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FUZZY SPEED CONTROLLER DESIGN OF MULTI-MACHINES SYSTEM

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Key words: Multimachines system (MSCS), Vector control, Hexa-phase inverter, Fuzzy logic control (FLC).

This work is devoted to a multimachine system using vector control and fuzzy logic regulator. A six-phase asynchronous machine is connected in series with a three-phase one fed by a single inverter and controlled independently is discussed in this paper. Thanks to the powerful digital signal processors, it is possible the control of such systems and this allows its integration in applications where the constraints of space and weight are of prime importance. In a real machine, the stator and rotor resistances are altered by temperature and the inductances are altered by the magnetizing current values and these changes if not incorporated in the control system block, the drive performance will degrade. This problem is solved by using fuzzy logic controller (FLC). Simulation results shows that FLC presents better performances and high robustness compared to the conventional proportional integral (PI) controller.

1. INTRODUCTION

Ac machines, induction in particular have dominated the field of electric machines. Recently, researchers are interested in machines with a number of phases greater than three. These machines are often called «multiphase machines».

This type of machine has large losses and to exploit this, it is possible to connect in series several machines supplied by a single static power converter with each machine in the group having an independent speed control. However, the use of multiphase converters associated with polyphase machines, generates additional degrees of freedom. Thanks to these, several polyphase machines can be connected in series in an appropriate transposition phases [1–4].

For some applications, series connection of multi-phases induction machines can be very interesting. The global system is defined as the domination of a series connected multi-machines one-converter system (MSCS). This system consists of several machines connected in series in an appropriate transposition of phases. The whole system is supplied by a single converter via the first machine. The control of each machine must be independent of others [5–7].

In [8], the author uses a classical PI controller to perform a speed control of series connected machines. However, PI controller parameters are highly affected by the system parameters, a temperature rise can cause a degradation of the control quality.

Seen from this major drawback, our contribution is to change conventional controllers PI with fuzzy logic controllers and test its robustness.

2. MODELING OF MULTI-MACHINE SYSTEM

The drive system is composed by two induction machines. The first one is a symmetrical six-phase induction motor IM(1) with its windings series connected with those of a second three-phase induction motor IM(2). The two motors are supplied by a single power converter which is a six-phase voltage source inverter (VSI).

Figure 1 presents the connecting and suppling schematic of the two motors and the converter [7–10]. The six-phase machine has the spacial displacement between any two consecutive stator phases equal to 60° (*i.e.* = 2 /6).

Only phases 1, 3 and 5 are used by the second machine IM(2), these phases are electrically displaced to each other by and angle of $2\pi/3$.

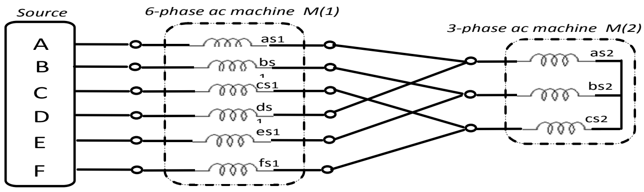

Fig. 1 – Connection diagram for series connection of a six-phase and a three-phase machine.

We note that a simple series connection of stator windings fails to ensure the desired performances. A solution is adopted to overcome this constraint, consisting of using an adequate stator windings transposition [11, 12]. This transposition resides of connecting in one point each two (electrically displaced to each other by π) of six-phase windings and connect them in series with the windings of the IM(1) [13–15].

In this way, currents pass through the six-phase windings going to neutralize at the connecting point. And in the same context, the current passing through one winding of IM(2) will be the half when passing through the windings of IM(1). This will generate in the air-gap of IM(1) two (equal in magnitude and opposed in phase) magneto-motive forces (MMF).

Therefore, a natural decoupling of the two motors will be possible by adopting the connection diagram shown in Fig. 1. According to Fig. 1, the stator and rotor voltages of the two machines can be written as follows [1–4]:

$$[v_s] = \begin{bmatrix} V_A \\ V_B \\ V_C \\ V_D \\ V_E \\ V_F \end{bmatrix} = \begin{bmatrix} v_{as1} + v_{as2} \\ v_{bs1} + v_{bs2} \\ v_{cs1} + v_{cs2} \\ v_{ds1} + v_{as2} \\ v_{es1} + v_{bs2} \\ v_{fs1} + v_{cs2} \end{bmatrix}. \quad (1)$$

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The relationship between the current source and the stator currents of each machine are given as follows:

$$[i_s]=[I_A \quad I_B \quad I_C \quad I_D \quad I_E \quad I_F] = [i_{as1} \quad i_{bs1} \quad i_{cs1} \quad i_{ds1} \quad i_{es1} \quad i_{fs1}] = [i_{s1}] \quad (2)$$

$$[i_{s2}]=\begin{bmatrix} i_{as2} \\ i_{bs2} \\ i_{cs2} \end{bmatrix}=\begin{bmatrix} I_A+I_D \\ I_B+I_E \\ I_C+I_F \end{bmatrix}. \quad (3)$$

