A New PI -Fuzzy Sliding Mode Controller .Application to the Dual Star Induction Machine (DSIM)

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Abstract- **This work investigates a simple design of the new PI-Fuzzy Sliding Mode Controller (FSMC) for speed regulation of an indirect field-oriented dual star induction motor (DSIM). The fuzzy controller is driven by the error of the speed, and it change. The sliding mode controller is designed based on a plant model. The influence of different combinations of the FLC and SMC on the performance control is investigated and illustrated by some simulation results at different dynamic operating conditions such as sudden change in command speed, step change in load torque and some key parameters deviation. Finally the proposed controller is insensitive to parameter variations and load disturbances.**

Index Terms- **IFOC, Dual Star Induction Machine (DSIM), Fuzzy Sliding Mode Controller (FSMC), key parameters variation, robustness.**

1. INTRODUCTION

Since the last of 1920s years, AC double star machines known as six phases machines have been used in many applications (such as pumps, fans, compressors, rolling mills, cement mills, mine hoists [14]) for there advantages in power segmentation, precision and electromagnetic torque pulsation minimization [1], [7], [15]. Double star machine supplied with non-sinusoidal waveforms causes perturbations in the torque (Harmonics in torque). Today, with semi conductors development, voltage sources inverters can operates with high commutation frequency and can gives sinusoidal waveforms, add at this multilevel structures which reduce harmonics in output voltages [2]. Nowadays the researchers concentrate their efforts to develop the techniques of control. Several techniques are developed as scalar control or field oriented control. The main difficulty in the asynchronous machine control resides in the fact that complex coupling exists between machine input variables, output variables and machine intern variables as the field, torque or speed. The space vector control assure decoupling between these variables, and the torque is made similar as the one of a DC machine [3], [4]. The origins of the space vector control, contrary to received ideas carry up at the end of the last century to A. Blondel works on the reaction of the two axes theory.

In this paper a space vector control is applied to the machine. This technique is based on field orientation, that it is the stator field, the rotating field or by rotor field orientation. The last one will be applied to the DSIM machine using mode sliding regulators and fuzzy regulators type. Fuzzy sliding mode regulators have been successfully used for a few numbers of non linear and complex processes, (hybrids) are robust and their performances are insensible to parameter variations contrary to conventional regulators. Recently several researchers make efforts to improve the robustness and performances of the (hybrid) by using sliding mode and neuron and genetic algorithms [6], [12].

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 Wye-connected three phase sets labelled As1 Bs1 Cs1 and As2 Bs2 Cs2 whose magnetic axes are displaced by an arbitrary angle Ị. The windings of each three phase set are uniformly distributed and have axes that are displaced 120° apart. The three phase rotor windings Ar, Br, Cr are also sinusoidal distributed and have axes that are displaced apart by 120° [1], [5].

The following assumptions are made:

- Motor windings are sinusoidally distributed;
- The two stars have same parameters;
- Flux path is linear.

The voltage equation is [2]:

$$\begin{cases} \left[V_{abc.s1}\right] = \left[R_{s1}\right]\left[I_{abc.s1}\right] + \dfrac{d}{dt}\varphi_{abc.s1} \\ \left[V_{abc.s2}\right] = \left[R_{s2}\right]\left[I_{abc.s2}\right] + \dfrac{d}{dt}\varphi_{abc.s2} \\ \left[V_{abc.r}\right] = \left[R_{r}\right]\left[I_{abc.r}\right] + \dfrac{d}{dt}\varphi_{abc.r} \end{cases} \quad (1)$$

$$\begin{bmatrix} \left[\varphi_{abc.s1}\right] \\ \left[\varphi_{abc.s2}\right] \\ \left[\varphi_{abc.r}\right] \end{bmatrix} = \begin{bmatrix} \left[L_{s1.s1}\right] & \left[L_{s1.s2}\right] & \left[L_{s1.r}\right] \\ \left[L_{s2.s1}\right] & \left[L_{s2.s2}\right] & \left[L_{s2.r}\right] \\ \left[L_{r.s1}\right] & \left[L_{r.s2}\right] & \left[L_{r.r}\right] \end{bmatrix} \begin{bmatrix} \left[I_{abc.s1}\right] \\ \left[I_{abc.s2}\right] \\ \left[I_{abc.r}\right] \end{bmatrix} \quad (2)$$

