SPEED CONTROL OF A DUAL STATOR WINDINGS INDUCTION MACHINE USING FUZZY LOGIC CONTROLLER

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Abstract: *This paper presents, first a simple model and an indirect field oriented control of a double star induction motor; seconds a fuzzy logic controller to control the speed of DSIM. To achieve a control of this machine two voltage source inverter of PWM techniques are introduced. A comparison with a traditionally (PI) controller is discussed. The computer simulations are provided to demonstrate good performances and robustness of the proposed fuzzy controller in presence of load disturbances and parameter variations.*

Key words: *Double star induction machine (DSIM), indirect field oriented control (IFOC), fuzzy logic controller (FLC), voltage source inverter (VSI).*

1. Introduction

In high power variable-speed AC machine drives, the performance, the robustness are required, and in many applications, such as ship propulsion and locomotive traction require a great reliability [1]−[3].

One typical solution to improved the reliability, the performance and the robustness is to increase the number of phases in the drive and to find suitable control techniques [4] [5]. Nowadays, multi-phase drives are used in all applications requiring reliability, since a multi-phase drives can operate with an asymmetric winding structure in case of loss of one or more inverter legs/machine phases [4] [6]. Other potential advantages of the multi-phase drives when compared to the standard three-phase are [2] [6]−[9]: (1) the possibility to divide the controlled power on more inverter legs, (2) the current stress of the semiconductor devices decreases proportionally with the phase number, (3) reducing the torque pulsations at high frequency, rotor harmonic currents, and current per phase without increasing the voltage per phase.

The double star induction machine has two sets of three-phases windings spatially phase shifted by 30 electrical degrees with isolated neutral points and each star windings is fed by a three-phase voltage source inverter (VSI). However, a disadvantage of multi-phase machine is the complexity of the control algorithm. The indirect field-oriented control (IFOC) method is today widely used in various AC drives applications to achieve high performance control of three phase machines, can be extended to multi-phase machines [8] [10] [11]. The controller design of an IFOC AC machine drives plays a crucial role in control performance, the conventional PI and PID controllers is employed in speed and current controller. These controllers are very sensitive to machine parameter variations, load disturbances and along with step changes of command speed [12]−[14].

In order to obtain high performance and robustness under all conditions operation, numerous methods such as fuzzy logic controller (FLC) have been proposed to replace PI controller schemes, because the FLC has several advantageous compared with PI and PID such as [13] [15]−[17]: (i) it provides a systematic method to incorporate human experience and implement nonlinear algorithms, characterized by a series of linguistic statements, into the controller, (ii) the design of the FLC does not need the exact mathematical model of the system, (iii) the FLC is comparatively strong robustness, (iiii) the response trajectory of a fuzzy controller will change significantly when the system parameter changes are occurred.

This paper, therefore, presents the mathematical modeling and a simple high performance fuzzy logic speed controller of an IFOC-DSIM fed by two PWMVSI. Furthermore, this paper provides a comparison between the performances of FL speed controller of indirect field oriented control DSIM with those obtained from conventional PI controller under various conditions operation (parameters and reference speed variations etc.). It is found that the proposed FLC is insensitive to rotor resistance and inertia variations, and load torque disturbances. The FLC could be a suitable replacement for the conventional PI controller for high-performance variable-speed AC machine drives.

2. Machine model

The modeling and control of DSIM in the original reference frame would be very difficult. For this reason, it is necessary to obtain a simplified model to control this machine. As consequence, also the mathematical modeling approach of DSIM is similar to the standard induction machine ones and usually it is obtained under the same simplifying assumptions: the windings are sinusoidally distributed and the rotor cage is equivalent to a three-phase wound rotor; the magnetic saturation and the core losses are neglected and both stars have the same parameters.