The electrical equations:

$$\begin{cases} [V_{sk}]=[R_{sk}].[i_{sk}]+\dfrac{\mathrm{d}}{\mathrm{d}t}[\varphi_{sk}] \\ [0]=[R_{rk}].[i_{rk}]+\dfrac{\mathrm{d}}{\mathrm{d}t}[\varphi_{rk}] \end{cases}, \quad (4)$$

where

$$\begin{cases} [\mathrm{j}_{sk}]=[L_{ssk}].[i_{sk}]+[M_{srk}].[i_{rk}] \\ [\varphi_{rk}]=[L_{rrk}].[i_{rk}]+[M_{rrk}].[i_{sk}] \end{cases}. \quad (5)$$

Knowing that k = 1 for IM(1) and k = 2 for IM(2) with:

$$[R_{seq}]=[R_{s1}]+\begin{bmatrix} [R_{s2}] & [R_{s2}] \\ [R_{s2}] & [R_{s2}] \end{bmatrix};$$

$$[L_{seq}]=[L_{s1}]+\begin{bmatrix} [L_{s2}] & [L_{s2}] \\ [L_{s2}] & [L_{s2}] \end{bmatrix}.$$

3. MODELING OF MSCS INTO THREE SUBSPACES (α, β), (*X*, *Y*), (O+, O-)

The original six dimensional systems of the MSCS can be decomposed into three orthogonal subspaces, (α, β), (x, y) and (o^+, o^-) [1], using the following transformation:

$X_{\alpha\beta o}=[T_6(\theta)]^{-1}.X_{abc}$ and $X_{dqo}=[T_6(\theta)]^{-1}.X_{\alpha\beta o}$

where X represents stator currents, stator flux, stator voltages in MSCS. The matrix $[T_6(\theta)]$ is given by:

$$[T_6]=\frac{1}{\sqrt{3}}\begin{bmatrix} 1 & \cos(\alpha) & \cos(2\alpha) & \cos(3\alpha) & \cos(4\alpha) & \cos(5\alpha) \\ 0 & \sin(\alpha) & \sin(2\alpha) & \sin(3\alpha) & \sin(4\alpha) & \sin(5\alpha) \\ 1 & \cos(2\alpha) & \cos(4\alpha) & \cos(6\alpha) & \cos(8\alpha) & \cos(10\alpha) \\ 0 & \sin(2\alpha) & \sin(4\alpha) & \sin(6\alpha) & \sin(8\alpha) & \sin(10\alpha) \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1/\sqrt{2} & -1/\sqrt{2} & 1/\sqrt{2} & -1/\sqrt{2} & 1/\sqrt{2} & -1/\sqrt{2} \end{bmatrix} \quad (6)$$

$$[T_3]=\sqrt{\frac{2}{3}}\begin{bmatrix} 1 & \cos 2\alpha & \cos 4\alpha \\ 0 & \sin 2\alpha & \sin 4\alpha \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \quad (7)$$

$$[\rho(\theta)]=\begin{bmatrix} \begin{bmatrix} \cos(\theta i) & -\sin(\theta i) \\ -\sin(\theta i) & \cos(\theta i) \end{bmatrix} & [0]_{2\times 4} \\ [0]_{4\times 2} & [I]_{4\times 4} \end{bmatrix}. \quad (8)$$

By applying the transformation matrix (6), the real equation system will be decomposed into three decoupled subsystems: the (α, β), (x,y) and homopolar (o) systems. The subsystem (α, β) is exactly similar to that of a three-phase IM whose variables are responsible for the electromechanical conversion of the energy in the six-phase IM. On the other hand, the variables of the subsystem (x,y) do not participate in the electromechanical conversion of energy. However, these variables are used for decoupled control of S3MC. Finally, the homopolar subsystem (o) contains the classical homopolar components.

Application of the transformations matrix (6) and (7) in conjunction with the first row of (4) leads to the decoupled model of the six-phase two-motor drive system. Source voltage equations that include equations of the two stator windings connected in series can be given as:

$$\begin{cases} V_{s\alpha}=R_{s1}i_{s\alpha1}+L_{s1}\dfrac{\mathrm{d}i_{s\alpha1}}{\mathrm{d}t}+M_1\dfrac{\mathrm{d}i_{r\alpha1}}{\mathrm{d}t} \\ V_{s\beta}=R_{s1}i_{s\beta1}+L_{s1}\dfrac{\mathrm{d}i_{s\beta1}}{\mathrm{d}t}+M_1\dfrac{\mathrm{d}i_{r\beta1}}{\mathrm{d}t} \end{cases} \quad (9)$$

$$\begin{cases} V_{sx}=R_{eq}i_{sx1}+(l_{s1}+2L_{s2})\dfrac{\mathrm{d}i_{sx1}}{\mathrm{d}t}+\sqrt{2}M_2\dfrac{\mathrm{d}i_{r\alpha2}}{\mathrm{d}t} \\ V_{sy}=R_{eq}i_{sy1}+(l_{s1}+2L_{s2})\dfrac{\mathrm{d}i_{sy1}}{\mathrm{d}t}+\sqrt{2}M_2\dfrac{\mathrm{d}i_{r\beta2}}{\mathrm{d}t} \end{cases} \quad (10)$$

$$\begin{cases} V_{so+}=R_{eq}i_{so+1}+(l_{s1}+2L_{s2})\dfrac{\mathrm{d}i_{so+1}}{\mathrm{d}t} \\ V_{so-}=R_{eq}i_{so-1}+l_{s1}\dfrac{\mathrm{d}i_{so-1}}{\mathrm{d}t} \end{cases}. \quad (11)$$

