FAULT DIAGNOSIS FOR INDUCTION MOTOR ROTOR BROKEN BAR BASED ON THE COMPARATIVE ANALYSIS OF CLASSICAL AND FUZZY PI REGULATORS FOR THE INDIRECT FIELD ORIENTED CONTROL

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Abstract: *A fault diagnosis method was presented for motor rotor broken bar fault based on the comparative analysis of Fuzzy logic and classical (proportional-integral) control techniques. We propose the modeling of the diagram multi windings of the induction motor allowing apprehending his behavior in presence or absence of failures. We were interested in the indirect field oriented control of the induction motor using regulators classical and fuzzy logic (PI) by taking account of the presence of the broken rotor bars.*
Keywords *: broken rotor bars, Field Oriented Control, Fuzzy logic controller, Induction motor, multiphase winding.*

1. INTRODUCTION

The diagnosis of the control of an induction motor ,became very important, because of the development which knew industrial environment especially for the electric drives. In this paper, the performance of fuzzy, classical PI controllers are compared in the indirect field oriented control of an induction motor with broken rotor bars.

The squirrel cage of an induction machine can be seen as a multiphase winding with shorted turns. Instead of a wound structure the rotor consists of Nr bars and two end rings, connecting the bars on both ends, as depicted in Fig. 1 and 2. At the end rings fins are located to force the circulation of air in the inner region of the machine.

The classical (P, PI, PID) control technique has been the basis in simple control systems. Its simplicity has been the main reason for its wide applications in industry. Since classical controllers are fixed-gain feedback controllers, they can't compensate the parameter variations in the plant and can't adapt changes in the environment. In classical conventional techniques, mathematical modeling of the plants and parameter tuning of the controller have to be done before implementing the controller. Most real systems, relevant from a control perspective, exhibit nonlinear behavior; furthermore, to model these systems are often troublesome, sometimes impossible using the laws of physics. Therefore, using a classical controller isn't suitable for nonlinear control application.

Fuzzy logic is a technique to embody human-like thinking into a control system. A fuzzy controller can be designed to emulate human deductive thinking, that is, the process people use to infer conclusions from what they know. Fuzzy control has been primarily applied to the control of processes through fuzzy linguistic descriptions.

2.BLOCK DIAGRAM OF INDUCTION MOTOR

2.1 MODEL OF ROTOR WINDING

For the analytical study of the performances of the engines of induction with rotor dissymmetries, we adopted the diagram multi equivalent rolling up which adapts well to the problem arising, because it describes the rotor like a whole of meshs inter-connected between them, each one formed by two adjacent bars and the portions of rings which connect them (figure 1).Starting from traditional assumptions which suppose that the permeability of iron is infinite, that the air-gap and that the stator f.m.m. is with sinusoidal distribution, one is smooth and constant calculates various inductances and mutual insurance companies which intervene in the equations of the circuit. The representation of the dynamics of the machine, with a reference mark binds to the rotor, is given by the following equations:

$$V_{ds} = R_s.I_{ds} - \frac{d\Phi_{ds}}{dt} + \omega_s.\phi_{qs} \qquad (1)$$

$$V_{qs} = R_s.I_{qs} - \frac{d\Phi_{qs}}{dt} + \omega_s.\phi_{ds} \qquad (2)$$

$$0 = R_r.I_{dr} + \frac{d\phi_{dr}}{dt} \qquad (3)$$

$$0 = R_r.I_{qr} + \frac{d\phi_{qr}}{dt} \qquad (4)$$

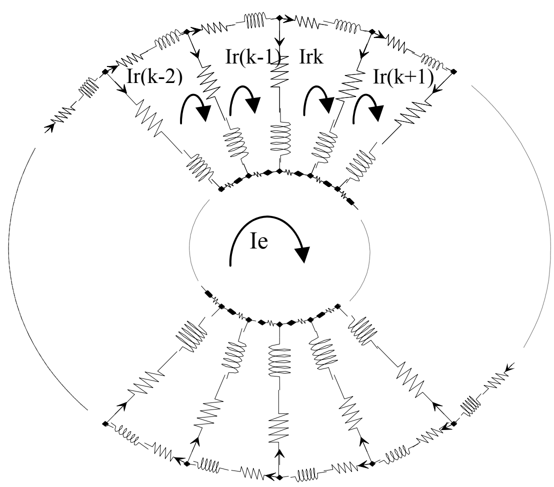


Fig .1. Electrical circuits equivalent of a cage rotor

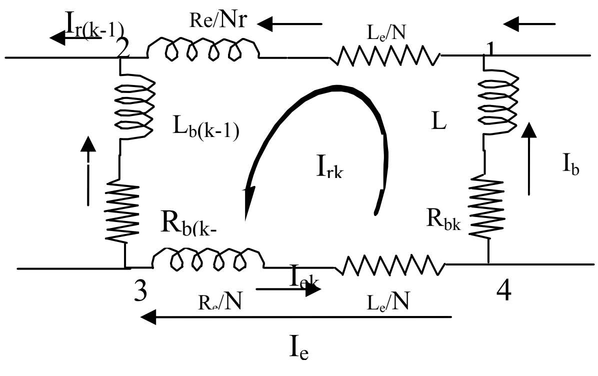


Fig.2. Rotor cage topology

Where :

$$x(t) = [isd(t) \quad isq(t) \quad ird(t) \quad isq(t) \quad Ie(t)]^T$$

The complete system is[6] [5] [1] :

$$\begin{bmatrix} L_{sc} & 0 & \cdots & \cdots & \cdots & -M_{sr}\cos j\alpha & \cdots & \cdots & 0 \\ 0 & L_{sc} & \cdots & \cdots & \cdots & -M_{sr}\sin j\alpha & \cdots & \cdots & 0 \\ \vdots & \vdots & L_{rp}+\frac{2L_e}{Nr}+2L_b & M_{rr}-L_b & M_{rr} & \cdots & M_{rr} & M_{rr}-L_b & -\frac{L_e}{Nr} \\ \vdots & \vdots & M_{rr}-L_b & L_{rp}+\frac{2L_e}{Nr}+2L_b & M_{rr}-L_b & M_{rr} & \cdots & M_{rr} & \vdots \\ -\frac{3}{2}M_{sr}\cos k\alpha & -\frac{3}{2}M_{sr}\sin k\alpha & & & & & & & \vdots \\ \vdots & \vdots & & & & & & & \vdots \\ \vdots & \vdots & M_{rr}-L_b & M_{rr} & \cdots & M_{rr} & M_{rr}-L_b & L_{rp}+\frac{2L_e}{Nr}+2L_b & -\frac{L_e}{Nr} \\ 0 & 0 & -\frac{L_e}{Nr} & \cdots & \cdots & \cdots & \cdots & -\frac{L_e}{Nr} & L_e \end{bmatrix} \frac{d}{dt}\begin{bmatrix} Ids \\ Iqs \\ I_{r0} \\ \vdots \\ I_{rj} \\ \vdots \\ I_{r(Nr-1)} \\ I_e \end{bmatrix} =$$

$$\begin{bmatrix} Vds \\ Vqs \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} - \begin{bmatrix} R_s & -WL_{sc} & \cdots & \cdots & M_{sr}W\sin j\alpha & \cdots & \cdots & 0 \\ -WL_{sc} & R_s & \cdots & \cdots & -M_{sr}W\cos j\alpha & \cdots & \cdots & 0 \\ 0 & 0 & 2\frac{R_e}{Nr}+R_{b0}+R_{b(Nr-1)} & -R_{b0} & 0 & 0 & -R_{b(Nr-1)} & -\frac{R_e}{Nr} \\ 0 & 0 & & & & & & \vdots \\ 0 & 0 & 0 & -R_{b(k-1)} & 2\frac{R_e}{Nr}+R_{bk}+R_{b(k-1)} & -R_{bk} & 0 & \vdots \\ 0 & 0 & & & & & & \vdots \\ 0 & 0 & -R_{b(Nr-1)} & 0 & 0 & -R_{b(Nr-2)} & 2\frac{R_e}{Nr}+R_{b(Nr-2)}+R_{b(Nr-1)} & -\frac{R_e}{Nr} \\ 0 & 0 & -\frac{R_e}{Nr} & \cdots & \cdots & \cdots & -\frac{R_e}{Nr} & R_e \end{bmatrix} \begin{bmatrix} Ids \\ Iqs \\ I_{r0} \\ \vdots \\ I_{rj} \\ \vdots \\ I_{r(Nr-1)} \\ I_e \end{bmatrix}$$

