2010 International Conference on Measuring Technology and Mechatronics Automation

Research on Direct Torque Control of Induction Motor Based on Genetic Algorithm and Fuzzy Adaptive PI Controller

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***Abstract*—A novel direct torque control strategy, using genetic algorithm on-line to optimize the fuzzy PI controller, is proposed. In this approach, according to speed error and its first time derivative, the proportional coefficient K_p and integral coefficient K_i can be on-line adjusted by fuzzy adaptive PI speed regulation, and the fuzzy logic adapter parameters are optimized by genetic algorithm to improve the self-adaptation of speed. Moreover, the second fuzzy logic controller is applied to select the voltage vector instead of the conventional hysteresis controllers. In this paper, a comparative study between fuzzy PI direct torque control and proposed approach shows that not only the speed response, overshoot and speed steady precision have been improved, but also the torque, flux and stator current ripples have been effectively decreased at low speed, and the robustness of the whole system has been enhanced.**

Keywords-direct torque control; fuzzy control; adaptive speed regulator; genetic algorithm; torque ripple

I. INTRODUCTION

Compared to vector control, direct torque control (DTC) is a new AC drive technology in induction motor. DTC has several advantages such as, fast torque response, accurate torque control even at low frequencies, parameter robustness. However, its disadvantages are low-precision speed control and remarkable torque and flux linkage ripples at low speed due to hysteresis controllers and inappropriate position of voltage space vector [1, 2, 3]. To overcome these problems, several investigations can be found. In traditional DTC speed control, conventional PI regulator has been most applied, but its parameters are fixed during control operation, that is difficult to achieve high performance requirement. When especially in a wide speed range, it is almost impossible that fast response and small overshoot, as well as high speed control precision can be ensured. Aiming at low-accuracy speed control, as in [2], sliding mode control can be used for speed regulator, but it is lack of adaptability for internal parameters and more difficult to be achieved. According to [3], conventional PID regulator has been replaced with the self-learning neural network, whereas it needs off-line training, so that dynamic real-time adjustment is implemented difficultly. In order to reduce torque ripple at low speed, as in [4], the inverter switching frequency can be increased. On one hand, the stator current harmonic component has been reduced, on the other hand, power loss has been enhanced largely. Moreover, the fixed inverter switching frequency has been presented in [5], to some extent, torque ripple has been decreased, but the reliability of system has also been reduced. For the above problems, in this paper, a novel controller is known as FLC-PI-GA, where the fuzzy logic controller is used on-line to adjust the PI parameters, in the meanwhile, genetic algorithm is developed to optimize the fuzzy logic controller. In addition, the second fuzzy logic controller is applied to optimize the switching table of voltage vector. The numerical simulation results of the proposed scheme have presented good performances compared to the fuzzy PI controller which can cause greatly flux and torque ripple at low speed.

II. SYSTEM CONSTRUCTION

The diagram of this technique is illustrated in Fig. 1. The fuzzy adaptive PI speed regulation, composed of PI speed regulation and fuzzy-parameters controller, can adjust and optimize the real-time parameters of kp and ki through fuzzy inference mechanism and genetic algorithm. The stator flux linkage and electromagnetic torque are observed by flux linkage and torque observers. According to electromagnetic torque error and stator flux linkage error as well as flux-angle, the system is controlled through a method that voltage vectors, selected properly by fuzzy controller, are exported to inverter [5].

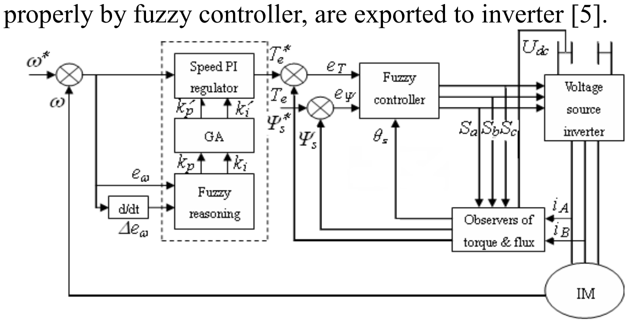


Figure 1. Block diagram of GA-Fuzzy DTC

A. *Design of Adaptive Fuzzy PI Speed Regulation*

Such fuzzy controller has two inputs and two outputs. Input variables are speed error ($e_\omega(k)$) and its rate of change ($\Delta e_\omega(k)$). Output values are k_p and k_i.

