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Fuzzy Gain-scheduling Proportional–integral Control for Improving the Speed Behavior of a Three-phases Induction Motor

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ABSTRACT

In this article, we have set up a vector control law of induction machine where we tried different type of speed controllers. Our control strategy is of type Field Orientated Control (FOC). In this structure we designed a Fuzzy Gain-Scheduling Proportional–Integral (Pi) controller to obtain best result regarding the speed of induction machine. At the beginning we designed a Pi controller with fixed parameters. We came up to these parameters by identifying the transfer function of this controller to that of Broïda (second order transfer function). Then we designed a fuzzy logic (FL) controller. Based on simulation results, we highlight the performances of each controller. To improve the speed behaviour of the induction machine, we have designend a controller called "Fuzzy Gain-Scheduling Proportional–Integral controller" (FGS-PI controller) which inherited the pros of the aforementioned controllers. The simulation result of this controller will strengthen its performances.

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1. INTRODUCTION

The DC machine has featured prominently in many fields in the early sixties. But this machine has a high price both in manufacturing and maintenance. Also, its rotation speed is limited due to the commutator and brush. In addition to that it is sensitive to corrosive environments. Nowadays the three-phase induction motor is the most used worldwide motor. This machine is characterized by a robust and simple design. The progress achieved in power electronics and microelectronics led to the development and implementation of complex algorithms for using the induction machine when the speed is variable like the scalar control [14] or the direct torque control [17].

Vector control introduced by Blaschke is a rather effective strategy. It consists to emulate the operation of the induction machine to that of the DC machine by decoupling the flow relative to the electromagnetic torque [5]. The most used controller in vector control strategy is the PI controller since it has good performance in some conditions [25]. According to the adopted method for setting the parameters of this controller, we can list two major kinds. In the first type, the parameters are chosen optimally by several methods such as Zeigler and Nicole [8]. This static configuration might make the controller sensible to parametric variation. In the second type the controller structure is the same except that there will be a real time configuration of the parameters. This adaptation makes this controller robust to parameters changes.

Sevral methods were used to in this context such as in [1] by sliding mode control or in [16] by hybrid Particle Swarm Optimization.The Fuzzy Gain-Scheduling Proportional–Integral controller belongs to the second type. Indeed it is a new concept of digital control and decision making based on fuzzy logic sets developed by Lotfi Zadah [11].

This paper starts with a reviewing of the model of the three-phase induction machine and the control law. Thereafter, we have detailed the Pi controller and the fuzzy logic controller used for speed regulation in adopted structure of control. Then, we have presented the steps to achieve the improved controller (Fuzzy Gain-Scheduling Proportional–Integral controller). At the end we have simulated the control strategy with the three controller and we have commented the obtained results.

2. MODEL OF THE INDUCTION MOTOR

The modeling step of the induction machine is essential for the development of control laws. Our model is based on the theory of Park. This theory is based on two processing; the transformation of Concordia which reduces the size of the matrix (three-phase to two-phase), and Park transformation which ensures the passage of the magnitudes alternatives to continuous quantities. We chose the transformation of Concordia and not that of Clarke simply because the first ensures the conservation of instantaneous power while the second ensures the preservation of the modules (the amplitudes) which is not appropriate for this type of control.

Park transformation is defined by:

$$\begin{pmatrix} X_{sd} \\ X_{sq} \end{pmatrix} = M(\theta_s).\begin{pmatrix} X_{s\alpha} \\ X_{s\beta} \end{pmatrix} \tag{1}$$

Concordia transformation is defined by:

$$\begin{pmatrix} X_{s\alpha} \\ X_{s\beta} \end{pmatrix} = P(0).\begin{pmatrix} X_{sa} \\ X_{sb} \\ X_{sc} \end{pmatrix} \tag{2}$$

With

$$M(\theta_s) = \begin{bmatrix} \cos\theta_s & \sin\theta_s \\ -\sin\theta_s & \cos\theta_s \end{bmatrix} \qquad P(0) = \sqrt{\frac{2}{3}}\begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{-\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \tag{3}$$