(5)

After the transformation of park, one has leads to a small-scale model:

$$\begin{bmatrix} Lsc & 0 & -\frac{Nr}{2}Msr & 0 & 0 \\ 0 & Lsc & 0 & \frac{Nr}{2}Msr & 0 \\ -\frac{3}{2}Msr & 0 & Lrc & 0 & 0 \\ 0 & \frac{3}{2}Msr & 0 & Lrc & 0 \\ 0 & 0 & 0 & 0 & Le \end{bmatrix} \frac{d}{dt}\begin{bmatrix} Ids \\ Iqs \\ Idr \\ Iqr \\ Ie \end{bmatrix} = \begin{bmatrix} Vds \\ Vqs \\ 0 \\ 0 \\ 0 \end{bmatrix} - \begin{bmatrix} R_s & -\omega L_{sc} & 0 & -\frac{N_r}{2}\omega M_{sr} & 0 \\ \omega L_{sc} & R & -\frac{N_r}{2}\omega M_{sr} & 0 & 0 \\ 0 & 0 & S_1 & S_2 & 0 \\ 0 & 0 & S_3 & S_4 & 0 \\ 0 & 0 & 0 & 0 & R_e \end{bmatrix} \begin{bmatrix} I_{ds} \\ I_{qs} \\ I_{dr} \\ I_{qr} \\ I_e \end{bmatrix} \quad (6)$$

Where :

$$S_1 = \frac{2}{16}\left[\left(2\frac{\mathrm{Re}}{Nr}+R_{b0}+R_{b15}\right)\cos^2 0\alpha + \left(2\frac{\mathrm{Re}}{Nr}+R_{b1}+R_{b0}\right)\cos^2 1\alpha + \cdots + \left(2\frac{\mathrm{Re}}{Nr}+R_{b14}+R_{b15}\right)\cos^2 15\alpha\right]$$

$$-\frac{4}{16}\left[\left(R_{b0}\cos 0\alpha\cos 1\alpha\right)+\left(R_{b1}\cos 1\alpha\cos 2\alpha\right)+\cdots+\left(R_{b15}\cos 15\alpha\cos 0\alpha\right)\right] \qquad (7)$$

$$S_2 = -\frac{2}{16}\left[\left(2\frac{\mathrm{Re}}{Nr}+R_{b0}+R_{b15}\right)\cos 0\alpha\sin 0\alpha - \left(2\frac{\mathrm{Re}}{Nr}+R_{b1}+R_{b0}\right)\cos 1\alpha\sin 1\alpha - \cdots - \left(2\frac{\mathrm{Re}}{Nr}+R_{b14}+R_{b15}\right)\cos 15\alpha\sin 15\alpha\right]$$

$$+\frac{2}{16}\left[\left(R_{b0}\sin 0\alpha\cos 1\alpha\right)+\left(R_{b1}\sin 1\alpha\cos 2\alpha\right)+\cdots+\left(R_{b15}\sin 15\alpha\cos 0\alpha\right)\right]+\frac{2}{16}\left[\left(R_{b0}\cos 0\alpha\sin 1\alpha\right)+\left(R_{b1}\cos 1\alpha\sin 2\alpha\right)+\cdots+\left(R_{b15}\cos 15\alpha\sin 0\alpha\right)\right] \quad (8)$$

$S_1 = S_4$, $S_2 = S_3$ (9)

2.2 MODELING OF THE BROKEN ROTOR BARS :

The Model shown previously , and rewritten below, makes it possible to simulate the broken rotor bars. If one wants to simulate the rupture of a bar or two bars the only values which will change are those of: S_1, S_2, S_3 and S_4 .

The broken rotor bars is one of the most frequent faults in the rotor. Our simulations we will allow to identify the signatures of this defect and to envisage the deteriorations generated in the engine.

To illustrate the total break of bar in the model of the machine, we increase the value of the broken bar of 11 times[6] [7].

