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A FUZZY LOGIC CONTROLLER FOR SYNCHRONOUS MACHINE

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Fuzzy logic or fuzzy set theory is recently getting increasing emphasis in process control applications. This paper presents an application of fuzzy logic to control the speed of a synchronous machine (SM). Based on the analysis of the SM transient response and fuzzy logic, a fuzzy controller is developed. The fuzzy controller generates the variations of the reference current vector of the SM speed control based on the speed error and its change. Digital simulation results shows that the designed fuzzy speed controller realises a good dynamic behaviour of the motor, a perfect speed tracking with no overshoot and a good rejection of impact loads disturbance. The results of applying the fuzzy logic controller to a SM give best performances and high robustness than those obtained by the application of a conventional controller (PI).

Keywords: synchronous motor, fuzzy logic, speed control

1 INTRODUCTION

The fuzzy logic control (FLC) has been an active research topic in automation and control theory since the work of Mamdani proposed in 1974 based on the fuzzy sets theory of Zadeh (1965) to deal with the system control problems which are not easy to be modeled [1].

The concept of FLC is to utilize the qualitative knowledge of a system to design a practical controller. For a process control system, a fuzzy control algorithm embeds the intuition and experience of an operator designer and researcher. The control doesn't need accurate mathematical model of a plant, and therefore, it suits well to a process where the model is unknown or ill-defined and particularly to systems with uncertain or complex dynamics. Of course, fuzzy control algorithm can be refined by adaptation based on learning and fuzzy model of the plant [2].

The fuzzy control also works as well for complex nonlinear multi-dimensional system, system with parameter variation problem or where the sensor signals are not precise. The fuzzy control is basically nonlinear and adaptive in nature, giving robust performance under parameter variation and load disturbance effect.

As an intelligent control technology, fuzzy logic control (FLC) provides a systematic method to incorporate human experience and implement nonlinear algorithms, characterized by a series of linguistic statements, into the controller. In general, a fuzzy control algorithm consists of a set of heuristic decision rules and can be regarded as an adaptive and nonmathematical control algorithm based on a linguistic process, in contrast to a conventional feedback control algorithm [3, 4]. The implementation of such control consists of translating the input variables to a language like: positive big, zero, negative small, etc. and to establish control rules so that the decision process can produce the appropriate outputs. Fuzzy control (FC) using linguistic information possesses several advantages such as robustness, model-free, universal approximation theorem and rules-based algorithm [5–7].

Recent literature has explored the potentials of fuzzy control for machine drive application [8, 9]. It has been shown that a properly designed direct fuzzy controller can outperform conventional proportional integral derivative (PID) controllers [9].

In this paper the application of fuzzy logic in synchronous speed control is described. The organization of this paper is as follows: in Section 2, the vector control principle for synchronous motor drive is presented; in Section 3, the proposed controller is described, and used to control the speed synchronous motor. Simulation results are given to show the effectiveness of this controller and finally conclusions are summarized in the last section.

2 SYNCHRONOUS MOTOR DRIVE

2.1 Machine equations

The more comprehensive dynamic performance of a synchronous machine can be studied by synchronously rotating d-q frame model known as Park equations. The dynamic model of synchronous motor in d-q frame can be represented by the following equations [10, 11]:

$$\begin{aligned} v_{ds} &= R_s i_{ds} + \frac{\mathrm{d}}{\mathrm{d}t}\Phi_{ds} - \omega\Phi_{qs}\,, \\ v_{qs} &= R_s i_{qs} + \frac{\mathrm{d}}{\mathrm{d}t}\Phi_{qs} + \omega\Phi_{ds}\,, \\ v_f &= R_f i_f + \frac{\mathrm{d}}{\mathrm{d}t}\Phi_f\,. \end{aligned} \tag{1}$$