The following voltage equations are written for a DSIM in the synchronous reference frame [11] [18] [19]:

$$v_{ds1} = R_s i_{ds1} + p\phi_{ds1} - \omega_s\phi_{qs1} \quad (1)$$
$$v_{qs1} = R_s i_{qs1} + p\phi_{qs1} + \omega_s\phi_{ds1} \quad (2)$$
$$v_{ds2} = R_s i_{ds2} + p\phi_{ds2} - \omega_s\phi_{qs2} \quad (3)$$
$$v_{qs2} = R_s i_{qs2} + p\phi_{qs2} + \omega_s\phi_{ds2} \quad (4)$$
$$0 = R_r i_{dr} + p\phi_{dr} - (\omega_s - \omega_r)\phi_{qr} \quad (5)$$
$$0 = R_s i_{qr} + p\phi_{qr} + (\omega_s - \omega_r)\phi_{dr} \quad (6)$$

The expressions for stator and rotor flux linkages are:

$$\phi_{ds1} = l_s i_{ds1} + L_m(i_{ds1} + i_{ds2} + i_{dr}) \quad (7)$$
$$\phi_{qs1} = l_s i_{qs1} + L_m(i_{qs1} + i_{qs2} + i_{qr}) \quad (8)$$
$$\phi_{ds2} = l_s i_{ds2} + L_m(i_{ds1} + i_{ds2} + i_{dr}) \quad (9)$$
$$\phi_{qs2} = l_s i_{qs2} + L_m(i_{qs1} + i_{qs2} + i_{qr}) \quad (10)$$
$$\phi_{dr} = l_r i_{dr} + L_m(i_{ds1} + i_{ds2} + i_{dr}) \quad (11)$$
$$\phi_{qr} = l_s i_{qr} + L_m(i_{qs1} + i_{qs2} + i_{qr}) \quad (12)$$

The torque and rotor dynamics equations can be expressed as

$$T_{em} = P\frac{L_m}{L_m + l_r}\left[\phi_{dr}\left(i_{qs1} + i_{qs2}\right) - \phi_{qr}\left(i_{qs1} + i_{qs2}\right)\right]$$

$$\frac{J}{P}p\omega_r = T_{em} - T_L - \frac{K_f}{P}\omega_r \quad (14)$$

Where ω_s, ω_r speed of synchronous reference frame and rotor electrical angular; p denotes differentiation w.r.t. time; l_s, l_r stator and rotor inductances; L_m resultant magnetizing inductance; P number of pole pairs; J moment of inertia; T_L load torque; K_f total viscous friction coefficient.

3. Indirect field oriented control of a DSIM

The indirect field oriented control theory applied to the DSIM aims at obtaining a decoupled control of the machine flux and torque. The *d*-axis is aligned with the rotor flux space vector. In ideal field oriented control, the rotor flux linkage axis is forced to align with the *d*-axis, and it follows that:

$$\phi_{dr} = \phi_r^* \quad (15)$$
$$p\phi_{dr} = \phi_{qr} = 0 \quad (16)$$

The commands/references voltage (v^*_{ds1}, v^*_{qs1}, v^*_{ds2} and v^*_{qs2}) are derived by substituting the (15) and (16) in (1)-(4)

$$v^*_{ds1} = R_s i_{ds1} + l_s p i_{ds1} - \omega^*_s\left(l_s i_{qs1} + T_r\phi^*_r\omega^*_{sl}\right) \quad (17)$$
$$v^*_{qs1} = R_s i_{qs1} + l_s p i_{qs1} + \omega^*_s(l_s i_{ds1} + \phi^*_r) \quad (18)$$
$$v^*_{ds2} = R_s i_{ds2} + l_s p i_{ds2} - \omega^*_s\left(l_s i_{qs2} + T_r\phi^*_r\omega^*_{sl}\right) \quad (19)$$
$$v^*_{qs2} = R_s i_{qs2} + l_s p i_{qs2} + \omega^*_s(l_s i_{ds2} + \phi^*_r) \quad (20)$$

The component references of stator current and slip speed ω_{sl} can be expressed as

$$\omega^*_{sl} = \frac{R_r L_m}{(L_m + l_r)\phi^*_r} i^*_{qs} \quad (21)$$

$$i^*_{ds} = \frac{1}{L_m}\phi^*_r \quad (22)$$

$$i^*_{qs} = \frac{(L_m + l_r)}{P L_m \phi^*_r} T^*_{em} \quad (23)$$

Where

$$i^*_{ds} = i^*_{ds1} + i^*_{ds2} \quad (24)$$
$$i^*_{qs} = i^*_{qs1} + i^*_{qs2} \quad (25)$$