3. INDIRECT FIELD-ORIENTED CONTROL OF AN INDUCTION MOTOR:

Concerning the speed regulation, this one is given by the functional diagram of regulation of figure (3). A regulator of the type pi was added with the assembly of decoupling [1]

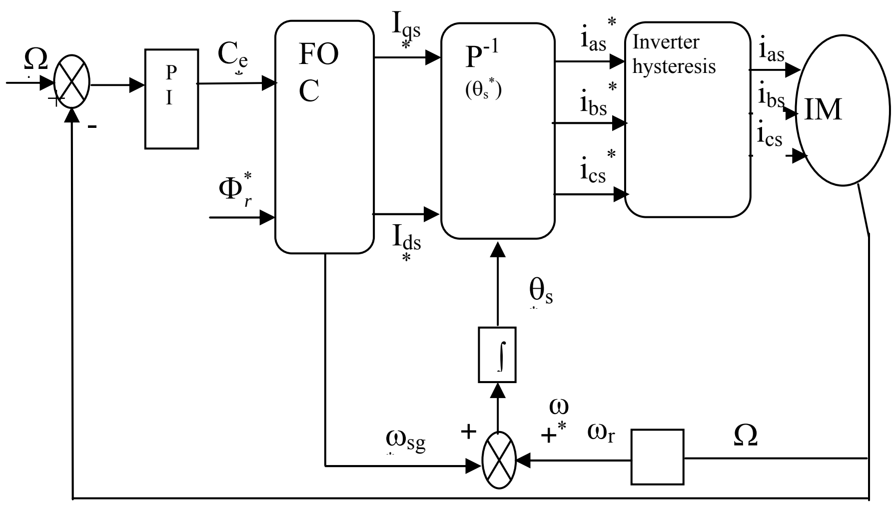


Fig.3. Speed regulation by the field orientation

3.1. SYNTHESIS OF THE CONVENTIONAL SPEED REGULATOR TYPE PI

The speed regulator makes it possible to determine the torque of reference, in order to maintain the speed of corresponding reference.
The mechanical equation gives:

$$\frac{\Omega(s)}{C_{em}(s)} = \frac{1}{f + Js} \qquad (10)$$

While associating with this function a regulator pi, it arrives:

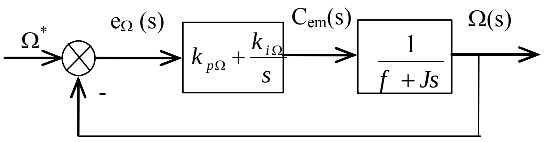


Fig .4. Functional diagram of regulation speed.

The transfer function in closed loop, calculated starting from the preceding diagram, is given by:

$$\frac{\Omega(s)}{\Omega^*(s)} = \frac{(k_{p\Omega}s + k_{i\Omega})\frac{1}{J}}{P(s)} \qquad (11)$$

The characteristic equation P (S) is:

$$P(s) = s^2 + \frac{f + k_{p\Omega}}{J}s + \frac{k_{i\Omega}}{J} = 0 \qquad (12)$$

While always imposing two combined complex poles $s_{1,2} = \rho(-1 \pm j)$, in closed ball and, by identification with the new wished characteristic equation, one arrives at:

$$k_{i\Omega} = 2J\rho^2 \quad et \quad k_{p\Omega} = 2\rho J - f \qquad (13)$$

The parameters of the speed regulator used as a whole of simulations which will be presented thereafter, are calculated for 001=ρ. The algorithm of simulation is carried out with one period of sampling of 0.5ms.

3.2. IMPLEMENTATION OF FUZZY LOGIC CONTROLLER :

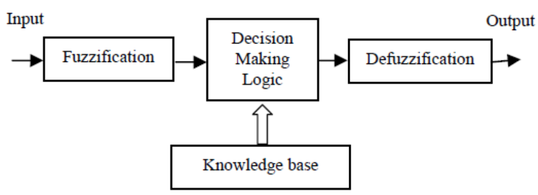


Fig 5. Fuzzy control system

In the case of the regulation speed, one usually needs the error ($e=W_{r\,ref}$. - $\rho\Omega$) and of derived from error (de) and sometimes of integration from error:

$$
\begin{aligned}
e(k) &= \Omega_{rref}(k) - \Omega_r(k) \\
de(k) &= e(k) - e(k-1)
\end{aligned}
\qquad (14)
$$

