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Fuzzy Control with Rotor Flux Orientation of the DFIG Motor Drive

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ABSTRACT

In This paper we present a new contribution of fuzzy logic for electrical machine control. We are interested to the control direction of the rotor flux applied to Doubly-Fed Induction Generators (DFIG)

At first, the principle of operation and modeling are applied to the DFIG is developed and introduced. Thereafter, the Fuzzy approach is applied to the FOC control, to improve the performance of the machines.

Finally, the simulation results of the two commands are validates on the environment Matlab / Simulink followed by a detailed analysis.

Indexing terms/Keywords

Doubly-Fed Induction Generators (DFIG); Vector Control; Fuzzy control; Robustness.

SUBJECT CLASSIFICATION

Revewlable Energies / Network Modeling and Simulation.

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1. INTRODUCTION

Doubly-Fed Induction Generators (DFIG) is an electric machine used principally in industrial applications since its construction is simple, its low cost, operational safety, Robustness, and especially its simple and economical maintenance compared to all other variable speed. From these advantages, it is more and more studied principally at the realization of robust control and its operation with or without speed sensor [1].

Currently the development and exploitation of new electronic technologies and informatics, have simplified the use of various applications DFIG, it gives opportunities for speed control with or without mechanical sensors, and control the flux of power to the characteristics regimes hypo- synchronous and hyper-

In this context, the Vector Command by Orientation Flux is applied to the DFIG successfully gave a good powerful tool

for control. The disadvantage of this command is the sensitivity to changes in parameters of the machine. Therefore many researches are mainly active in the robustness of the control face to parametric variations of the system. The application of controllers based on fuzzy logic CFL give better results compared to the conventional control for nonlinear systems [6].

In this work, we present two techniques to control two power converters that are based on the control flow direction and control by fuzzy logic. An analysis of the dynamic performance of the machine is validated in the environment Matlab / Simulink. $(K_e = 0.002; K_{de} = 0.008; k_{du} = 145$

First, the modeling system is presented. Second, develop a study of the orientation control flux DFIG is studied with an interpretation of simulation results. Finally, will focus on fuzzy speed control of DFIG with a discussion of results.

However, having a reflection with respect to the elements most commonly found in these systems, it is possible to define a general structure of an electric device control, which is shown in Fig.1:

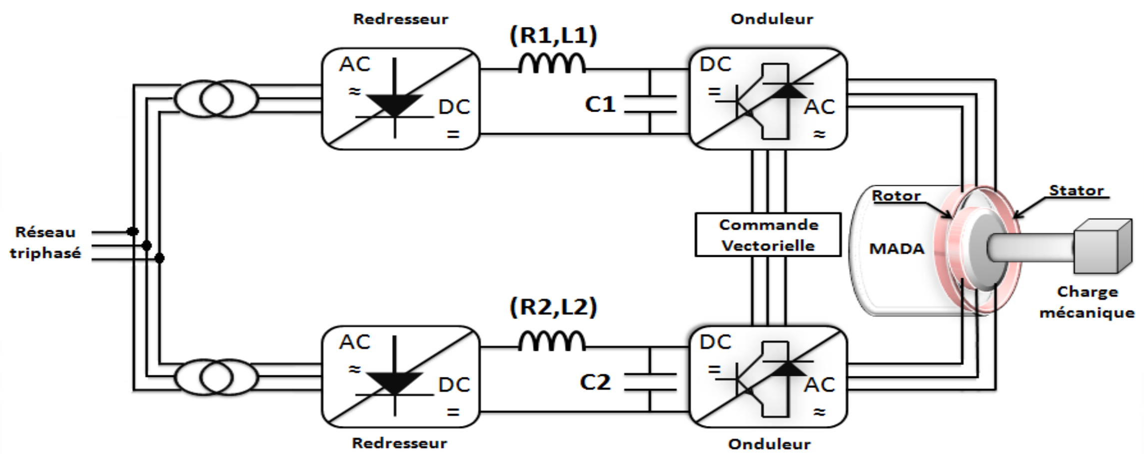


Fig.1: Architecture of the Control

2. DFIG Model system

2.1. Electric equations

The Electrical equations of the DFIG in the landmark Park (the dq coordinate system) can be written by the following relations:

$$\begin{cases} V_{sd} = R_s . I_{sd} + \dfrac{d\varphi_{sd}}{dt} - \omega_s . \varphi_{sq} \\ V_{sq} = R_s . I_{sq} + \dfrac{d\varphi_{sq}}{dt} - \omega_s . \varphi_{sd} \\ V_{rd} = R_r . I_{rd} + \dfrac{d\varphi_{rd}}{dt} - \omega_r . \varphi_{rq} \\ V_{rq} = R_r . I_{rq} + \dfrac{d\varphi_{rq}}{dt} - \omega_r . \varphi_{rq} \end{cases} \quad (1)$$

With $\omega_r = \omega_s - P.\omega$

2.2. Magnetic equations

$$\begin{cases} \varphi_{sd} = L_s.I_{sd} + M_{sr}.I_{rd} \\ \varphi_{sq} = L_s.I_{sq} + M_{sr}.I_{rq} \\ \varphi_{rd} = L_r.I_{rd} + M_{sr}.I_{sd} \\ \varphi_{rq} = L_r.I_{rq} + M_{sr}.I_{sq} \end{cases} \tag{2}$$

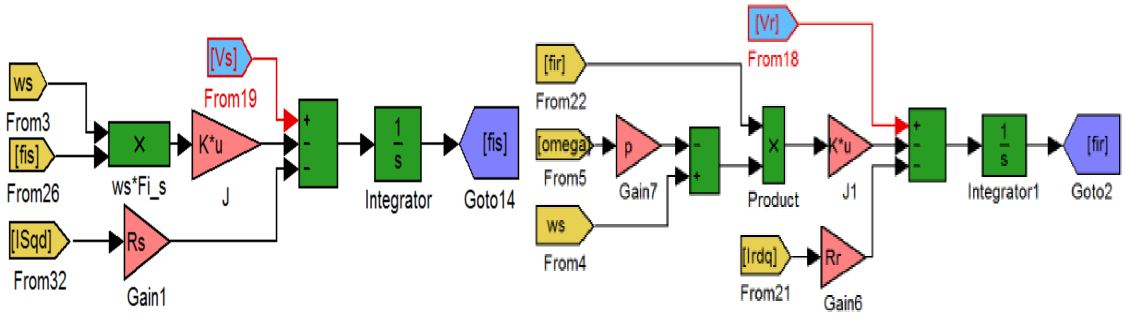


Fig.2: Model components in the dq landmark, rotor flux and the stator flux.