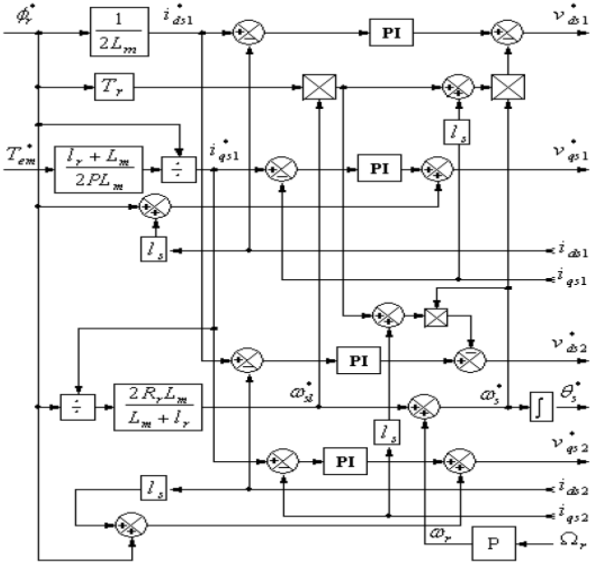


Fig. 1. IFOC based on PI controllers.

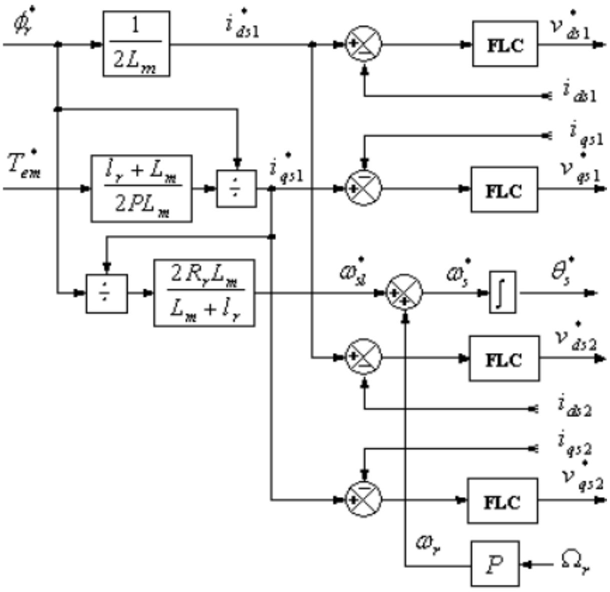


Fig. 2. IFOC based on FL controllers.

$$T_r = \frac{l_r}{R_r} \quad (26)$$

The *d*- and *q*-axes currents are relabeled as flux-producing (i^*_{ds}) and torque-producing (i^*_{qs}) components of the stator current phases, respectively. T_r denotes the rotor time constant.

For generate two sets of command/reference voltage vectors (v^*_{ds1}, v^*_{qs1}, v^*_{ds2} and v^*_{qs2}) two independent pairs of PI controllers are introduced as shows in Fig. 1, when we replace the PI by the FLC, the non-linear terms $\omega^*_s()$ in (17)-(20) can be eliminated since the FLC is non-linear regulator, a new IFOC diagram block based on FLC is developed Fig. 2.

4. Fuzzy logic speed controller for IFOC-DSIM

The main feature of fuzzy logic controllers (initiated by Mamdani and Assilian based on Fuzzy Set Theory suggested by Zadeh in 1965 [20] [21]) is that linguistic, imprecise knowledge of human experts is used.

A comprehensive review on the design and implementation of FLC's are found in a number of nonlinear processes and complex systems [15]. It is known that FLC consists of input, output scaling factors, fuzzification, fuzzy inference and defuzzification, by providing an algorithm; they convert the linguistic control strategy based on expert knowledge into an automatic control strategy [22].

The schematic diagram of the FL speed control of DSIM based on IFOC is shown in Fig. 3. The reference speed is compared with the actual speed $E=\Omega^*-\Omega_r$; this error and the change in error $\Delta E(k)=E(k)-E(k\ -1)$ are used as the input of FLC. The error and change in error are scaled by G_e and $G_{\Delta E}$ respectively for normalize them in the universe of discourse [−1, 1].

