Speed Control of Induction Machines Using Fuzzy Algorithm with Hierarchical Structure

Ho-Seok Lee, Soon-Bong Cho, and Dong-Seok Hyun

Abstract

A new speed controller based on the fuzzy algorithm with hierarchical structure is presented. The input variables of the controller are speed error and its derivative(change of error), where the output variable is the change of torque current command. Several comparisons were performed with conventional PI (proportional plus integral) controller and proposed controller. These controllers are applied to the laboratory model drive system with 2.2kW induction motor. Some simulation and experimental results show that the speed controller using fuzzy algorithm is more robust than the conventional PI controller.

I. Introduction

The PI controller is widely used in speed control fields because of the simplicity and the good performance[1]. However, the speed control systems have not been a desired response to the change of the load torque, the load inertia moment and the variation of the system parameters. Thereby the phenomena are occurred in the overshoot and oscillation of the motor speed, the torque and the long settling time. Modern control theory such as state observer and model reference adaptive control can be applied in order to solve above problems. The theory is to estimate load torque or moment of load inertia and so the system may have a excellent performances. However, it requires the exact mathematical modelling of plant and the high speed processor for real time calculation because of complicate algorithm.

Recently, the speed control of electrical drives using fuzzy algorithm was proposed, mostly to improve the performance of conventional PI controllers[2-13]. The performance of the fuzzy controller was almost the same as that of the PI controller when first-order linear process were used. Furthermore, the fuzzy controller was significantly better when a first-order with time delay model was used. More importantly, the fuzzy controller was stable when a nonlinear process model was controlled, but the PI controller was unstable[14]. Fuzzy controller is based on a general scheme where the speed error and its derivative are evaluated and fuzzified exploiting suitable membership functions. Then the fuzzified input variables are sent to the inference stage where control outputs are deduced from evaluating linguistic rules. Finally, the output variables are obtained with a defuzzification.

Although it has been shown by early papers that such controllers work better than conventional PI controllers, the fuzzy controller has some steady state error that deteriorates overall system performance. As a solution, an improved controller that has two tables for a coarse and fine control was proposed.

In the present work, a different approach is presented. The method for reducing the state error is to zoom the range of fuzzy variable for adjusting the magnitude of fuzzy variables. We use the zooming windows that expand and shrink regarding magnitude of input variables. By adopting the new method, a high performance speed controller is implemented in this paper. A vector controlled induction machine drive system is considered as the basis of a simulation and experimental prototype. It has been realized to practically confirm the validity of the proposed controller algorithm.

II. Construction of the Speed Controllers

1. Conventional PI Controller

Conventional PI control is a well-established and popular technique for industrial process control. This is due to its simplicity both from the design and the gain tunning point of view.

A typical block diagram of speed control loop of induction

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motor is shown in Fig.1.

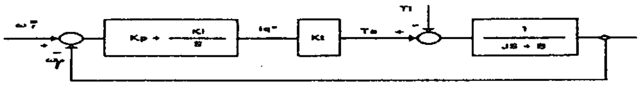


Fig. 1. Structure of PI speed control loop of induction motor.

where

ω_r^* : *speed reference*
ω_r : *actual speed*
K_p : *proportional constant*
K_i : *integral constant*
K_t : *torque constant*
T_e : *developed torque*
J : *inertia moment of load*
T_l : *load torque*
B : *viscous friction*

The speed response transfer function $G_s(S)$, the torque response transfer function $G_t(S)$ are given by (1) and (2).

$$G_s(S) = \frac{\omega_r(S)}{\omega_r^*} = \frac{Kt \cdot Kp \cdot S + Kt \cdot Ki}{J \cdot S^2 + (Kt \cdot Kp + B) \cdot S + Kt \cdot Ki} \tag{1}$$

$$G_t(S) = \frac{\omega_r(S)}{Tl(S)} = \frac{S}{J \cdot S^2 + (Kt \cdot Kp + B) \cdot S + Kt \cdot Ki} \tag{2}$$

We can obtain the damping ratio(ζ), the natural frequency(ω_n), the damping natural frequency(ω_d) from the characteristic equation of above transfer function as follows:

$$\zeta = \frac{(Kt \cdot Kp + B)}{J} \cdot \frac{1}{(2 \cdot \omega_n)} \tag{3}$$

$$\omega_n = \sqrt{\frac{Kt \cdot Ki}{J}} \tag{4}$$

$$\omega_d = \omega_n \cdot \sqrt{(1 - \zeta^2)} \tag{5}$$

Typically, the gains of the conventional PI controller are derived from the performance indices as like ISE, IAE in the extremely small region. With this constant gains, it is operated along the full range, therefore the desired speed and torque response can not be respected. In the conventional PI controller with constant gain, as the load inertia moment changes, the natural frequency and the damping ratio of the system will be change. Therefore the overshoot and oscillation may be occurred in speed and torque response.