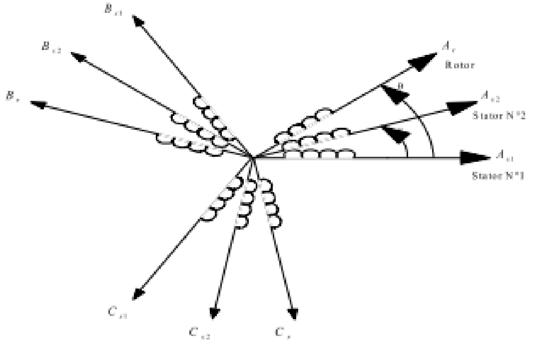


Fig1 schematic of the dual star

$$\begin{cases} [V_{abc.s1}] = [v_{as1} v_{bs1} v_{cs1}]^T ; [V_{abc.s2}] = [v_{as2} v_{bs2} v_{cs2}]^T \\ [I_{abc.s1}] = [i_{as1} i_{bs1} i_{cs1}]^T ; [I_{abc.s2}] = [i_{as2} i_{bs2} i_{cs2}]^T \\ [V_r] = [v_{ar} v_{br} v_{cr}]^T ; [I_r] = [i_{ar} i_{br} i_{cr}]^T \\ [R_{s1}] = [R_{s2}] = \mathrm{Diag}[R_s]_{(3\times3)} ; [R_r] = \mathrm{Diag}[R_r]_{(3\times3)} \end{cases}$$

The detail of the submatrixes is given at the Appendix.
where

$R_{s1} = R_{s2}$, $L_{s1} = L_{s2}$ and L_{ms} are the stator resistance, leakage inductance and magnetizing inductance;

R_r, L_r and L_{mr} the rotor resistance, leakage inductance and magnetizing inductance

M_{sr} Maximal mutual inductance between stator and rotor.

The electromagnetic torque can be expressed [7]:

$$T_{em} = \left[[I_{abc.s1}] \frac{\delta}{\delta\theta} [L_{s1.r}] [I_{abc.r}] + [I_{abc.s2}] \frac{\delta}{\delta\theta} [L_{s2.r}] [I_{abc.r}] \right] \quad (3)$$

The Park model of DSIM is presented below in the references frame at the rotating field (d, q) [5], [16], [17],

$$\begin{cases} v_{ds1} = R_{s1} i_{ds1} + p\varphi_{ds1} - \omega_s \varphi_{qs1} \\ v_{qs1} = R_{s1} i_{qs1} + p\varphi_{qs1} + \omega_s \varphi_{ds1} \\ v_{ds2} = R_{s2} i_{ds2} + p\varphi_{ds2} - \omega_s \varphi_{qs2} \\ v_{qs2} = R_{s2} i_{qs2} + p\varphi_{qs2} + \omega_s \varphi_{ds2} \\ v_{dr} = R_r i_{dr} + p\varphi_{dr} - (\omega_s - \omega_r) \varphi_{qr} \\ v_{qr} = R_r i_{qr} + p\varphi_{qr} + (\omega_s - \omega_r) \varphi_{dr} \end{cases} \quad (4)$$

