Indirect Rotor Field-oriented Control (IRFOC) of a Dual Star Induction Machine (DSIM) Using a Fuzzy Controller

Radhwane Sadouni, Abdelkader Meroufel

Intelligent Control and Electrical Power Systems Laboratory (ICEPS)
Djillali Liabes University, BP 89 Sidi Bel-Abbes, Algeria
redouanesadouni@gmail.com; ameroufel@yahoo.fr

Abstract: We present in this paper, a comparative study between a PI regulator and fuzzy regulator for a control speed of a Dual Star Induction Machine (DSIM) supplied with a two PWM voltage source inverter (VSI) and decoupled by field-oriented control (FOC).The simulation results illustrate the robustness and efficiency of the fuzzy regulator to the parametric variations.

Keywords: dual star induction machine (DSIM); field-oriented control (FOC); fuzzy logic

1 Introduction

In industrial applications in which high reliability is demanded, a multi-phase induction machine instead of traditional three-phase induction machine is used. The advantages of multi-phase drive systems over conventional three-phase drives are: the total rating of system is multiplied, the torque pulsations will be smoothed, the rotor harmonic losses as well as the harmonics content of the DC link current will be reduced. And the loss of one machine phase does not prevent the machine working, thus improving the system reliability [1].

A common type of multiphase machine is the dual star induction machine (DSIM), also known as the six phase induction machine. These machines have been used in many applications (pumps, fans, compressors, rolling mills, cement mills, mine hoists …[2]) due to their advantages in power segmentation, reliability, and minimized torque pulsations. Such segmented structures are very attractive for high-power applications since they allow the use of lower rating power electronic devices at a switching frequency higher than the one usually used in three-phase AC machine drives [3].

The main difficulty in the asynchronous machine control resides in the fact that complex coupling exists between the field and the torque. The space vector control assures decoupling between these variables, and the torque is made similar to that of a DC machine [4].

In Field-oriented Control (FOC), three types of orientation exist: rotor field orientation, stator field orientation and rotating field orientation. In this paper, the rotor field-oriented control is applied to the DSIM using PI and fuzzy regulators.

2 Machine Model

A schematic of the stator and rotor windings for a machine dual three phase is given in Fig. 1. The six stator phases are divided into two wyes-connected three-phase sets labeled A_{s1}, B_{s1}, C_{s1} and A_{s2}, B_{s2}, C_{s2} whose magnetic axes are displaced by an angle $\alpha=30°$. The windings of each three-phase set are uniformly distributed and have axes that are displaced $120°$ apart. The three-phase rotor windings A_r, B_r, C_r are also sinusoidally distributed and have axes that are displaced apart by $120°$ [5].

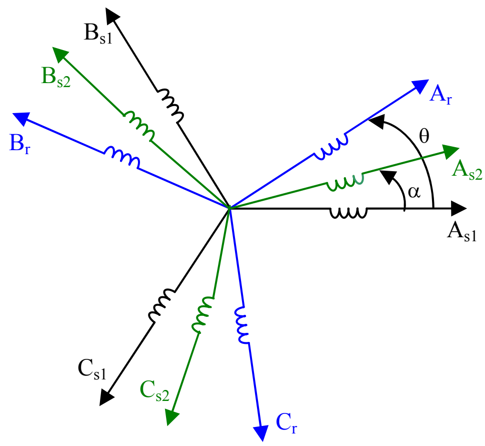

Figure 1
Windings of the dual star induction machine

The following assumptions are made: [4], [6]:

- Motor windings are sinusoidally distributed;
- The two stars have the same parameters;
- The magnetic saturation, the mutual leakage inductances and the core losses are negligible;
- Flux path is linear.

The voltage equations of the dual star induction machine are as follow [7] [8]:

$$
\begin{aligned}
[V_{s1}] &= \begin{bmatrix} V_{sa1} \\ V_{sb1} \\ V_{sc1} \end{bmatrix} = [R_{s1}][I_{s1}] + \frac{d}{dt}[\Phi_{s1}] \\
[V_{s2}] &= \begin{bmatrix} V_{sa2} \\ V_{sb2} \\ V_{sc2} \end{bmatrix} = [R_{s2}][I_{s2}] + \frac{d}{dt}\left[\Phi_{s2}\right] \\
[0] &= \begin{bmatrix} V_{ra} \\ V_{rb} \\ V_{rc} \end{bmatrix} = [R_{r}][I_{r}] + \frac{d}{dt}[\Phi_{r}]
\end{aligned}
\quad (1)
$$

Where:

$R_{sa1} = R_{sb1} = R_{sc1} = R_{s1}$: Stator resistance 1.