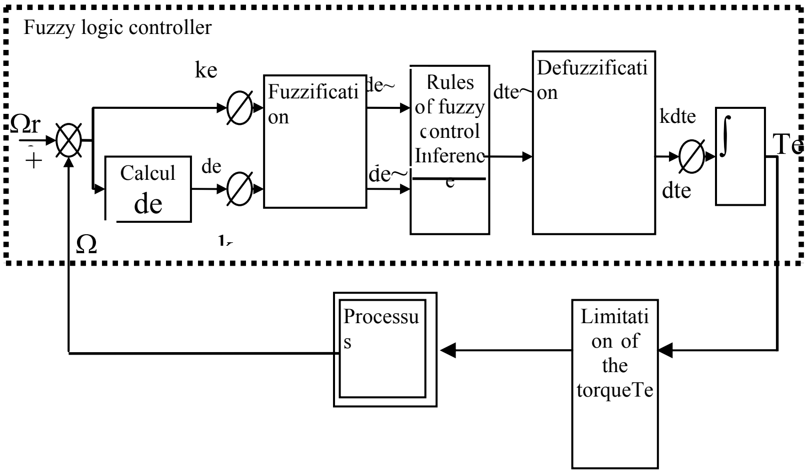


Fig. 6. speed Fuzzy PI controller

3.2.1.CONCEPT OF FUZZY LOGIC

The idea of formulating the control algorithms by logical rules introduced the implementation of human understanding and human thinking in control algorithms. The lack of analytical description makes the fuzzy control conceptually different from conventional control. [9]

3.2.2.MEMBERSHIP FUNCTIONS

The Fuzzy Logic Controller initially converts the crisp error and change in error variables into fuzzy variables and then are mapped into linguistic labels. Membership functions are associated with each label as shown in the Fig. 7 which consists of two inputs and one output.

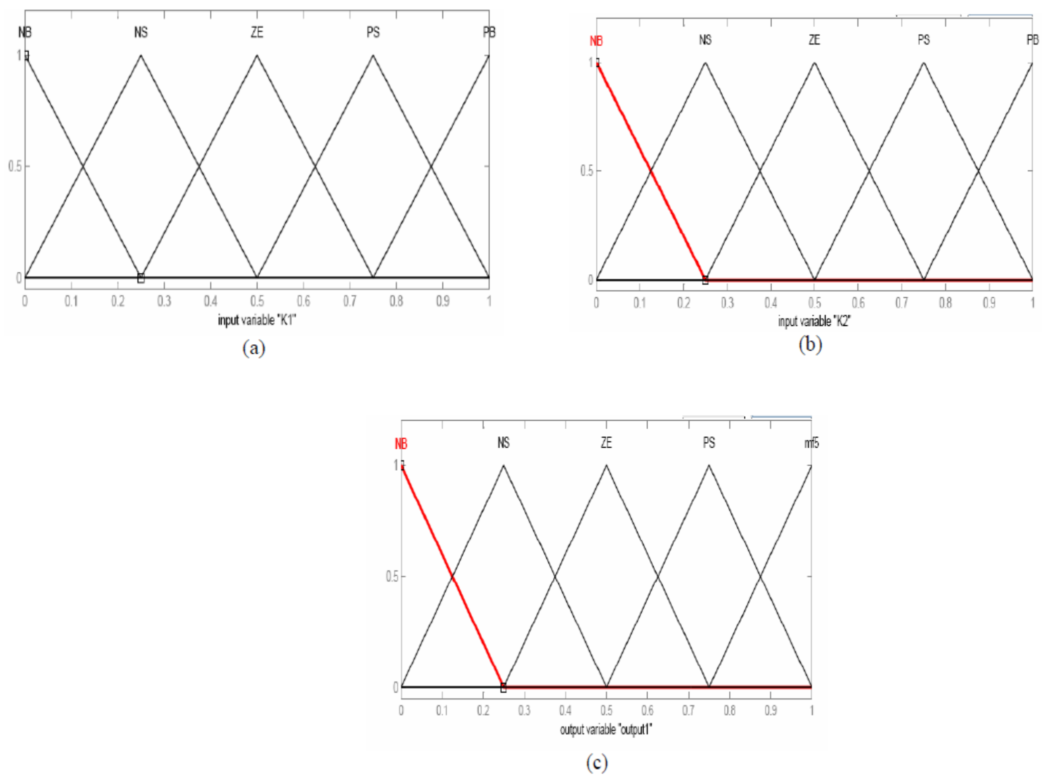


Fig 7 (a) Membership function for input variable (b) Membership function for input variable
(c) Membership function for output variable[8]