θ_s is the rotation angle of the rotate stator field (angle between the stator and the d-axis)
The electrical equations in the referential (a, b, c) are: [2]

At the stator:

$$U_{s(a,b,c)} = [R_s]i_{s(a,b,c)} - \dot{\phi}_{s(a,b,c)} \tag{4}$$

$$R_s = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \quad U_{s(a,b,c)} = \begin{bmatrix} U_{sa} \\ U_{sb} \\ U_{sc} \end{bmatrix} \quad i_{s(a,b,c)} = \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} \quad \phi_{s(a,b,c)} = \begin{bmatrix} \phi_{sa} \\ \phi_{sb} \\ \phi_{sc} \end{bmatrix}$$

R_s are the stator resistances, U_s(a,b,c) are the stator voltages, i_s(a,b,c) are the stator currents and Φ_s(a,b,c) are the magnetic flow to the stator.

At the rotor:

$$U_{r(a,b,c)} = [R_r]i_{r(a,b,c)} - \dot{\phi}_{r(a,b,c)} \tag{5}$$

$$R_r = \begin{bmatrix} R_r & 0 & 0 \\ 0 & R_r & 0 \\ 0 & 0 & R_r \end{bmatrix} \qquad U_{r(a,b,c)} = 0$$

R_r are the rotor resistances, U_r(a,b,c) are the rotor voltages, i_r(a,b,c) are the rotor currents and Φ_r(a,b,c) are the magnetic flow to the rotor. The magnetic equations in the referential (a, b, c) are: [2]

At the stator:

$$\phi_{s(a,b,c)} = [\chi_s] i_{s(a,b,c)} - [\chi_M] i_{r(a,b,c)} \tag{6}$$

$$\chi_s = \begin{bmatrix} l_s & M_s & M_s \\ M_s & l_s & M_s \\ M_s & M_s & l_s \end{bmatrix} \qquad \chi_M = M_{sr} \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\Pi}{3}) & \cos(\theta + \frac{2\Pi}{3}) \\ \cos(\theta - \frac{2\Pi}{3}) & \cos(\theta) & \cos(\theta + \frac{2\Pi}{3}) \\ \cos(\theta + \frac{2\Pi}{3}) & \cos(\theta - \frac{2\Pi}{3}) & \cos(\theta) \end{bmatrix}$$

[χ] is the matrix of inductances, M_s is the mutual inductance between two stator phases, l_s is the own stator inductance, M_{sr} is the mutual inductance between stator and rotor and $\theta$is the angle between the stator and the rotor.

At the rotor:

$$\phi_{r(a,b,c)} = [\chi_M] i_{s(a,b,c)} - [\chi_r] i_{r(a,b,c)} \tag{7}$$

$$\chi_r = \begin{bmatrix} l_r & M_r & M_r \\ M_r & l_r & M_r \\ M_r & M_r & l_r \end{bmatrix}$$

l_r is the own rotor inductance and M_r is the mutual inductance between two rotor phases. The mechanical equation of the machine is:

$$J \frac{d\Omega}{dt} = T_{em} - T_r \tag{8}$$

Ω is the real speed, T_{em} is the electromagnetic torque, T_r is the resistive torque and J is the moment of inertia. Applying the theorem of Ferrari, we get

$$T_{em} = -n_p L_M \left(i_{s(a,b,c)} I_{r(a,b,c)} \right) = n_p \frac{L_M}{L_r} \left(\phi_{r(a,b,c)} i_{s(a,b,c)} \right) \tag{9}$$

L_M is the Cyclic mutual inductance, n_p is the number of pole pairs, L_r is the cyclic rotor inductance. If we apply the Park transformation to the equations (9) we get:

$$T_{em} = n_p \frac{L_M}{L_r} \left(I_{sq} \Phi_{rd} - I_{sd} \Phi_{rq} \right) \tag{10}$$

Where I_{sd} isthe stator current (d-axis), $I_{sq}$is the stator current (q-axis), Φ_{rd} is the rotor magnetic flow (d-axis) and Φ_{rq} is the rotor magnetic flow (q-axis).

