Fuzzy Gain Scheduling of PI Controller for Dual Star Induction Machine fed by a Matrix Converter

B. Meliani, A. Meroufel, and H. Khouidmi
Department of Electrical Engineering, Djillali L iabès University of Sidi Bel-Abbès-Algeria
Email: melfat06@yahoo.fr

***Abstract*—the aim of this paper is to present a full digital implementation of a field orientation controlled Double Star induction Machine, and a PI controller is designed to control the speed, the machine is fed by a matrix converter. The advent of vector control technique has partially solved DSIM control problems because they are sensitive to drive parameter variations and performance may deteriorate if conventional controllers are used. Fuzzy logic and neural network Based controllers are considered as potential candidates for such an application. In this paper the fuzzy logic system is used on-line to generate the PI controller parameters. Simulink results for a 4.5 kW six-phase induction machine are presented and analyzed using a matlab environment. Obtained results demonstrated that the proposed control scheme is able to obtain high performances.**

***Index Terms*— Dual star; induction machine; Field Oriented Control; adaptive PI controllers; Fuzzy Logic.**

I. Introduction

The dual star induction motor drive fed by a matrix converter is superior to the conventional PWM-VS inverter because of the lack of bulky DC-link capacitors with limited life time, the bi-directional power flow capability, the sinusoidal input/output currents, and adjustable input power factor. Furthermore, because of a high integration capability and a higher reliability of the semiconductor device structures, the matrix converter topology is recommended for extreme temperatures and critical volume/weight applications. However, only a few of the practical matrix converters have been applied to induction motor drive system because the implementation of the switch devices in the matrix converter is difficult and modulation technique and commutation control are more complicated than the conventional PWM inverter [1].

The DSIM it is desirable to control the flux and torque separately in order to have the same performances as those of DC motors. One way of doing this is by using the field oriented control. This method assures the decoupling of flux and torque [3]. The vector-controlled DSIM with a conventional PI speed controller is used extensively in industry, because has easily implemented. Alongside this success, however the problem of tuning PI-controllers has remained an active research area. Furthermore, with changes in system dynamics and variations in operating points PI-Controllers should be returned on a regular basis. This has triggered extensive research on the possibilities and potential of the so-called adaptive PI controllers. Loosely defined, adaptive PI-controllers avoid time-consuming manual tuning by providing optimal PI controller settings automatically as the system dynamics or operating points change [6]-[7]. There are two methods of tuning the PI-Controller; they are the conventional Ziegler-Nichols method and the Intelligence methods such as the Fuzzy Logic**,** In [8] fuzzy rules and reasoning are utilized on-line to determine the controller parameters based on the error signal and its first difference In the direct field-oriented control, the speed control of DSIM requires speed feedback which is usually obtained from mechanical transducers mounted on the motor shaft.

II. Double Star Induction Modeling

The machine studied is represented by two stators windings: $sa_1, sb_{1,} sc_1$ and $sa_2, sb_{2,} sc_2$ which are displaced by $\alpha = 30^0$ and the rotorical phases: ra, rb, rc, this is a most rugged and maintenance free machine

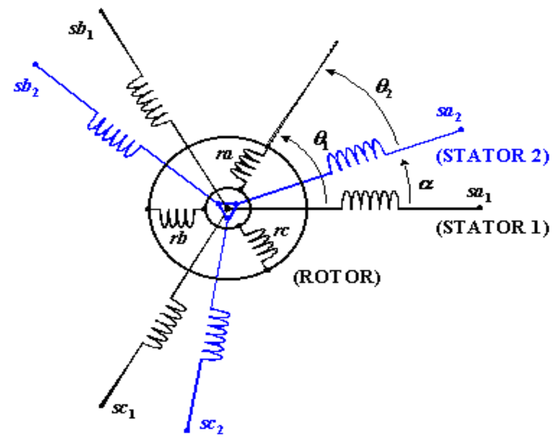

Figure 1. Double stator winding representation

The following assumptions have been made in deriving the machine model

- Machine windings are sinusoidally distributed
- Machine magnetic saturation and the mutual leakage inductances are neglected
- The two stars have same parameters

