Direct Vector Control Scheme For a Dual Stator Induction Machine (DSIM) Using Fuzzy Logic controller

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Abstract. This paper presents the direct vector control scheme for a dual stator induction machine fed by a two pulse width modulation voltage source inverters. The simulation results show that the direct vector control with Fuzzy controller provides good dynamic performances and presents a great robustness and efficiency.

Keywords: *Dual Stator Induction Machine (DSIM); Direct Vector Control (DVC); Pulse Width Modulation (PWM); Flux Estimation; Fuzzy Controller.*

1. Introduction

In the industrial applications that high reliability is demanded, 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: 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, so improving the system reliability [1].

A common type of multiphase machine is the dual stator induction machine (DSIM),is 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]) for 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].

In the asynchronous machines, a strong coupling between the mechanical part which represents the torque and the electrical part which represents the field exists, which will be make the control of these machines very difficult.

The vector control ensures the decoupling between field and torque and made the control of the asynchronous machine similar to that of a DC motor, where there exists a natural decoupling between field and torque.

In this paper a direct vector control with rotor field orientation is applied to the dual stator induction machine using a Fuzzy speed controller.

2. Machine Modelling

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 α=30°. The windings of each three phase set

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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° [4].
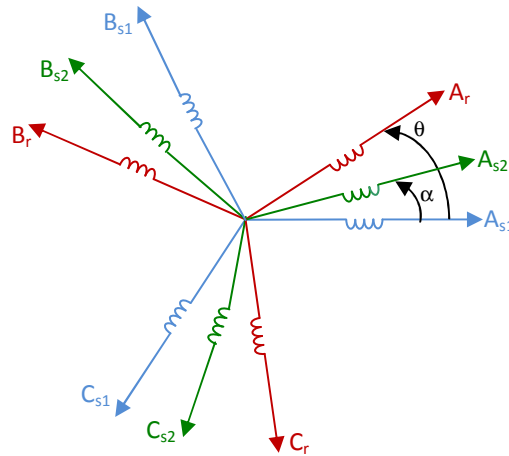

Fig. 1: Windings of the dual stator induction machine

The voltage equations of the dual stator induction machine are as follow [5]:

$$[V_{s1}] = \begin{bmatrix} V_{sa1} \\ V_{sb1} \\ V_{sc1} \end{bmatrix} = [R_{s1}][I_{s1}] + \frac{d}{dt}[\Phi_{s1}]$$

$$[V_{s2}] = \begin{bmatrix} V_{sa2} \\ V_{sb2} \\ V_{sc2} \end{bmatrix} = [R_{s2}][I_{s2}] + \frac{d}{dt}[\Phi_{s2}]$$

$$[0] = \begin{bmatrix} V_{ra} \\ V_{rb} \\ V_{rc} \end{bmatrix} = [Rr][Ir] + \frac{d}{dt}[\Phi_r]$$

(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.

$$[R_{s1}] = \begin{bmatrix} R_{s1} & 0 & 0 \\ 0 & R_{s1} & 0 \\ 0 & 0 & R_{s1} \end{bmatrix} ; \; [R_{s2}] = \begin{bmatrix} R_{s2} & 0 & 0 \\ 0 & R_{s2} & 0 \\ 0 & 0 & R_{s2} \end{bmatrix} ; \; [R_r] = \begin{bmatrix} R_r & 0 & 0 \\ 0 & R_r & 0 \\ 0 & 0 & R_r \end{bmatrix}$$

(2)

$$[I_{s1}] = \begin{bmatrix} I_{sa1} \\ I_{sb1} \\ I_{sc1} \end{bmatrix} ; \; [I_{s2}] = \begin{bmatrix} I_{sa2} \\ I_{sb2} \\ I_{sc2} \end{bmatrix} ; \; [I_r] = \begin{bmatrix} I_{ra} \\ I_{rb} \\ I_{rc} \end{bmatrix}$$

(3)

$$[\Phi_{s1}] = \begin{bmatrix} \Phi_{sa1} \\ \Phi_{sb1} \\ \Phi_{sc1} \end{bmatrix} ; [\Phi_{s2}] = \begin{bmatrix} \Phi_{sa2} \\ \Phi_{sb2} \\ \Phi_{sc2} \end{bmatrix} ; [\Phi_r] = \begin{bmatrix} \Phi_{ra} \\ \Phi_{rb} \\ \Phi_{rc} \end{bmatrix}$$