The expressions for stator and rotor flux are:

$$\begin{cases} \varphi_{ds1} = L_{s1} i_{ds1} + L_m (i_{ds1} + i_{ds2} + i_{dr}) \\ \varphi_{qs1} = L_{s1} i_{qs1} + L_m (i_{qs1} + i_{qs2} + i_{qr}) \\ \varphi_{ds2} = L_{s2} i_{ds2} + L_m (i_{ds1} + i_{ds2} + i_{dr}) \\ \varphi_{qs2} = L_{s2} i_{qs2} + L_m (i_{qs1} + i_{qs2} + i_{qr}) \\ \varphi_{dr} = L_r i_{dr} + L_m (i_{ds1} + i_{ds2} + i_{dr}) \\ \varphi_{qr} = L_r i_{dr} + L_m (i_{qs1} + i_{qs2} + i_{qr}) \end{cases} \quad (5)$$

with $p = \frac{d}{dt}$; $\frac{3L_m}{2} = L_{ms} = L_{mr} = L_{sr}$

In the induction machines, rotor windings are short-circuited

Hence, i.e. $v_{dr} = 0; v_{qr} = 0.$

A. Mechanical Equation

The mechanical equation is given by [5], [7]:

$$J\frac{d\Omega}{dt} = T_{em} - T_r - K_f \Omega \quad (6)$$

With

$$T_{em} = p \frac{L_m}{L_m + L_r} \left[\varphi_{dr} (i_{qs1} + i_{qs2}) - \varphi_{qr} (i_{ds1} + i_{ds2}) \right] \quad (7)$$

3. 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. With this new technique of control and microprocessor development we can obtain speed and torque control performances comparable at those of DC machine [9].

By applying this principle $(\varphi_{dr} = \varphi_r^*, \varphi_{qr} = 0)$ equations (4) (5) and (7), the final expression of the electromagnetic torque is:

$$T_{em}^* = p \frac{L_m}{L_r + L_m} \varphi_r^* (i_{qs1}^* + i_{qs2}^*) \quad (8)$$

And

$$\omega_g^* = \frac{R_r}{L_m + L_r} (i_{qs1}^* + i_{qs2}^*) \quad (9)$$

$$\begin{cases} v_{ds1}^* = R_{s1} i_{ds1} + L_{s1} p i_{ds1} - \omega_s^* (L_{s1} i_{qs1} + T_r \varphi_r^* \omega_g^*) \\ v_{qs1}^* = R_{s1} i_{qs1} + L_{s1} p i_{qs1} + \omega_s^* (L_{s1} i_{ds1} + \varphi_r^*) \\ v_{ds2}^* = R_{s2} i_{ds2} + L_{s2} p i_{ds2} - \omega_s^* (L_{s2} i_{qs2} + T_r \varphi_r^* \omega_g^*) \\ v_{qs2}^* = R_{s2} i_{qs2} + L_{s2} p i_{qs2} + \omega_s^* (L_{s2} i_{ds2} + \varphi_r^*) \end{cases} \quad (10)$$

The goal of the regulation is to assure a best robustness to intern or extern perturbations.

In this work, a new PI-fuzzy sliding mode regulator has been used. The decoupling bloc scheme in voltage (Indirect Field Oriented Control IFOC) is given in Fig (5) .

Accepting that $i_{ds1}^* = i_{ds2}^*$ and $i_{qs1}^* = i_{qs2}^*$

4. SILDING MODE CONTROL

A sliding mode controller is a variable structure controller. Basically, a includes several different continuous functions that can map plant state to a control surface, and the switching among different functions is determined by plant state that is represented by a switching function [5, 6, 7,11]. Without lost of generality, consider the design of a sliding mode controller for the following second order system: C_{ref} , is the inputs to the IFOC system ; the following is a possible choice of the structure of a sliding mode controller [8, 9]:

$$\dot{s}_1 = -k.sign(s_1) \quad (11)$$

Where $\dot{s}_1$ is called surface change which is used when the system state is in the sliding mode. K *is* a constant and it is the maximal value of the controller output s_1 is called switching function because the control action switches its sign on the one sides of the switching surface $s_1 = 0$, s_1 is defined as:

$$s_1 = (y_2 - \omega_{ref}) \tag{12}$$

Where $sign(s)$ is a *sign* function, which is defined as:

$$sign(s_1) = \begin{cases} sign(s_1) = 1, s_1 \geq 0 \\ sign(s_1) = -1, s_1 < 0 \end{cases} \tag{13}$$