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The mathematical model of the machine is written as a set of state equations, both for the electrical and mechanical parts, the voltage equation is[2]:

$$\begin{aligned}
[V_{dqs1}] &= R_{s1}.[I_{dqs1}] + \frac{d}{dt}[\Phi_{dq1}] - \omega_s.[\Phi_{qds1}] \\
[V_{dqs2}] &= R_{s2}.[I_{dqs2}] + \frac{d}{dt}[\Phi_{dq2}] - \omega_s.[\Phi_{qds2}] \\
[V_{dqr}] &= R_r.[I_{dqr}] + \frac{d}{dt}[\Phi_{dqr}] - (\omega_s - \omega_r).[\Phi_{qdr}]
\end{aligned} \tag{1}$$

with:

$$\begin{aligned}
[\Phi_{dqs12}] &= L_{s12}[I_{dqs12}] + L_m(I_{dqs1} + I_{dqs2} + I_{dqr}) \\
[\Phi_{dqr}] &= L_{s12}[I_{dqr}] + L_m(I_{dqs1} + I_{dqs2} + I_{dqr})
\end{aligned} \tag{2}$$

the electrical state variables in the “dq”system are the flux represented by vector [Φ□], while the input variable in the “dq”system are expressed by vector [V].

$$\frac{d}{dt}[\Phi] = [A].[\Phi] + [B].[V] \tag{3}$$

with:

$$[\Phi] = [\Phi_{dqs1} \quad \Phi_{dqs2} \quad \Phi_{dqr}]^T, [V] = [V_{dqs1} \quad V_{dqs2} \quad V_{dqr}]^T$$

the equation of the electromagnetic torque is:

$$T_e = p\frac{L_m}{L_m + L_r}\left[(I_{qs1} + I_{qs2}).\Phi_{dr} + (I_{ds1} + I_{ds2}).\Phi_{qr}\right] \tag{4}$$

$R_{s1,}$ R_{s2} and R_r are respectively the per phase stator resistance and the per phase rotor resistance.
L_{s12} and L_r are respectively the per phase stator self inductance and the per phase rotor self inductance.
L_m is the mutual inductance between stator and rotor.
the equation of flux is:

$$[\Phi_{dqm}] = L_m(I_{dqs1} + I_{dqs2} + I_{dqr}) \tag{5}$$

or:

$$[\Phi_{dqm}] = L_a.\left(\frac{\Phi_{dqs1}}{L_{s1}} + \frac{\Phi_{dqs2}}{L_{s2}} + \frac{\Phi_{dqr}}{L_r}\right) \tag{6}$$

where

$$L_a = \frac{1}{\frac{1}{L_m} + \frac{1}{L_{s1}} + \frac{1}{L_{s2}} + \frac{1}{L_r}} \tag{7}$$

the state matrix A and vector B in the d-q axis are:

$$[A] = \begin{bmatrix} a_{11} & a_{12} & a_{13} & 0 & a_{15} & 0 \\ a_{21} & a_{22} & 0 & a_{24} & a_{25} & 0 \\ a_{31} & 0 & a_{33} & a_{34} & 0 & a_{36} \\ 0 & a_{42} & a_{43} & a_{44} & 0 & a_{46} \\ a_{51} & a_{52} & 0 & 0 & a_{55} & a_{56} \\ 0 & 0 & a_{63} & a_{64} & a_{65} & a_{66} \end{bmatrix} \tag{8}$$

$$[B] = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{9}$$

where:

$$a_{11} = a_{33} = \frac{L_a}{T_{s1}L_{s1}} - \frac{1}{T_{s1}}$$

$$a_{12} = a_{24} = -a_{31} = -a_{42} = \omega_s, a_{15} = a_{35} = \frac{L_a}{T_{s1}L_r}$$

$$a_{21} = a_{43} = \frac{L_a}{T_{s2}L_{s1}}, a_{22} = a_{44} = \frac{L_a}{T_{s2}L_{s2}} - \frac{1}{T_{s2}}$$