4.1. Fuzzification interface

The fuzzification interface transform the accurate input variables to fuzzy variables according to the prescribed membership functions and gives the degree of each crisp input belongs to the corresponding fuzzy set. In this paper, seven linguistic values are adapted and membership function for triangular type is adopted as shown in Fig. 4. The linguistic variables are represented by positive big (PB), positive medium (PM), positive small (PS), zero environ (ZE), negative small (NS), negative medium (NM) and negative big (NB), for E and ΔE Fig. 4(a) and for the output ΔT_{em} Fig. 4(b).

4.2. Fuzzy inference

The fuzzy inference related the inputs E_N and ΔE_N with the change in output control ΔT^*_{em}. The control rules are represented as: **IF** (condition) **THEN** (action) rules, for example, if E_N is PB and ΔE_N is NB then ΔT^*_{em} is PB. A 7×7 rule base for the conventional FLC is given in Tab. 1, to obtain the control decision. The Max-Min inference method is used. It is possible to generate several control actions. The output of the fuzzy controller is the reference torque.

4.3. Defuzzification

The defuzzification operation produce a non-fuzzy output control action that best represents the recommended control actions of the different rules; seven singleton membership functions are selected for the command torque presents in the table 1. For calculate the crisp value of the output command torque, the centre of area is used equa (27).

$$\Delta T_N = \frac{\sum_{i=1}^{m}\mu(\Delta T_{emi})\Delta T_{emi}}{\sum_{i=1}^{m}\mu(\Delta T_{emi})} \qquad (27)$$

Where, m is the total number of rules (49 rules); $\mu(\Delta T_{emi})$ – the membership grade for i^{th} rule; ΔT_{emi} – the position of the singleton in rule i^{th}.

Finally the reference electromagnetic torque T^*_{em} (input of IFOC block in Fig. 3) is obtained by the following equations [23] [24]

$$\Delta T^*_{em} = G_T \Delta T_N \qquad (28)$$

$$T^*_{em}(k) = T^*_{em}(k-1) + \Delta T^*_{em}(k) \qquad (29)$$

Where, k is the sampling instant.

Tab. 1. Fuzzy rules for computation of ΔT_{emi}.

		ΔE_N						
	ΔT_{emi}	**NB**	**NM**	**NS**	**ZE**	**PS**	**PM**	**PB**
E_N	**NB**	NB	NB	NB	NB	NM	NS	ZE
	NM	NB	NB	NB	NM	NS	ZE	PS
	NS	NB	NB	NM	NS	ZE	PS	PM
	ZE	NB	NM	NS	ZE	PS	PM	PB
	PS	NM	NS	ZE	PS	PM	PB	PB
	PM	NS	ZE	PS	PM	PB	PB	PB
	PB	ZE	PS	PM	PB	PB	PB	PB

5. Simulation results

Many tests were performed to evaluate the performance of the FLC of an IFOC-DSIM, In order to compare the performances of the speed-control IFOC-DSIM; the same tests are made with the PI controller. The speed responses are observed under different operating conditions such as a sudden change in command speed, step change in load, etc. Some sample results are presented in the following section.

Table 2 shows the parameter of the used DSIM for simulation whose general specifications are 4.5kW, 2753rpm, 220/380V, 2 poles.

Tab. 2. DSIM parameters used for simulation.

Stator resistance R_s	3.72Ω
Rotor resistance R_r	2.12Ω
Stator leakage inductance l_s	0.022 H
Rotor leakage inductance l_r	0.006 H
Resultant magnetizing inductance L_m	0.3672 H
Moment of inertia J	0.0662 kg.m^2
Viscous friction coefficient K_f	0.001 kg.m^2/s