3. CONTROLL LAW

We have taken in this work the Field Orientated Control. In this strategy, the d-axis component of the stator current acts as excitement and allow adjusting the value of the magnetic flow on the machine. The q-axis component acts as the induced current and controls the torque. The aim of this strategy is to find a law as [$T_{em}=K\Phi_i$] which can directly control the torque by the i_{sq} current. This is guaranteed simply by canceling one of the terms. If we cancel [$\Phi_{rq} = 0$] and [$\Phi_{rd}=\Phi_r$] the torque will depend only on i_{sq} and the equation (10) becomes:

$$T_{em} = n_p \frac{L_M}{L_r} \Phi_r i_{sq} \tag{11}$$

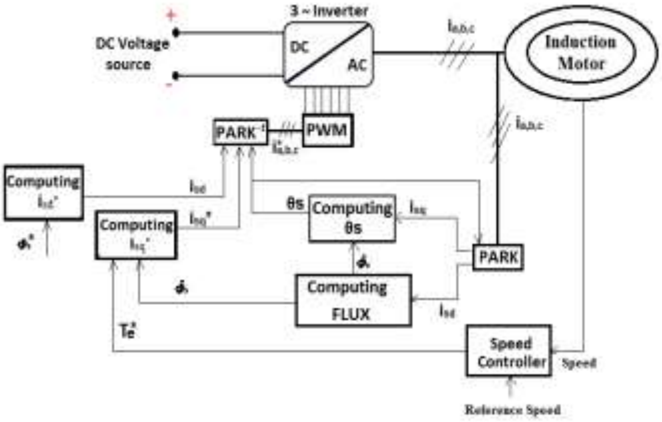


Figure 1. Block Diagram Schematic of the Control Strategy

3.1. Inverter

The inverter used is composed of three arms mounted in parallel. In each arms two IGBT transistors are connected in series. All IGBT transistrors are controlled by a current regulator PWM. Hysteresis current control method allows switching on the transistors when the error between the signal and its sets exceeds the setpoint amplitude. In result the actual current is forced to follow the reference current in the hysteresis band. The Figure 2 illustrates the operating principle of the hysteresis regulator.

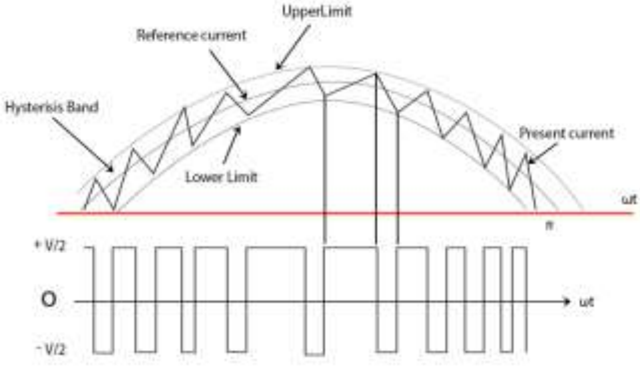


Figure 2. The Operating Principle of the Hysteresis Regulator

3.2. Φ_r and θ_s Calculation

The rotor magnetic flow is calculated by :

$$\Phi_r = \frac{L_M \, i_{sd}}{1 + p.\tau_r} \tag{12}$$

τ_r= L’r/Rr: rotor time constant, L’r=LM+Lr and p is the Laplace operator. On dq axis, the angular pulse θ_s related to one phase of the stator is defined by:

$$\hat{\omega}_s = \hat{\omega} + \hat{\omega}_r = n_p \Omega + \frac{L_M}{\tau_r} \frac{i_{sq}}{\hat{\Phi}_r} \tag{13}$$

$$\hat{\theta}_s = \int \hat{\omega}_s \, dt \tag{14}$$

ω_r is the electrical angular rotor pulse, ω_s is the electrical angular stator pulse and ω is the electric rotation speed.