(4)

The expressions for stator and rotor flux are [5]:

$$\begin{bmatrix} [\Phi_{s1}] \\ [\Phi_{s2}] \\ [\Phi_r] \end{bmatrix} = \begin{bmatrix} [L_{s1s1}] & [L_{s1s2}] & [L_{s1r}] \\ [L_{s2s1}] & [L_{s2s2}] & [L_{s2r}] \\ [L_{rs1}] & [L_{rs2}] & [L_{rr}] \end{bmatrix} \cdot \begin{bmatrix} [I_{s1}] \\ [I_{s2}] \\ [I_r] \end{bmatrix} \tag{5}$$

Where:

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

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

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

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

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

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

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

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

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

The expression of the electromagnetic torque is then as follows [5] [6] [7]:

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

The Park model of the dual stator induction machine in the references frame at the rotating field (*d, q*), is defined by the following equations system (7) [8].

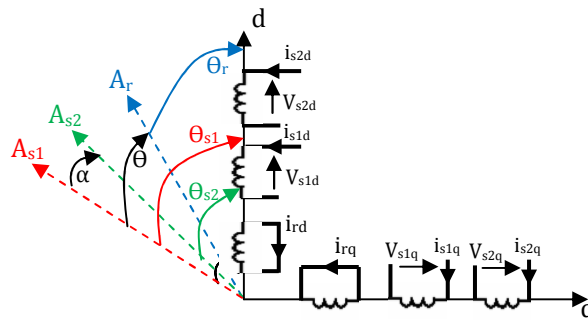The figure 2 represents the model of the DSIM in the Park frame.

Fig. 2: Representation of DSIM in the Park frame

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

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Where:

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

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

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

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

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

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

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

The mechanical equation is given by:

$$J\frac{d\Omega}{dt} = T_{em} - T_L - F_r\Omega \tag{9}$$

With:

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

3. Direct Vector Control Speed Regulation

For the direct vector control, the rotor flux magnitude will be controlled by feedback. For this purpose, a field rotor estimator is achieved from currents measurements (i_{ds} and i_{qs}) and the rotor currents pulsation (ω_r). The speed regulation scheme by Direct Vector Control of the DSIM is given in Figure 3.
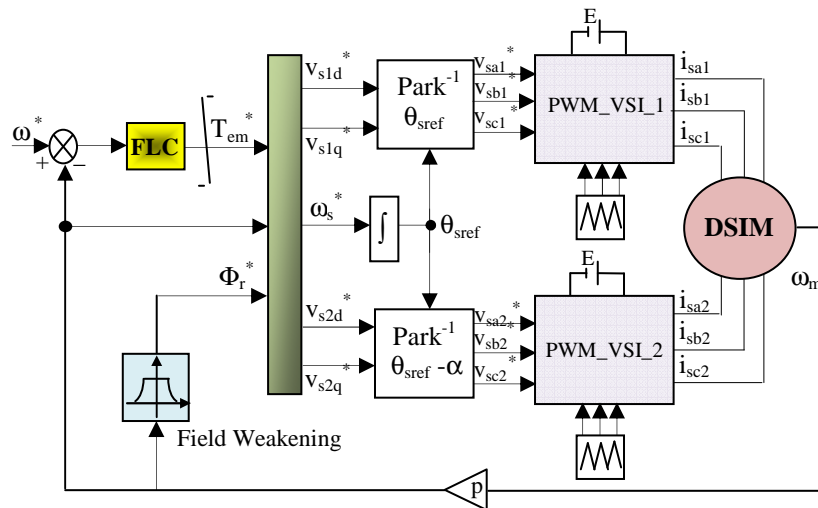

Fig. 3: Indirect method fuzzy speed regulation

The application of the field oriented control consists on the orientation of the rotor flux vector along the "d" axis which can be expressed by considering ($\emptyset_{qr}=0$ and $\emptyset_{dr}=\emptyset_r^*$) [9] [10]. The finals expressions of the electromagnetic torque and slip speed are:

$$Tem = p \frac{L_m}{(L_m + L_r)} \Phi_r{}^* (I_{s1q}{}^* + I_{s2q}{}^*)$$

(12)

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

(13)