Speed error: $e_\omega(k) = \omega^*(k)\text{-}\omega(k)$ (1)

Rate of change about speed:

$$\Delta e_\omega(k) = (e(k)\text{-}e(k\text{-}1))/T_s \quad (2)$$

Its universe of discourse is quantified range from -1 to 1. The linguistic variables of e and Δe are E and ΔE respectively, and the definition of fuzzy set numbers are 7 and 3. The corresponding membership functions are shown in Fig. 2.

The universe of discourse of output values (k_p and k_i) both are from 0 to 1. The linguistic variables are K_P and K_I, and both of the fuzzy set numbers are 4. The corresponding membership functions are shown in Fig. 3.

After step response analysis, the rules of fuzzy control can be obtained from stability, respond speed, overshoot, steady-state accuracy and DTC characteristics of system. All of them are shown in TABLE Ⅰ.

TABLE I. FUZZY RULES FOR COMPUTING K_P/K_I

K_P, K_I		**E**						
		NB	***NM***	***NS***	***Z***	***PS***	***PM***	***PB***
□E	***N***	B,Z	M,S	S,M	M,B	S,M	M,S	B,Z
	Z	B,Z	M,S	B,M	Z,B	B,M	M,S	B,Z
	P	B,Z	M,M	B,B	Z,B	B,B	M,M	B,Z

According to the simulation results of direct torque control in induction motor, the ranges of kp and ki are [1, 5] and [0, 2] respectively. The final actual output values of kp and ki can be obtained from linear transform by under formulas.

$$\begin{cases} k_p = 1 + 4k_{p0} \\ k_i = 2k_{i0} \end{cases} \tag{3}$$

k_{p0} and k_{i0} are the crisp values of vague output values.

B. Fuzzy Genetic Optimization Algorithm

GA is a stochastic global search optimization algorithm, based on natural selection and genetic mechanism. The noticeable characteristics are simple general-purpose, efficient and practical, good robustness. GA has been widely applied in combinatorial optimization, machine learning, adaptive control and artificial life et al. Also GA can be applied to the automatic generation of knowledge base of an optimal fuzzy logic controller. The main steps of the Gain the optimization process of the FLC controllers are itemized as follows [6, 7]:

- Choose the population size, the maximal generation number, the crossover rate, and the mutation rate.
- Start with an initial population of solutions that constitutes the first generation.
- Define the fitness function.
- Evaluate fitness value for each chromosome of the population.
- Generate the offspring with the crossover rate and mutation rate in Step 1, in which the ranking mechanism is used for selecting chromosomes.
- Select the population of the new generation from the parents and the offspring in Step 5 according to their corresponding fitness values.
- Repeat the procedure from Step 4 to Step 6 until the termination condition is met.

The fuzzy adaptive controller consists of two inputs ($e_\omega(k)$ and $\Delta e_\omega(k)$) and two outputs (k_p and k_i). We use GA to search the appropriate parameter values and to modify the decision tables of FLC, where the chromosome is made up of decision table, coded each membership function by a integer number from 0 to 4. In which number 4 expresses the number of membership function of two outputs, number 0 indicates no output. According to [7], the parameters are set as follows:

- Initial population size: 20.
- Maximum number of generation: 120.
- Crossover probability: 0.7.
- Mutation probability: 0.01.
- Minimum criteria:

$$J = \int_0^t e^2 dt = \int_0^t (\omega^* - \omega)^2 dt \tag{4}$$

Figs. 2 and 3 show the pre and post optimization of membership functions for the input variables and output parameters, respectively.