. The control strategy adopted here will guarantee the system trajectories move toward and stay on the sliding surface $s_1 = 0$, from any initial condition if the following condition meets:

$$s_1 \dot{s}_1 \prec 0 \tag{14}$$

5. FUZZY CONTROL

A fuzzy controller comprises four principle elements; fuzzification, fuzzy control rules, fuzzy inference engine, defuzzification, the design of the fuzzy controller is described as follows:

5.1Fuzzification

In the proposed fuzzy controller, the system variables are defined as follows:

$$e = \omega_r - \omega_{ref} \tag{15}$$

Δe :is change of the error.

$k_{\Delta e}$:is the gain of the fuzzification.

k_e :is the gain of the fuzzification.

$\omega_r = y_2$:is the speed rotation of the rotor .

5.2 Fuzzy inference engine

In a fuzzy inference engine, fuzzy logic principles are used to combine the fuzzy IF_THEN rules in the fuzzy control rules.

Where (k) is calculate by a fuzzy inference mechanism. Because the data manipulated in the fuzzy inference mechanism is based on fuzzy set theory, the associated fuzzy sets involved in the fuzzy control rules are defined as follows:

NG : Negative big	**NG :** Negative big
NS : Negative small	**NS :** Negative small
EZ : Zero	**EZ :** Zero
PS : Positive small	**PS :** Positive small
PG : Positive big	**PG :** Positive big

And their universe of discourses are assigned to be between [-1, 1] for the inputs (e and Δe), and [-1, 1] for the output variable Δu).

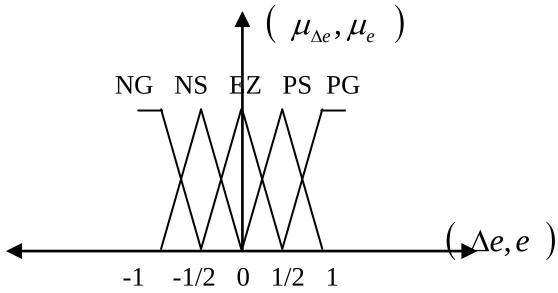


Fig. 2: Membership functions of inputs e and Δe

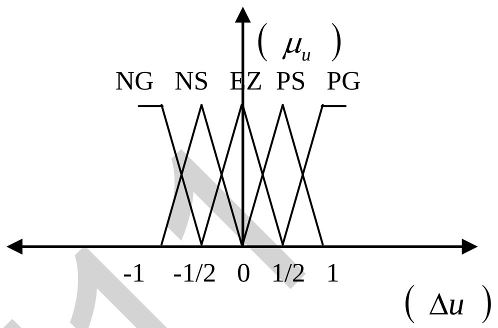


Fig. 3: Membership functions of output Δu

With fuzzy inference mechanism, the parameter Δu is transformed to an adjustable control and hence the sliding mode s1 can not be used to control the system .

5.3. Fuzzy control rules

The fuzzy inference mechanism contains twenty-five rules for each output. The resulting fuzzy inference rules for the tow outputs variables Δu are as follows:

$e/\Delta e$	NG	NS	ZE	PS	PG
NG	NG	NG	NS	NS	EZ
NS	NG	NS	NS	EZ	PS
ZE	NS	NS	EZ	PS	PS
PS	NS	EZ	PS	PS	PG
PG	EZ	PS	PS	PG	PG

5.4. Defuzzification

The fuzzy output Δu can be calculated by the centre of area defuzzification as:

$$\Delta u = \frac{\sum_{i=1}^{25} w_i c_i}{\sum_{i=1}^{25} w_i} = \frac{\begin{bmatrix} c_1 & \cdots & c_{25} \end{bmatrix} \begin{bmatrix} w_1 \\ \vdots \\ w_{25} \end{bmatrix}}{\sum_{i=1}^{25} w_i} = \upsilon^T W \tag{16}$$