The stators voltage equations are:

$$V_{s1d}{}^* = R_{s1} I_{s1d} + L_{s1} \frac{d}{dt} I_{s1d} - \omega_s{}^* (L_{s1} I_{s1q} + Tr\, \Phi r^* w_{sr}{}^*)$$

$$V_{s1q}{}^* = R_{s1} I_{s1q} + L_{s1} \frac{d}{dt} I_{s1q} + \omega_s{}^* (L_{s1} I_{s1d} + \Phi r^*)$$

$$V_{s2d}{}^* = R_{s2} I_{s2d} + L_{s2} \frac{d}{dt} I_{s2d} - \omega_s{}^* (L_{s2} I_{s2q} + Tr\, \Phi r^* w_{sr}{}^*)$$

$$V_{s2q}{}^* = R_{s2} I_{s2q} + L_{s2} \frac{d}{dt} I_{s2q} + \omega_s{}^* (L_{s2} I_{s2d} + \Phi r^*)$$

(14)

With: $Tr = \frac{(L_m + L_r)}{Rr}$

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

$$V_{s1d} = R_{s1} I_{s1d} + L_{s1} \frac{d}{dt} I_{s1d}$$

$$V_{s1q} = R_{s1} I_{s1q} + L_{s1} \frac{d}{dt} I_{s1q}$$

$$V_{s2d} = R_{s2} I_{s2d} + L_{s2} \frac{d}{dt} I_{s2d}$$

$$V_{s2q} = R_{s2} I_{s2q} + L_{s2} \frac{d}{dt} I_{s2q}$$

(15)

The equation system (15) shows that stator voltages $(V_{s1d}, V_{s1q}, V_{s2d}, V_{s2q})$ are directly related to 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:

$$V_{s1d}{}^* = V_{s1d} - V_{s1dc}$$

$$V_{s1q}{}^* = V_{s1q} + V_{s1qc}$$

$$V_{s2d}{}^* = V_{s2d} - V_{s2dc}$$

$$V_{s2q}{}^* = V_{s2q} + V_{s2qc}$$

(16)

With:

$$V_{s1dc} = \omega_s{}^* (L_{s1} I_{s1q} + Tr\, \Phi r^* w_{sr}{}^*)$$

$$V_{s1qc} = \omega_s{}^* (L_{s1} I_{s1d} + \Phi r^*)$$

$$V_{s2dc} = \omega_s{}^* (L_{s2} I_{s2q} + Tr\, \Phi r^* w_{sr}{}^*)$$

$$V_{s2qc} = \omega_s{}^* (L_{s2} I_{s2d} + \Phi r^*)$$

(17)

For a perfect decoupling, we add stator currents 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 (Direct Field Oriented Control DFOC) is given in Figure 4.