$$\begin{cases} I_{sd} = \dfrac{1}{\sigma.L_s}.\varphi_{sd} - \dfrac{M_{sr}}{\sigma.L_r}.\varphi_{sd} \\ I_{sq} = \dfrac{1}{\sigma.L_s}.\varphi_{sq} - \dfrac{M_{sr}}{\sigma.L_s.L_r}.\varphi_{sq} \\ I_{rd} = \dfrac{1}{\sigma.L_r}.\varphi_{rd} - \dfrac{M_{sr}}{\sigma.L_r.L_s}.\varphi_{sd} \\ I_{rq} = \dfrac{1}{\sigma.L_r}.\varphi_{rq} - \dfrac{M_{sr}}{\sigma.L_r.L_s}.\varphi_{sq} \end{cases} \tag{3}$$

With $\sigma = 1 - \dfrac{M^2}{L_r.L_s}$

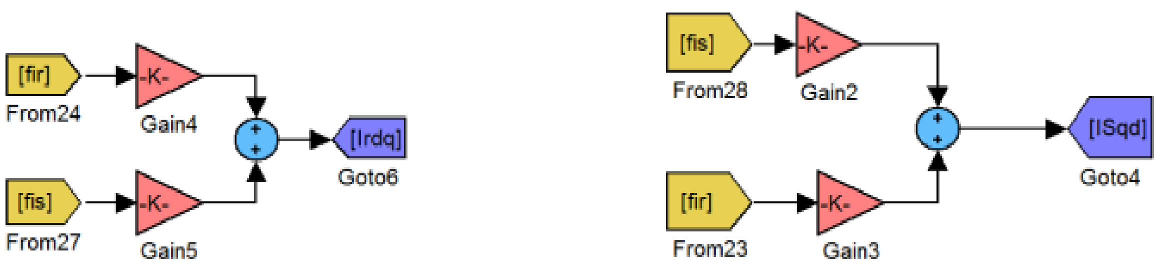


Fig.3: Model stator and rotor currents in the dq landmark

2.3. Mechanics equation

The electromagnetic torque of the DFIG is as follows:

$$\begin{cases} C_{em} = P(\varphi_{sq}.I_{sq} - \varphi_{sq}.I_{sd}) \\ C_{em} = P(\varphi_{rq}.I_{sq} - \varphi_{rd}.I_{rq}) \end{cases} \quad (4)$$

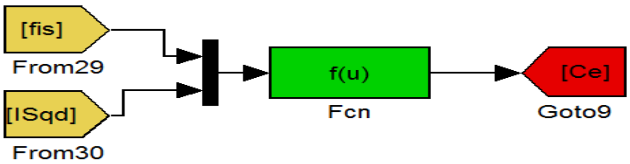


Fig.4: Simulink model of the electromagnetic torque

The fundamental relation of dynamics is:

$$C_{em} = C_r + J.\frac{d\Omega}{dt} + f.\Omega \quad (5)$$

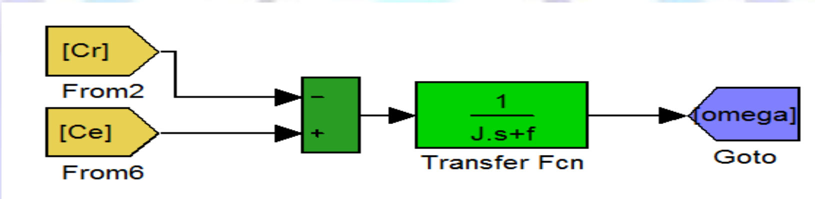


Fig.5: Simulink model of the velocity Ω.

d, q : Indices components direct axis and quadrature axis.
S, R : Indices of the stator and rotor.
θ_s , θ_r : Angle tracking of the stator flux and rotor relative to the benchmark.
ψ : mechanical rotor frequency (rad/s).
J : Moment of inertia.
f : Coefficient of viscous friction.

I_d, I_q : two-phase stator currents and rotor in a rotating frame.
V_d, V_q : two-phase stator voltages and rotor in a rotating frame.

$\varphi_{sd,q}$,$\varphi_{rd,q}$: stator and rotor resistances and Flux two-phase in a rotating frame.

R_s, R_r : stator and rotor resistances.

L_s, L_r : stator and rotor cyclic coefficient of inductance.

M_{sr} : coefficient of mutual inductance cyclic stator / rotor.

σ : dispersion coefficient.
P : number of pole pairs of the machine.
w_s, w_r : angular speed (pulsation) electrical stator and rotor.
C_r : Couple resistant.
C_{em} : Electromagnetic Coulpe.
Ω : Speed of rotation of the machine.

3. Modeling of power Electronic Components.

3.1. Rectifier Model

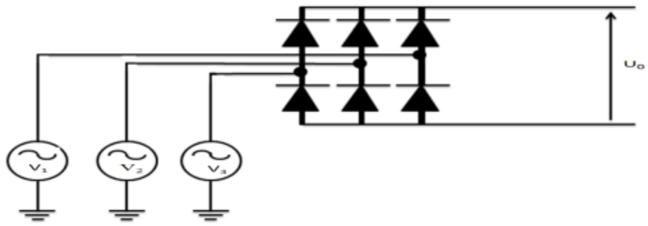


Fig.6: Structure of three-phase rectifier.

The rectified voltage determined by the following equation:

$$V_0 = V_{moy} = \frac{3\sqrt{3}}{\pi}.V_{\max} \tag{6}$$

3.2. Inverter Model

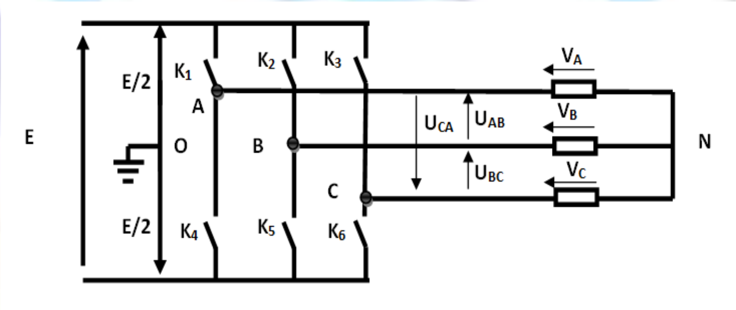


Fig.7: Schematic diagram of the three-phase inverter.

$$\begin{cases} V_A = \frac{2}{3}V_{AO} - \frac{1}{3}V_{BO} - \frac{1}{3}V_{CO} \\ V_B = -\frac{1}{3}V_{AO} + \frac{2}{3}V_{BO} - \frac{1}{3}V_{CO} \\ V_C = -\frac{1}{3}V_{AO} - \frac{1}{3}V_{BO} + \frac{2}{3}V_{CO} \end{cases} \tag{7}$$

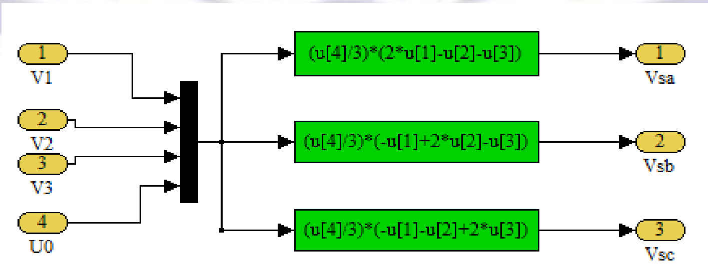


Fig.8: Simulink Model of the three-phase inverter.