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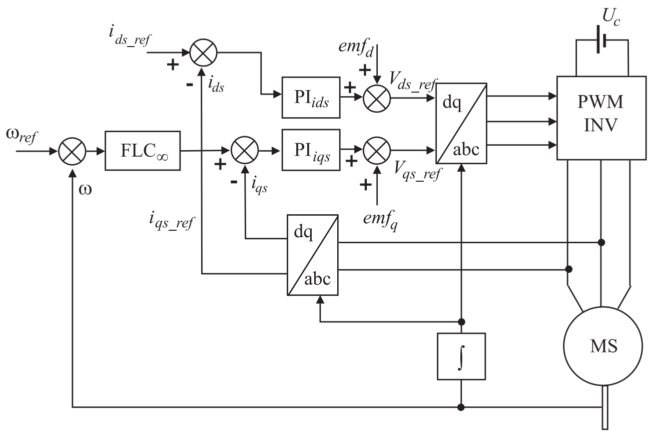

Fig. 1. System Configuration of Field-Oriented Synchronous Motor

The mechanical equation of synchronous motor can be represented as:

$$J\frac{\mathrm{d}}{\mathrm{d}t}\Omega = C_e - C_r - B\Omega\,. \tag{2}$$

Where the electromagnetic torque is given in d-q frame:

$$C_e = p\big(\Phi_{ds} i_{qs} - \Phi_{qs} i_{ds}\,. \tag{3}$$

In which: $\Omega = \frac{\mathrm{d}}{\mathrm{d}t}\Theta$, $\Theta = \int \Omega \mathrm{d}t$, $\omega = \frac{\mathrm{d}}{\mathrm{d}t}\Theta_e = p\Omega$, $\Theta_e = p\Theta$.

The flux linkage equations are:

$$\begin{aligned} \Phi_{ds} &= L_{ds} i_{ds} + M_{fd} i_f\,, \\ \Phi_{qs} &= L_{qs} i_{qs}\,, \\ \Phi_f &= L_f i_f + M_{fd} i_{ds}\,. \end{aligned} \tag{4}$$

Where R_s – stator resistance, R_f – field resistance, L_{ds}, L_{qs} – respectively direct and quadrature stator inductances, L_f – field leakage inductance, M_{fd} – mutual inductance between inductor and armature, Φ_{ds} and Φ_{qs} – respectively direct and quadrature flux, Φ_f – field flux, C_e – electromagnetic torque, C_r – external load disturbance, p – pair number of poles, B – is the damping coefficient, J – is the moment of inertia, ω – electrical angular speed of motor. Ω – mechanical angular speed of motor, Θ – mechanical rotor position, Θ_e – electrical rotor position.

2.2 Description of the system

The schematic diagram of the speed control system under study is shown in Fig. 4. The power circuit consists of a continuous voltage supply which can provided by a six rectifier thyristors and a three phase GTO thyristors inverter whose output is connected to the stator of the synchronous machine [12]. The field current i_f of the synchronous machine, which determines the field flux level is controlled by voltage v_f. The parameters of the synchronous machine are given in the Appendix [13].

The self-control operation of the inverter-fed synchronous machine results in a rotor field oriented control of the torque and flux in the machine. The principle is to maintain the armature flux and the field flux in an orthogonal or decoupled axis. The flux in the machine is controlled independently by the field winding and the torque is affected by the fundamental component of armature current i_{qs}. In order to have an optimal functioning, the direct current i_{ds} is maintained equal to zero [10, 11].

Substituting (4) in (3) and denoting $\lambda = pM_{fd} i_f$, the electromagnetic torque can be rewritten for $i_f = constant$ and $i_{ds} = 0$ as follow:

$$C_e(t) = \lambda i_{qs}(t) \tag{5}$$

In the same conditions, it appears that the v_{ds} and v_{qs} equations are coupled. We have to introduce a decoupling system, by introducing the compensation terms:

$$\begin{aligned} emf_d &= \omega L_{qs} i_{qs}\,, \\ emf_q &= -\omega L_{ds} i_{ds} - \omega M_{af} i_f\,. \end{aligned} \tag{6}$$

Figure 1 shows the schematic diagram of the speed control of synchronous motor using fuzzy sliding mode control.