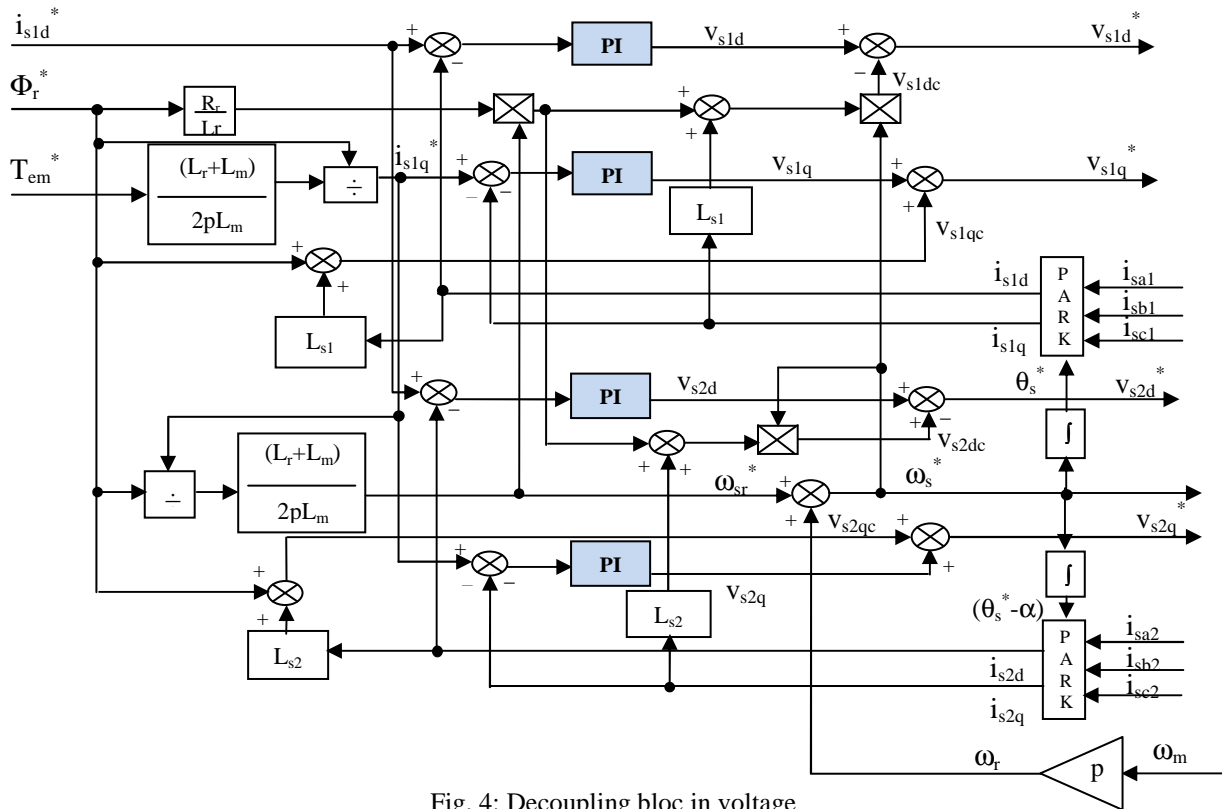Fig. 4: Decoupling bloc in voltage

4. Fuzzy Logic Control

Traditional control design methods use mathematical models of a system and its inputs to design controllers that analyze their effectiveness. Fuzzy logic control uses Fuzzy sets and Fuzzy inference to derive control laws in which no precise model of the plants exist, and most of the a priori information is available only in qualitative form. The basic idea of Fuzzy logic control is to make use of expert knowledge and experience to build a rule base with linguistic rules [11].

The Fuzzy controller operation, in general, is typically divided into the following three categories: Fuzzification, inference engine and Defuzzification. The Fuzzification block means that real world variables are translated in terms of Fuzzy sets. A control algorithm is coded using Fuzzy statements in the block containing the knowledge base by taking into account the control objectives and the system behaviour. In a Fuzzy inference engine, the control actions are encoded by means of Fuzzy inference rules. The appropriate Fuzzy sets are defined on the domains of the involved variables, and Fuzzy logic operators and inference methods are formalized in computational terms. The results of the Fuzzy computations are translated in terms of real values for the Fuzzy control action in the Defuzzification block [12]. Figure 5 shows the structure of a Fuzzy controller.
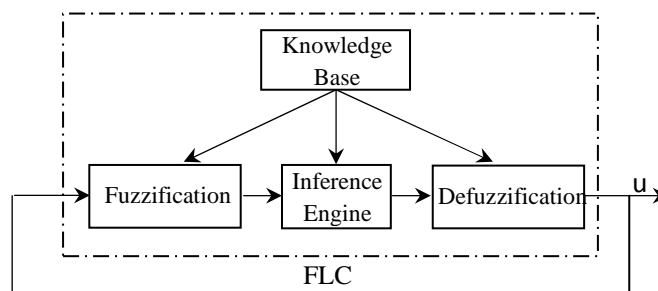

Fig.5 : Fuzzy Logic controller

The number of linguistic value (negative large, negative small, zero equal, positive small, … etc.), represented by the membership functions, can vary (for example three, five, seven, nine,…). In this paper we are used a Fuzzy logic controller with three membership functions (Negative Large, Zero Equal, Positive Large).
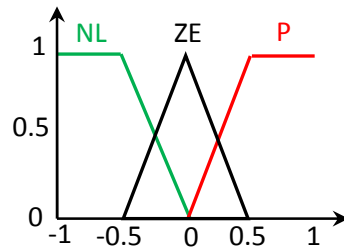

Fig.6 : Fuzzyfication with three membership

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 [15]. An example of rule type: if *e* is negative large, *de* is positive large, then *u* is zero equal, where: *e* (speed error: is calculated with comparison between reference speed and speed signal feedback) and *de* (The derivative of the error) represent two input variables of the Fuzzy regulator and *u* represents the control variable (output).