Where $\upsilon = [c_1 \ \cdots \ c_{25}]$, c_1 troughs c_{25} are the centre of the membership functions of Δu and

$$W = [w_1 \ \cdots \ w_{25}] \Big/ \sum_{i=1}^{25} w_i \qquad (17)$$

6. FUZZY SLIDING MODE CONTROL (FSMC)

A block diagram of the proposed PI-fuzzy sliding mode speed controller for an indirect field oriented Induction motor drive is shown in fig.4,which consists of the induction motor drive ,the sliding mode controller and the fuzzy controller ,in the design of the proposed controller, the parameters of the sliding mode controller can be determined according to the design method of a conventional sliding mode controller ,the inputs of the fuzzy controller are the error (e) ,and the error change Δe ,

When the switching function errors (s1) is larges, the sliding mode is control the value of the (C_{ref}).

The value of (k) is constant for a particular type of the conventional (SMC),but the gain of our PI_ fuzzy sliding FLC does not remain fixed while the controller is in operation ,rather it is modified in each sampling time by the gain (α) .

Depending on the trend of the controlled process output, the reason behind this

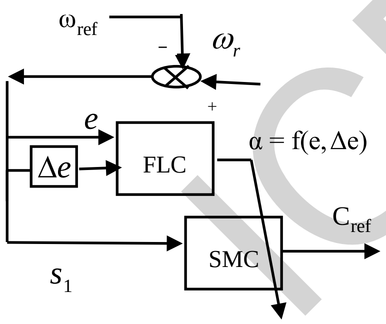


Fig 4: The block diagram of the proposed controller.

On _line gain, variation is to make the controller respond according to the desired performance specifications. We already explained how the desired variation in (α) can be achieved using the rule base in fig (Fuzzy control rules)

Let the output of the Fuzzy controller engine for adaptation gain is given as:

$$k = f(\alpha) \qquad (18)$$

Where (k) is calculates by a fuzzy inference mechanism (FLC).

Where C_{ref} is calculate by a sliding mode controller SMC).

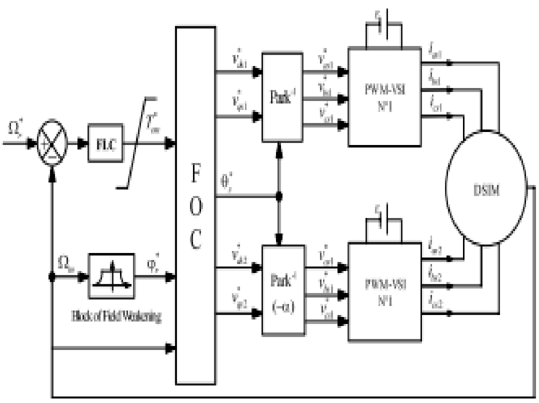
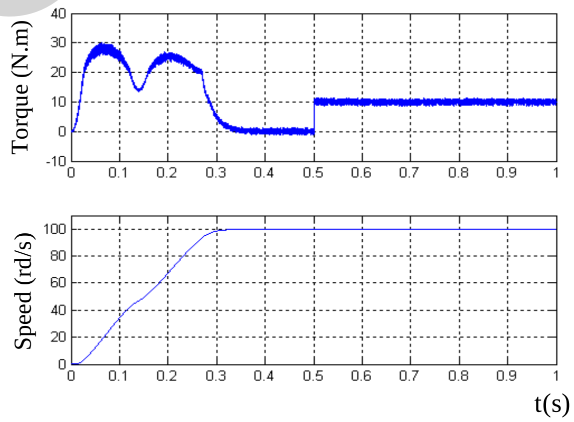


Fig (5) Speed fuzzy sliding mode controller for DISM

7. RESULTS AND DISCUSSIONS

Figs. 6. and 7 show that, the speed reaches its reference value at 0..3s without overtaking, the electromagnetic torque compensate the resistant torque et and presents at starting a value equal to 30N.m. The Fig. 9 and 8, show respectively the behaviour of the DSIM when Rr is 100% increased of its nominal value and J is increased 100% of its nominal value. The simulation results show the insensibility of the control with fuzzy (PI_fuzzy sliding mode regulator) at Rr variations, only the inertia variation increase the inversion time of the speed but without overtaking.