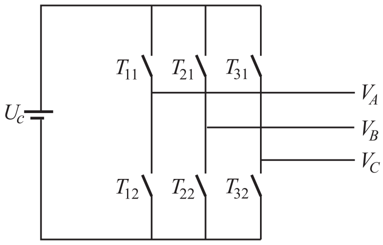

Fig. 2. Voltage inverter

The blocks FLC$_\omega$, PI$_{id}$ and PI$_{iq}$ are regulators, the first is the fuzzy controller for speed, the second is the proportional integral (PI) regulator for direct current and the third is the PI regulator for the quadrature current. To avoid the appearance of an inadmissible value of current, a saturation bloc is used.

2.3 Voltage inverter

The power circuit of a three-phase bridge inverter using six switch device is shown in Fig. 2. The dc supply is normally obtained from a utility power supply through a bridge rectifier and LC filter to establish a stiff dc voltage source [10].

The switch T_{ci} ($c \in \{1,2,3\}$, $i \in \{1,2\}$) is supposed perfect. The simple inverter voltage can be presented by logical function connexion in matrix form as [12, 14].

$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}\begin{bmatrix} F_{11} \\ F_{21} \\ F_{31} \end{bmatrix} U_c\,, \tag{7}$$

where the logical function connexion F_{c1} is defined as: $F_{c1} = 1$ if the switch T_{c1} is closed, $F_{c1} = 0$ if the switch T_{c1} is opened, U_c is the voltage feed inverter.

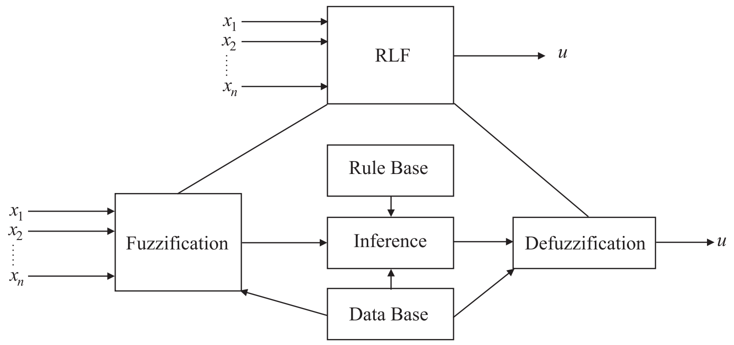

Fig. 3. The structure of a fuzzy logic controller

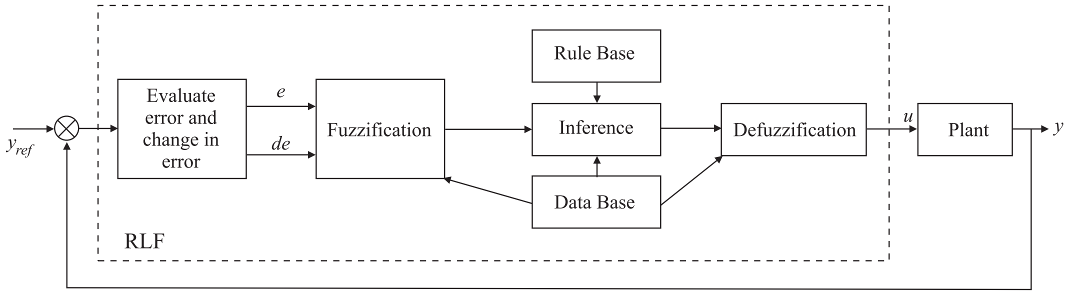

Fig. 4. Basic structure of fuzzy control system

3 FUZZY LOGIC CONTROL

3.1 Fuzzy logic principle

The structure of a complete fuzzy control system is composed from the following blocs: Fuzzification, Knowledge base, Inference engine, Defuzzification.

Figure 3 shows the structure of a fuzzy logic controller.

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 universe of discourse, and the fuzzy sets (characterized by membership function) cover the whole universe of discourse. The shape fuzzy sets can be triangular, trapezoidale, *etc* [15, 16].