$$a_{25} = a_{46} = \frac{L_a}{T_{s2}L_r}, a_{51} = a_{63} = \frac{L_a}{T_{s1}L_r}$$

$$a_{52} = a_{64} = \frac{L_a}{T_{s2}L_r}, a_{55} = a_{66} = \frac{L_a}{T_rL_r} - \frac{1}{T_r}$$

$$a_{56} = -a_{65} = \omega_r, T_s = \frac{L_s}{R_s}, T_r = \frac{L_r}{R_r}$$

and $\omega_r = \omega_s - \omega_m$

III. MATRIX CONVERTER MODELING

A matrix converter is a variable amplitude and frequency power supply that converts the three phase line voltage directly. It is very simple in structure and has powerful controllability. The real development of the matrix converter starts with the work of Venturini and Alesina who proposed a mathematical analysis and introduced the low frequency modulation matrix concept to describe the low frequency behavior of the matrix converter [1]. In this, the output voltages are obtained by multiplication of the modulation matrix or transfer matrix with the input voltages. The basic diagram of a matrix converter can be represented by Fig. 2.

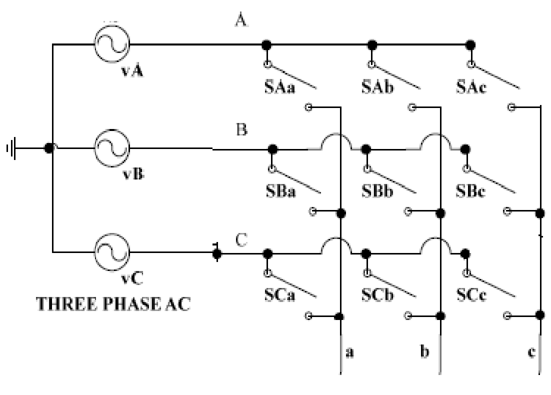

Figure 2. Basic structure of matrix converter

The existence function provides a mathematical expression for describing switching patterns. The existence function for a single switch assumes a value of unity when the switch is closed and zero when the switch is open. For the matrix converter shown in Figure2, the existence function for each of the switches is expressed by the following equations:

$$S_{kj} = \begin{cases} 1, \ switch \ S_{kj} \ closed \\ 0, \ switch \ S_{kj} \ open \end{cases} \tag{10}$$

where k= {A, B, C} is input phase and j={a, b, c} is output phase.

The above constraint can be expressed in the following form:

$$S_{Aj} + S_{Bj} + S_{Cj} = 1 \tag{11}$$

with the above restrictions a 3 X 3 matrix converter has 27 possible switching states.

the mathematical expression that represents the operation of a three phase ac to ac Matrix Converter can be expressed as follows:

$$\begin{bmatrix} v_a(t) \\ v_b(t) \\ v_c(t) \end{bmatrix} = \begin{bmatrix} S_{Aa}(t) & S_{Ba}(t) & S_{Ca}(t) \\ S_{Ab}(t) & S_{Bb}(t) & S_{Cb}(t) \\ S_{Ac}(t) & S_{Bc}(t) & S_{Cc}(t) \end{bmatrix} * \begin{bmatrix} v_A(t) \\ v_B(t) \\ v_C(t) \end{bmatrix} \tag{12}$$

$$\begin{bmatrix} i_A(t) \\ i_B(t) \\ i_C(t) \end{bmatrix} = \begin{bmatrix} S_{Aa}(t) & S_{Ba}(t) & S_{Ca}(t) \\ S_{Ab}(t) & S_{Bb}(t) & S_{Cb}(t) \\ S_{Ac}(t) & S_{Bc}(t) & S_{Cc}(t) \end{bmatrix}^T * \begin{bmatrix} i_a(t) \\ i_b(t) \\ i_c(t) \end{bmatrix} \tag{13}$$

where va, vb and vc and iA, iB and iC are the output voltages and input currents respectively. To determine the behavior of the MC at output frequencies well below the switching frequency, a modulation duty cycle can be defined for each switch. The modulation duty cycle MKj for the switch SKj in Figure.2 is defined as in equation (14) below.