4. Vector control of DFIG

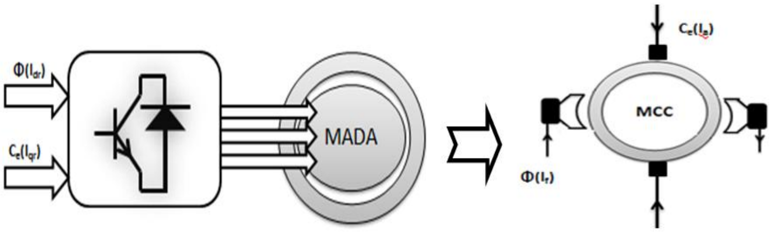


Fig.9: Principle of control orientation of the flux

The Following of the approach used for a field-oriented control, two methods of the vector control can be distinguished [4], that is:

- ✓ The direct method (DFOC).
- ✓ The indirect method (IFOC).

In this work we are interested in the direct method (DFOC) applied the double fed asynchronous machine with the rotor flux orientation and with the aim to get a good decoupling between the magnitudes along the axes d and q.

$$V_{tsq} = V_{sq} - \frac{M_{sr}}{L_r}.V_{rq} \qquad V_{tsd} = V_{sd} - \frac{M_{sr}}{L_r}.V_{rd}$$

and

$$V_{trq} = V_{rq} - \frac{M_{sr}}{L_s}.V_{sq} \qquad V_{trd} = V_{rd} - \frac{M_{sr}}{L_s}.V_{sd} \tag{8}$$

We focus mainly on the orientation of the rotor flux we have:

$$\varphi_{rq} = 0 \Leftrightarrow \varphi_{rd} = \varphi_r \tag{9}$$

The expressions of the rotor currents:

$$\varphi_{rq} = 0 \Rightarrow \begin{bmatrix} I_{rq} = -\frac{M_{sr}}{L_r}.I_{sq} \\ I_{sq} = -\frac{L_r}{M_{sr}}.I_{rq} \\ I_{sd} = \frac{\varphi_{rd}}{M_{sr}}.I_{rq} \\ I_{rd} = 0 \end{bmatrix} \tag{10}$$

The expression of the Couple equation becomes:

$$\left.\begin{matrix} I_{rd} = 0 \\ \varphi_{rq} = 0 \end{matrix}\right\rangle \begin{matrix} C_{em} = p.M_{sr}(I_{sq}.I_{rd} - I_{rd}.I_{sq}) \\ C_{em} = -p\varphi_{rd}I_{rq} = -pM_{sr}I_{sd}I_{rq} \end{matrix} \tag{11}$$

With $\varphi_{sq} = -\sigma\frac{L_sL_r}{M_{sr}}$

On the axis of the rotor flux is given: $\varphi_{rd} = L_rL_{rd} + M_{sr}I_{sd}$

Hence:

$$\begin{cases} V_{tsd} = R_s I_{sd} + \sigma L_s \dfrac{dI_{sd}}{dt} - R_r \dfrac{M_{sr}}{L_r} I_{rd} - \varphi_{sq}\omega_s + \dfrac{M_{sr}}{L_r}\varphi_{rq}(\omega_s - \omega) \\ V_{tsq} = R_s I_{sq} + \sigma L_s \dfrac{dI_{sq}}{dt} - R_r \dfrac{M_{sr}}{L_r} I_{rq} + \varphi_{sd}\omega_s - \dfrac{M_{sr}}{L_r}\varphi_{rd}(\omega_s - \omega) \\ V_{trd} = R_r I_{rd} + \sigma L_r \dfrac{dI_{rd}}{dt} - R_s \dfrac{M_{sr}}{L_s} I_{sd} - \varphi_{rq}(\omega_s - \omega) + \dfrac{M_{sr}}{L_s}\varphi_{sq}\omega_s \\ V_{trq} = R_r I_{rq} + \sigma L_r \dfrac{dI_{rq}}{dt} - R_s \dfrac{M_{sr}}{L_s} I_{sq} + \varphi_{rd}(\omega_s - \omega) - \dfrac{M_{sr}}{L_s}\varphi_{sd}\omega_s \end{cases} \tag{12}$$

Hence:

$$\begin{cases} V_{tsd} = V_{tsdc} + V_{tsdc1} = R_s I_{sd} + \sigma L_s \dfrac{dI_{sd}}{dt} + V_{tsdc1} \\ V_{tsq} = V_{tsqc} + V_{tsqc1} = R_s I_{sq} + \sigma L_s \dfrac{dI_{sq}}{dt} + V_{tsqc1} \\ V_{trd} = V_{trdc} + V_{trdc1} = R_r I_{rd} + \sigma L_r \dfrac{dI_{rd}}{dt} + V_{trdc1} \\ V_{trq} = V_{trqc} + V_{trqc1} = R_r I_{rq} + \sigma L_r \dfrac{dI_{rq}}{dt} + V_{trqc1} \end{cases} \tag{13}$$

Where V_{tsdc1}, V_{tsqc1}, V_{trdc1} and V_{trqc1} are considered compensation terms.

The Transfer Functions connect the stator and rotor components of each axis are given by:

$$\begin{aligned} \frac{I_{sq}(s)}{V_{tsqc}(s)} = \frac{I_{sd}(s)}{V_{tsd}(s)} = \frac{1}{R_s + \sigma L_s.s} \\ \frac{I_{rq}(s)}{V_{trqc}(s)} = \frac{I_{rd}(s)}{V_{trd}(s)} = \frac{1}{R_r + \sigma L_r.s} \end{aligned} \tag{14}$$

The various references to regulate current to the rotor flux orientation are:

$$\begin{aligned} I^*_{sd} = \frac{1}{M_{sr}}\varphi^*_{rd} \qquad I^*_{sq} = \frac{L_r}{p.M_{sr}.\varphi^*_{rd}} C^*_{em} \\ I^*_{sq} = -\frac{1}{p.\varphi^*_{rd}} C^*_{em} \qquad I^*_{rd} = 0 \end{aligned} \tag{15}$$

In the vector control the electromagnetic torque Cem and currents are controlled by PI correctors. The control variables are the voltages V_{Sd}, V_{Sq}, V_{Rd} and V_{Rq}.