As Eq.(3)-(5), when the load inertia moment is increased, the damping ratio and natural frequency are decreased and the overshooting and rising time is increased. In the case of the regardless of the change of the load inertia moment, the use of the constant Kt, Ki of the PI controller make the desired transient response impossible, so the some different controller ,which has the variable gains, is required. Also the system has the nonlinear dynamic characteristics, it is difficult to make the numerical system formula (what is quantitative!) as the operating point of the system. So the alternative, a controller that has controllable gains as the operating point of the system, is required.

2. *Fuzzy Controller with Hierarchical Structure*

In the general structure of fuzzy controller, there exists some steady state error caused by limit of control boundary. In this paper, we use a new fuzzy controller with hierarchical structure. This controller is expanded or shrunk with magnitude of controller input. Moreover it has a good dynamic response as well as a good steady state performance. Fig. 2(a) describes the structure of proposed fuzzy controller.

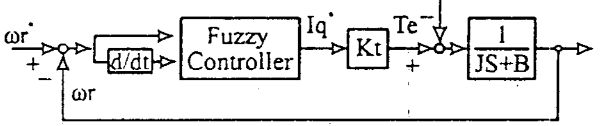


Fig. 2. (a) The structure of proposed fuzzy controller.

1) *Fuzzy controller scheme*

The fuzzy controller accomplishes four elementary functions; Fuzzification, Fuzzy Rule, Fuzzy Inference and Defuzzification. Fig.2(b) describes the fuzzy logic controller.

(1) the fuzzification algorithm used for the controller inputs;
(2) the fuzzy control rules;
(3) type of fuzzy logic used for the fuzzy control rules; and
(4) the defuzzification algorithm used for the controller output.

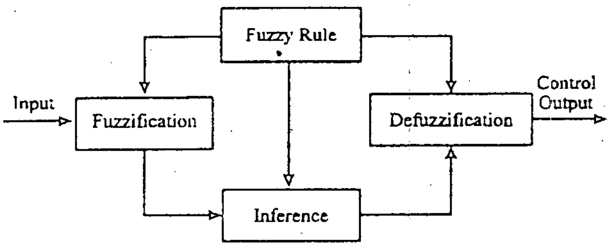


Fig. 2. (b) Fuzzy controller.

(1) *Fuzzification*

Input variables of fuzzy controller are the speed error e(k), and its derivative(change of error) ce(k). At a sampling point k, e(k), ce(k) are expressed as follows:

$$e(k) = \omega_r^*(k) - \omega_r(k) \tag{6}$$

$$ce(k) = e(k) - e(k-1) \tag{7}$$

where $\omega_r^*(k)$ and $\omega_r(k)$ are the speed command and the actual speed of the induction motor, respectively. The output variable is the change in torque current command, ΔIq(k), and we can obtain the following equation,

$$Iq(k) = Iq(k-1) + \Delta Iq(k) \tag{8}$$

The input variables are quantized to 14 levels as shown in table 1. We have used exponential quantization to ensure a good performance of the proposed fuzzy controller. we can construct membership function of fuzzy variable as shown in table 2.

Table 1. Quantization of input variables.