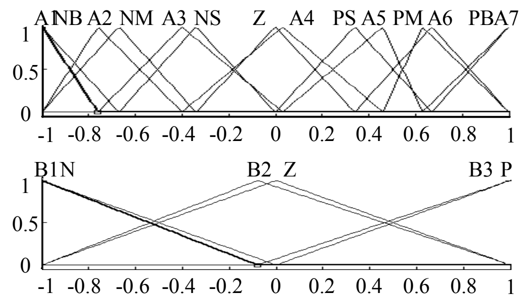


Figure 2. Membership functions of E and ΔE

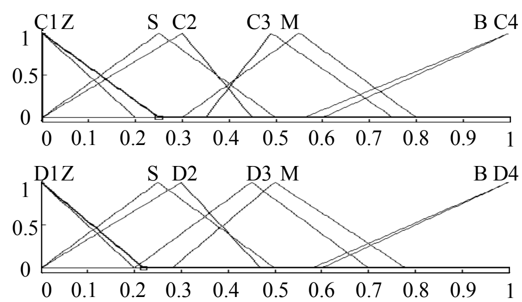


Figure 3. Membership functions of output K_P and K_I

After the parameters are optimized by GA, the resulting fuzzy rule bases are represented in TABLE Ⅱ. For example, the first rule is:

if E is *A1* and ΔE is *B1* so K_P is *C4* and K_I is *D1*.

TABLE II. OPTIMAL FUZZY RULES FOR COMPUTING K_P/K_I

K_P, K_I		**E**						
		A1	***A2***	***A3***	***A4***	***A5***	***A6***	***A7***
ΔE	***B1***	4, 1	3, 1	1, 4	2, 4	2, 3	3, 1	4, 1
	B2	4, 1	3, 1	4, 2	1, 4	3, 2	4, 1	4, 1
	B3	4, 1	3, 2	4, 3	1, 4	4, 4	3, 3	4, 1

C. Design of Voltage Vector Fuzzy Controller

Hysteresis loop controllers are used for flux linkage and torque adjusting in traditional DTC. It is easy to choose the same voltage vector that could enlarge torque pulsation when torque error and flux error are too big or small [3, 4]. Fuzzy control strategy has been introduced into DTC. And input variables including stator flux linkage error e_ψ, torque error e_T, and flux-angle θ_s along with inverter output S_i are fuzzified using the appropriate fuzzy sets [3, 4, 8, 9]. Following a switching table optimization is designed to choose voltage space vector accurately. The membership functions of inputs-outputs are shown in Figs. 4, 5.

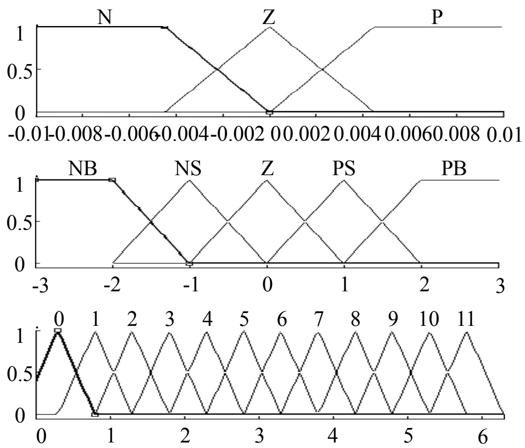


Figure 4. Membership functions of input variables

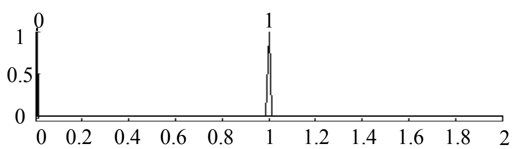


Figure 5. Membership function of output variable

According to inherent law of input and output, this system has 180 fuzzy inference rules. Integrated voltage vectors fuzzy control array (TABLE Ⅲ) are speculated by law and Mamdani fuzzy reasoning.

Above control rules are described by signs about EF, ET, θ and S, such as:

if EF is M_i and ET is N_i and θ is θ_i, then S is S_i.

TABLE III. FUZZY RULES OF VOLTAGE VECTOR

EF	ET	θ_0	θ_1	θ_2	θ_3	θ_4	θ_5	θ_6	θ_7	θ_8	θ_9	θ_{10}	θ_{11}
P	PB	2	2	3	3	4	4	5	5	6	6	1	1
	PS	1	2	2	3	3	4	4	5	5	6	6	1
	Z	0	0	0	0	0	0	0	0	0	0	0	0
	NS	1	1	2	2	3	3	4	4	5	5	6	6
	NB	6	1	1	2	2	3	3	4	4	5	5	6
N	PB	3	3	4	4	5	5	6	6	1	1	2	2
	PS	3	4	4	5	5	6	6	1	1	2	2	3
	Z	0	0	0	0	0	0	0	0	0	0	0	0
	NS	5	5	6	6	1	1	2	2	3	3	4	4
	NB	5	6	6	1	1	2	2	3	3	4	4	5
Z	PB	2	3	3	4	4	5	5	6	6	1	1	2
	PS	2	3	3	4	4	5	5	6	6	1	1	2
	Z	0	0	0	0	0	0	0	0	0	0	0	0
	NS	0	0	0	0	0	0	0	0	0	0	0	0
	NB	6	6	1	1	2	2	3	3	4	4	5	5