$R_{sa2} = R_{sb2} = R_{sc2} = R_{s2}$: Stator resistance 2.

$R_{ra} = R_{rb} = R_{rc} = R_{r}$: Rotor resistance.

$$
[R_{s1}] = \begin{bmatrix} R_{s1} & 0 & 0 \\ 0 & R_{s1} & 0 \\ 0 & 0 & R_{s1} \end{bmatrix} ; \ [R_{s2}] = \begin{bmatrix} R_{s2} & 0 & 0 \\ 0 & R_{s2} & 0 \\ 0 & 0 & R_{s2} \end{bmatrix} ; \ [R_{r}] = \begin{bmatrix} R_{r} & 0 & 0 \\ 0 & R_{r} & 0 \\ 0 & 0 & R_{r} \end{bmatrix} \quad (2)
$$

$$
[I_{s1}] = \begin{bmatrix} I_{sa1} \\ I_{sb1} \\ I_{sc1} \end{bmatrix} ; \ [I_{s2}] = \begin{bmatrix} I_{sa2} \\ I_{sb2} \\ I_{sc2} \end{bmatrix} ; [I_{r}] = \begin{bmatrix} I_{ra} \\ I_{rb} \\ I_{rc} \end{bmatrix} \quad (3)
$$

$$
[\Phi_{s1}] = \begin{bmatrix} \Phi_{sa1} \\ \Phi_{sb1} \\ \Phi_{sc1} \end{bmatrix} ; [\Phi_{s2}] = \begin{bmatrix} \Phi_{sa2} \\ \Phi_{sb2} \\ \Phi_{sc2} \end{bmatrix} ; [\Phi_{r}] = \begin{bmatrix} \Phi_{ra} \\ \Phi_{rb} \\ \Phi_{rc} \end{bmatrix} \quad (4)
$$

The expressions for stator and rotor flux are [7]:

$$
\begin{bmatrix} [\Phi_{s1}] \\ [\Phi_{s2}] \\ [\Phi_{r}] \end{bmatrix} = \begin{bmatrix} [L_{s1s1}] & [L_{s1s2}] & [L_{s1r}] \\ [L_{s2s1}] & [L_{s2s2}] & [L_{s2r}] \\ [L_{rs1}] & [L_{rs2}] & [L_{rr}] \end{bmatrix} . \begin{bmatrix} [I_{s1}] \\ [I_{s2}] \\ [I_{r}] \end{bmatrix} \quad (5)
$$

Where:

$[L_{s1s1}]$: Inductance matrix of the star 1.

$[L_{s2s2}]$: Inductance matrix of the star 2.

$[L_{rr}]$: Inductance matrix of the rotor.

$[L_{s1s2}]$: Mutual inductance matrix between star 1 and star 2.

$[L_{s2s1}]$: Mutual inductance matrix between star 2 and star 1.

$[L_{s1r}]$: Mutual inductance matrix between star 1 and rotor.

$[L_{s2r}]$: Mutual inductance matrix between star 2 and rotor.

$[L_{rs1}]$: Mutual inductance matrix between rotor and star 1.

$[L_{rs2}]$: Mutual inductance matrix between rotor and star 2.

The expression of the electromagnetic torque is then as follows [7] [9] [10]:

$$T_{em} = \left(\frac{p}{2}\right)\cdot\left([I_{s1}]\frac{d}{d\theta}[L_{s1r}][I_r] + [I_{s2}]\frac{d}{d\theta}[L_{s2r}][I_r]\right) \quad (6)$$

The Park model of the dual star induction machine in the references frame at the rotating field (*d, q*) is defined by the following equations system (7) [11].

Figure 2 represents the model of the DSIM in the Park frame.