Quan. Level	e(K)	ce(K)
-6	$e(K)<-32\times E$	$ce(K)<-32\times CE$
-5	$-32\times E\le e(K)<-16\times E$	$-32\times CE\le ce(K)<-16\times CE$
-4	$-16\times E\le e(K)< -8\times E$	$-16\times CE\le ce(K)< -8\times CE$
-3	$-8\times E\le e(K)< -4\times E$	$-8\times CE\le ce(K)< -4\times CE$
-2	$-4\times E\le e(K)< -2\times E$	$-4\times CE\le ce(K)< -2\times CE$
-1	$-2\times E\le e(K)< -1\times E$	$-2\times CE\le ce(K)< -1\times CE$
-0	$-1\times E\le e(K)< 0$	$-1\times CE\le ce(K)< 0$
+0	$0\le e(K)< 1\times E$	$0\le ce(K)< 1\times CE$
1	$1\times E\le e(K)< 2\times E$	$1\times CE\le ce(K)< 2\times CE$
2	$2\times E\le e(K)< 4\times E$	$2\times CE\le ce(K)< 4\times CE$
3	$4\times E\le e(K)< 8\times E$	$4\times CE\le ce(K)< 8\times CE$
4	$8\times E\le e(K)< 16\times E$	$8\times CE\le ce(K)< 16\times CE$
5	$16\times E\le e(K)< 32\times E$	$16\times CE\le ce(K)< 32\times CE$
6	$32\times E\le e(K)$	$32\times CE\le ce(K)$

Table 2. Discrete-value expression of membership function.

Fuzy Variables	Quantization level													
	-6	-5	-4	-3	-2	-1	-0	+0	1	2	3	4	5	6
NB	1.0	0.7	0.3	0	0	0	0	0	0	0	0	0	0	0
NM	0.3	0.7	1.0	0.7	0.3	0	0	0	0	0	0	0	0	0
NS	0	0	0.3	0.7	1.0	0.7	0.3	0	0	0	0	0	0	0
NZ	0	0	0	0	0	0.3	1.0	0	0	0	0	0	0	0
PZ	0	0	0	0	0	0	0	1.0	0.3	0	0	0	0	0
PS	0	0	0	0	0	0	0	0.3	0.7	1.0	0.7	0.3	0	0
PM	0	0	0	0	0	0	0	0	0	0.3	0.7	1.0	0.7	0.3
PB	0	0	0	0	0	0	0	0	0	0	0	0.3	0.7	1.0

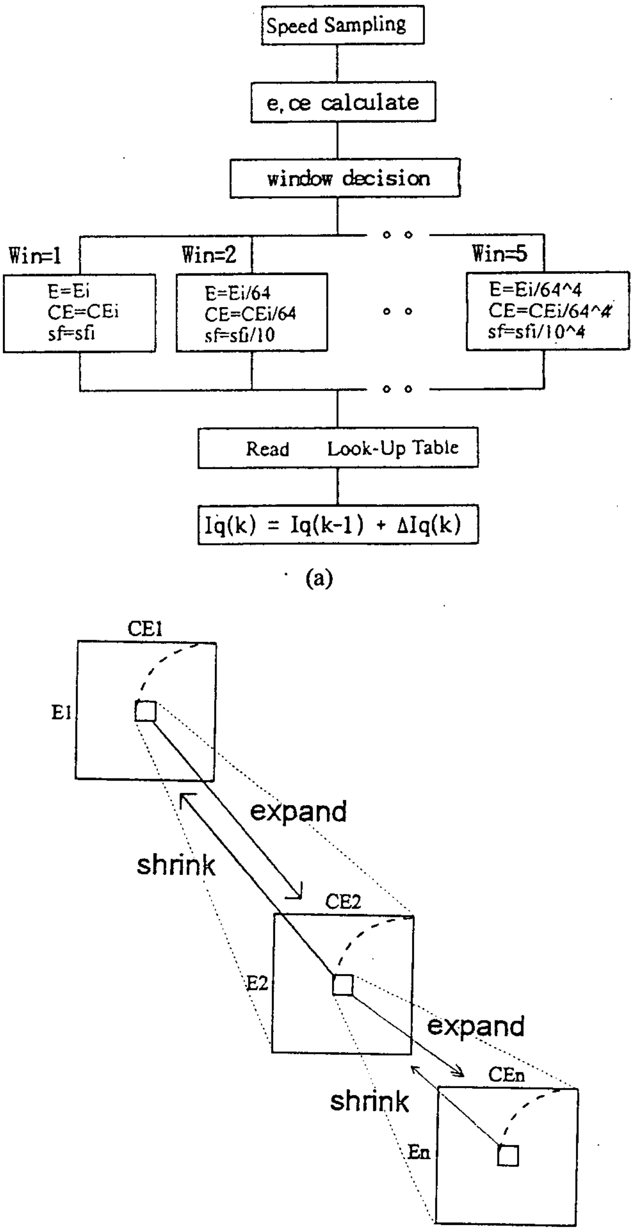
(2) Fuzzy rule

For the purpose of shortening the rising time and reducing the overshoot of the system response, we have used the fuzzy control rules as shown in table 3.