$$M_{kj} = \frac{t_{kj}}{T_s} \tag{14}$$

where t_{kj} is the one time for the switch S_{kj} between input phase k={A, B, C} and j={a, b, c} and T_s is the period of the PWM switching signal or sampling period. In terms of the modulation duty sycle, equations 12, and 13 can be rewritten as given below.

$$\begin{bmatrix} v_a(t) \\ v_b(t) \\ v_c(t) \end{bmatrix} = \begin{bmatrix} M_{Aa}(t) & M_{Ba}(t) & M_{Ca}(t) \\ M_{Ab}(t) & M_{Bb}(t) & M_{Cb}(t) \\ M_{Ac}(t) & M_{Bc}(t) & M_{Cc}(t) \end{bmatrix} * \begin{bmatrix} v_A(t) \\ v_B(t) \\ v_C(t) \end{bmatrix} \tag{15}$$

$$\begin{bmatrix} i_A(t) \\ i_B(t) \\ i_C(t) \end{bmatrix} = \begin{bmatrix} M_{Aa}(t) & M_{Ba}(t) & M_{Ca}(t) \\ M_{Ab}(t) & M_{Bb}(t) & M_{Cb}(t) \\ M_{Ac}(t) & M_{Bc}(t) & M_{Cc}(t) \end{bmatrix}^T * \begin{bmatrix} i_a(t) \\ i_b(t) \\ i_c(t) \end{bmatrix}$$

$$M_{Aj} + M_{Bj} + M_{Cj} = 1 \tag{16}$$

j={a, b, c}

the high-frequency synthesis technique introduced by Venturini and Alesina in [4] allows the use of low frequency continuous functions, referred to as the modulation matrix m(t), to calculate the existence functions for each switch of the matrix converter. Thus, the aim when using the Alesina and Venturini modulation method is to find a modulation matrix which satisfies the following set of equations.

$$v_o(t) = m(t).v_i(t) \tag{17}$$

$$i_i(t) = m(t)^T .i_o(t) \tag{18}$$

where the input voltages $v_i(t)$ are given by the following set of functions

$$v_i(t) = V_{in} \begin{bmatrix} \cos(\omega_i t) \\ \cos(\omega_i t - \frac{2\pi}{3}) \\ \cos(\omega_i t + \frac{2\pi}{3}) \end{bmatrix} \tag{19}$$

and the desired output voltages $v_o(t)$ are

$$v_o(t) = V_o \begin{bmatrix} \cos(\omega_o t) \\ \cos(\omega_o t - \frac{2\pi}{3}) \\ \cos(\omega_o t + \frac{2\pi}{3}) \end{bmatrix} \tag{20}$$

output currents $i_o(t)$ can be expressed as:

$$i_o(t) = I_o \begin{bmatrix} \cos(\omega_o t + \varphi_o) \\ \cos(\omega_o t - \frac{2\pi}{3} + \varphi_{\grave{a}}) \\ \cos(\omega_o t + \frac{2\pi}{3} + \varphi_o) \end{bmatrix} \tag{21}$$

where φ_o is the phase angle of the linear load.

finally, the desired input current has an arbitrary phase φ_i. This angle can be set to 0 to obtain unity input power factor of the matrix converter.

$$i_i(t) = I_i \begin{bmatrix} \cos(\omega_i t + \varphi_i) \\ \cos(\omega_i t - \frac{2\pi}{3} + \varphi_i) \\ \cos(\omega_i t + \frac{2\pi}{3} + \varphi_i) \end{bmatrix} \tag{22}$$

The elements of matrix m(t) that satisfy equations 17 and 18 are given by

$$m_{ij}(t) = \frac{1}{3}\alpha\left\{1 + q\cos\left[(\omega_o - \omega_i) + \frac{2}{3}\pi(i-j)\right]\right\} + \frac{1}{3_1}\alpha_2\left\{1 + q\cos\left[(\omega_o - \omega_i) + \frac{2}{3}\pi(2-i-j)\right]\right\} \tag{23}$$

where $\alpha_1 = \frac{1}{2}\left[1 + \frac{\tan(\varphi_1)}{\tan(\varphi_o)}\right]$, $\alpha_2 = 1 - \alpha_1$, $q = \frac{V_o}{V_i}$