3.2.3.KNOWLEDGE RULE BASE

The mapping of the fuzzy inputs into the required output is derived with the help of a rule base as given in Table 1.

Each rule of the FLC is characterized with an IF part, called the antecedent, and with a THEN part called the consequent. The antecedent of a rule contains a set of conditions and the consequent contains a conclusion. If the conditions of the antecedents are satisfied, then the conclusions of the consequent apply. Considering the first rule, it can be interpreted as: IF change in speed error is NH and change is speed is NH, THEN the output will be NH.

3.2.4.DEFUZZIFICATION

Generally the output obtained is fuzzy in nature and has to be converted into a crisp value by using any Defuzzification technique [8].

e \ Δe o/p	NB	NS	ZE	PS	PB
NB	NB	NB	NS	NS	ZE
NS	NB	NS	NS	ZE	PS
ZE	NS	NS	ZE	PS	PS
PS	NS	ZE	PS	PS	PB
PB	ZE	PS	PS	PB	PB

Table 1 : Fuzzy Controller Operations

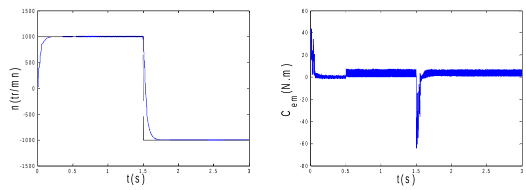
4. SIMULATION RESULTS

The classical and fuzzy regulator (PI) was simulated at any operation condition such as healthy condition and broken bars failures in side of rotor squirrel cage induction motor ; results of simulation thus allowing to compare the two types of regulators (classical and fuzzy).

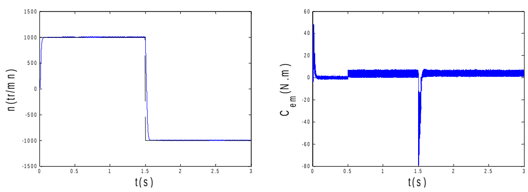
The motor parameters (ABB) :

U:220/380V. $I_n = 4.5/2.6A$. $\Omega_n = 2850\,tr/\min$ $P_n = 1.1\,KW$, $Rs = 7.828\ \Omega$, $J = 0.006093\ Kg\ m^2$, $f = 0.00725\ Nm\ s/rd$, Ray = 0.03575 m, Length = 0.065 m, Air-gap = 0.00025 m, $Ns = 160$, $Nr = 16$, $Lsl = 0.018\ H$, $Rbsain = 150\ 10^{-6}\ \Omega$, $R = 0.00165\ \Omega$, $\mathrm{Re} = 72\ 10^{-6}\ \Omega$, $Lb = 10^{-7}\ H$, $Le = 10^{-7}\ H$

4.1 MOTOR WITHOUT FAULT



(a)



(b)

Fig.8: Comparison results evolution speed, torque , simulation with model, operational machine in load Cr= 3.5 N.m
(a) PI regulator (b) Fuzzy regulator

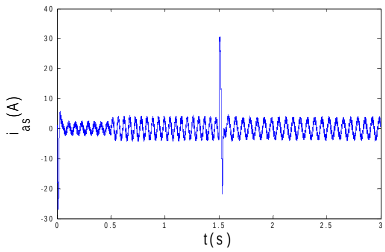


Fig 9. stator current, simulation with reduced model, operational machine charges some, Cr=3.5N.m.