For the inverter section, the reference voltages (V^*_{Sa}, V^*_{Sb}, V^*_{Sc}) and (V^*_{Ra}, V^*_{Rb}, V^*_{Rc}) are calculated by the inverse Park transformation from the variables (V_{Sd}, V_{Sq}, V_{Rd}, V_{Rq}, θ_S et θ_R). Thus, we can consider the diagram of control given by the following figure:

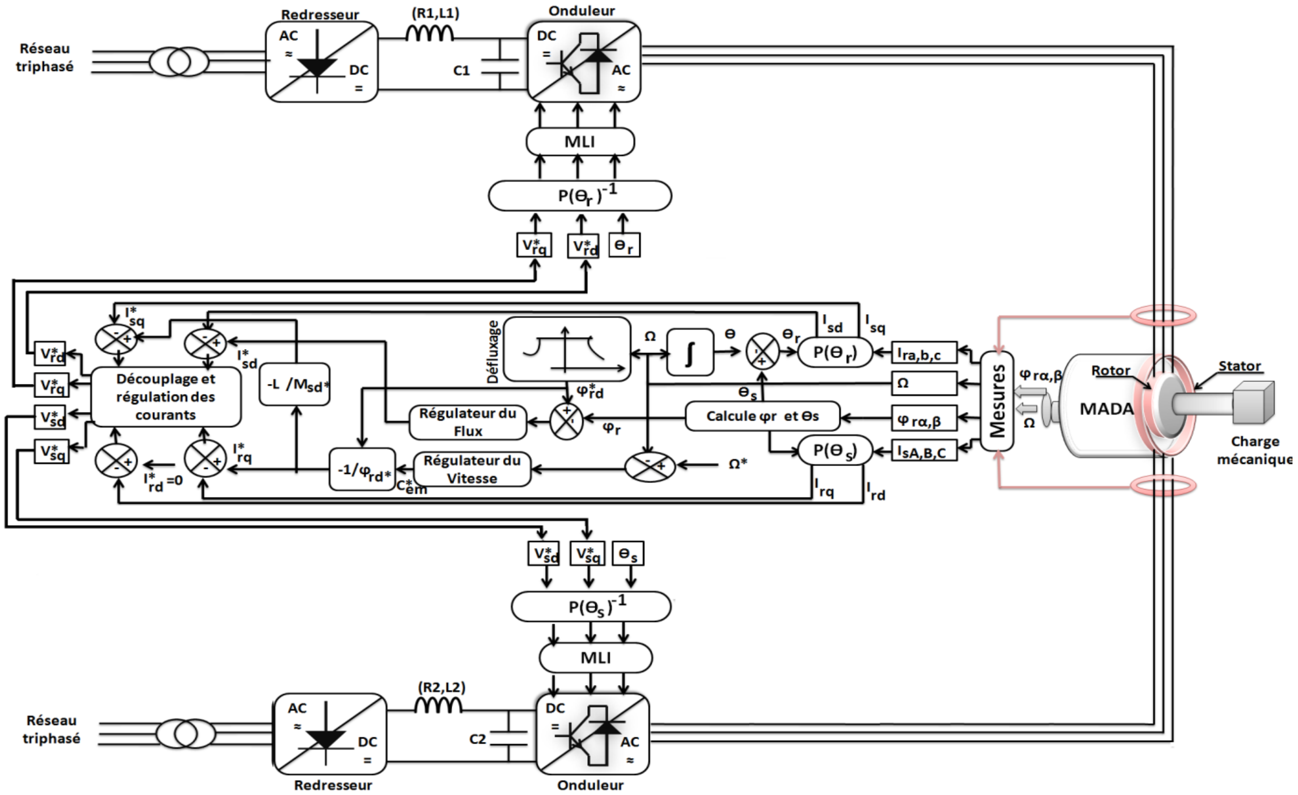
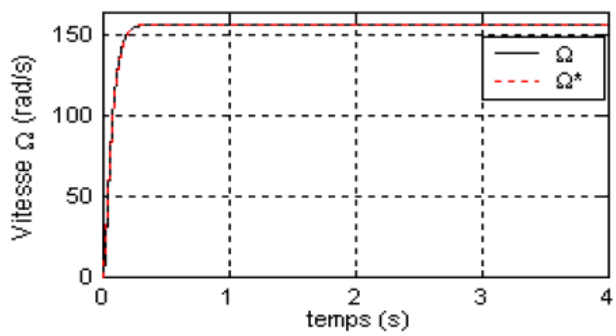


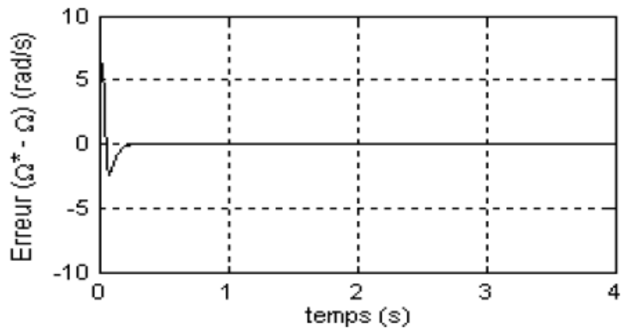
Fig.10: Block diagram of the direct vector control of DFIG.

5. Simulation result

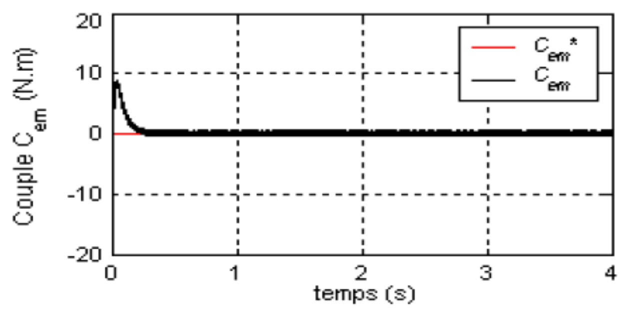
5.1. Step response velocity



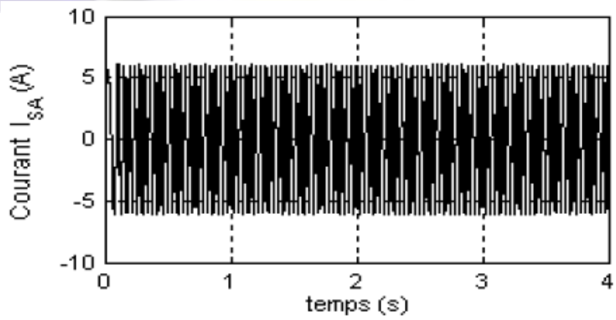
(a)



(b)



(c)



(d)

Fig.11: (a) (b) (c) (d) Setting the velocity Ω and the electromagnetic torque MADA classical PI controller by a speed step.