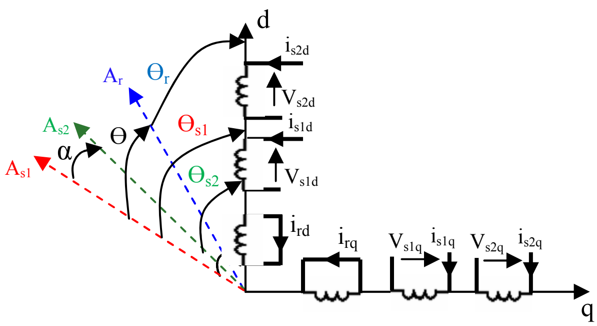

Figure 2
Representation of DSIM in the Park frame

$$\begin{cases} V_{s1d} = R_{s1} I_{s1d} + \frac{d}{dt}\Phi_{s1d} - \omega_s \Phi_{s1q} \\ V_{s1q} = R_{s1} I_{s1q} + \frac{d}{dt}\Phi_{s1q} + \omega_s \Phi_{s1d} \\ V_{s2d} = R_{s2} I_{s2d} + \frac{d}{dt}\Phi_{s2d} - \omega_s \Phi_{s2q} \\ V_{s2q} = R_{s2} I_{s2q} + \frac{d}{dt}\Phi_{s2q} + \omega_s \Phi_{s2d} \\ 0 = R_r I_{rd} + \frac{d\Phi_{rd}}{dt} - \omega_{sr} \Phi_{rq} \\ 0 = R_r I_{rq} + \frac{d\Phi_{rq}}{dt} + \omega_{sr} \Phi_{rd} \end{cases} \quad (7)$$

Where:

$$\Phi_{s1d} = L_{s1} I_{s1d} + L_m (I_{s1d} + I_{s2d} + I_{rd})$$

$$\Phi_{s1q} = L_{s1} I_{s1q} + L_m (I_{s1q} + I_{s2q} + I_{rq})$$

$$\Phi_{s2d} = L_{s2} I_{s2d} + L_m (I_{s1d} + I_{s2d} + I_{rd}) \quad (8)$$

$$\Phi_{s2q} = L_{s2} I_{s2q} + L_m (I_{s1q} + I_{s2q} + I_{rq})$$

$$\Phi_{rd} = L_r I_{rd} + L_m (I_{s1d} + I_{s2d} + I_{rd})$$

$$\Phi_{rq} = L_r I_{rq} + L_m (I_{s1q} + I_{s2q} + I_{rq})$$

L_m: Cyclic mutual inductance between stator 1, stator 2 and rotor.

The mechanical equation is given by [8]:

$$J \frac{d\Omega}{dt} = T_{em} - T_r - F_r \Omega \quad (9)$$

With :

$$T_{em} = p \frac{L_m}{L_r + L_m} \left[\Phi_{rd}(I_{s1q} + I_{s2q}) - \Phi_{rq}(I_{s1d} + I_{s2d}) \right] \quad (10)$$

3 Voltage Source Inverter Modelling

The voltage source inverter (VSI) is a static converter constituted by switching cells generally with transistors or thyristors GTO for high powers (Figure 3). The operating principle can be expressed by imposing on the machine the voltages with variable amplitude and frequency starting from a standard network 220/380 V – 50 Hz [12].Voltages at load neutral point can be given by the following expression [13]:

$$\begin{bmatrix} V_{an} \\ V_{an} \\ V_{an} \end{bmatrix} = \frac{E}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} K_{11} \\ K_{12} \\ K_{13} \end{bmatrix} \quad (11)$$

This modelling for the two converters that feed the DSIM.

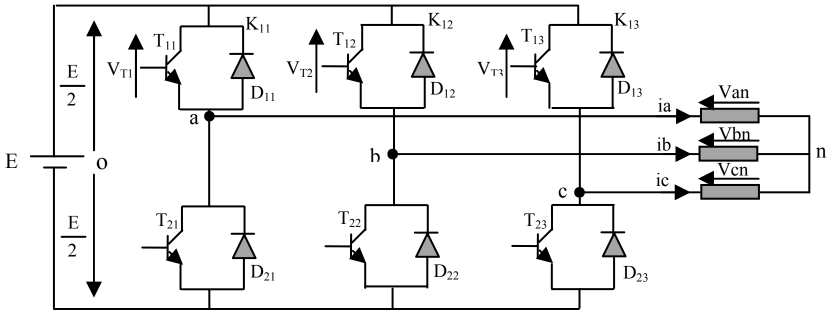

Figure 3
Voltage Source Inverter scheme

4 Field-oriented Control

The objective of space vector control is to assimilate the operating mode of the asynchronous machine at the one of a DC machine with separated excitation, by decoupling the torque and the flux control. The IRFOC consists in making $\Phi_{qr}=0$ while the rotor direct flux Φ_{dr} converges to the reference Φ_r^* [4] [14].