With the following restrictions $\alpha_1 \geq 0$, $\alpha_2 \geq 0$, $0 \leq q \leq \frac{1}{2}$

IV. SPEED CONTROL OF THE DSIM BY AN ADAPTIVE FUZZY CONTROLLER

Gain scheduling means a technique where PI controller parameters (K_p and K_i gains) are tuned during control of the system in a predefined way [8], It enlarges the operation area of linear controller (PI) to perform well also with a nonlinear system. The diagram of this technique is illustrated in fig 3.

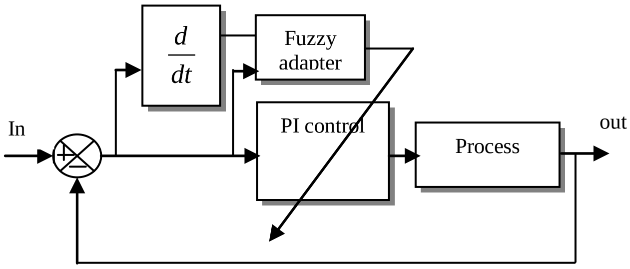

Figure 3. PI control system with fuzzy gain adapter

The fuzzy inference mechanism adjusts the PI parameters and generates new parameters during process control, so that the fuzzy logic adapts the PI parameters to operating conditions based on the error and its first time difference.The parameters of the PI controller used in the direct chain K_p and K_i are normalized into the range between zero and one by using the following linear transformations [7]:

$$\begin{aligned} K'_p &= (K_p - K_{p\min})/(K_{p\max} - K_{p\min}) \\ K'_i &= (K_i - K_{i\min})/(K_{i\max} - K_{i\min}) \end{aligned} \tag{24}$$

The inputs of the fuzzy adapter are: The error e and the first time difference of the error Δe normalized using a predefined maximum error and a maximum first time difference. The outputs are the normalized value of the proportional action K'_p and of the integral action K'_i. the inference engine, based on the input fuzzy sets, uses the appropriate IF-THEN rules in the knowledge base to make decisions, where the Max operation is used for the premises and the Min operation is used for the implication. The associated fuzzy sets involved in the fuzzy control rules are defined as follows: **NB** : negative big , **PM** : Positive medium, **NM** : negative medium, **PB** : Positive big, **NS** : Negative small, **B** : Big, **ZE** : Zero, **PS** : Positive small, **S:** Small

The fuzzy rules may be extracted from operator's expertise or based on the step response of the process [8]. The tuning rules for K'_p and K'_i are given in tables 1 and 2 respectively.

TABLE I
FUZZY RULES BASE FOR COMPUTING K'_p

Δe \ e	NB	NM	NS	ZE	PS	PM	PB
NB	B	B	B	B	B	B	B
NM	B	B	B	B	B	B	S
NS	S	S	B	B	B	S	S
ZE	S	S	S	B	S	S	S
PS	S	S	B	B	B	S	S
PM	S	B	B	B	B	B	S
PB	B	B	B	B	B	B	B

TABLE II
FUZZY RULES BASE FOR COMPUTING K'_i

Δe \ e	NB	NM	NS	ZE	PS	PM	PB
NB	B	B	B	B	B	B	B
NM	B	S	S	S	S	S	B
NS	B	B	S	S	S	B	B
ZE	B	B	B	S	B	B	B
PS	B	B	S	S	S	B	B
PM	B	S	S	S	S	S	B
PB	B	B	B	B	B	B	B