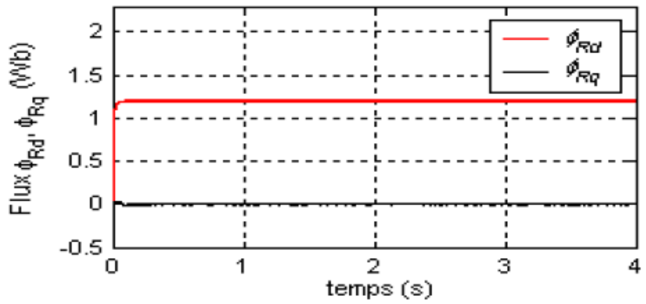


Fig.12: Response components rotorique flux.

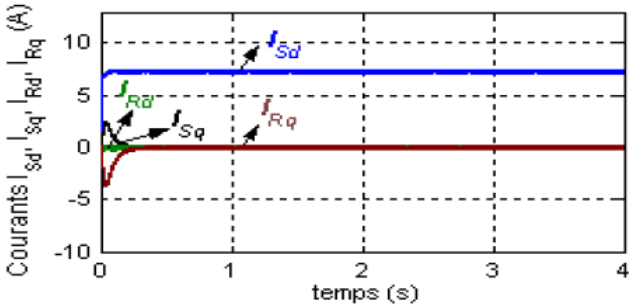
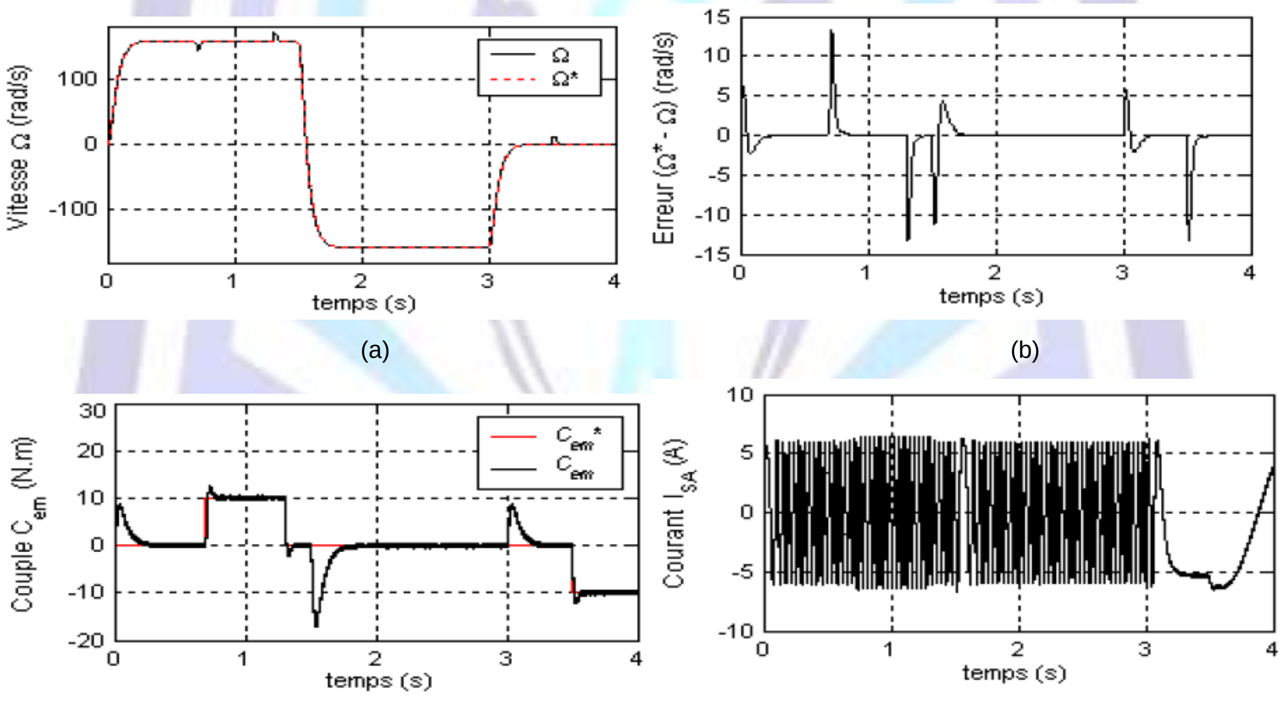


Fig.13: Isd and Isq response

5.2. Answer application of rated load and change speed and sense of rotation



(a) (b) (c) (d)

Fig.14: (a) (b) (c) (d) Adjusting the Ω speed and torque of DFIG by the classic PI controller when changing the direction of rotation with application of the load 10 N.m

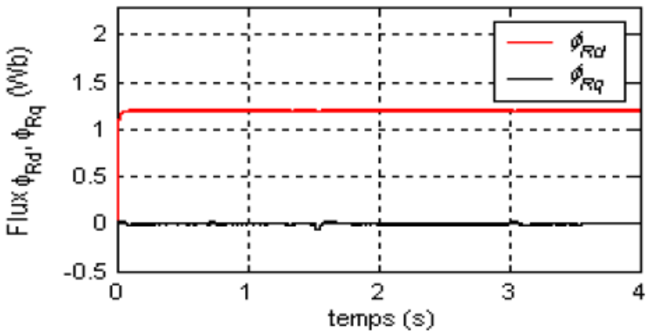


Fig.15: Response components rototique flux when changing the direction of rotation with application of the load 10 N.m

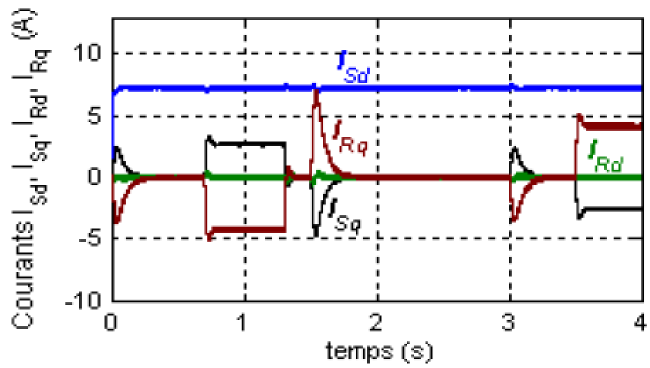


Fig.16: Response of components rototique current and stator current during a change of the direction of rotation with load application 10 N.m

5.3. Interpretations

In view of simulation results, we can observe the goods facts of the vector control endow the structure of speed regulation PI.