Rotor voltage equations of six-phase machine and three-phase machine are:

$$\begin{cases} 0=R_{r1}.i_{r\alpha1}+L_{m1}\dfrac{\mathrm{d}i_{s\alpha1}}{\mathrm{d}t}+L_{r1}\dfrac{\mathrm{d}i_{r\alpha1}}{\mathrm{d}t}+\omega_{r1}\left(L_{m1}i_{s\beta1}+L_{r1}i_{r\beta1}\right) \\ 0=R_{r1}.i_{r\beta1}+L_{m1}\dfrac{\mathrm{d}i_{s\beta1}}{\mathrm{d}t}+L_{r1}\dfrac{\mathrm{d}i_{r\beta1}}{\mathrm{d}t}+\omega_{r1}\left(L_{m1}i_{s\beta1}+L_{r1}i_{r\alpha1}\right) \end{cases} \quad (12)$$

$$\begin{cases} 0=R_{r2}.i_{r\alpha2}+\sqrt{2}L_{m2}\dfrac{\mathrm{d}i_{sx1}}{\mathrm{d}t}+L_{r2}\dfrac{\mathrm{d}i_{r\alpha1}}{\mathrm{d}t}+\omega_{r2}\left(\sqrt{2}L_{m2}i_{sy1}+L_{r2}i_{r\beta2}\right) \\ 0=R_{r2}.i_{r\beta2}+\sqrt{2}L_{m2}\dfrac{\mathrm{d}i_{sy1}}{\mathrm{d}t}+L_{r2}\dfrac{\mathrm{d}i_{r\beta2}}{\mathrm{d}t}-\omega_{r2}\left(\sqrt{2}L_{m2}i_{sx1}+L_{r2}i_{r\alpha2}\right) \end{cases}, \quad (13)$$

with

$$\begin{cases} L_{s1}=l_{s1}+\dfrac{3}{2}L_{ms1} \\ M_1=\dfrac{3}{\sqrt{2}}L_{sr1} \\ L_{r1}=l_{r1}+\dfrac{3}{2}L_{mr1} \end{cases}; \quad \begin{cases} L_{s2}=l_{s2}+\dfrac{3}{2}L_{ms2} \\ M_2=\dfrac{3}{\sqrt{2}}M_{sr2} \\ L_{r2}=l_{r2}+\dfrac{3}{2}L_{mr2} \end{cases}. \quad (14)$$

Application of (6) in conjunction with (1) yields:

$$\begin{bmatrix} v_{s\alpha} \\ v_{s\beta} \\ v_{sx} \\ v_{sy} \\ v_{so+} \\ v_{so-} \end{bmatrix}=[T_6]\begin{bmatrix} v_{sa1}+v_{sa2} \\ v_{sb1}+v_{sb2} \\ v_{sc1}+v_{sc2} \\ v_{sd1}+v_{sa2} \\ v_{se1}+v_{sb2} \\ v_{sf1}+v_{sc2} \end{bmatrix}=\begin{bmatrix} v_{s\alpha} \\ v_{s\beta} \\ v_{sx1}+\sqrt{2}v_{s\alpha2} \\ v_{sy1}+\sqrt{2}v_{s\beta2} \\ v_{so+} \\ v_{so-} \end{bmatrix} \quad (15)$$

and

$$\begin{cases} i_{s\alpha}=i_{s\alpha1} \\ i_{s\beta}=i_{s\beta1} \end{cases}; \quad \begin{cases} i_x=i_{sx1}=\dfrac{i_{s\alpha2}}{\sqrt{2}} \\ i_y=i_{sy1}=\dfrac{i_{s\beta2}}{\sqrt{2}} \end{cases}; \begin{cases} i_{o+}=i_{so+1} \\ i_{o-}=i_{so-1} \end{cases}. \quad (16)$$

Torque equations of the two machines are:

$$\begin{cases} T_{em1} = P_1 M_1 (i_{rd} I_{isq1} - i_{sd} i_{rq1}) \\ T_{em2} = P_2 M_2 (i_{rd2} i_{sy1} - i_{sx} i_{rq2}) \end{cases}. \quad (17)$$

As can be seen to equations (9) to (13) and (17), that flux/torque producing stator currents of the six-phase machine are the source (α, β) current components, while the flux/torque producing stator currents of the three-phase machine are the source (x, y) current components. This indicates the possibility of independent vector control of two machines. It therefore follows that independent vector control of the two machines can be realized with a single six-phase inverter.