Table-I represent a table of rules for two linguistic variables of input; the speed error «*e*» and its variation «*de*» and the output variable «*du*».

Table-I: Rules bases for speed control

du		e		
		NL	ZE	PL
de	NL	NL	NL	ZE
	ZE	NL	ZE	PL
	PL	ZE	PL	PL

The diagram block of simulation and the Fuzzy speed controller structure are given in Fig.7 and Fig.8:
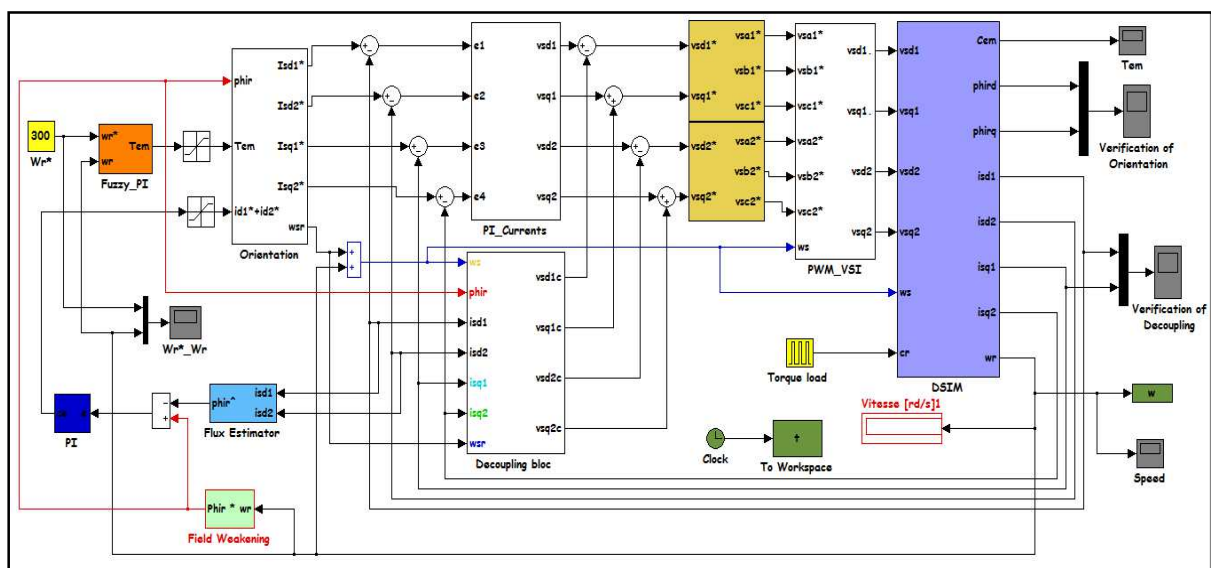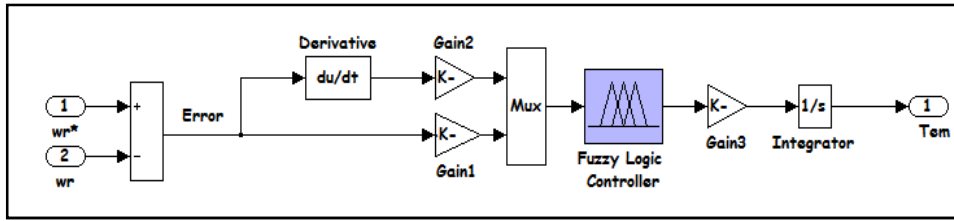

Fig.7 : Diagram block of simulation

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Fig.8 : Structure of Fuzzy speed controller