For different profiles, speed follows its benchmark relatively well with a low tracking error during the transient phase and cancels at permanent regime. Excellent orientation of the rotor flux on the direct axis is observed. Which affects the electromagnetic torque, which perfectly follows the reference torque, representing the control law generated by the controller Peak current and starting torque are well controlled and lower than they were for the single process.

During the evolution of instructions, especially when reversing rotation, changing the direction of the torque does not degrade the direction of flow. There is a good sensitivity to load disturbances, with a rejection time of relatively low. Also to the application or deleting of load torque controller reacts instantly to the electromagnetic torque reference to produce as appropriate acceleration or deceleration, and thus reach the desired speed.

6. Fuzzy speed control of the DFIG

This section is devoted to the application of fuzzy control the speed of the asynchronous machine double alimentation.il logic is to replace the PI speed control circuit diagram illustration of the double-fed asynchronous machine by a fuzzy PI controller. In order to operate some features of the system to define the control law this allows us to obtain a control system for high performance [7]. Systems Based on the fuzzy control are mainly used in the fields of decision-making, pattern recognition, modeling and process control, performing tasks usually handled by humans. Generally, the most standard type and most used in the control systems is the fuzzy controller MAMDANI type [8], it contains the input fuzzification which transformed the real variables into linguistic variables, and the output is the defuzzicateur operation the reverse. As shown in the following figure: consists of four main parts namely:

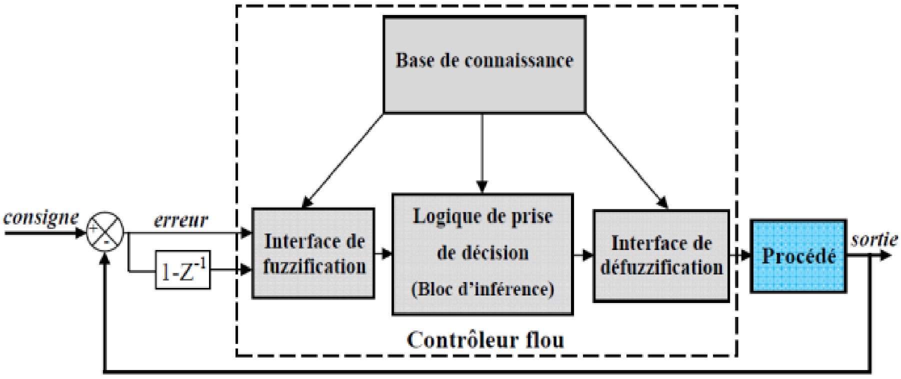


Fig.17: Basic architecture of a fuzzy control such MAMDANI

6.1. Operating Principle

The observation of the double-fed asynchronous machine in the speed control by vector control shows that the control variables are the speed error and the variation of the error, the reference speed may be controlled by an external operator.

For the fuzzy controller as shown in Figure is used:

A proportional-integral structure with as input error and speed variation Ω relative to its benchmark.

An output representative of the electromagnetic torque variation

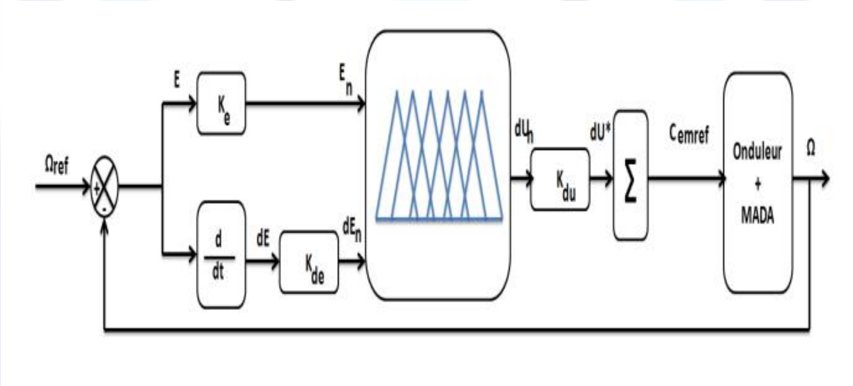


Fig.18: Block diagram of fuzzy PI-controller

Where the input-output variables can be normalized as follows:

$$E_n = \frac{E}{K_e} \qquad dE_n = \frac{dE}{K_e} \qquad dU_n = \frac{dU_n}{K_{dU_n}} \qquad (16)$$

E: the error rate, it is defined by: $E(k) = \Omega * (k) - \Omega(k)$

dE: the derivative of the error, it is approximated by:

$$dE(k) = E(k) - E(k-1)$$

$$U * (k) - U * (k-1) + dU * (k) = C*_{em}(k)$$

K_e, K_{de} and K_{du} are gains associated with standardization of e and, respectively, which can be constant or variable. The right choice of these ensures the stability and improves the dynamic and static performance of the target system to adjust. For membership functions were chosen for each variable triangular and trapezoidal shapes are used on a universe of discourse normalized in the interval [-1 1]. As shown in the following figure:

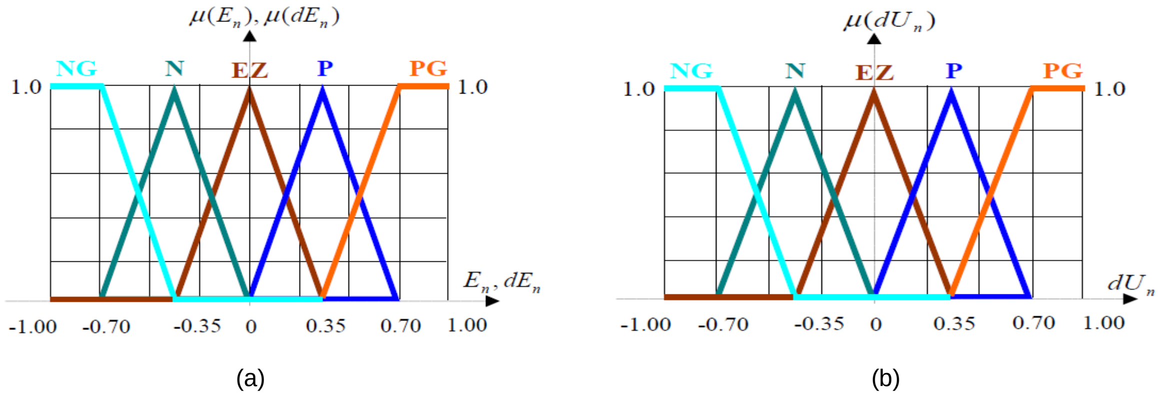


Fig.19: (a) Membership function of the output variable, (b) Membership functions of the standard inputs.

