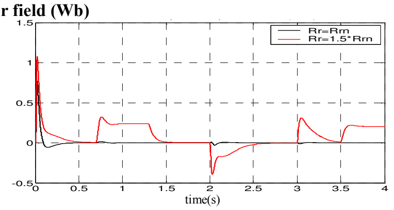
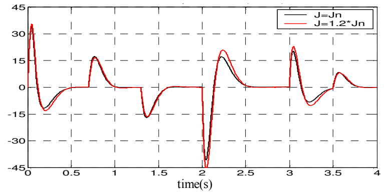
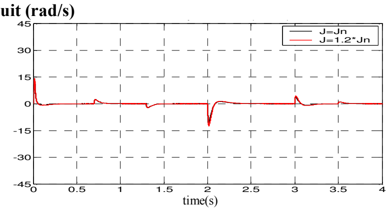


Fig.10. Answer of the PI controller with variation of the rotoric resistance ($R_R = 1.5\, R_{RN}$)

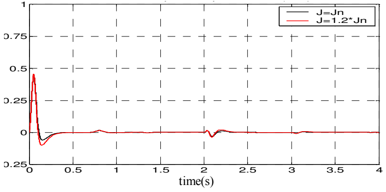
Fig.11. Answer of the FLC controller with variation of the rotoric resistance ($R_R = 1.5\, R_{RN}$)

Error of pursuit (rad/s)





Quadratic rotor field (Wb)



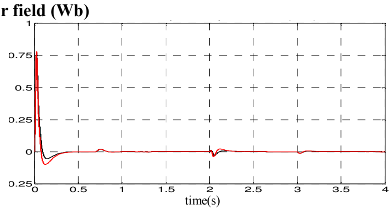


Fig.12. Answer of the PI controller with variation of the rotor inertia ($J = 1.2\, J_N$)

Fig.13 Answer of the FLC controller with variation of the rotor inertia ($J = 1.2\, J_N$)

5. Possible improvements

The observation of results obtained shows two major problems that reduce the efficiency of the speed control by the indirect field oriented control based on the fuzzy approach:

- the resurgence of the decoupling between the flux and electromagnetic torque, owed to a bad orientation of the flux for variations of rotoric resistance during the transient phases;
- the insufficiency of robustness for strong parametric variations.

In the objective to remedy these disadvantages, and to ameliorate the behavior of the system considered, we present briefly two solutions (that will make the object of another paper). The first solution consists in the integration of a fuzzy adaptive structure in the indirect field oriented control to correct the influence of parametric variations, but also to compensate uncertainties owed to the load torque.

The second concerns the estimate of rotoric resistance, and so permits in all time to consider the actual value of this resistance.

The figure 6 shows the proposed adaptive structure:

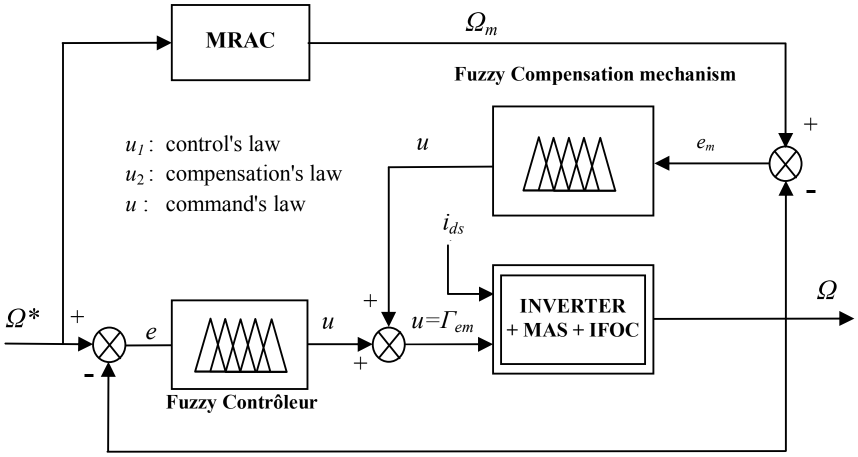


Fig .6. Fuzzy adaptive structure

This structure is constructed around:

- the fuzzy controller conceived in this work,
- a model of reference (MRAC) defining the desired performances,
- a fuzzy mechanism of compensation, delivering a signal to correct the controller's actions to adapt them to variations of rotoric resistance and uncertainties of load.