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 R. 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, such as:

$$R^{(i)}: \textbf{If } x_1 \text{ is } F_1 \text{ and } x_2 \text{ is } F_2 \dots \text{ and } x_n \text{ is } F_n \quad \textbf{THEN } Y \text{ is } G^{(i)},\ i=1,\dots,M \tag{8}$$

where: $(x_1, x_2, \dots, x_n)$ is the input variables vector, Y is the control variable, M is the number of rules, n is the number fuzzy variables, $(F_1, F_2, \dots F_n)$ are the fuzzy sets.

For the given rule base of a control system, the fuzzy controller determines the rule base to be fired for the specific input signal condition and then computes the effective control action (the output fuzzy variable) [15, 17].

The composition operation is the method by which such a control output can be generated using the rule base. Several composition methods, such as max-min or sup-min and max-dot have been proposed in the literature.

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 [17, 18].

3.2 Fuzzy logic controller

The general structure of a complete fuzzy control system is given in Fig. 4. The plant control u is inferred from the two state variables, error (e) and change in error Δe [15].

The actual crisp input are approximates to the closer values of the respective universes of discourse. Hence, the fuzzyfied inputs are described by singleton fuzzy sets.

The elaboration of this controller is based on the phase plan. The control rules are designed to assign a fuzzy set

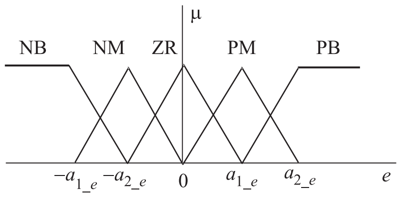

Fig. 5. Membership functions for input e

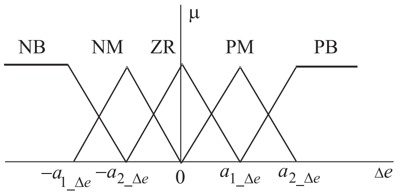

Fig. 6. Membership functions for input Δe

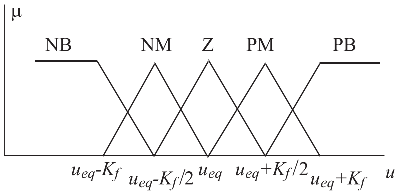

Fig. 7. Membership functions for output u

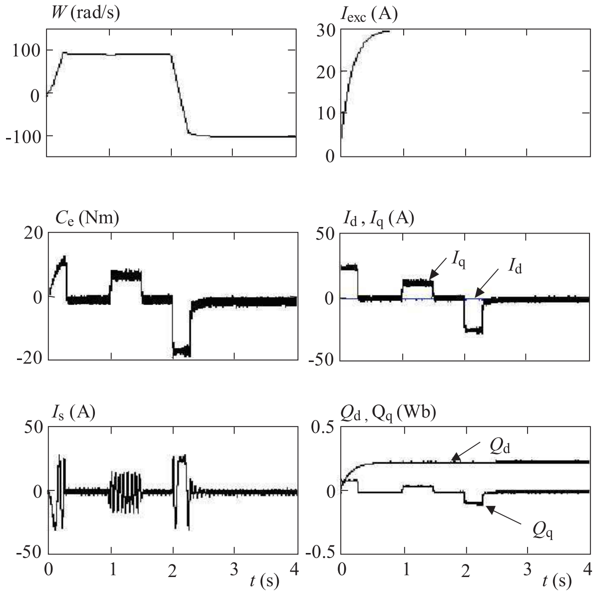

Fig. 8. Simulation results of speed control with fuzzy logic

of the control input u for each combination of fuzzy sets of e and Δe [19, 20].

Table 1 shows one of possible control rule base. The rows represent the rate of the error change $\dot{e}$ and the columns represent the error e. Each pair $(e, \dot{e})$ determines the output level NB to PB corresponding to u.