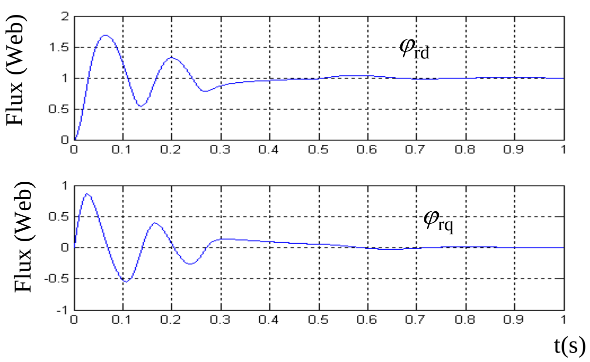
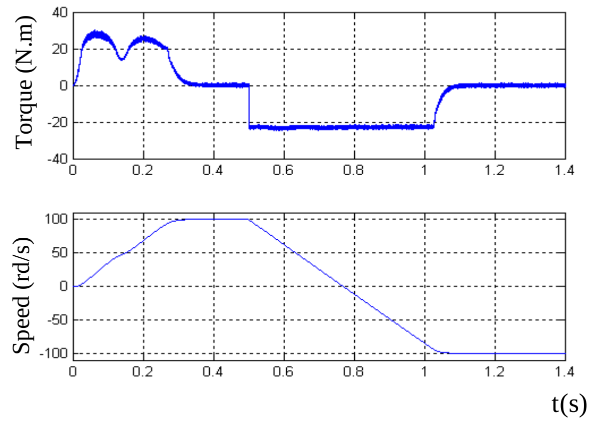


Fig. 6: The response of the machine when it is operated at 100 [rad/sec] under load 10 N.m is suddenly applied at 0.5 sec



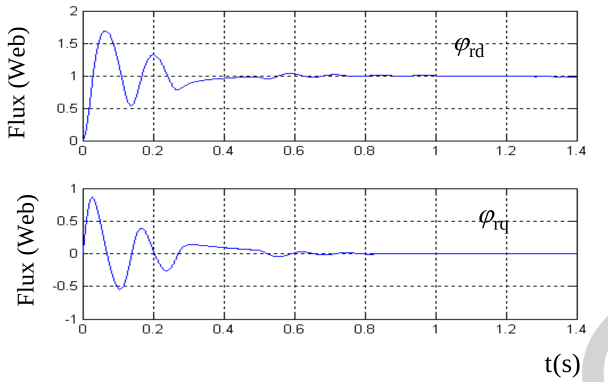


Fig. 7**:** The response of the machine when it is operated at -100 [rad/sec] under no load is suddenly applied at 0.5 sec.

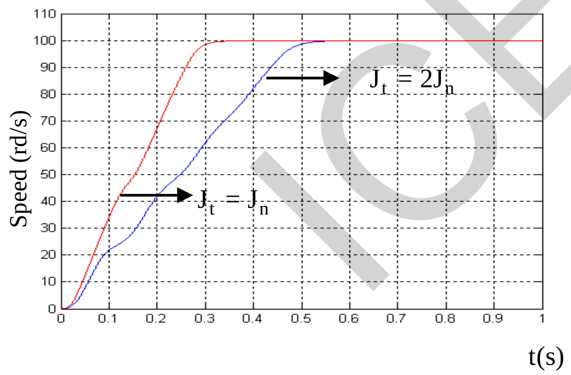


Fig. 8: Simulated results test of robustness the fuzzy sliding mode controller ($J=J_n$, $J=2*J_n$)