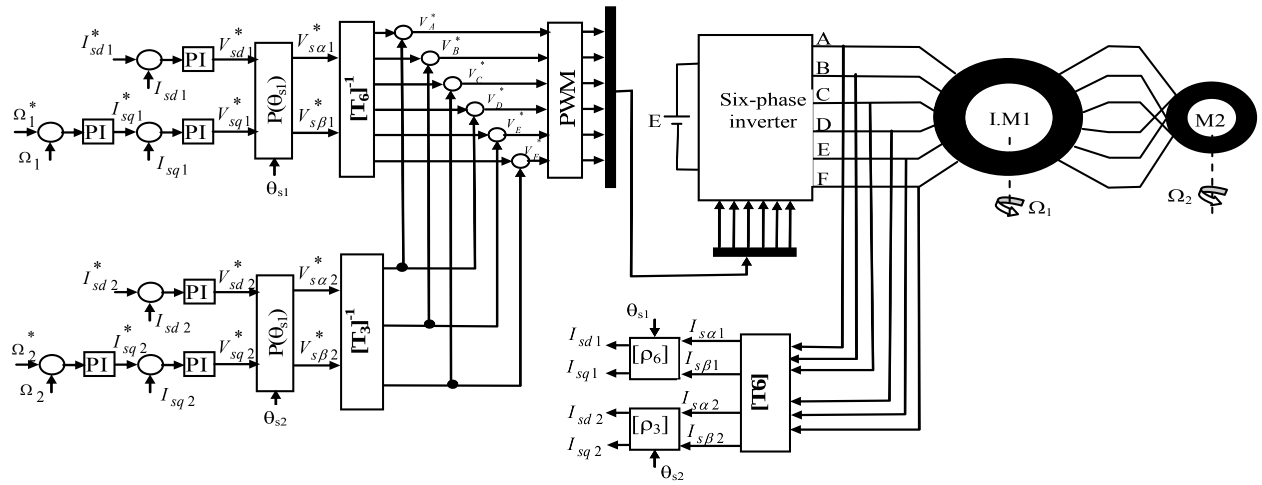

Fig. 2 – Indirect rotor flux oriented controller for the two-motor drive.

4. VECTOR CONTROL OF THE TWO-MOTOR DRIVE

With the transformation (8), the components of the plane (α, β) to equations (9) to (13) can be expressed in the (d, q) plane. The two series-connected machines can be controlled independently using rotor-flux oriented control principles (Fig. 2).

5. SIMPLIFIED MODEL OF SERIES-CONNECTED TWO-MOTOR DRIVE

If the plane (d, q) is perfectly directed, we suppose that the component $\varphi_{rq,k} = 0$. This simplifies the model of the MSCS as follows:

$$\begin{cases} \dfrac{d\varphi_{r\alpha1}}{dt} = \dfrac{M_1}{T_{r1}} i_{s\alpha1} - \dfrac{1}{T_r}\varphi_{r\alpha1} \\ \dfrac{d\varphi_{r\beta1}}{dt} = \dfrac{M_1}{T_{r1}} i_{s\beta1} - (\omega_{s1} - p_1\Omega_{m1})\varphi_{r\alpha1} \\ \dfrac{d\Omega_{m1}}{dt} = \dfrac{p_1 M_1}{J_1 L_{r1}}\varphi_{r\alpha1} i_{s\alpha1} - \dfrac{1}{J_1} C_{r1} \end{cases} \quad (18)$$

$$\begin{cases} \dfrac{d\varphi_{r\alpha2}}{dt} = \sqrt{2}\dfrac{M_2}{T_{r2}} i_{sx} - \dfrac{1}{T_{r2}}\varphi_{r\alpha2} \\ \dfrac{d\varphi_{r\beta2}}{dt} = \sqrt{2}\dfrac{M_2}{T_{r2}} i_{sy} - (\omega_{s2} - p_2\Omega_{m2})\varphi_{r\alpha2} \\ \dfrac{d\Omega_{m2}}{dt} = \sqrt{2}\dfrac{p_2 M_2}{J_2 L_{r2}}\varphi_{r\alpha2} i_{s\alpha2} - \dfrac{1}{J_2} C_{r2} \end{cases} \quad (19)$$

By introducing the angular speeds of sliding, the following equation is obtained:

$$\frac{d\theta_{sl}}{dt} = \omega_{sl,k} = (\omega_{s,k} - p_k\Omega_{m,k}) = \frac{M_k}{T_{r,k}} \cdot \frac{i^s}{\varphi_{rd,k}}, \quad (20)$$

where $i^s = \begin{cases} i_{s\beta} & \text{for } k = 1 \\ \sqrt{2}.i_{sy} & \text{for } k = 2 \end{cases}$.