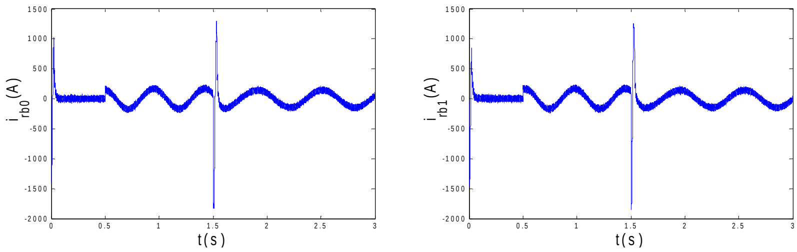
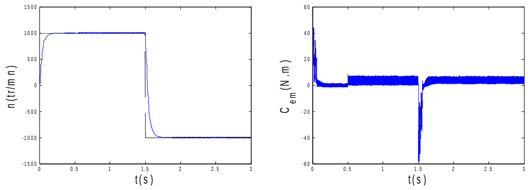


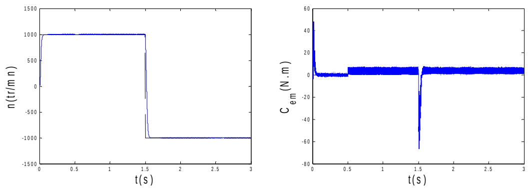
Fig 10. Currents in the rotor bars: I_{rb0}, I_{rb1}, simulation with total model, operational machine charges some, Cr= 3.5 N.m

4.2 MOTOR WITH FAULT

A. MOTOR WITH BROKEN ROTOR BAR



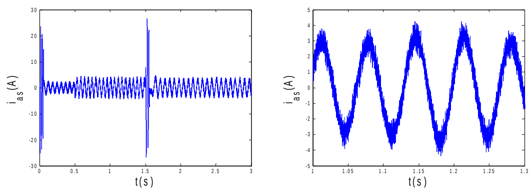
(a)



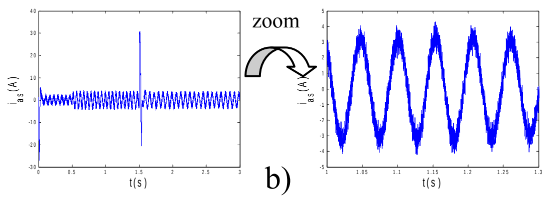
(b)

Fig 11. Comparison results evolution of speed, torque electromagnetic, simulation with the reduced model, machine at fault and load: rupture of a bar with t=1s

(a) PI regulator (b) Fuzzy regulator



(a)



b)

Fig 12. stator current, motor with fault, load Cr= 3.5Nm

(a) PI regulator (b) Fuzzy regulator

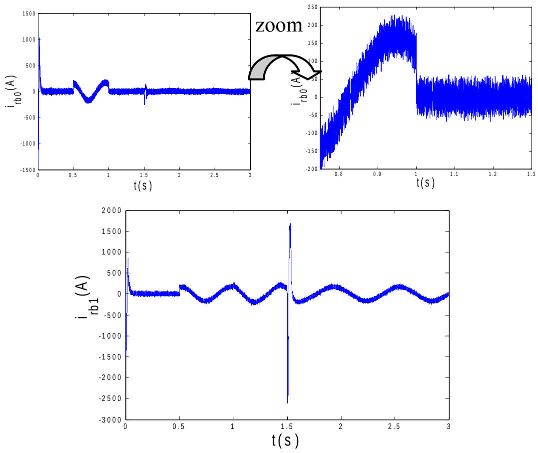
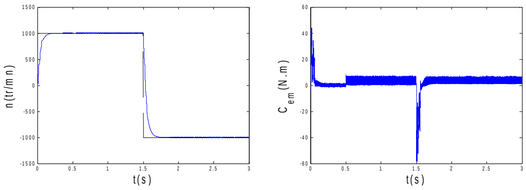
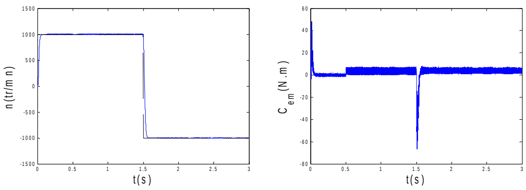


Fig 13. Currents in the rotor bars: I_{rb0}, I_{rb1}, machine in defect, simulation with total model, broken rotor bar r_{b0} to t= 1s