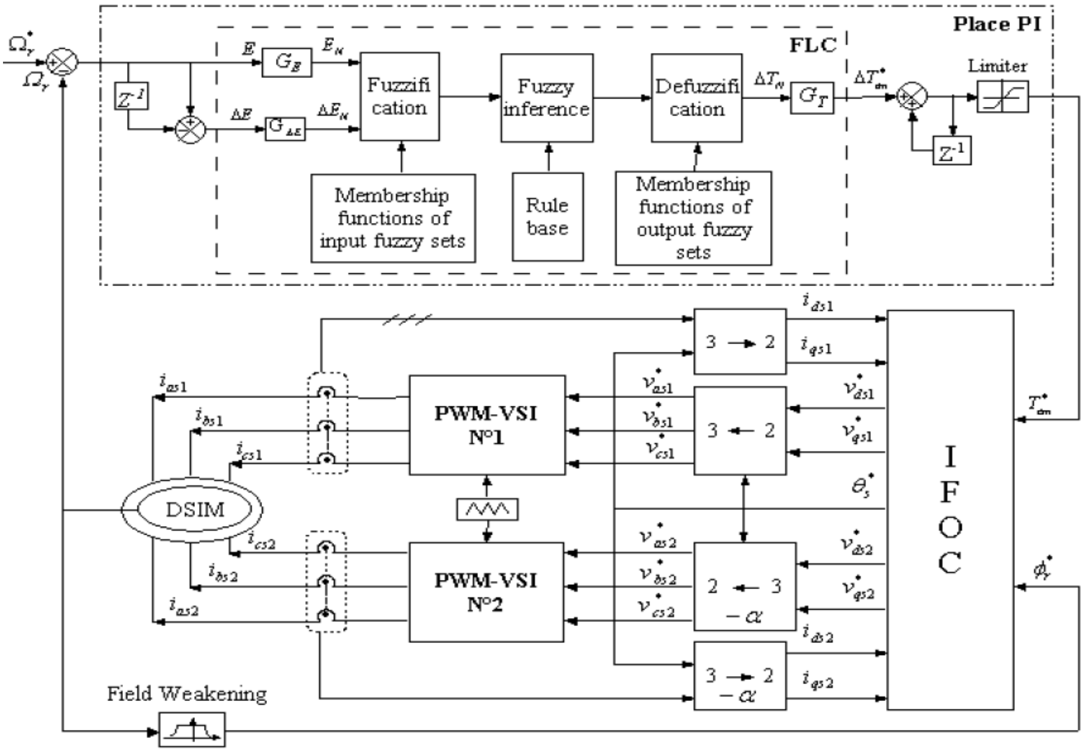
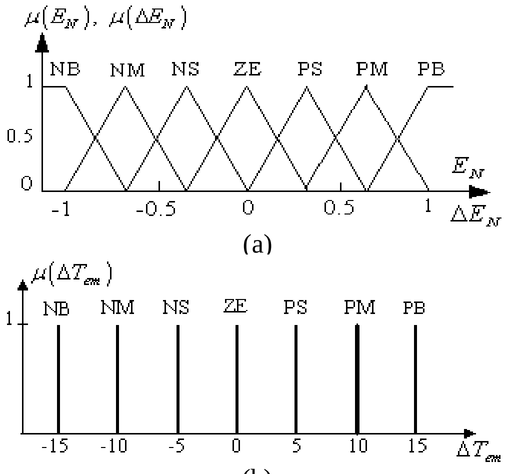


Fig. 3. Block diagram of fuzzy speed control of IFOC-DSIM.



(a)

(b)

Fig. 4. Membership functions of (a) E, ΔE, (b) ΔTem.

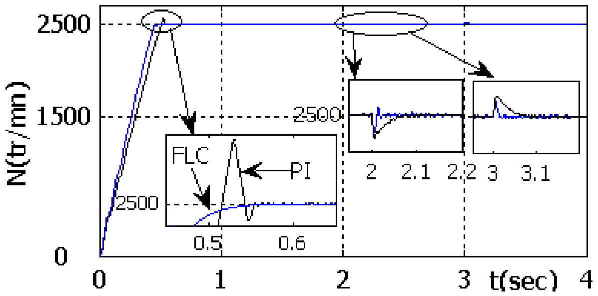
The PI controller is tuned at rated conditions in order to make a fair comparison between the speed control of the DSIM-IFOC by a PI and a FLC is presented in all figures. This comparison shows clearly that the FLC gives good performances and it's more robust than PI.