By applying this principle ($\Phi_{qr}=0$ and $\Phi_{dr}=\Phi_r^*$) to equations (7) (8) and (10), the finals expressions of the electromagnetic torque and slip speed are:

$$T_{em} = p\frac{L_m}{L_m + L_r}\Phi_r^*(I_{s1q}^* + I_{s2q}^*) \qquad (12)$$

$$w_{sr}^* = \frac{R_r L_m}{(L_m + L_r)\Phi_r^*}(I_{s1q}^* + I_{s2q}^*) \qquad (13)$$

The stators voltage equations are:

$$\begin{aligned}
V_{s1d}^* &= R_{s1}I_{s1d} + L_{s1}\frac{d}{dt}I_{s1d} - \omega_s^*(L_{s1}I_{s1q} + T_r\Phi_r^* w_{sr}^*)\\
V_{s1q}^* &= R_{s1}I_{s1q} + L_{s1}\frac{d}{dt}I_{s1q} + \omega_s^*(L_{s1}I_{s1d} + \Phi_r^*)\\
V_{s2d}^* &= R_{s2}I_{s2d} + L_{s2}\frac{d}{dt}I_{s2d} - \omega_s^*(L_{s2}I_{s2q} + T_r\Phi_r^* w_{sr}^*)\\
V_{s2q}^* &= R_{s2}I_{s2q} + L_{s2}\frac{d}{dt}I_{s2q} + \omega_s^*(L_{s2}I_{s2d} + \Phi_r^*)
\end{aligned} \qquad (14)$$

The torque expression shows that the reference fluxes and stator currents in quadrate are not perfectly independent. Thus, it is necessary to decouple the torque and flux control of this machine by introducing new variables:

$$
\begin{aligned}
V_{s1d} &= R_{s1} I_{s1d} + L_{s1} \frac{d}{dt} I_{s1d} \\
V_{s1q} &= R_{s1} I_{s1q} + L_{s1} \frac{d}{dt} I_{s1q} \\
V_{s2d} &= R_{s2} I_{s2d} + L_{s2} \frac{d}{dt} I_{s2d} \\
V_{s2q} &= R_{s2} I_{s2q} + L_{s2} \frac{d}{dt} I_{s2q}
\end{aligned}
\tag{15}
$$

The equation system (15) shows that the stator voltages *(V_{s1d}, V_{s1q}, V_{s2d}, V_{s2q})* are directly related to the stator currents (I_{s1d}, I_{s1q}, I_{s2d}, I_{s2q}). To compensate the error introduced at decoupling time, the voltage references (V_{s1d}^*, V_{s2d}^*, V_{s1q}^*, V_{s2q}^*) at constant flux are given by:

$$
\begin{aligned}
V_{s1d}^* &= V_{s1d} - V_{s1dc} \\
V_{s1q}^* &= V_{s1q} + V_{s1qc} \\
V_{s2d}^* &= V_{s2d} - V_{s2dc} \\
V_{s2q}^* &= V_{s2q} + V_{s2qc}
\end{aligned}
\tag{16}
$$

With:

$$
\begin{aligned}
V_{s1dc} &= \omega_s^* (L_{s1} I_{s1q} + T_r \Phi_r^* w_{sr}^*) \\
V_{s1qc} &= \omega_s^* (L_{s1} I_{s1d} + \Phi_r^*) \\
V_{s2dc} &= \omega_s^* (L_{s2} I_{s2q} + T_r \Phi_r^* w_{sr}^*) \\
V_{s2qc} &= \omega_s^* (L_{s2} I_{s2d} + \Phi r^*)
\end{aligned}
\tag{17}
$$

For a perfect decoupling, we add stator current regulation loops (I_{s1d}, I_{s1q}, I_{s2d}, I_{s2q}) and we obtain at their output stator voltages (V_{s1d}, V_{s1q}, V_{s2d}, V_{s2q}).The decoupling bloc scheme in voltage (Field-oriented control FOC) is given in Figure 4.