The membership functions with 7 in number for each for the inputs e and Δe are defined in the range [-1, 1] (Figure.4), and for the outputs with 2 number are defined in the range [0, 1] (Figure. 5). By using the membership functions shown in Figure.4.we have the following conditions

$$\sum_{i=1}^{m} u_i = 1 \tag{25}$$

Then, the defuzzification yields the following:

$$k'_p = \sum_{j=1}^{m} u_j k'_{p.j} \tag{26}$$

$$k'_i = \sum_{j=1}^{m} u_j k'_{i.j} \tag{27}$$

here $k'_{p.j}$ is the value k'_p corresponding to the grade μ_i for the jth rule. $k'_{i.j}$ is obtained in the same way. Once k'_p , k'_i are obtained, the PI controller parameters are calculated from the following equation

$$\begin{aligned} k_i &= (k_{i\max} - k_{i\min})k'_i + k_{i\min} \\ k_p &= (k_{p\max} - k_{p\min})k'_p + k_{p\min} \end{aligned} \tag{28}$$

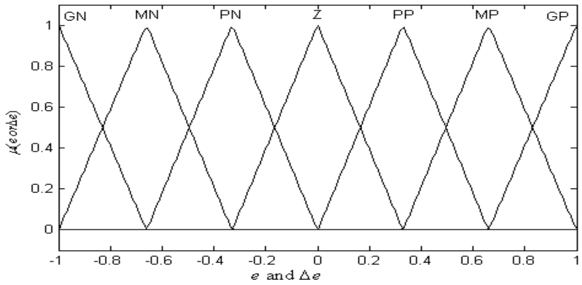

Figure 4. Membership functions *e* and *de* .

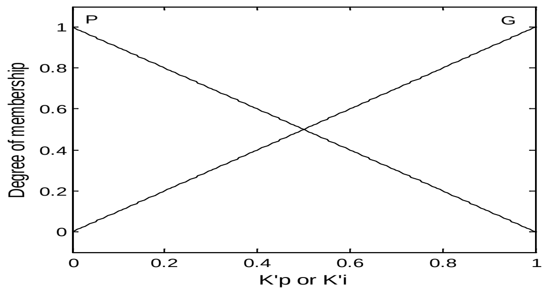

Figure 5. Membership functions K'_p and K'_i

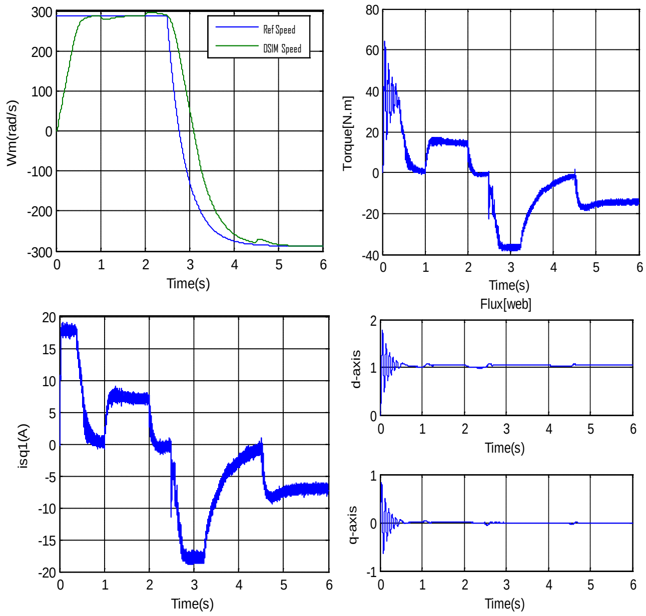

Figure7. Simulated results of adaptive PI controller for DSIM

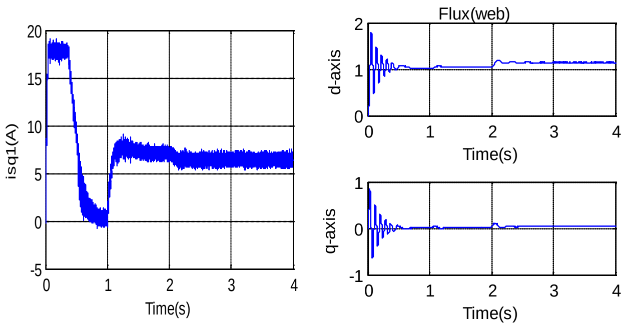

Figure 8. Simulated results of adaptive PI controller for DSIM with variation of the rotor resistance at t=2s