III. RESULTS

The simulations of the DTC induction motor drive were carried out using the Matlab/Simulink simulation package. The overall block diagram of FLC-PI-GA DTC of induction motor is depicted in Fig. 6.

The induction motor used for simulations has the following parameters:

P_N = 4 kW, T_N = 25 N·m, U_N = 380 V, I_N = 0.48 A, f_N = 50 Hz, P_N = 2, R_s = 5.5 Ω, R_r = 3.5 Ω, L_s = L_r = 0.366 H, L_m = 0.34 H, n_N = 1440 rpm, J = 0.0075 kg·m^2.

Figs. 7, 8 show the comparison between the settling performance and the disturbance rejection capability of the FLC-PI DTC motor drive using GA optimization and those of the DTC motor drive using a classical FLC-PI controller. Initially the motor is started up with no load, rising to 5 N·m at 0.3 s. A 2 N·m load disturbance is applied during a period of 0.2 s. The sampling time has been set to 50μs. Moreover, the reference flux used is 1 Wb and the reference speed used is 8 rpm. TABLE Ⅳ shows the comparison of errors obtained in two different control strategies.

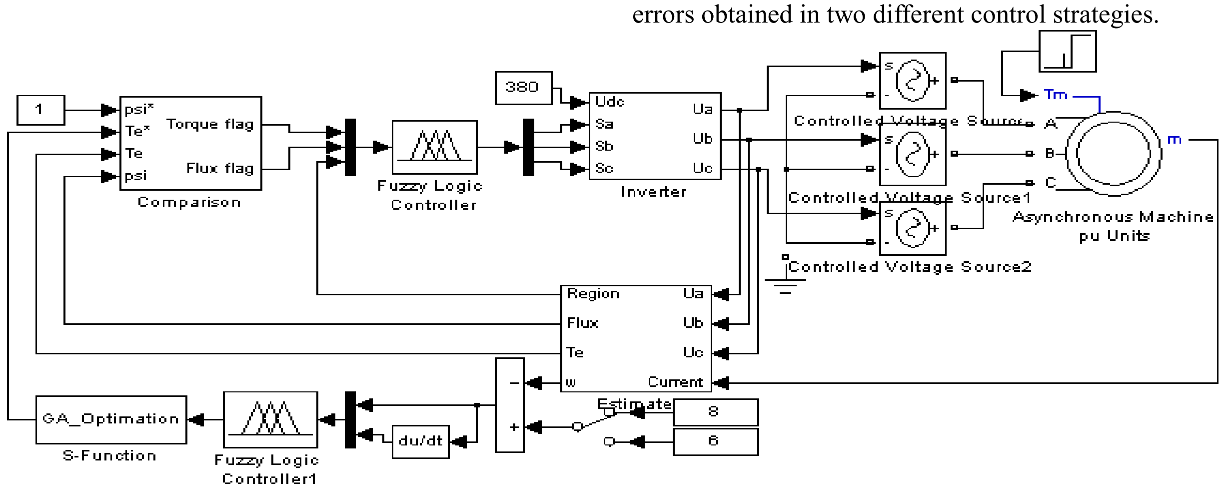


Figure 6. Simulation block diagram of GA-Fuzzy DTC

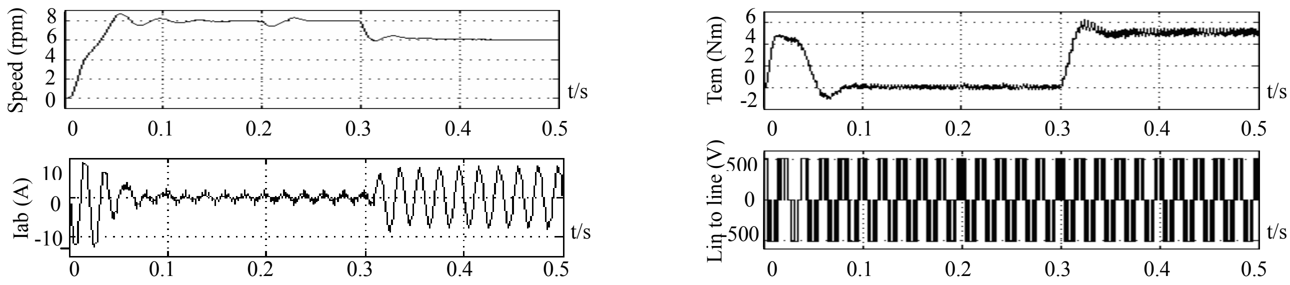


Figure 7. Simulation results for the FLC-PI DTC

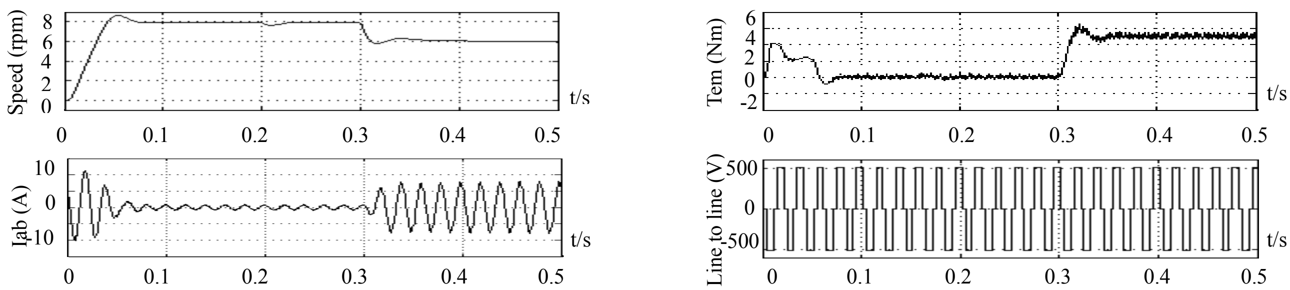
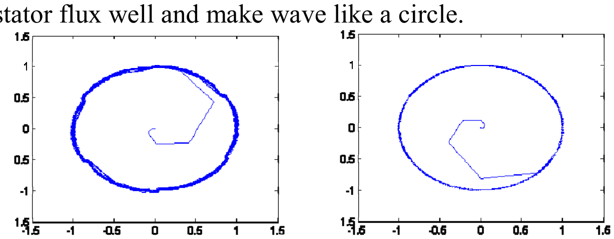


Figure 8. Simulation results for the FLC-PI-GA DTC