With this condition, the fluxes and torques for MSCS are:

$$\begin{cases} \varphi_{r\alpha1} = \dfrac{M_1}{1 + T_{r1}p} i_{s\alpha1} \\ T_{em1} = \dfrac{p_1 M_1}{L_{r1}}\varphi_{r\alpha1} i_{s\beta1} \end{cases} \quad (21)$$

$$\begin{cases} \varphi_{r\alpha2} = \sqrt{2}\dfrac{M_2}{1 + T_{r2}p} i_{sx} \\ T_{em2} = \sqrt{2}\dfrac{p_2 M_2}{L_{r2}}\varphi_{r\alpha2} i_{sy} \end{cases}. \quad (22)$$

According to (21) and (22), six-phase machine's flux/torque are controllable by inverter (α, β) axis current components, while flux and torque of the three-phase machine can be controlled using inverter (x, y) current components.

6. FUZZY LOGIC CONTROLLER

Fuzzy logic controller (FLC) is usually used in induction machine drives. Due to its simplicity, (no mathematical model or speed closed-loop is required), the FLC method became very useful in induction machine drives used in speed control systems.

The membership function (MF) of the associated input and output variables is generally predefined on a common universe of discourse. For the successful design of FLC's, proper selection of input and output scaling factors (gains) or tuning of the other controller parameters are crucial jobs, which in many cases are done through trial and error to achieve the best possible control performance [16, 17].

The fuzzy logic control is based on these four elements: a bases rule, an inference mechanism, a fuzzification interface and a defuzzification interface. The interface used in this work is Mamdani's procedure based on max-min decision. For the defuzzification, the center of area (COA) method is employed.

The structure of FLC is shown in Fig. 3. For our study, the input of the fuzzy controller is the error of speed E, as well as its variation ΔE, the output of the regulator will be the torque's increment ΔT_{em}. It is enough to integrate this value in order to have the value of the electromagnetic torque T_{em}.

There will be forty-nine IF-THEN rules for fuzzy scalar control for speed control. Figure 4a shows membership functions of input variables E and ΔE respectively and output variable, which are of conventional triangular shapes. Each membership is divided into seven fuzzy. The membership is divided into seven fuzzy sets:

NH: Negative High, PS: Positive Small, ZE: Zero
NM: Negative Medium, PM: Positive Medium
NS: Negative Small, PH: Positive High

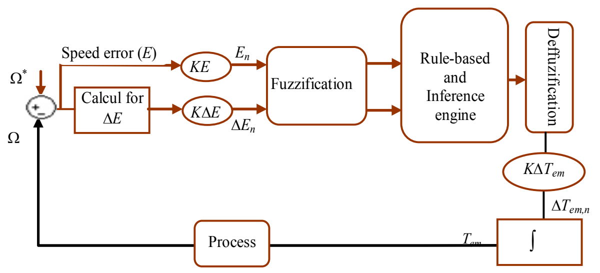

Fig. 3 – Block diagram of speed fuzzy controller.

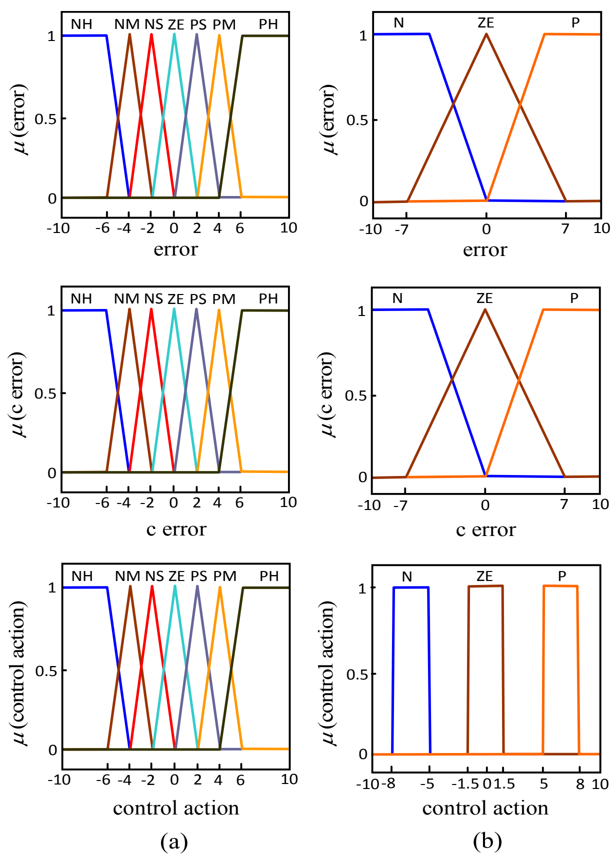

Fig. 4 – Membership functions of input/output variables: a) speed; b) current.

The rule-based table for output variable was shown in Table 1, it consisting of 49 linguistic rules and giving the change of the output of fuzzy logic controller in terms of two inputs E and ΔE.

In Table 1, some of the rules are interpreted: IF E is PM and ΔE is PM THEN ΔT_{em} is PH. Here, both the speed error and the change error are positive medium. Therefore, we need positive high ΔT_{em} to achieve a fast response.