5. Results and Discussion

By using of the Matlab/Simulink environment, the simulation results are given by the following figures:
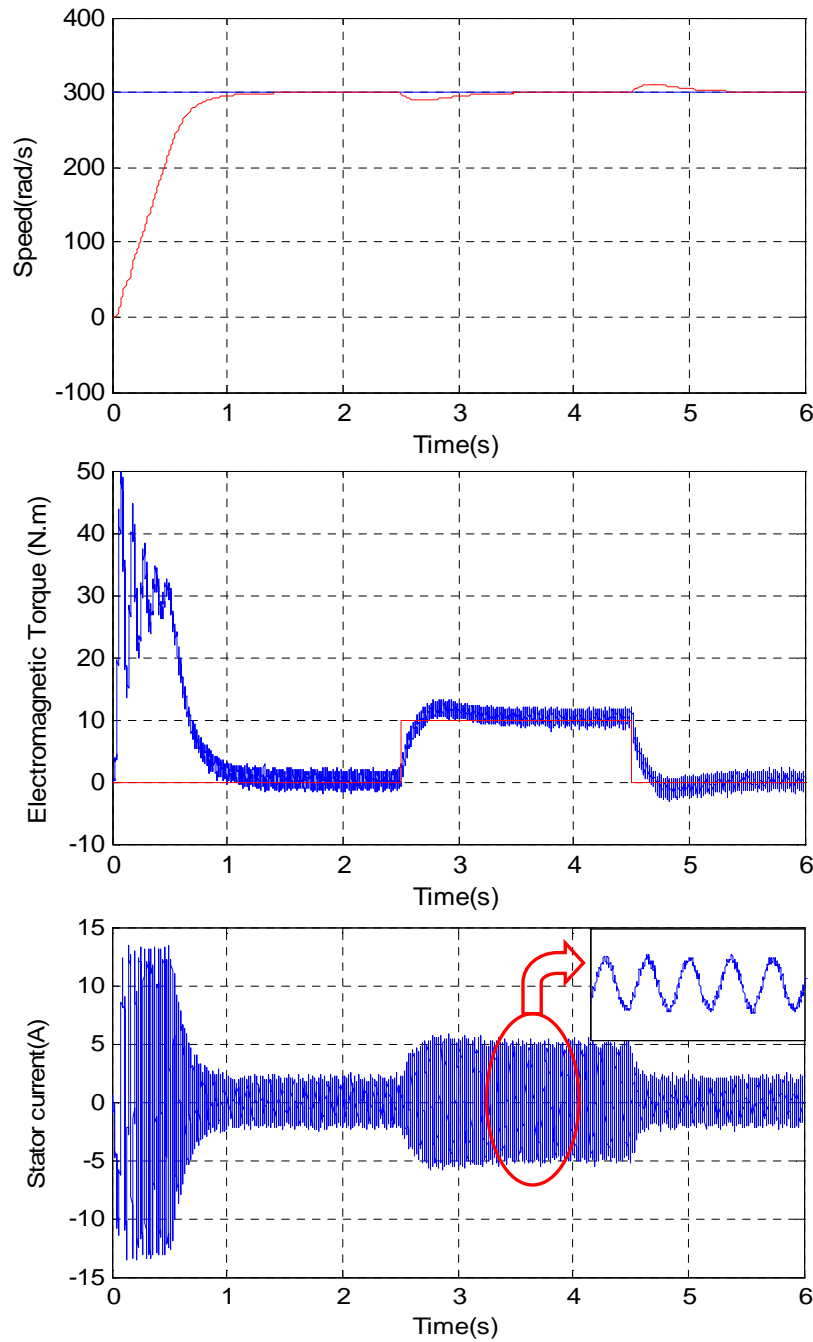