The Fig. 5 presents the transient responses for IFOC of DSIM drive using the proposed PI and FLC with applying a step increase in load (from zero to rated torque) then removing the load after 1 *second*, the reference speed is *2500 rpm*. At both speeds, the FLC offers a faster response time with no overshoot, and rejects the load disturbance very quickly with smaller overshoot/undershoot, Fig. 5(a), the overshoot of PI is *51rpm* and the maximum drop of speed is *38rpm*. The harmonics magnitude of electromagnetic torque produced by the FLC is inferior than produced by PI, Fig. 5(b).

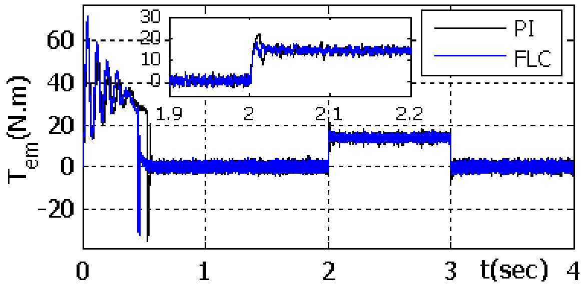
The Fig. 6 presents the speed and electromagnetic torque response of the DSIM to a step change in command speed at no load. The change in command speed is realized as following: ([0 1] sec Ω^*=*1000rpm*), (]1 2] sec Ω^*=*2000rpm*) and (]2 3] sec Ω^*=*2500rpm*). The rotor speed obtained by the FLC track very quickly the desired reference speed than the one obtained with PI, Fig. 6(a). The Fig. 6(b) shows that the DSIM developed an electromagnetic torque in any change of speed reference for forcing the actual rotor speed to follow the desired reference.

The Fig. 7 presents the performances of FLC and PI speed control when the rotor resistance is changed. It is shown that the FLC insensitive to constant time variation contrary to the PI, the speed oscillations appeared at the applying of load torque, Fig. 7(a). These oscillations due to the electromagnetic torque harmonics, Fig. 7(b).

The Fig. 8 presents the performances of FLC and PI speed control when the moment of inertia is varied. It is shown that the FLC gives the same performances obtained when the moment of inertia not varied, Fig. 8(a), contrary to the PI controller, Fig. 8(b).

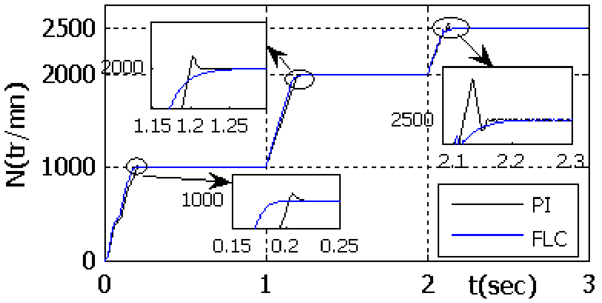


(a) Rotor speed (rpm).

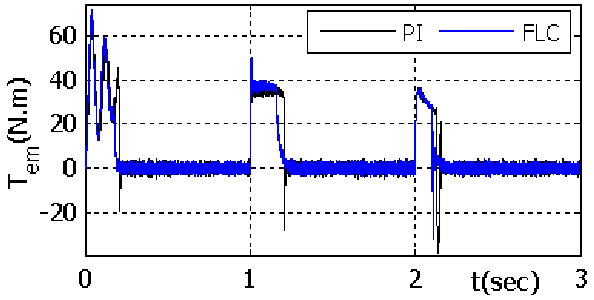


(b) Electromagnetic torque (N.m).

Fig. 5. Simulated responses to step reference speed from standstill to 2500 rpm followed by applying rated load torque (14N.m) then removing the load after 1 sec.

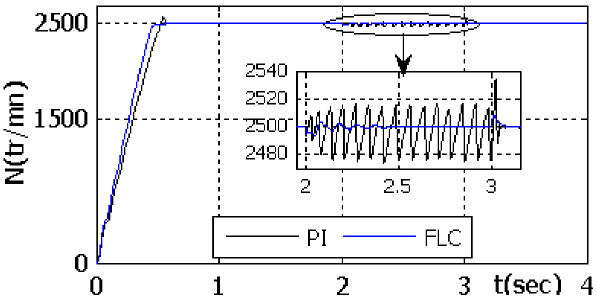


(a) Rotor speed (rpm).