The same steps used for the conception of the speed controller will be repeated for the currents controller, only we have:

- Input error E: instead of being equal to $E = \Omega^* - \Omega$, it will be equal with $E = i_{ds}^* - i_{ds}$ for the first fuzzy controller of current i_{ds} and $E = i_{qs}^* - i_{qs}$ for the second fuzzy controller of current i_{qs};
- The output of the fuzzy controller *is* V_{ds} for the i_{ds} current controller and V_{qs} for the i_{qs} current controller.

The internal loop is faster than the external one (condition of subjection). We represent the input/output variables by membership function, as shown if Fig. 4b, each one divided into 3 fuzzy sets. The rule-based table for output variable is presented in Table 2, it consists of 9 linguistic rules and gives the change of the output of fuzzy logic controller in terms of two inputs E and ΔE for each current's controller (i_{ds2} and i_{qs2}). Each membership function is also assigned with three fuzzy sets: P (positive), N (negative) and ZE (zero).

7. SIMULATION RESULTS

The simulation results of vector speed control of the two series connected machines in (MSCS) with the implementation of the fuzzy controller is developed in MATLAB. The decoupling and independent control of the two machines is demonstrated.

The first test consists in presentation of the global system simulation results: two series-connected machines with their drive: The three-phase induction machine is accelerating from standstill to reference speed N_2 = 100 rad/s, a load torque of 4 Nm is applied between time t = 1 s and t = 2.5 s, while the six-phase induction machine is started at t = 1.5 s, After the acceleration transient time expired and the speed settled at N_1 = 50 rad/s, a torque of 39 Nm is applied at the time t = 2 s.

Figure 5 shows the speeds, torques and stator currents. It is clear that the dynamic performances are good and we can notice that the IM(2)'s electromagnetic torque and speed are not affected by the starting operation of the IM(1).

In the Fig. 6: The six-phase induction machine turn at a constant speed equal to 50 rad/s, a load torque of 39 Nm is applied at t = 1 s while the three-phase motor is started at t = 1.5 s to settle at speed of 100 rad/s at the end of acceleration transient time. We notice that the speed and torque of the IM(1) are not affected by the acceleration period of the IM(2).

Figures 7 and 8 show the performances when the speed of I.M(1) is changed from + 50 rad/s to –50 rad/s at t = 1.5 s while the other IM(2) direction is kept unchanged and vice versa, the direction of the IM(2) is changed from +100 to –100 rad/s while that of IM(1) is kept unchanged. Simulation results show that the performances (the electro-mechanical quantities) of both machines are unaffected and decoupled control is preserved.

The second test consists of the robustness test of the system. An example of the robustness of the fuzzy controller compared with the conventional PI controllers. We change the motor parameters and without realizing any adjustment in the controllers the speed regulation is tested in a motor control. The new six-phase motor parameters are: R_r = 6 Ω, R_s = 4.6 Ω, L_m = 0.2 H, L_r = 0.12 H, L_s = 0.184 H, J = 0.12 kg m^2. Figure 9 shows the stator currant and speed of the six-phase machine controlled with PI and fuzzy logic controllers, a load torque of 39 Nm is applied at t = 1 s to the new machine, without readjusting the controllers. Figure 9a shows the response of the six-phase machine controlled with PI controllers. The performance of the system becomes wrong when the load changes at t = 1 s, the system becomes instable. But, with the fuzzy logic controllers the speed regulation is correct as shown in Fig. 9 b.

For the stator currant it is clear that the harmonics is also considerably low while using FLC (Fig. 9a) than PI (Fig. 9 b). This is an example of the robustness of the FLC controller compared with the conventional PI controllers.

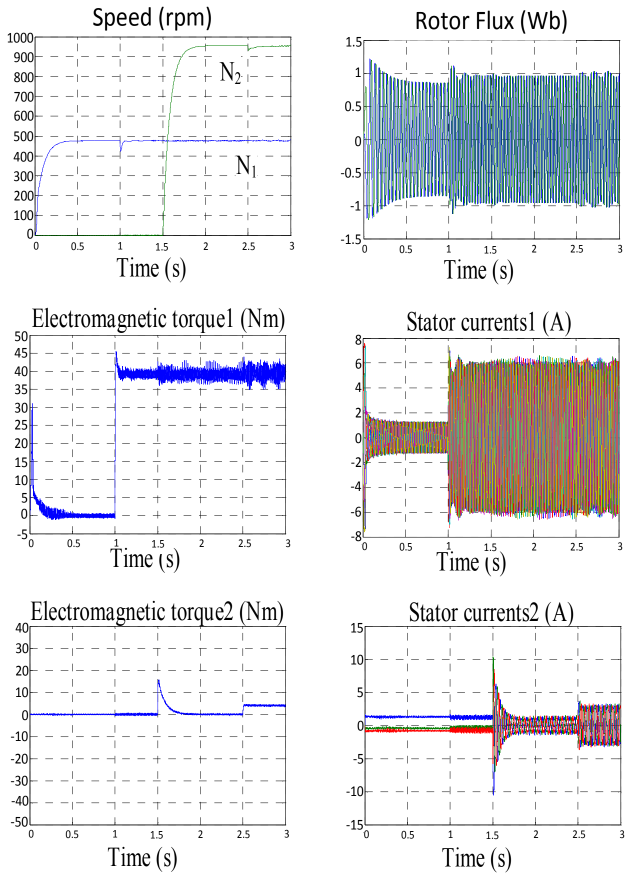

Fig. 6 – Performance of indirect vector controlled system: acceleration of IM(1) from 0 to 50 rad/s using fuzzy controller.