Fig. 9: Speed regulation using fuzzy controller, with load torque (T_L =10N.m) between [2.5 4.5] s
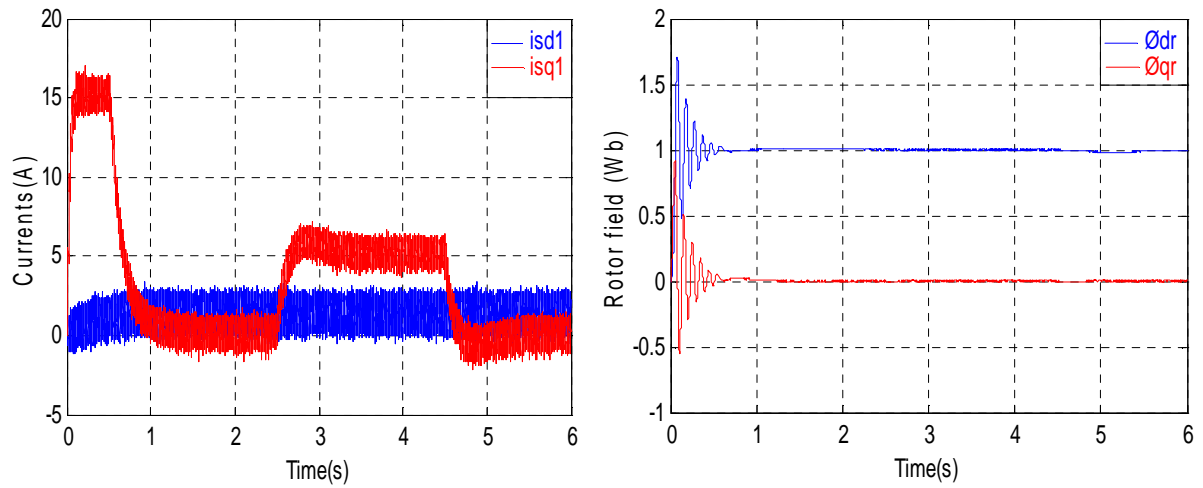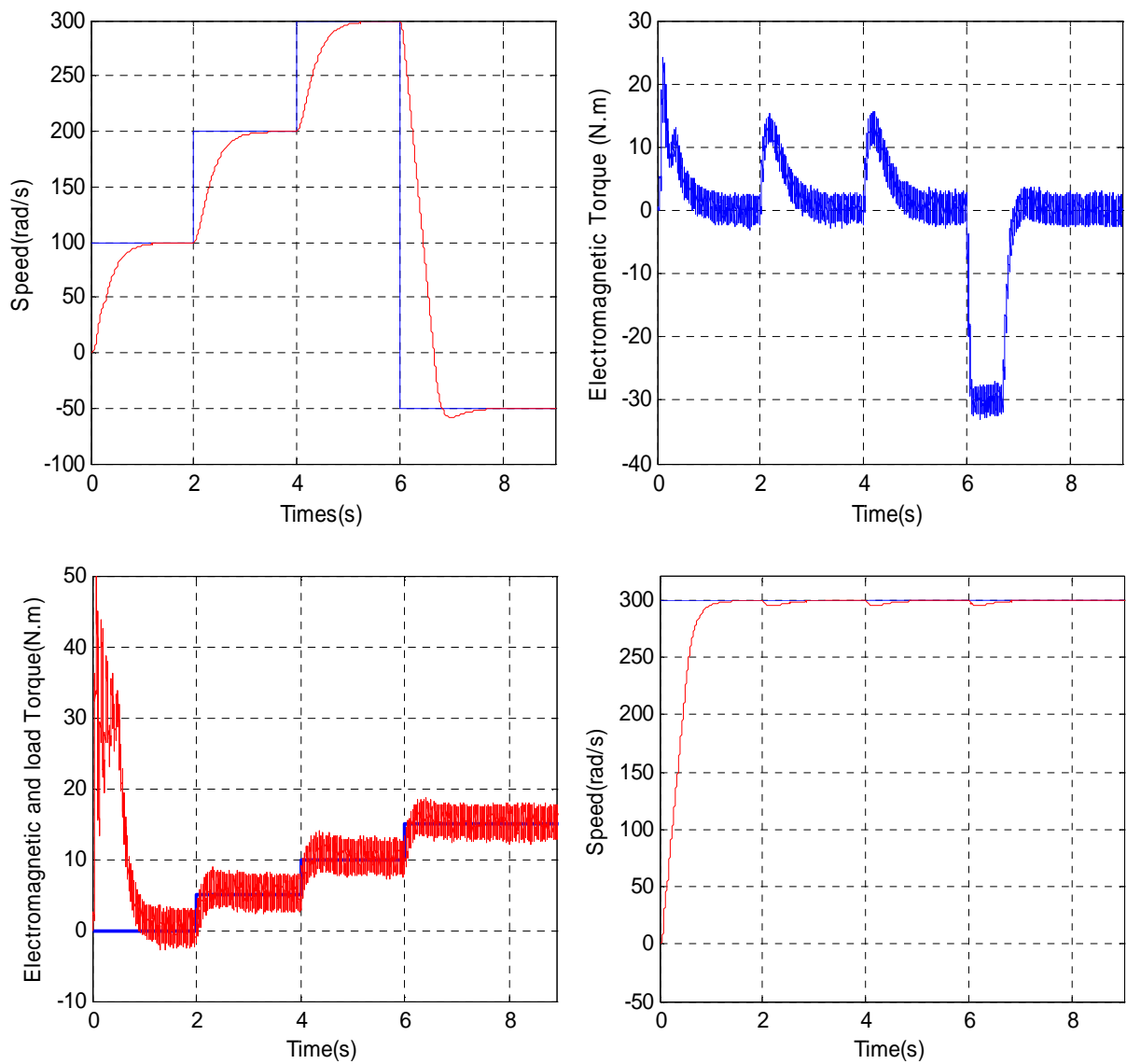
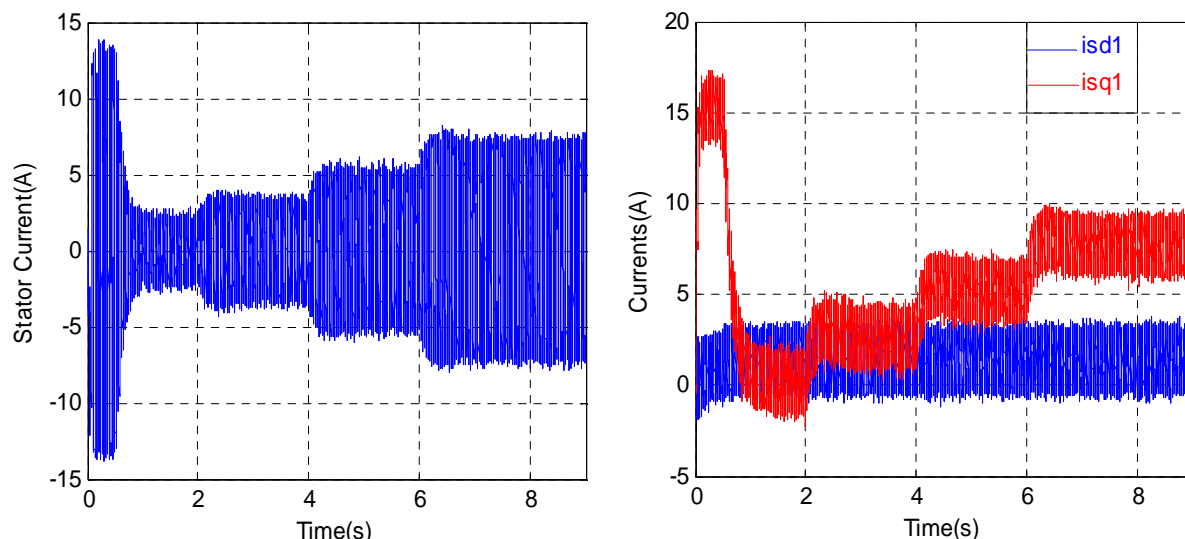Fig. 10: Decoupling and rotor field orientation