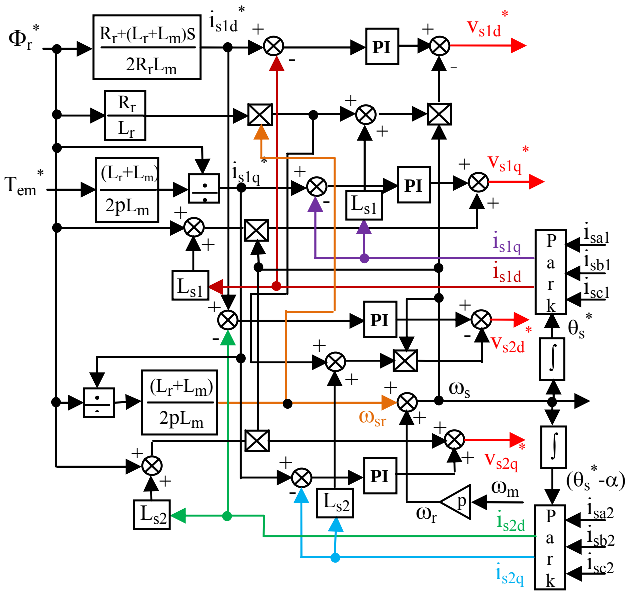

Figure 4
Decoupling bloc in voltage

5 Indirect Method Speed Regulation

The principle of this method consists in not using rotor flux magnitude but simply its position calculated with reference sizes. This method eliminates the need to use a field sensor, but only the one of the rotor speed [15].

The speed regulation scheme by IFOC of the DSIM is given in Figure 5.

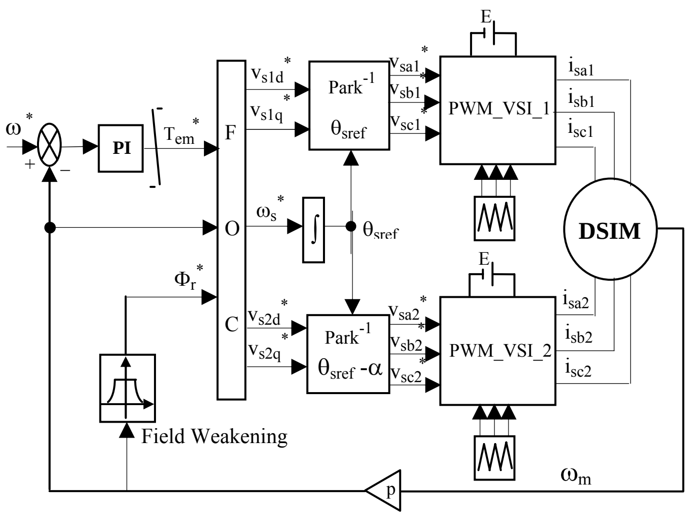

Figure 5
Indirect method speed regulation

5.1 Robustness Tests

The robustness of the indirect method speed regulation of the DSIM is visualized for two tests: the first is the varying of rotor resistance R_r ($R_r = 2R_{rn}$ at $t = 1$ s); the second increasing of inertia J ($J = 2J_n$ at $t = 1$ s).

5.2 Results and Discussion

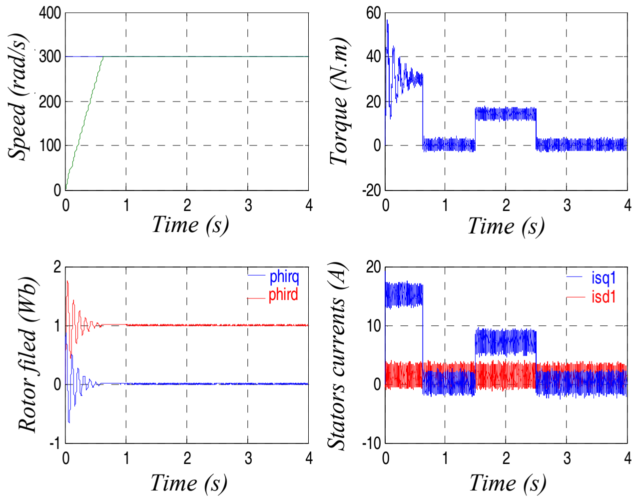

Figure 6
Indirect method speed regulation with load torque $T_r = 14$ N.m between [1.5 2.5] s