Control rule was obtained from regularized linguistic expression based on sign and size of e(k) and ce(k). This table was composed from applying full boundary of input variables. Using only one table, there exist some steady state errors.

Table 3. Fuzzy rule table.

	NB	NM	NS	NZ	PZ	PS	PM	PB
NB	NB	NB	NM	NM	M,	NS	NS	PZ
NM	NB	NM	NM	NM	NS	NS	NS	PS
NS	NM	NM	NM	NS	NS	NS	PZ	PS
NZ	NM	NM	NS	NS	NZ	NZ	PS	PM
PZ	NM	NS	NS	PZ	PS	PS	PS	PM
PS	NS	NS	NZ	PS	PS	PS	PM	PM
PM	NS	PZ	PS	PS	PM	PM	PM	PB
PB	NZ	PS	PS	PM	PM	PM	PM	PB



(a)

(b)

Fig. 3. (a) The flowchart of the fuzzy controller with hierarchical structure. (b) Illustrating the proposed fuzzy controller.

In order to improve the transient response and to force the steady-state error to equal approximately zero, we make use of the fuzzy controller with hierarchical structure as shown in Fig.3(a), (b). The feature of this controller is that the range of input variables is continuously expanded or shrunk according to the value of speed error.

(3) Fuzzy inference and Defuzzification

The fuzzy inference method used is the simplified product-sum-gravity method.[15] PID controllers cannot be constructed by min-max-gravity method known as Mamdani's fuzzy reasoning method. However, PID controllers can be realized by fuzzy control methods of "product-sum-gravity method" and "simplified fuzzy reasoning method". Therefore, PID controls are shown to be a special case of fuzzy controls. Furthermore, extrapolative reasoning can be excuted by the product-sum-gravity method and simplified fuzzy reasoning method by extending the range of membership functions of antecedent parts of fuzzy rules from [0, 1] to (-∞, ∞).

As a special case of product-sum-gravity method, we can give a simplified fuzzy reasoning method for the following fuzzy reasoning form;

Rule 1: A_1 and B_1 → Z_1
Rule 2: A_2 and B_1 → Z_2

Rule n: A_n and B_n → Z_n (9)
Fact: X_0 and Y_0

Cons: Zo

where Z_1, Z_2, · · · Z_n, Z_o are not fuzzy sets but real numbers in Z.

The consequence Zo by the simplified fuzzy reasoning method is obtained as following(see Fig. 4). The degree of fitness of the fact 「X_o and Y_o」 to the antecedent part 「Ai and Bi」 is given as

$$hi = \mu_{Ai}(Xo) \cdot \mu_{Bi}(Yo) \tag{10}$$

The degree of fitness(h_i) may be regarded as the degree with which Z_i is obtained. Therefore, the final consequence Zo of eq. 9 is obtained as the weighted average of Z_i by the degree hi. Namely,

$$Z_0 = \frac{h_i \cdot Z_1 + h_2 \cdot Z_2 + \cdot \cdot \cdot + h_n \cdot Z_n}{h_1 + h_2 + \cdot \cdot \cdot + h_n} \tag{11}$$

Note that the simplified reasoning method is regarded as a special case of product-sum-gravity method, but not a special case of min-max-gravity method.

For real time control, we have used the fuzzy control table as shown in table 4. And the output variable is the change of torque current command, $\Delta Iq(k)$. Then, we can obtained the torque command as eq. 12.

$$Iq(k) = Iq(k-1) + sf \cdot Fuzzy\ table[E(k), CE(k)] \tag{12}$$

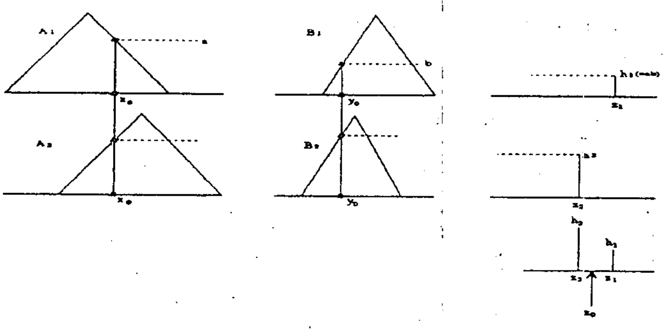


Fig. 4. Simplified fuzzy reasoning method.