Subsets fuzzy membership was noted as follows:

NG: Negative-Grand; NP: Negative-Petit; PP: Positive-Small; PG: Positive Great. NM: Negative-Medium; EZ: Environ-Zero; PM: Positive Medium

As mentioned, each of the two linguistic inputs fuzzy controllers has five fuzzy sets, which gives a set of twenty-five rules for determining the variable controller output based on input variables are represented by matrix following inference:

dU_n / E_n \ dE_n	NG	NP	EZ	PP	PG
NG	NG	NG	NP	NP	EZ
NP	NG	NP	NP	EZ	PP
EZ	NP	NP	EZ	PP	PP
PP	NP	EZ	PP	PP	PG
PG	EZ	PP	PP	PG	PG

Si E_n est PG et dE_n est PG alors dU_n est PG

Fig.20: Matrix inference

The overall scheme of fuzzy speed control of DFIG with decoupling state feedback is detailed in the following figure:

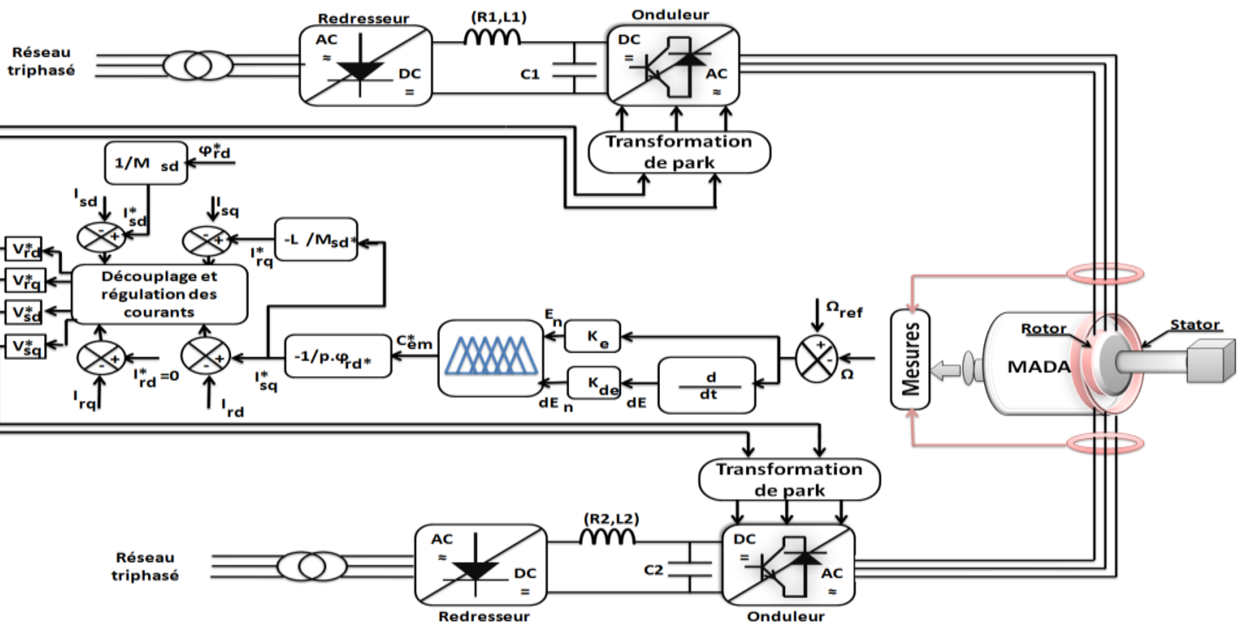


Fig.20: Block diagram of the fuzzy speed control of MADA.

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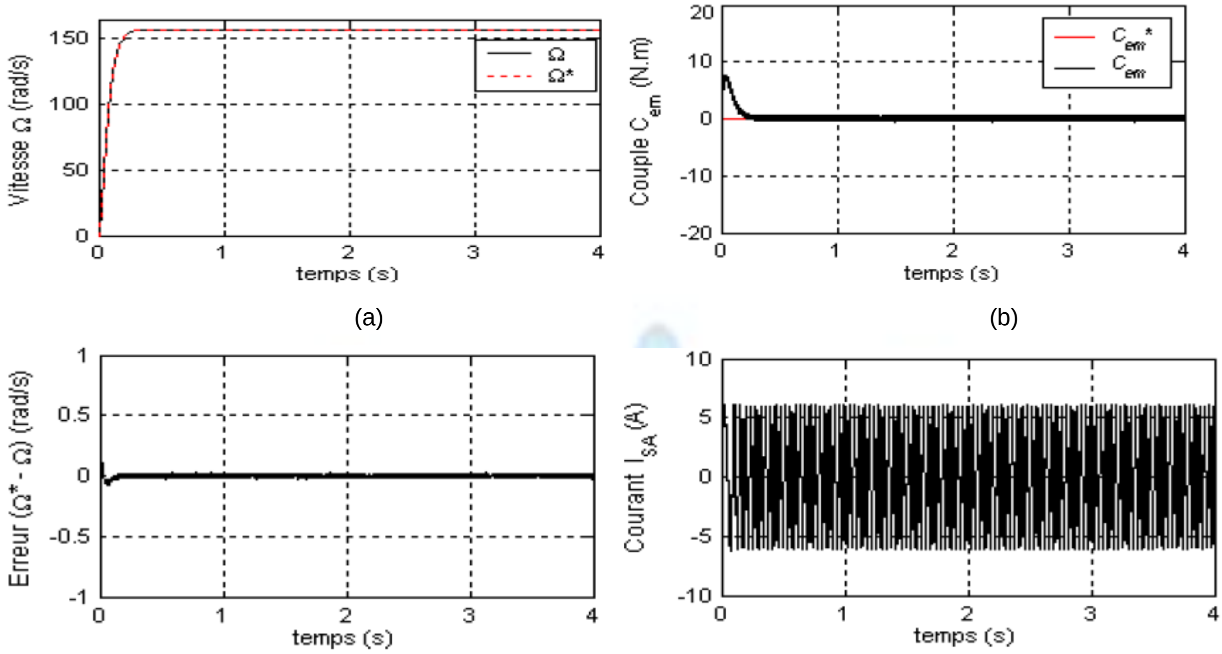
6.2. Simulation results

The values of the fuzzy controller gains are chosen after many tests adjustment (K_e =0.002 ; K_{de} =0.008 ; K_{du} = 145).

The results obtained for the various simulation tests, are exposed to the figures:

- **Step response speed**



(a) (b) (c) (d)

Fig.21: Speed control of MADA by fuzzy PI controller.

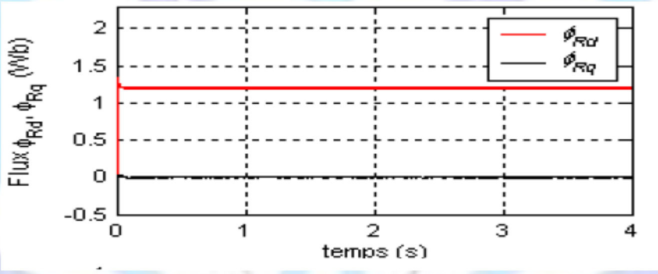


Fig.22: Response components rototique flux.