Here NB is negative big, NM is negative medium, ZR is zero, PM is positive medium and PB is positive big, are labels of fuzzy sets and their corresponding membership functions are depicted in Figs. 5, 6 and 7, respectively.

The continuity of input membership functions, reasoning method, and defuzzification method for the continuity of the mapping $u_{fuzzy}(e, \dot{e})$ is necessary. In this paper, the triangular membership function, the max-min reasoning method, and the center of gravity defuzzification method are used, as those methods are most frequently used in many literatures [15, 18].

Table 1. Rules Base for speed control

Du		DE$_n$				
		NB	NM	ZR	PM	PB
E$_n$	NB	NB	NB	NM	NM	ZR
	NM	NB	NM	NM	ZR	PM
	ZR	NM	NM	ZR	PM	PM
	PM	NM	ZR	PM	PM	GP
	PB	ZR	PM	PM	GP	GP

4 SIMULATION AND RESULTS

In order to validate the control strategies as discussed above, digital simulation studies were made the system described in Fig. 1. The speed and currents loops of the drive were also designed and simulated respectively with fuzzy control and PI control. The feedback control algorithms were iterated until best simulation results were obtained.

The speed loop was closed, and transient response was tested with both PI current control and fuzzy speed control. The simulation of the starting mode without load is done, followed by reversing of the reference $\omega_{ref} = \pm 100$ red/s at $t_3 = 2s$. The load $s\,(C_r = 7$ Nm) is applied at $t_1 = 1$ s and eliminated at $t_2 = 1.5$ s.

The simulation is realized using the SIMULINK software in MATLAB environment. Figure 8 shows the performances of the fuzzy controller.

The control presents the best performances, to achieve tracking of the desired trajectory. The fuzzy controller rejects the load disturbance rapidly with no overshoot and with a negligible steady state error. The current is limited in its maximal admissible value by a saturation function. The decoupling of torque-flux is maintained in permanent mode.

The reason for superior performance of fuzzy controlled system is that basically it is adaptive in nature and the controller is able to realize different control law for each input state (E and CE).

Robustness

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).

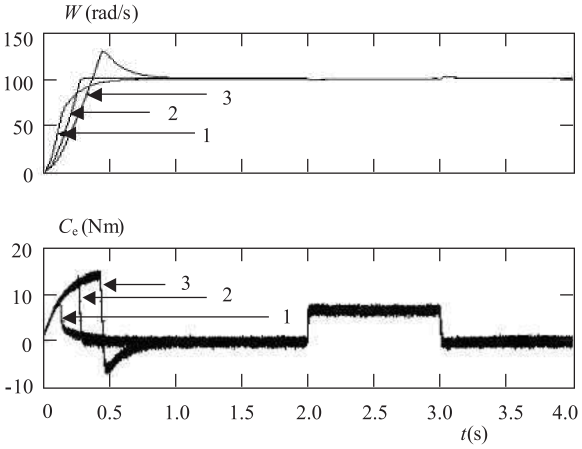

Fig. 9. Test of robustness for different values of the moment of inertia: 1) $-50\,\%$, 2) nominal case, 3) $+50\,\%$.

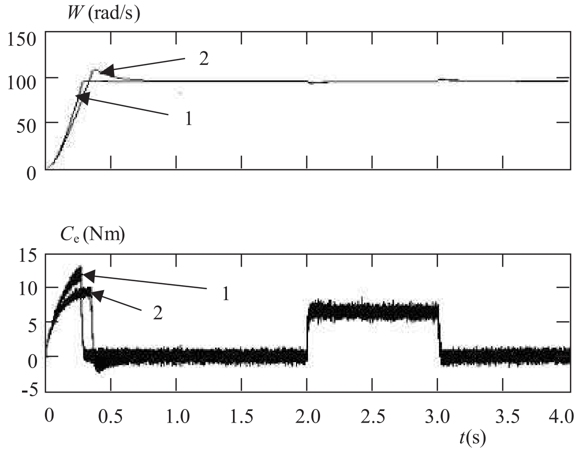

Fig. 10. Test of robustness for different values of stator and rotor resistances: 1) nominal case, 2) $+50\,\%$.