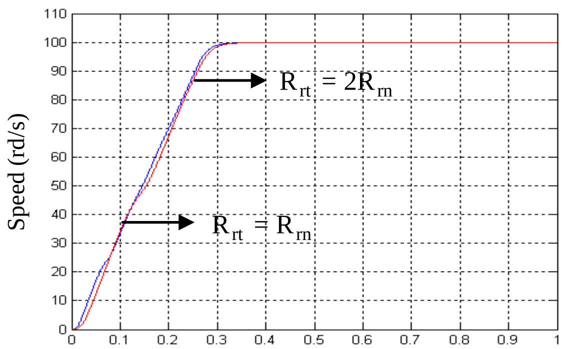


Fig.9**:** Simulated results test of robustness the fuzzy sliding mode controller (Rr; Rr ; 2*Rr)

8. CONCLUSION

In this paper, a model of a double star asynchronous machine is presented using Park transformation. The simulation results have shown that the PI-fuzzy sliding mode regulators has a very interesting dynamic performances compared with the conventional PI- fuzzy regulator and sliding mode controller , It allows to have fast response without overtaking and minimize in the case of the rotation sense change. Otherwise, the robustness tests have shown that it is insensitive to rotor resistance variation.

APPENDIX

The sub matrixes

$$\left[L_{s1.s2}\right]=\begin{bmatrix} L_{s1}+L_{ms} & -L_{ms}/2 & -L_{ms}/2 \\ -L_{ms}/2 & L_{s1}+L_{ms} & -L_{ms}/2 \\ -L_{ms}/2 & -L_{ms}/2 & L_{s1}+L_{ms} \end{bmatrix}$$

$$\left[L_{s2.s2}\right]=\begin{bmatrix} L_{r}+L_{ms} & -L_{ms}/2 & -L_{ms}/2 \\ -L_{ms}/2 & L_{s2}+L_{ms} & -L_{ms}/2 \\ -L_{ms}/2 & -L_{ms}/2 & L_{s2}+L_{ms} \end{bmatrix}$$

$$\left[L_{r.r}\right]=\begin{bmatrix} L_{r}+L_{mr} & -L_{mr}/2 & -L_{mr}/2 \\ -L_{mr}/2 & L_{r}+L_{mr} & -L_{mr}/2 \\ -L_{mr}/2 & -L_{mr}/2 & L_{r}+L_{mr} \end{bmatrix}$$

$$\left[L_{s1.s2}\right]=L_{ms}\begin{bmatrix} \cos(\alpha) & \cos(\alpha+2\pi/3) & \cos(\alpha+4\pi/3) \\ \cos(\alpha+4\pi/3) & \cos(\alpha) & \cos(\alpha+2\pi/3) \\ \cos(\alpha+2\pi/3) & \cos(\alpha+4\pi/3) & \cos(\alpha) \end{bmatrix}$$

$$\left[L_{s1.r}\right]=L_{sr}\begin{bmatrix} \cos(\theta) & \cos(\theta+2\pi/3) & \cos(\theta+4\pi/3) \\ \cos(\theta+4\pi/3) & \cos(\theta) & \cos(\theta+2\pi/3) \\ \cos(\theta+2\pi/3) & \cos(\theta+4\pi/3) & \cos(\theta) \end{bmatrix}$$

$$\left[L_{s1.r}\right]=L_{sr}\begin{bmatrix} \cos(\gamma) & \cos(\gamma+2\pi/3) & \cos(\gamma+4\pi/3) \\ \cos(\gamma+4\pi/3) & \cos(\gamma) & \cos(\gamma+2\pi/3) \\ \cos(\gamma+2\pi/3) & \cos(\gamma+4\pi/3) & \cos(\gamma) \end{bmatrix}$$

With

$\gamma = \theta - \alpha$

$$\left[L_{s2.s1}\right]=\left[L_{s1.s2}\right]^T ;\left[L_{r.s1}\right]=\left[L_{s1.r}\right]^T ;\left[L_{r.s2}\right]=\left[L_{s2.r}\right]^T$$

REFERENCES

[1] D. Hadiouche, H. Razik and A. Rezzoug, "On the modeling and design of dual-stator windings to minimize circulating harmonic

currents for VSI fed AC machines," IEEE Trans. Ind. Appl., vol. 40, no. 2, pp. 506–515, March/April 2004.