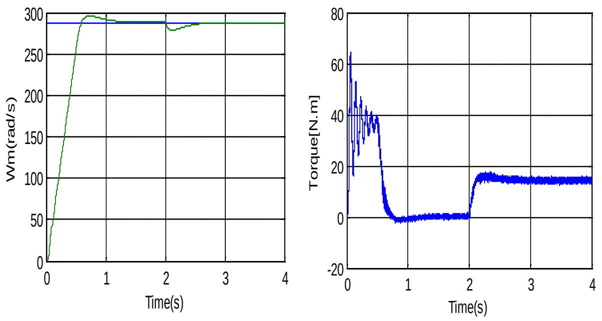

Figure 9. Simulated results of adaptive PI controller for DSIM with variation of the rotor inertia (+10%J)

V. SIMULATION RESULTS

The SIMULINK model for indirect field oriented of the 4.5 Kw cage rotor DSIM associated with fuzzy logic based adaptive PI controller is shown in Fig.6. The machine is fed by a matrix converter. The parameters of the induction motor are summarized in Appendix.

The first test concerns a no-load starting of the motor with a reference speed ω_{ref} = 288 rad/sec. and a nominal load disturbance torque (14N.m) is suddenly applied between 1sec and 2sec, followed by a consign inversion (-288rad/sec) at 2.5sec. At 4.5s, a -14Nm load disturbance is applied during a period of 2 s. this test has for object the study of controller behaviors in pursuit and in regulation.

The test results obtained are shown in Fig.7. The speed of the motor reaches ω_{ref} at 0.2 s with almost no overshoot. It then begins to oscillate inside a 0.4% error strip around ω_{ref} , The fuzzy controller rejects the load disturbance very quickly with no overshoot and with a negligible steady state error.

In order to test the robustness of the used method we have studied the effect of the parameters uncertainties on the performances of the speed control. To show the effect of the parameters uncertainties, we have simulated the system with different values of the parameter considered and compared to nominal value (real value). The Fig.8 and Fig.9 show respectively the behavior of the DSIM when R*r* is 10% increased of its nominal value and J is increased 10% of its nominal value. An increase of the moment of inertia gives best performances, but it presents a slow dynamic response. The figures show that the proposed controller gave satisfactory performances thus judges that the controller is robust

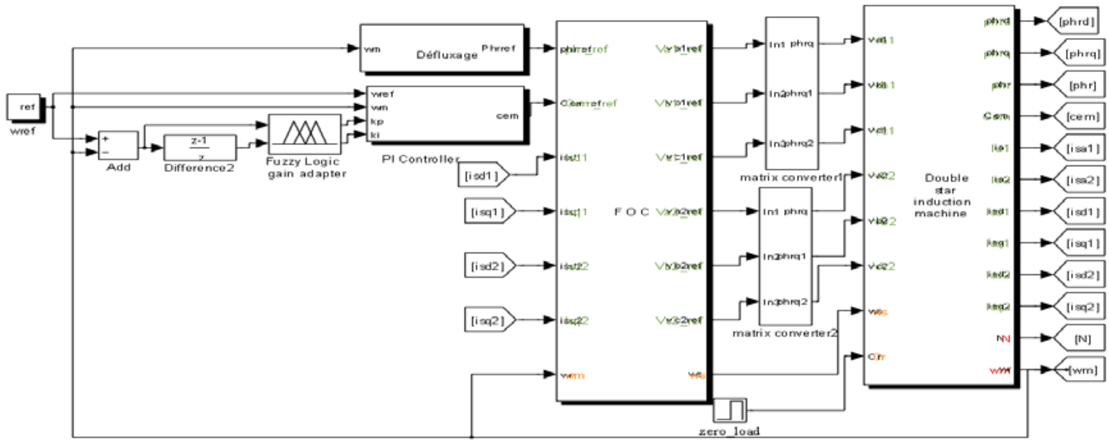

Figure 6. Simulink diagram for DSIM control systems

VI. CONCLUSION

This paper presents a study of an application of speed control by fuzzy logic based adaptive PI controller for a double stator induction machine based on the indirect field oriented control, The machine is fed by a matrix converter, Simulation results on control robustness with speed variation parameters variation and the torque resistant are given. The results show that the controller could compensate for this kind of disturbances. The plant is also tested for the tracking property using different types of reference signals. Satisfactory performance was observed for most reference tracks and the results demonstrated the effectiveness of the proposed structure and the proposed control scheme it is believed will constitute a major step in the evolution of intelligent control.