3.3. Compute of the Current References

The reference current I_{sd}* is calculated using the rotor flux reference, or by the following relation:

$$i_{sd}^* = \frac{\phi_r^*}{L_M} \tag{15}$$

$$i_{sq}^* = \frac{T_{em}^*}{\hat{\Phi}_r} \frac{L_r}{L_M n_p} \tag{16}$$

4. SPEED CONTROLLER DESIGN

In order to find an effective method for improving the speed behaviour of the induction machine, we present in this section the controllers used on this work. We start with two static configured controlers: the Pi controller and the fuzzy logic controller. Then we combine these two technics in one controller with a real time configuration.

4.1. Classic Speed Controller

The PI (proportional integral) speed controller scheme is given by the Figure 3. We did not choose the Pid controller because it may affects the swiftness of response.

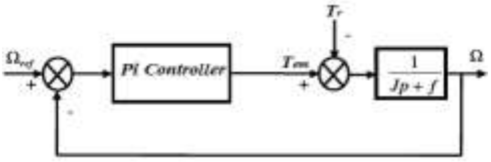


Figure 3. The Loop of Speed Control with Pi Controller

Ω_{ref} is the reference speed and ***f*** is the coefficient of viscous friction. The calculation of the coefficients K_p and K_i is given by the folwing equations: ($K_p$and k_i are Coefficients of the PI controller)

$$\Omega = \frac{1}{Jp+f}\left(\frac{K_p p + K_i}{p}\right)\left(\Omega_{ref} - \Omega\right) - \frac{1}{Jp+f} T_r \tag{17}$$

$$\Omega = \left(\frac{K_p p + K_i}{Jp^2 + \left(K_p + f\right)p + K_i}\right)\Omega_{ref} - \frac{P}{Jp^2 + \left(K_p + f\right)p + K_i} T_r \tag{18}$$

The transfer function (18) can be identified in a second-order system in the form: [5]

$$F(p) = \frac{1}{1 + \frac{2\xi}{\omega_n} p + \frac{p^2}{\omega_n^2}} \tag{19}$$

4.2. Fuzzy Logic Controller

The Fuzzy logic (FL) is currently arousing interest of all those who feel the need to formalize empirical methods to design artificial systems performing the tasks usually handled by humans. The diagram of speed control loop by a Fuzzy logic controler is well summarized by the Figure 4 [11].

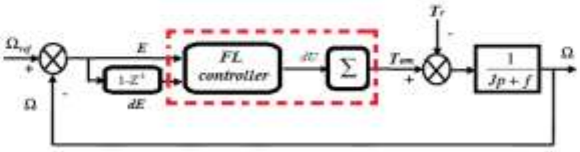


Figure 4. The Loop of Speed Control with FL Controller

In the Figure 4, as in the following, we note: E : the error, it is defined by:

$$E(k) = \Omega_{ref} - \Omega \tag{20}$$

$$dE(k) = \frac{E(k) - E(k-1)}{T_e} \tag{21}$$

T_e is the sampling Time. The controller output is given by:

$$T^*_{em}(k) = T^*_{em}(k-1) + du(k) \tag{22}$$

The design of a FL controller requires the crossing through the steps of fuzzification, find the inference rules and the step of deffuzification.

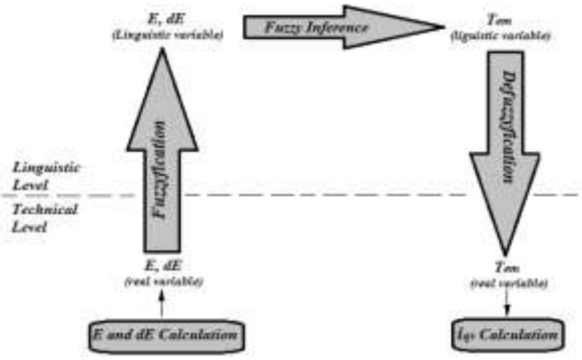
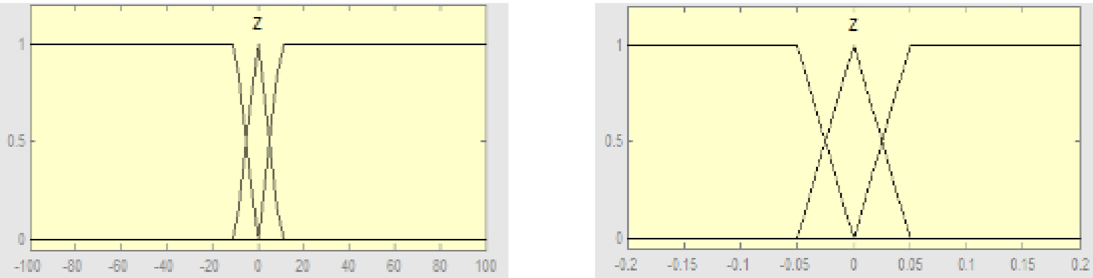