[2] M. Merabtene et E. R. Dehault, "Modélisation en vue de la commande de l'ensemble covertisseur-machine multi-phases fonctionnant en régime dégradé," Sixième conférence des jeunes chercheurs en génie électrique, JCGE'3, Saint-Nazaire, pp. 193–198, 5 et 6 Juin 2003.

[3] G.A. CAPOLINO et Y.Y. FU, "Commande des machines asynchrones par flux orienté : principe, méthode et simulation," Journée d'études SEE, Lille, 2 Décembre 1992.

[4] E.Y.Y.HO and P. C. SEN, "Decoupling control of induction motor drives," IEEE Trans. Ind. Elect., vol. 35, no 2, pp. 253–262, May 1988.

[5] G. K. Singh, K. Nam and S. K. Lim, "A simple indirect field-oriented control scheme for multiphase induction machine," IEEE Trans. Ind. Elect. vol. 52, no. 4, pp. 1177–1184, August 2005.

[6] K. Rajani, N. Mudi and R. Pal, "A Robust Self-Tuning Scheme forPI-And PD-Type Fuzzy Controllers," IEEE Trans. Fuzzy. System., vol. 7,no. 1, pp. 2–16, February 1999.

[7] D. Hadiouche, "Contribution à l'étude de la machine asynchrone double étoile modélisation, alimentation et structure," Thèse de doctorat.Université Henri Poincaré, Nancy-1, Soutenue le 20 Décembre 2001.

[8] G. Séguier, Electronique de Puissance, Editions Dunod 7ème édition. Paris, France, 1999.

[9] Y. Fu, "Commande découplées et adaptatives des machines asynchrones triphasées," Thèse de doctorat, Université MontpellierII,1991.

[10] D. Khmessi, "Commande de position des machines asynchrones avec pilotage vectoriel," Thèse de magister, Ecole militaire polytechnique à Alger, 2000.

[11] Gang Feng, "A survey on analysis and design of model- based fuzzy control systems," IEEE Trans. Fuzzy. System., vol. 14, no. 5, pp. 676– 697, october 2006.

[12] J. godjevace, Idées nettes sur la logique floue, Editions Presses Polytechniques et Universitaires Romandes, Suisse, 1980.

[13] A. Kalantri, M. Mirsalim and H. Rastegar, "Adjustable speed drive based on fuzzy logic for a dual three-phase induction machine,"Electrics Drives II, Electrimacs. August 18–21, 2002.

[14] Y. Zhao and T. A. Lipo, "Space vector PWM control of dual three phase induction machine using vector space decomposition," IEEETrans. Ind.Appl., vol. 31, no. 5, pp. 1100–1109,September/October 1995.

[15] E. Levi, "Recent developments in high performance variable-speed multiphase induction motor drives," sixth nternational symposiumnikola tesla October 18–20, 2006, Belgrade, SASA, Serbia.

[16] D. Beriber, E. M. Berkouk, A. Talha and M. O. Mahmoudi, "Study and control two two-level PWM rectifiers-clamping bridge-two three-level NPC VSI cascade. Application to double stator induction machine," 35th Annual IEEE Electronics Specialists Conference, pp.3894–3899, Aachen, Germany, 2004.

[17] V. Pant, G. K. Singh and S. N. Singh, "Modeling of a multi-phase induction machine under fault condition," IEEE International Conference on Power Electronics and Drive Systems, PEDS'99, pp. 92– 97, July 1999, Hong Kong.

[18] C. Lee, "Fuzzy logic in control systems: Fuzzy logic control, part II," IEEE Trans. Systems. Man, and Cybernetics, vol. 20, no. 2, pp. 419– 433, March/April, 1990.

[19] M. P. Veeraiah and S. M. Chitralekha Mahanta, "Fuzzy proportional integral–proportional derivative (PI-PD) controller," Proceeding of the 2004 American control conferences, pp. 4028–4033, Boston Massachusetts June 30 – July 2, 2004.