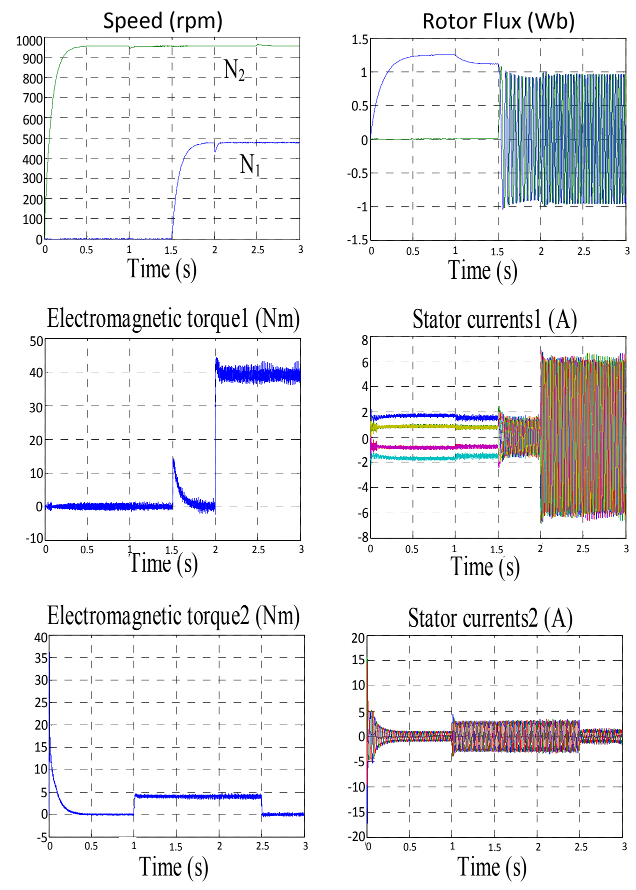

Fig. 5 – Performance of indirect vector controlled system: acceleration of IM(2) from 0 to 100 rad/s using fuzzy controller.

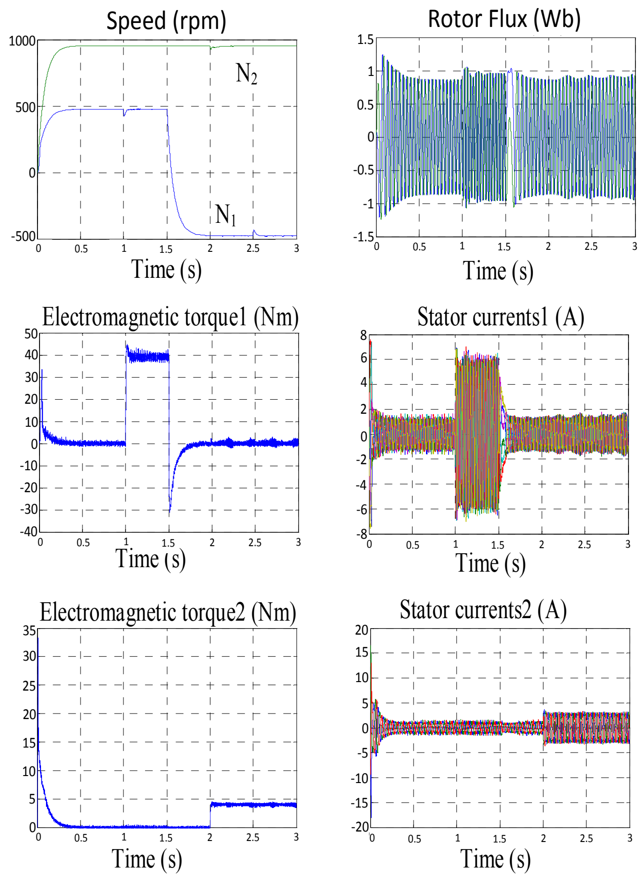

Fig. 7 – Performance of indirect vector controlled system: the IM(1) reverses from +50 to –50 rad/s using fuzzy controller.