APPENDIX

TABLE III
DSIM PARAMATERS

N nominal values	Value	IS-Unit
Power	4.5	kW
Frequency	50	Hz
Voltage (Δ/Y)	220/380	V
Current (Δ/Y)	5.6	A
Speed	2751	rpm
Constant	**Value**	**IS-Unit**
Poles of pair	1	
$Rs_1 = Rs_2$	3.72	Ω
Rr	2.12	Ω
$Ls_1 = Ls_2$	0.022	H
Lr	0.006	H
L_m	0.3672	H
J	0.0625	Kgm^2
K_f	0.001	$Nm(rad/s)^{-1}$

REFERENCES

[1] S. Sunter, H. Altun and J.C. Clare: “A Control Technique for Compensating the Effects of Input Voltage variations on Matrix Converter Modulation Algorithms”, Electric Power Components and Systems, Taylor and Francis, Vol. 30, 2002, pp. 807 – 822.

[2] D. Hadiouche, “Contribution to the study of dual stator induction machines: modelling, supplying and structure”, Ph. D. dissertation (in french), GREEN, Faculty of Sciences and Techniques, University Henri Poincaré-Nancy I, France, Dec. 2001.

[3] Bojoi R., Tenconi A., Griva G., Profumo F., ”Vector Control of Dual-Three-Phase induction-Motor Drives Using Two Current Sensors ”, IEEE Trans. on Industry Applications, vol. 42, no. 5, pp. 1284-1292, September/October 2006..

[4] M. Venturini, and A. Alesina, “Analysis and design of optimum-amplitude nineswitch direct AC-AC converters,” IEEE Trans. on Power Electronics, vol. 4, pp. 101 - 112, Jan. 1989.

[5] Narayanaswamy. P.R. Iyer ,“ Carrier Based Modulation Technique for Three Phase Matrix Converters – State of the Art Progress,” IEEE Region 8 SIBIRCON-2010, Irkutsk Listvyanka, Russia, July 11 — 15, 2010

[6] Zhen-Yu Zhao, M. Tomizuka, S. Isaka : "Fuzzy Gain Scheduling of PID Controllers," *IEEE Trans. On Systems, Man. and Cybernetics, Vol 23.n°5 (1993)*

[7] Jeyalakshmi .V et. al., “On Line Tuning Of Intelligent Controller For Induction Drive System”, *International Journal of Engineering Science and Technology. 2(10), 2010, 5350-5356*

[8] A. Hazzab1, A. Laoufi1, I. K. Bousserhane1, M. Rahli, “Real Time Implementation of Fuzzy Gain Scheduling of PI Controller for Induction Machine Control”, *International Journal of Applied Engineering Research ISSN 0973 4562 Vol.1 No.1 (2006) pp. 51-60*

Bouziane Meliani is with Department of Electrical Engineering, Intelligent Control and Electrical Power Systems Laboratory (ICEPSL), Djillali Liabès University of Sidi Bel-Abbès-Algeria (e-mail: melfat06@yahoo.fr).

Abdelkader Meroufel is with the Department of Electrical Engineering, Intelligent Control and Electrical Power Systems Laboratory (ICEPSL), Djillali Liabès University of Sidi Bel-Abbès-Algeria (e-mail: ameroufel@yahoo.fr).

Houari Khouidmi is with Hassiba Benbouali University 151 Hay Es-Salam, 02000 Chlef Algeria (e-mail:houarikhouidmi@yahoo.fr)