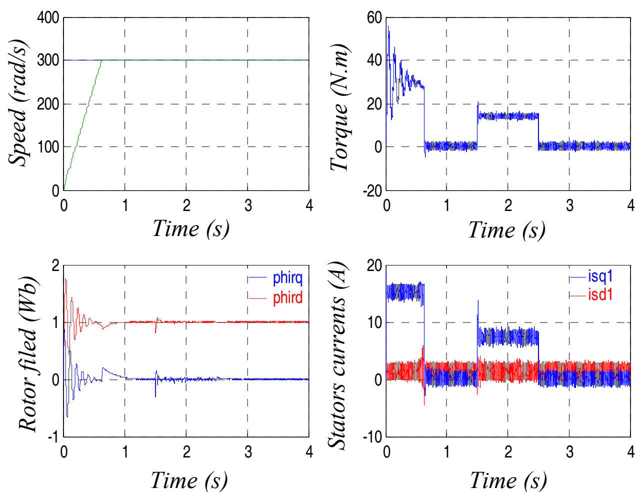

Figure 7
DSIM Comportment with rotor resistance variation ($R = 2R_n$ at $t = 1$ s)

The speed reaches its reference value (*300 rad/s*) after (*0.78 s*) with an overtaking of (*0.32%)* of the reference speed (Figure 6). The perturbation reject is achieved at *(0.1 s)*. The electromagnetic torque compensates the load torque and reaches at starting *(60 N.m)*.

Simulation results show the regulation sensibility with PI for rotor resistance variation. We note that the decoupling is affected. The inertia variation increases the inversion time of rotating direction (Figures 7 and 8).

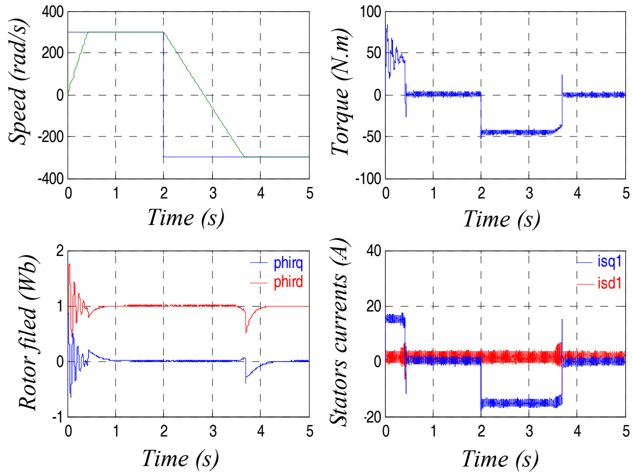

Figure 8
DSIM Comportment with inertia variation ($J=2J_n$ at t=1 s)

6 Fuzzy Logic Principle

The fuzzy logic control (FLC) has been an active research topic in automation and control theory since Mamdani proposed in 1974 based on the fuzzy sets theory of Zadeh (1965) to deal with the system control problems that are not to model [16].

The structure of a complete fuzzy control system is composed of the following blocs: Fuzzification, Knowledge base, Inference engine, Defuzzification. Figure 9 shows the structure of a fuzzy controller [16].

The Fuzzification module converts the crisp values of the control inputs into fuzzy values. A fuzzy variable has values which are defined by linguistic variables (fuzzy sets or subsets) such as: low, medium, high, big, slow . . . where each is defined by a gradually varying membership function. In fuzzy set terminology, all the possible values that a variable can assume are named the universe of discourse, and the fuzzy sets (characterized by membership function) cover the whole universe of discourse. The membership functions can be triangular, trapezoidal … [16].

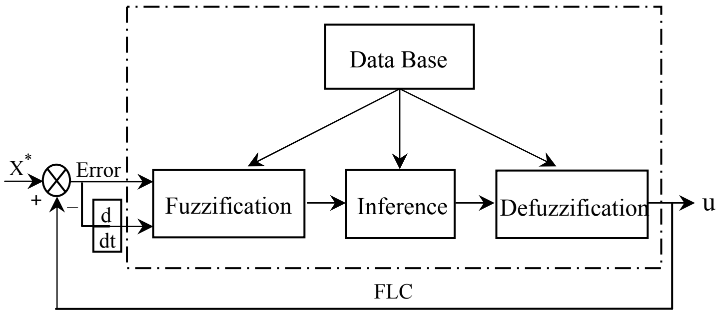

Figure 9
Fuzzy controller structure

The number of linguistic value (small negative, middle negative, positive...), represented by the membership functions can vary (for example three, five or seven). An example of Fuzzyfication is illustrated in (Figure 10) for a single variable of x with triangular membership function; the corresponding linguistic values are characterized by the symbols likewise:

NL: Negative Large.