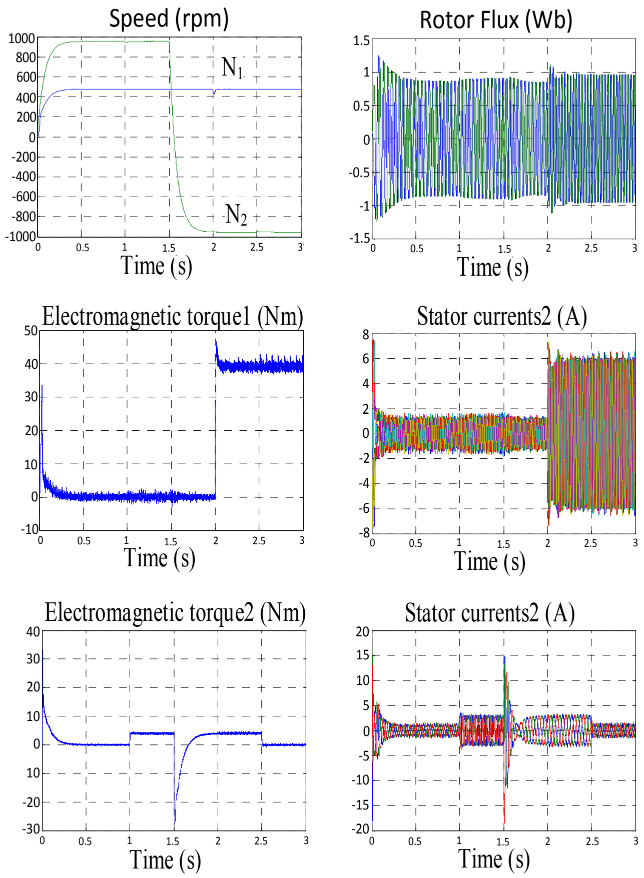

Fig. 8 – Performance of indirect vector controlled system: the IM(2) reverses from +100 to –100 rad/s using fuzzy controller.

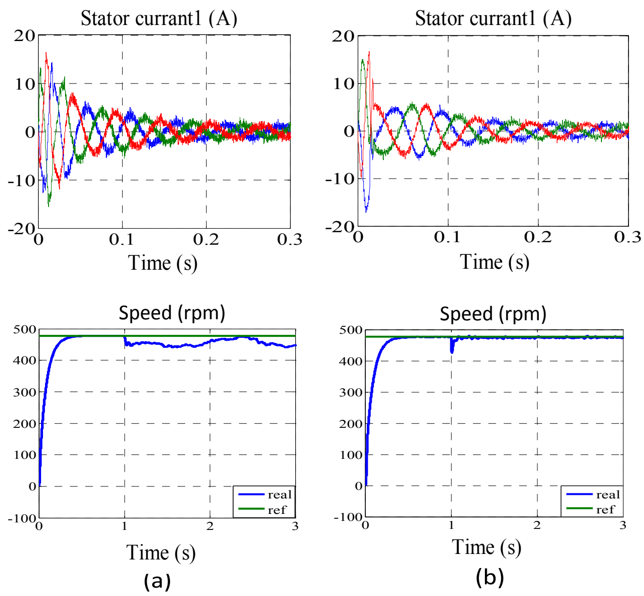

Fig. 9 – Test of robustness of the fuzzy controller and PI with applied load torque 39 Nm at $t = 1$ s: a) PI controllers; b) fuzzy controllers.

Table 1

The rule base for controlling the speed

ΔE_Ω \ E_Ω	NH	NM	NS	ZE	PS	PM	PH
NH	NH	NH	NH	NH	NM	NS	ZE
NM	NH	NH	NH	NM	NS	ZE	PS
NS	NH	NH	NM	NS	ZE	PS	PM
ZE	NH	NM	NS	ZE	PS	PM	PH
PS	NM	NS	ZE	PS	PM	PH	PH
PM	NS	ZE	PS	PM	PH	PH	PH
PH	ZE	PS	PM	PH	PH	PH	PH

Table 2

The rule base for controlling the currents

ΔE_i \ E_i	N	ZE	P
N	N	N	ZE
ZE	N	ZE	P
P	ZE	P	P

8. CONCLUSION

With the aim of improving the behavior of a MSCS the object of the study presented in this paper is the application of a fuzzy controller, with its main modules such as fuzzification, rules, inferences, and deffuzification. The robustness has been compared with classical PI and fuzzy controllers. Simulation results showed better performance of the proposed FLC of the two machines and a very high robustness over the conventional PI controller. For a further work in this subject, we propose: a fault diagnostic of the system.

9. APPENDIX

1. Six-phase IM data:
rated power P_n = 5.5 kW, nominal currant I_n = 6 A, stator resistance R_s = 2.3 Ω, rotor resistance R_r = 3 Ω, stator inductance L_s = 0.203 H, rotor inductance L_r = 0.203 H, mutual inductance L_m = 0.2 H, rated phase stator voltage V_n = 220 V, pole pair number p = 1, rotor speed N = 1000 rpm, viscous friction coefficient K_f = 0.006 Nms/rad, moment of inertia J = 0.06 kgm^2.

2. Three-phase IM data:
rated power P_n = 1 kW, stator resistance R_s = 4.67 Ω, rotor resistance R_r = 8 Ω, stator inductance L_s = 0.374 H, rotor inductance L_r = 0.374 H, mutual inductance L_m = 0.243 H, rated phase stator voltage V_n = 220 V, pole pair number p = 3, rotor speed N = 2830 rpm, viscous friction coefficient K_f = 0.001 Nms/rad, moment of inertia J = 0.023 kgm^2.

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