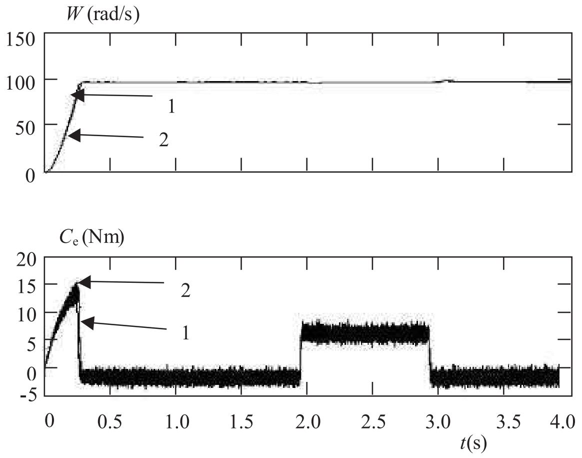

Fig. 11. Test of robustness for different values of stator and rotor inductances: 1) nominal case, 2) $+20\,\%$.

Three cases are considered:

1. The moment of inertia ($\pm 50\,\%$).
2. The stator and rotor resistances ($+50\,\%$).
3. The stator and rotor inductances ($+20\,\%$).

To illustrate the performances of control, we have simulated the starting mode of the motor without load, and the application of the load ($C_r = +7$ Nm) at the instance $t_1 = 2$ s and it's elimination at $t_2 = 3$ s; in presence of the variation of parameters considered (the moment of inertia, the stator resistances, the stator inductances) with speed step of $+100$ rad/s.

Figure 9 shows the tests of robustness realized with the fuzzy control for different values of the moment of inertia.

Figure 10 shows the tests of robustness realized with the fuzzy control for different values of stator and rotor resistances.

Figure 11 shows the tests of robustness realized with the fuzzy control for different values of stator and rotor inductances.

For the robustness of control, a decrease or increase of the moment of inertia J, the resistances or the inductances doesn't have any effects on the performances of the technique used (Figs. 10 and 11). An increase of the moment of inertia gives best performances, but it presents a slow dynamic response (Fig. 9). The fuzzy control gives to our controller a great place towards the control of the system with unknown parameters.

5 CONCLUSION

The paper presents a new approach to robust speed control for synchronous motor. The paper develops a simple robust controller to deal with parameters uncertain and external disturbances and takes full account of system noise, digital implementation and integral control. The control strategy is based on FLC approaches.

A complete fuzzy logic control based synchronous motor has been described. The system was analyzed and designed, and performances were studied extensively by simulation to validate the theoretical concept. The simulation results show that the proposed controller is superior to conventional controller in robustness and in tracking precision. The simulation study clearly indicates the superior performance of fuzzy control, because it is inherently adaptive in nature. It appears from the response properties that it has a high performance in presence of the plant parameters uncertain and load disturbances. It is used to control system with unknown model. The control of speed by FLC gives fast dynamic response with no overshoot and negligible steady-state error. The decoupling, stability and convergence to equilibrium point are verified.

Appendix

Three phases SM parameters: Rated output power 3 HP, Rated phase voltage 60 V, Rated phase current 14 A, Rated field voltage $v_f = 1.5$ V, Rated field current $i_f = 30$ A, Stator resistance $R_s = 0.325\,\Omega$, Field resistance $R_f = 0.05\,\Omega$, Direct stator inductance $L_{ds} = 8.4\,\mathrm{mH}$, Quadrature stator inductance $L_{qs} = 3.5\,\mathrm{mH}$, Field leakage inductance $L_f = 8.1\,\mathrm{mH}$, Mutual inductance between inductor and armature $M_{fd} = 7.56\,\mathrm{mH}$, The damping coefficient $B = 0.005\,\mathrm{N\,m/s}$, The moment of inertia $= 0.05\,\mathrm{kg\,m^2}$, Pair number of poles $= 2$.