Fig. 9 (a) (b) presents the stator flux trajectory that steadily runs at a speed of 8 rpm and given flux linkage of 1Wb. The latter can improve obviously the accuracy of the stator flux well and make wave like a circle.



(a) FLC-PI DTC system (b) FLC-PI-GA DTC system

Figure 9. Stator flux trajectory of DTC

TABLE IV. ERRORS IN TWO CONTROL STRATEGIES

	Speed Ripple	Rise Time	Stator current Ripple	Flux Ripple	Torque Ripple
FLC-PI	0.07	0.098	1.1	0.0008	0.4
FLC-PI-GA	0.025	0.045	0.85	0.00023	0.25

IV. CONCLUSION

Fuzzy adaptive PI controller has been used as DTC speed regulator, fuzzy reasoning rules are on-line optimized by genetic algorithm. So the parameters of k_p and k_i can be dynamically adjusted real-timely. Therefore, experiments enhance the adjustment ability of DTC system' speed, and further expedite speed response which has high precision.

The observation precision of stator flux linkage, affected by fuzzy controller, is better than the traditional hysteresis comparator's. Besides, the employment of fuzzy controller can decrease torque ripple at low speed. , as well as advance the static and dynamic performance of the whole system.

ACKNOWLEDGMENT

This study is supported by Innovation Project of Guangxi Graduate Education (2009105950802M08) and Guangxi Key Laboratory of Manufacturing System & Advanced Manufacturing Technology (0842006_024_Z). The authors wish to express sincere gratitude to the reviewers for their invaluable suggestions and comments.

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