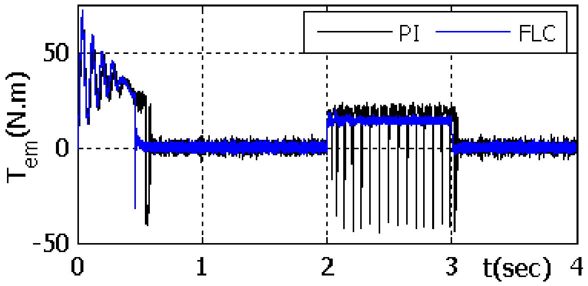


(b) Electromagnetic torque (N.m).

Fig. 6. Simulated responses to a stairs of reference speed with no load.

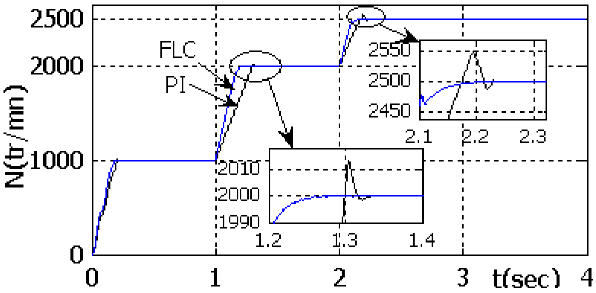


(a) Rotor speed (rpm).

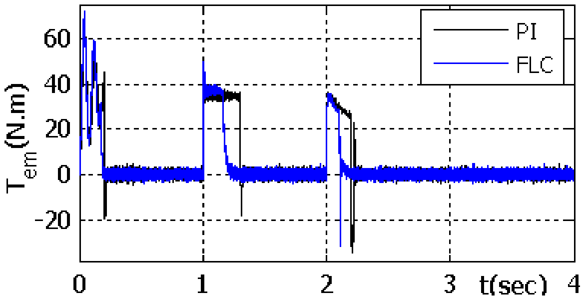


(b) Electromagnetic torque (N.m).

Fig. 7. Simulated responses for a step reference speed with an increased rotor resistance *(*$\Delta R_r\%$ *= +50%* at *t = 1s* followed by applying load torque (*14N.m*) at *t = 2sec* then removing the load after 1 sec.



(a) Rotor speed (rpm).



(b) Electromagnetic torque (N.m).

Fig. 8. Simulated responses for a stairs of reference speed with an increased moment of inertia ($\Delta J\%$ = +50%) at t = 1sec under no load.

6. Conclusion

In this paper, the performances of speed FL and PI controllers for indirect field-oriented DSIM drive are presented, the simulation results show that the FLC gives a superior performances compared with traditional controller (PI). The robustness tests show too that the FLC is more robust than the PI controller with the parameter (rotor resistance, moment of inertia) variations.

The FLC is an useful tool for replacing the PI in all applications (high power variable-speed multi-phase induction machine drives) requiring a good performance and a great robustness.

References

[1] Jahns T. M., "Improved reliability in solid-state ac drives by means of multiple independent phase-drive units," *IEEE Trans. Ind. Appl.*, vol. IA16, no. 3, pp. 321–331, 1980.

[2] Alcharea R., Nahidmobarakeh B., Betin F. and Capolino G. A., "Direct torque control (DTC) for six-phase symmetrical induction machine under open phase fault," *In IEEE, MELECON'08. The 14th IEEE Mediterranean.*, pp. 508–513, May. 2008.

[3] Fu J. R., Lipo T. A., "Disturbance-free operation of a multiphase current-regulated motor drive with an opened phase," *IEEE Trans. Ind. Appl.*, vol. 30, no. 5, pp. 1267–1274, Jan. 1994.

[4] Aroquiadassou G., Henao H., Capolino G. A., Boglietti A. and Cavagnino A., "A simple circuit-oriented model for predicting six-phase induction machine performances," *IEEE 32nd Annual Conference on Industrial Electronics, IECON*'06. pp.1441–1446, Paris (France), Nov. 2006.