Fig. 11: Simulation results with speed and load torque variation

The speed reaches its reference value after (*1.4s*) without overtaking. The perturbation reject is achieved at *(0.9s)*, and the machine develop an electromagnetic torque for compensate the load torque by a call of current between 2.5 and 4.5 second.

When we apply a load torque (it is a mechanical size) the electrical part remains insensitive (the current isd_1) and only the mechanical part which will react (the current isq_1). Thus, there is a good decoupling.

The direct rotor field *($\emptyset_{dr}$)* follows the reference value (*1Wb)* and the quadrature component ($\emptyset_{qr}$) is null. Thus, the orientation is assured.

The direct field oriented control with fuzzy speed regulator proves its robustness with speed and load torque variation (Fig. 11).

6. Conclusion

In this paper, the Direct Vector Control of a Dual Stator Induction Machine (DSIM) using Fuzzy controller is presented. The simulation results show the robustness, the efficiency and the good dynamic performances (speed response without overshoot, zero state error,…) of fuzzy regulator. Otherwise, the fuzzy controller synthesis is realized without take in account the machine model.

7. References

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Appendix

Table I. Dual Stator Induction Machine parameters

P_n [kw]	4.5	R_r [Ω]	2 .12	J [kg.m²]	0.0625
V_n [V]	220	L_{s1} [H]	0.022	F_r [Nms/r]	0.001
I_n [A]	6.5	L_{s2} [H]	0.022	f [Hz]	50
R_{s1} [Ω]	3.72	L_r [H]	0.006	p	1
R_{s2} [Ω]	3.72	L_m [H]	0.367	Cos ϕ	0.8