NS: Negative Small.

ZE: Zero Equal.

PS: Positive Small.

PL: Positive Large.

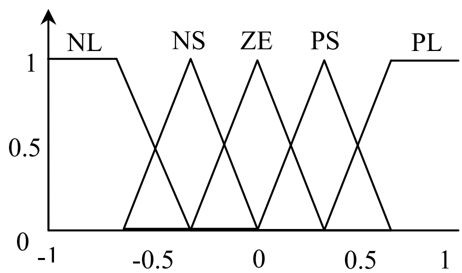

Figure 10
Fuzzyfication with five membership functions

A fuzzy control essentially embeds the intuition and experience of a human operator, and sometimes those of a designer and researcher. The data base and the rules form the knowledge base which is used to obtain the inference relation. The data base contains a description of input and output variables using fuzzy sets. The rule base is essentially the control strategy of the system. It is usually obtained from expert knowledge or heuristics; it contains a collection of fuzzy conditional statements expressed as a set of *If-Then* rules [16]. An example of a rule type: if x1 is positive large, x2 is zero equal, then, u is positive small, where: x1 and x2 represent two input variables of the regulator likewise: the gap of variable to regulate and its variation, and u represent the control variable (output).

Table 1 presents a two linguistic variables of input; the speed error « *e* » and its variation « *de* » and the output variable « *du* ».

Table 1
Rules base for speed control

du		*e*				
		NL	*NS*	*ZE*	*PS*	*PL*
de	*NL*	*NL*	*NL*	*NS*	*NS*	*ZE*
	NS	*NL*	*NS*	*NS*	*ZE*	*PS*
	ZE	*NS*	*NS*	*ZE*	*PS*	*PS*
	PS	*NS*	*ZE*	*PS*	*PS*	*PL*
	PL	*ZE*	*PS*	*PS*	*PL*	*PL*

The mathematical procedure of converting fuzzy values into crisp values is known as 'Defuzzification'. A number of Defuzzification methods have been suggested. The choice of Defuzzification methods usually depends on the application and the available processing power. This operation can be performed by several methods of which center of gravity (or centroid) and height methods are common [16].

7 Speed Control by Fuzzy Regulator

The principle of the fuzzy speed control is the same one as that given in Figure 5, but we have changed the classical PI speed controller with a fuzzy logic controller (FLC); the other current regulators remain of classical type. The principle scheme of the speed regulation by fuzzy logic is given in Figure 11.

7.1 Results and Discussion

The speed reaches its reference value after (*0.43 s*) without overtaking. The electromagnetic torque compensates the load torque and presents at starting a value equal to *(80 N.m)* (Figure 12).

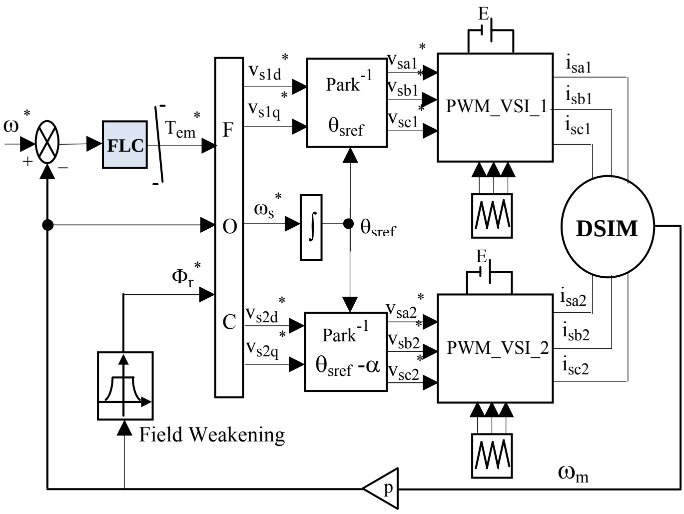

Figure 11

Indirect method fuzzy speed regulation

The simulation results show the insensitivity of fuzzy control to machine parameters variation (Increasing of R_r and J of *100%* of theirs nominal value) (Figure 13, and Figure 14). The inversion time of the speed is without overtaking, with a negative torque equal to *(45 N.m)* (Figure 14). Direct rotor field *(Φ_{dr})* follows the reference value (*1 Wb)* and the quadrature component (*Φ_{qr})* is null.