[5] Fnaiech M. A., Betin F., Nahid B., Capolino G. A., "Control position of a faulted six phase induction machine (6PIM) using sliding mode control," *In IEEE, MELECON'08. The 14th IEEE Mediterranean.*, pp. 502–507, May. 2008.

[6] Bojoi R., Levi E., Farina F., Tenconi A. and Profumo F., "Dual three phase induction motor drive with digital current control in the stationary reference frame," *IEE Proc. Electr. Power Appl.*, vol. 153, no. 1, pp. 129–139. Jan. 2006.

[7] Hadiouche D., "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 Poincare-Nancy I, France*, Dec. 2001.

[8] Bojoi R., Tenconi A., Griva G., and Profumo F., "Vector control of dual-three-phase induction-motor drives using two current sensors," *IEEE Trans. Ind.*, vol. 42, no. 5, pp. 1284–1292, Sept/Oct. 2006.

[9] Donghua P., Hongxing Wu, Fengxiang Wang, Kan Deng, "Study on dual stator winding induction generator system based on fuzzy control" *IEEE Vehicle Power and Propulsion Conference (VPPC)*, Harbin, China, September 3-5, 2008.

[10] Yong-le Ai, Kamper M. J. and Le Roux A. D., "Novel direct field and direct torque control of six-phase induction machine with special phase current waveform," *In IEEE. Ind. App. Conf, 41st IAS.2006.*, vol. 2, pp. 805–812.

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

[12] Yi S. Y. and Chung M. J., "Robustness of fuzzy logic control for an uncertain dynamic system," *IEEE Trans. Fuzzy Syst.*, vol. 6, pp. 216–224, May. 1998.

[13] Uddin M. N., Radwan T. S. and Rahman M. A., "Performances of fuzzy-logic-based indirect vector control for induction motor drive," *IEEE Trans. Ind. App.*, vol. 38, no. 5, pp. 1219–1225, Sep/Oct. 2002.

[14] Krishnan R., Doran F., "Study of parameter sensitivity in high performance inverter fed induction motor drive systems," *IEEE Trans. Ind. Appl.*, vol. 23, pp. 623635, Jul/Aug. 1987.

[15] Butt C. B., Hoque M. A. and Rahman M. A., "Simplified fuzzy-logic based MTPA speed control of IPMSM drive," *IEEE Trans. Ind. App.*, vol. 40, no. 6, pp. 1529–1535, Nov/Dec. 2004.

[16] Liaw C. M., Lin F. J., "Position control with fuzzy adaptation for induction servomotor drive," *IEE Proc. Elec. Power Appl.*, vol. 142, no. 6, pp. 397–404, Nov. 1995.

[17] Li Zhen and Xu L., "Fuzzy learning enhanced speed control of an indirect field-oriented induction machine drive," *IEEE Trans. Cont. Sys. Techno.*, vol. 8, no. 2, pp. 270–278, Mar. 2000.

[18] Liop T. A., "A d-q model for six phase induction machines," *in Proc. ICEM'80*, pp. 860–870, Athens, Greece, 1980.

[19] Singh G. K., "Modeling and experimental analysis of a self-excited six-phase induction generator for stand-alone renewable energy generation," *Renewable Energy Elsevier.*, vol. 33, pp. 1605–1621, 2007.

[20] Mamdani E. H. and Assilian S., "An experiment in linguistic synthesis with a fuzzy logic controller," *Internat. J. Man-Machine Stud.*, vol. 7, pp. 1–13, 1975.

[21] Zadeh L. A., "Fuzzy sets," *Inform. and control.*, vol. 8, pp. 338–353, Jan. 1965.

[22] Lee C. C., "Fuzzy logic in control systems: fuzzy logic controller Parts I & II," *IEEE Trans. Sys, Man and Cyber.*, vol. 20, no. 2, pp. 404–435, Mar/Apr, 1990.

[23] Lee J., "On methods for improving performance of PI-type fuzzy logic controllers," *IEEE Tran. Fuzz. Sys.*, vol. 1, no. 4, pp. 298–301, Nov. 1993.

[24] Mudi R. K., Pal N. R., "A robust self-tuning scheme for PI- and PD type fuzzy controllers," *IEEE Trans, Fuzzy Syst.*, vol. 7, pp. 1–16, Feb. 1999.