Figure 5. Steps to Design FL Controller

The fuzzification is the first step to designing a fuzzy controller. At this level we define the membership degrees of the fuzzy variable to its fuzzy set according to the real value of the input variable. We opted for triangular and trapezoidal functions for the input variables (Figure 6). They allow easy implementation and short duration when evaluated in real time.

Through the inference rules, we can set the decisions of the fuzzy controller. They are expressed as "IF THEN". In the fuzzy rules we involve the operators "AND" and "OR". The operator "AND" refers variables within a rule, while the "OR" operator binds the different rules. There are a several ways to interpret these two operators. The inference method called Mamdani (also called Max-Min method), makes the operator "AND" by the "Min" function and linking all the rules ("OR" operator) is ensured by the "Max" function [4].



(a). E(k) (b). dE(k)

Figure 6. Fuzzification Step

Table 1. Basic rules for the speed controller

Rule N°	E	dE	T_{em}*
1	P	P	P
2	P	Z	P
3	P	N	P
4	Z	P	P
5	Z	Z	Z
6	Z	N	N
7	N	P	N
8	N	Z	N
9	N	N	N

The Defuzzification converts fuzzy sets output into a suitable real variable. Several Defuzzification strategies exist; we used the method of "gravity center". The gravity center abscissa of the membership function resulting from the inference rules is the output value of the controller. We have therefore:

$$\chi_{out} = \frac{\int x\mu\ (x)dx}{\int \mu(x)dx} \tag{23}$$

χ_{out} is the output value and μ is the degree of membership. This is the method which gives generally better results. The results are stable relationships to changes in fuzzy set solution, and therefore the system inputs.

4.3. Fuzzy Gain-Scheduling PI Controller Design

Fuzzy logic has the ability to support the treatment of imprecise variables and to give objective decisions by an approximate knowledge. This controller provides good robustness against external disturbances, howver its respons is not fast. On the other hand, the Pi controller has a fast response and it is sensitive against external disturbances and parmetr change. That's why we we chose to schedule the coefficients of the the pi controller by fuzzy logic, in order to improve obtained results.