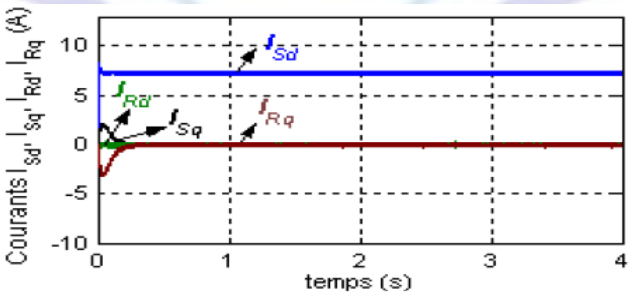


Fig.23: Response components rototique current and stator current.

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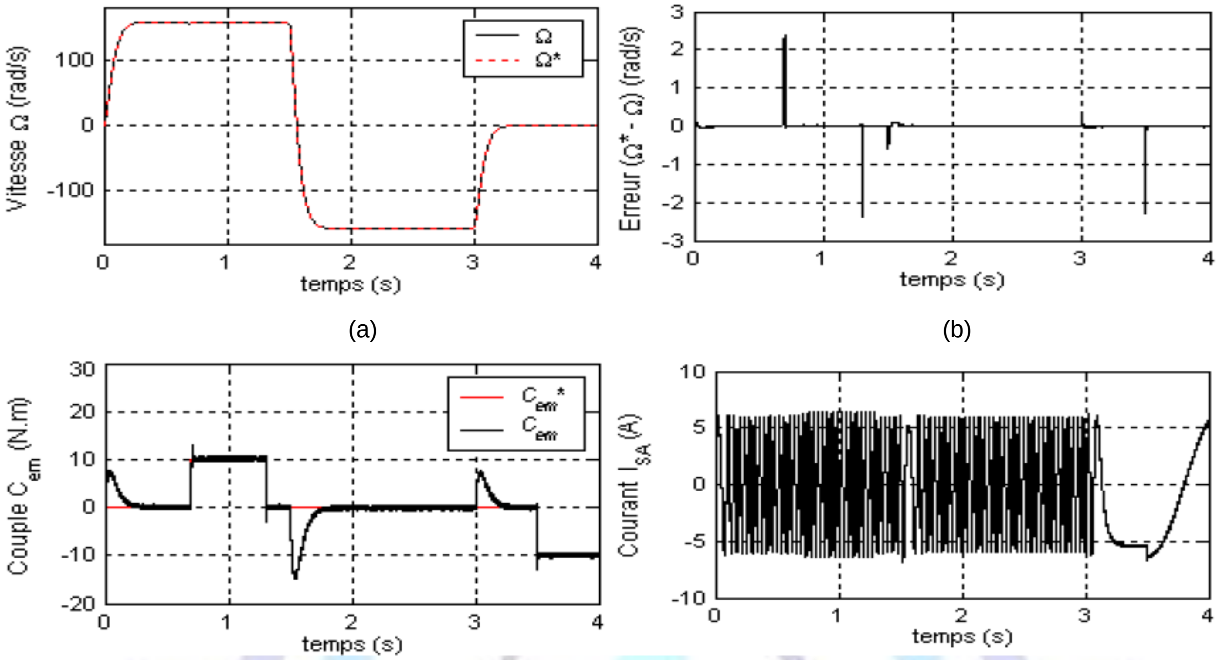
➢ **Answer application of rated load and change speed and direction of rotation**



(c) (d)

Fig.24: Adjusting the Ω speed and torque of DFIG by the of fuzzy PI-controller when changing the direction of rotation with application of the load 10 N.m

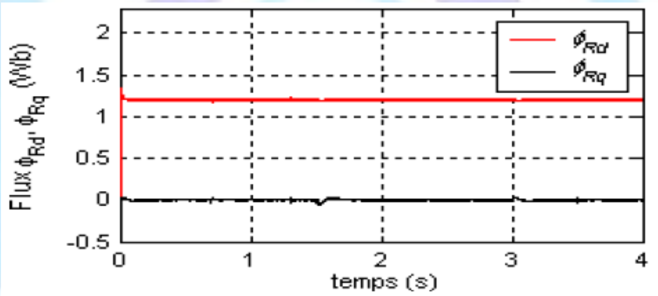


Fig.25: Response components rototique flux

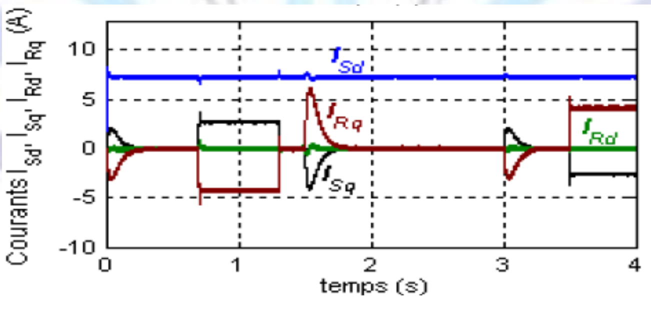


Fig.26: Response components rototique current and stator current.

6.3. Interpretations

The results show, for the fuzzy controller used excellent performance, not only pursuit but also regulating, with a very good speed tracking reference zero static error, and this in all cases studied profiles. These results in a tracking error much lower than that obtained using the conventional PI structure. We also note that the orientation of the rotor flux is perfectly realized, of over electromagnetic torque developed reproduced satisfactorily its reference C_{em}^*. This showing perfect adaptation of fuzzy control to vector control. We have noticed that despite the fact that the conventional PI controller to be recognized for their reaction rate with their proportional share fuzzy control comes with the settings used to overcome during transient phases. The low sensitivity and disturbance rejection are excellent; the fuzzy approach also gives the best performance in terms of speed deviation and time of release.

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7. Conclusion

The aim of this work was devoted to modeling , simulation and analysis of an asynchronous machine dual power, powered by a voltage inverter PWM , we present the principle of vector control of MADA . In the following, we highlighted the improvement in the PI fuzzy controller on the dynamic performance of MADA over conventional PI controller. The originality of our work was to combine the simulation experiments of different control algorithms , to define a control structure realizing the best value simplicity / performance.

ANNEXE

DFIG parameters used in simulation

Stator resistance	Rs=1.2 mΩ
Rotor resistance	Rr=1.8 mΩ
Stator inductance	Ls = 0.1554 mH
Rotor inductance	Lr = 0.1554 mH
Mutual inductance	M=0.15
Moment of inertia	0.07 Kg.m2
Coefficient of viscous friction	0.001
Number of pole pairs	2

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