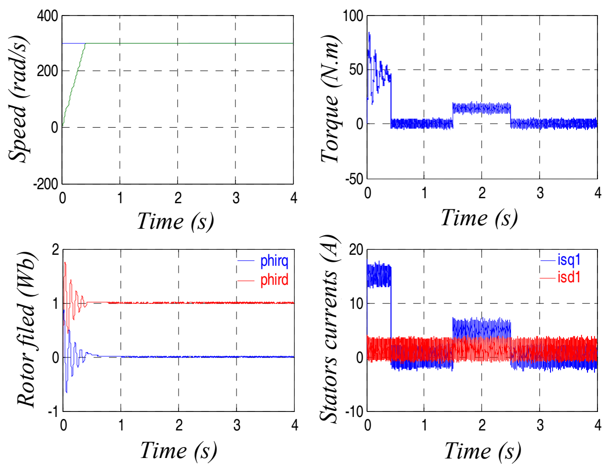

Figure 12

Speed regulation using fuzzy regulator, with applying resistant torque (T_r =14 N.m) between [1.5 2.5] s

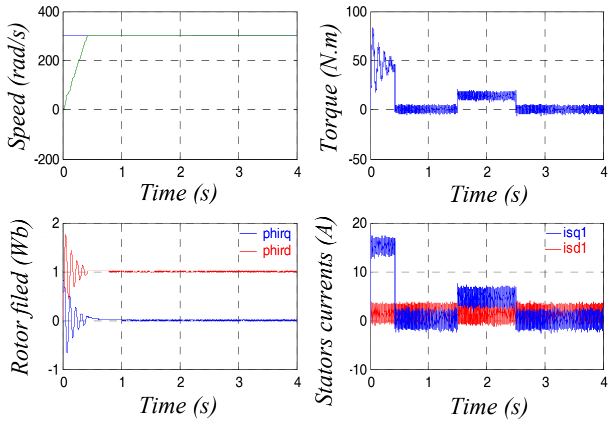

Figure 13
DSIM Comportment with rotor resistance variation (R = 2 R_n at t = 1 s)

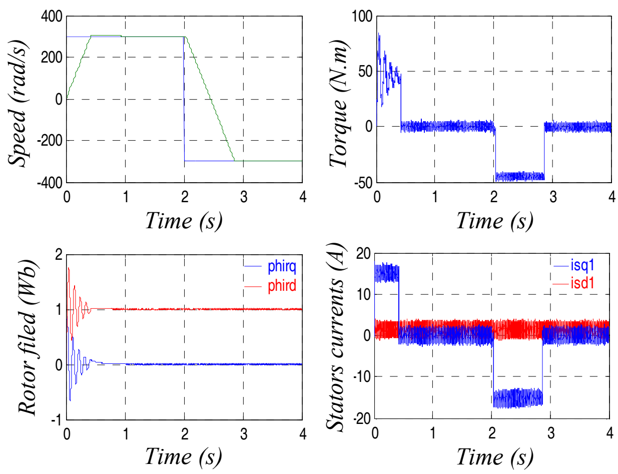

Figure 14
DSIM Comportment with inertia variation (J=2J_n at t=1 s)

Conclusions

In this paper we are presented a Field-oriented Control (FOC) of a Dual Star Induction Machine (DSIM). Two types of regulator are tested for the machine speed regulation: a PI regulator and a fuzzy regulator. The simulation results show the sensitivity of PI regulators to the parameters variation of the DSIM. The fuzzy regulator has very good dynamic performances compared with the conventional PI regulator: (a small response time, overtaking negligible, a small speed inversion time). Additionally, the robustness tests show that the fuzzy regulator is insensitive to parameters variation (rotor resistance and inertia); this returns to the fact that the fuzzy regulator synthesis is realized without taking into account the machine model.

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