REFERENCES

[1] MAMDANI, E. H.: Applications of Fuzzy Algorithms for Simple Dynamic Plants, Proc. IEE **121** (1974), 1585–1588.

[2] FANG-MING YU—HUNG-YUAN CHUNG—SHI-YUAN CHEN: Fuzzy Sliding Mode Controller Design for Uncertain Time-Delayed Systems with Nonlinear Input, Fuzzy Sets Syst. **140** (2003), 359-374.

[3] SOUSA, G. C. D.—BOSE, B. K.: Fuzzy Set Theory Based Control of a Phase-Controlled Converter DC Machine Drive, IEEE Transaction on Industry Applications **30** No. 1 (Jan/Feb 1994), 34–44.

[4] YAGER, R. G.: Fuzzy Logics and Artificial Intelligence, Fuzzy Sets and Systems **90** (1997), 193–198.

[5] KIM, Y. T.—BIEN, Z.: Robust Self-Learning Fuzzy Controller Design for a Class of Nonlinear MIMO System, Fuzzy Sets and Systems **111** (2000), 117–135.

[6] LEE, C. C.: Fuzzy Logic in Control System: Fuzzy Logic Controller — Part I/II, IEEE Trans. Systems Man. Cybernet **20** (1990), 404-435.

[7] TIMOTHY, J. R.: Fuzzy Logic with Engineering Application, McGraw-Hill, New York, 1995.

[8] TANG, Y.—XU, L.: Fuzzy Logic Application for Intelligent Control of a Variable Speed Drive, IEEE PES Winter Meet., 1994.

[9] HEBER, B.—XU, L.—TANG, Y.: Fuzzy Logic Enhanced Speed Control of an Indirect Field Oriented Induction Machine Drive, IEEE PESC Meet., 1995, pp. 1288–1294.

[10] BOSE, B. K.: Power Electronics and AC Drives, Prentice Hall, Englewood Cliffs, Newjersey, 1986.

[11] STURTZER, G.—SMIGIEL, E.: Modélisation et commande des moteurs triphasés, Edition Ellipses, 2000.

[12] CAMBRONNE, J. P.—LE MOIGNE, P.—HAUTIER, J. P.: Synthèse de la commande d'un onduleur de tension, Journal de Physique III, France (1996), 757–778.

[13] NAMUDURI, C.—SEN, P. C.: A Servo-Control System Using a Self-Controlled Synchronous Motor (SCSM) with Sliding Mode Control, IEEE Trans. on Industry Application **IA-23** No. 2 (March/April 1987).

[14] RAMDANI, A. Y.—BENDAOUD, A.—MEROUFEL, A.: Réglage par mode glissant d'une machine asynchrone sans capteur mécanique., Rev. Roum. Sci. Techn. — Electrotechn. et Energ. (2004), 406–416.

[15] CIRSTEA, M. N.—DINU, A.—KHOR, J. G.—McCORMICK, M.: Neural and Fuzzy Logic Control of Drives and Power Systems, Newnes, Oxford, 2002.

[16] BOSE, B. K.: Expert System, Fuzzy logic, and Neural Network Applications in Power Electronics and Motion Control, Proceedings of the IEEE **82** No. 8 (Aug 1994), 1303–1321.

[17] BÜHLER, H.: Réglage par logique floue, Presse Polytechniques et Universitaires Romandes, Lausanne, 1994.

[18] SPOONER, J. T.—MAGGIORE, M.—ORDONEZ, R.—PASSINO, K. M.: Stable Adaptative Control and Estimation for Nonlinear System, Neural and Fuzzy Approximator Techniques, Willey-Interscience, 2002.

[19] RACHID, A.: Systèmes de régulation, Masson, Paris,, 1996.

[20] BAGHLI, L. Contribution à la commande de la machine asynchrone, utilisation de la logique floue, des réseaux de neurone et des algorithmes génétiques: Thèse de doctorat STIMA – NANCY, 1999.

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