B. MACHINE WITH BROKEN TWO BARS

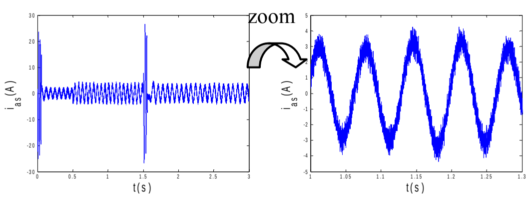


(a)

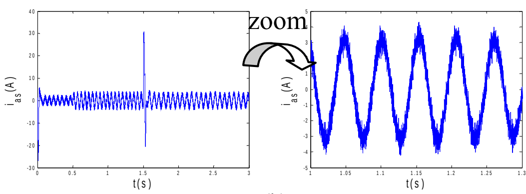


(b)

Fig 14. evolutions of speed, torque, machine in load and: 2 broken bars
(a) PI regulator (b) Fuzzy regulator



(a)



(b)

Fig 15. stator current, machine in load and, 2 broken rotor bars
(a) PI regulator (b) Fuzzy regulator

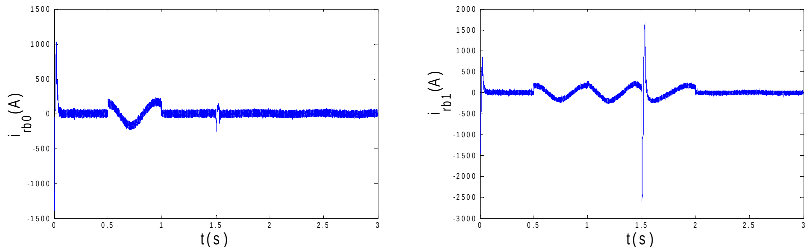


Fig 16. currents in the rotor bars: I_{rb0}, I_{rb1}, Machine in load and, simulation with total model: 1 broken bar r_{b0} in t=1s, 2 broken bar r_{b1} in t=2s

We simulated in the figure (8) an inversion of the speed of +1000 rpm with - 1000 rpm. This change of the direction of rotation proceeds with maximum couple and the time of inversion in load is about 0.3 S.
The response time speed is about 0.2 S, a level of torque of 3.5 N.m is applied to t=0.4s. The mode thus established, we carry out the simulation of a first rupture of bar by an increase of 11 times the resistance of this bar. After a transitory mode very in short, the second bar is broken with t=2s. the speed remains always not very disturbed by this defect.
One will see the regulation speed, in the case of the defects, or one simulates the rupture of a bar, and also the rupture of two bars.
In the figure (12), we observe a deformation on the level of the stator current, at the time of the breaks of bars.
The figure (16) illustrates the currents of bars I_{rb0}, I_{rb1}, in the presence of a rupture of bar rb0 to t=1s and rb1 with t=2s. The currents circulating in the adjacent bars with the broken bars are much higher has their face value. It is thus concluded that there is a default risk of each one in measurement or the electric and thermal constraints are redistributed on the adjacent drivers .
The effects of the break of bar (oscillation of W and Cem) believes quickly with the number of bars broken; from where one observes:
- Increase in the amplitude of the oscillations. The great amplitude of the oscillations accelerate the deterioration of the machine.
- The amplitude of the currents of the stator phases is proportional to the number of broken bars.
- at the time of the rotor faults, the currents in the broken bars practically fall to zero, while the currents in the close bars become unbalanced. The currents which led the broken bars distributes then in the close bars.
The reaction of the regulators with fuzzy logic at the time of application of load is also characterized by a smaller variation and a shorter time compared to the traditional regulators

7. CONCLUSION

In this paper, the influence of broken bars rotor in the indirect field oriented control of an induction machine is investigated. A comparison of two regulators based on the classical and fuzzy PI is presented. Taking into account the results, fuzzy logic PI seems to provide to replace conventional pi to improve the performances of this last and thus of vectorial control. Fuzzy logic pi is far from sensitive to the variations of the parameters of the system, (with regard to the breaks of the bars, which influence rotor resistance, or the increase is about 11) as with the external disturbances what justifies its robustness. It makes it possible to obtain very weak boarding times compared to traditional pi thanks to the broad physical fields of the variation of the error and the variation of order.
The simulation results have enabled to us to judge the robustness of fuzzy controller comparing with the classical control.

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