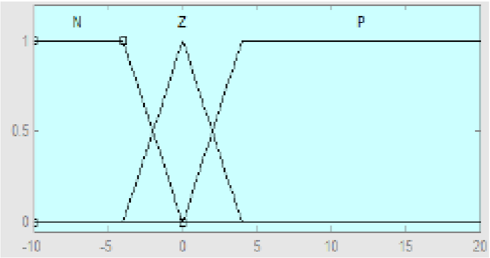


Figure 7. Defuzzification Step

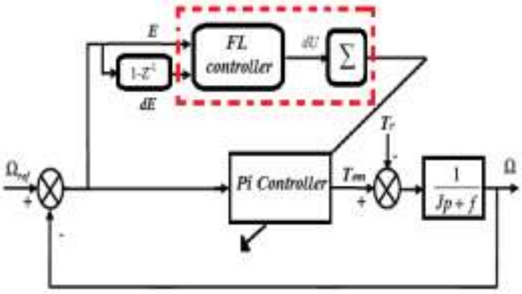
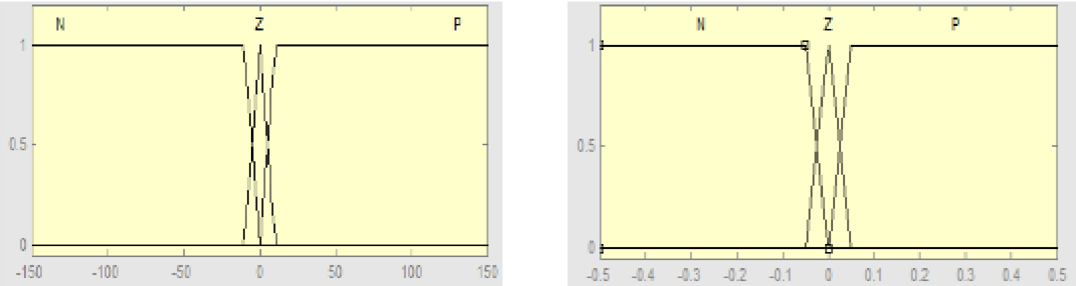
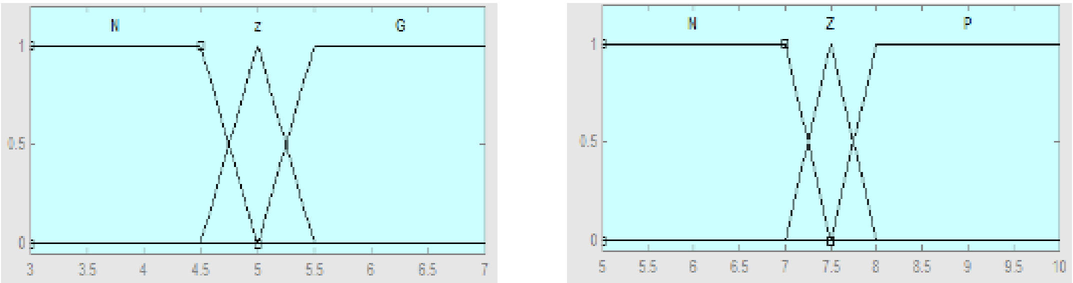


Figure 8. The Loop of Speed Control with Gain-Scheduling Technic



(a). E(k) (b). d E(k)



(c). K_p^* (d). K_i^*

Figure 9. The Fuzzification and Defuzzification Step for Scheduling Coeficient of Pi Controller

Table 2. Basic Rules For Ki
(Integrator Coefficient of the Scheduled Pi)

Rule N°	E	dE	Ki
1	P	P	P
2	P	Z	P
3	P	N	P
4	Z	P	P
5	Z	Z	Z
6	Z	N	N
7	N	P	N
8	N	Z	N
9	N	N	N

Table 3. Basic Rules For K_p
(Proportional Coefficient of the Scheduled Pi)

Rule N°	E	Kp
1	N	N
2	Z	Z
3	P	P

5. SIMULATION RESULTS

All the simulations are carried out on an induction machine whose parameters are listed in the appendix (Table 5). In addition to that and in order to identify the performance of different controller used, we varied the setpoint of speed and we applied disturbances on the resistif torque as shown in Table 4.

Table 4. Variation of the Setpoint of Speed and the Disturbances on the Resistif Torque

Time (s)	T_r (N/m)	$Speed_{ref}$ (rad/s)
[0,2]	0	100
[2,3]	4	100
[3,6]	4	110
[6,8]	5	90
[8,9]	0	90
[9,10]	0	100

Table 5. Induction machine parameters

Variable	Value
Nominal power	1Kw
Stator resistance	0.435Ω
Stator inductance	2mH
Rotor resistance	0.816 Ω
Stator inductance	2mH
Mutual inductance	69,3mH
Inertia	0,089Kg.m^{-2}
Friction Factor	0,005N.m.s
Pole pairs	2

The following curve show the whole speed behavior of all controllers previously detailed