This technique doesn't require the determination of the model of the motor, and lead also to a simple algorithm, with a weak rate of calculation.

To achieve the estimation of the rotoric resistance, we can use the method proposed by L.J.Garces in the reference [8] that consists to create a mechanism of adaptation that introduces a function F bound to the reactive power:

$$F = \frac{1}{\omega_s}.\left[\left(v_{Sd} - \sigma.L_S.\frac{di_{Sd}}{dt}\right).i_{Sq} - \left(v_{Sq} - \sigma.L_S.\frac{di_{Sq}}{dt}\right).i_{Sd}\right] + \left(i_{Sd}^2 - i_{Sq}^2\right).\sigma.L_S \qquad (14)$$

If we consider the condition of orientation of the field ($\varphi_{Rq} = 0$, $\varphi_R = \varphi_{Rd}$) and a constant value for the flux, they acquire following expression for function F:

$$F_0 = \frac{1}{L_R}.\varphi_R^2 \qquad (15)$$

Consequently, the difference ($EF = F - F_0$) is representative of changes of the rotoric resistance, and will be used for the correction of its value in the algorithm of control. The fuzzy logic can used this difference to conceive a mechanism of estimation. Input variables will be the difference EF and its variation *dEF*; the output will deliver the estimated value of the rotoric resistance, this after integration of the increment of the rotoric constant of time, addition in its real value and the introduction of the rotoric inductance.

The fig 7 illustrates the structure of the fuzzy mechanism for the estimation of rotoric resistance.

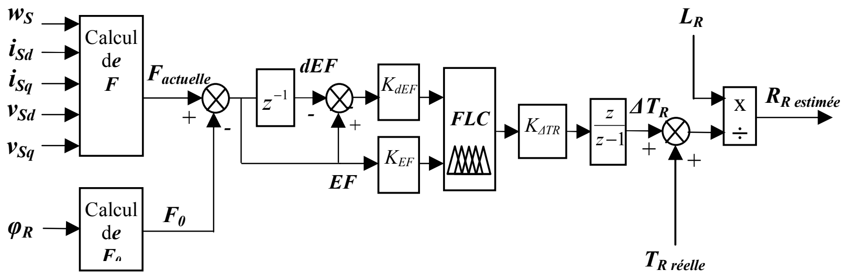


Fig.7. Structure of the fuzzy mechanism for the estimation of the rotoric

6. Conclusion

This article shows that the association of a fuzzy logic controller and a indirect field oriented control correctly achieves correctly the speed regulation of a three-phase induction motor. The confrontation of results gotten, with a controller designed with the fuzzy logic approach and a classic controller PI, shows a remarkable behavior of the fuzzy adjustment in regulation and in pursuit. The method of control by oriented field having a strong sensitivity to the variations of the motor's parameters, we note better performances opposite the robustness.

However this type of controller is not able to compensate the very big parametric variations, and in spite of the fact that fuzzy logic controller is more robust than controller PI; it cannot assure a satisfactory working when the parameters of the process are subjected to the strong variations. A technique integrating an adaptive structure will be desirable to cure this inconvenience.

Nomenclature

v_{ds} , v_{qs} : direct and quadratic stator voltage,
i_{ds} , i_{qs} : direct and quadratic stator currents,
φ_{Rd} , φ_{Rq} : direct and quadratic ,
φ_{RN} : nominal magnetic flux of the rotor,
ω_S , ω_R : electric pulsation of statoric and rotoric currents
Ω_R : pulsation (speed) of rotation of the rotor,
Ω_N : nominal throbbing or pulsation of rotation,
Ω^* : throbbing or pulsation (speed) of reference,
θ_S : angle between stator axis and direct axis of Park,
Γ_R : load torque,
E , e : error of the speed (absolute and normalized),
dE, de : variation of the speed error (absolute and normalized)
dCi_{Sq} , di_{Sq}^* : fuzzy value of order and deterministic value of order,
i_{Sq}^* : increment of the order value,

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