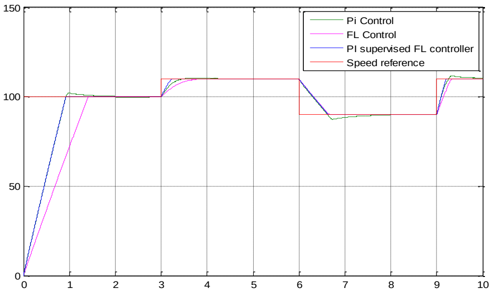
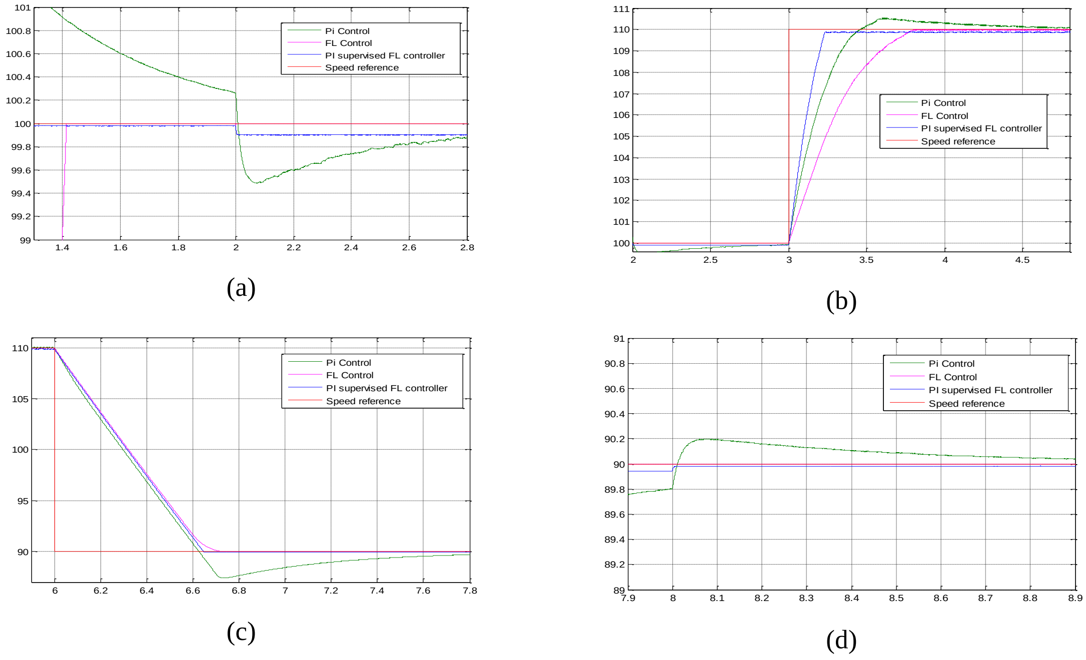


Figure 10. The Speed Behavior of the Different Controllers Used

To highlight the performance of the three controllers, we zoom in Figure 10 (precisely when applying disturbances and when we change the setpoint). Figure 11 shows the speed behavior for each controller:



(a)

(b)

(c)

(d)

Figure 11. The Speed Behavior for the Different Controller Used (zoom)

Based on Figure 11, we can say that the classic Pi controller has a fast response, but it is very sensitive to disturbance. The fuzzy logic controller has shown its robustness against disturbances that we have applied and to the change on the setpoint. However it is the least fast among the three controllers. The results of the Scheduled Pi controller are very satisfactory results in terms of speed, stabilty and insensitivity to disturbance. Indeed this technic has proved its efficiency since it presents no overtake compared to the setpoint (gap of 0.01 rad/s) if we compare this result to that of [1] in which the overtake is remarkable (gap of 50 rad/s) with a classical vector control or [3] which the overtake is remarkable (gap of 20 rad/s) with the sliding mode control. Also, both [1] and [3] did not expose their controller to disturbance or setpoint change which highlights the performance of our designed controller against the other ontroller.

6. CONCLUSION

In this work we have introduce a Vector control structure which includes a magnetic flux estimation to avoid the use of a physical sensor. In this structure, we have detailed two different controllers which are the classic PI and the FL controller. Then, we designed a Fuzzy Gain-Scheduling Pi controller. We note that the Pi supervised fuzzy inherited the advantages of both Pi and fuzzy Controller. We note that the rise time with a fuzzy supervised Pi controller is fast and also robust against the reference changing and the imposition of a disturbance (Tr change).

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