Table 4. Fuzzy control table(Look up table).

		Change of Error													
		-6	-5	-4	-3	-2	-1	-0	+0	1	2	3	4	5	6
Error	-6	-6	-6	-5	-5	-4	-3	-2	-2	-2	-2	-2	-1	-1	0
	-5	-6	-6	-5	-5	-4	-3	-2	-2	2-	-2	-2	-1	0	1
	-4	-5	-5	-4	-4	-4	-3	-2	-2	-2	-1	-1	0	1	1
	-3	-5	-5	-4	-4	-3	-3	-2	-2	-1	-1	0	1	2	2
	-2	-4	-4	-4	-3	-3	-2	-2	-2	-1	0	1	1	2	2
	-1	-4	-4	-3	-3	-2	-2	-2	-1	0	1	1	2	2	2
	-0	-4	-3	-3	-2	-2	-2	-1	0	1	2	2	2	3	3
	+0	-3	-3	-2	-2	-2	-1	0	1	2	2	2	3	3	4
	1	-2	-2	-2	-1	-1	0	1	2	2	2	3	3	4	4
	2	-2	-2	-1	-1	0	1	2	2	2	3	3	4	4	4
	3	-2	-2	-1	0	1	1	2	2	3	3	4	4	5	5
	4	-1	-1	0	1	1	2	2	2	3	4	4	4	5	5
	5	-1	0	1	2	2	2	2	2	3	4	5	5	6	6
	6	0	1	1	2	2	2	2	2	3	4	5	5	6	6

III. Simulation Results

The proposed controller was simulated and tested for a 3kVA inverter and 2.2kW induction machine. Fig. 5 is the block diagram of induction machine vector controlled drive system that is used in simulation and experiment. And the machine is characterized by the Table 5.

The performance of the proposed system is the compared with that of the PI controllers. Speed response and load torque response of proposed controller are compared with those of a conventional PI controller. Fig. 6 shows the simulation for step response of speed with PI controller. In this simulation, we apply speed reference changing from 800 rpm to 1000 rpm and 1000 rpm to 800 rpm. Fig. 6(a) shows the corresponding actual speed, and Fig. 6(b) shows the corresponding speed error. Fig. 7 shows the simulation for step response of speed with proposed fuzzy controller with hierarchical structure. Other simulation conditions in this figure are same as those of Fig. 6.

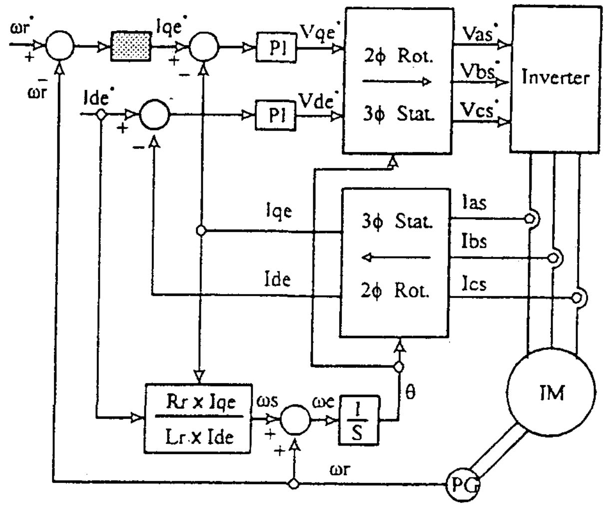
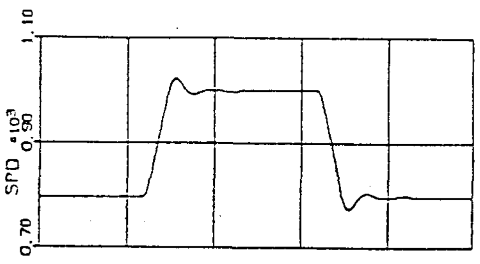


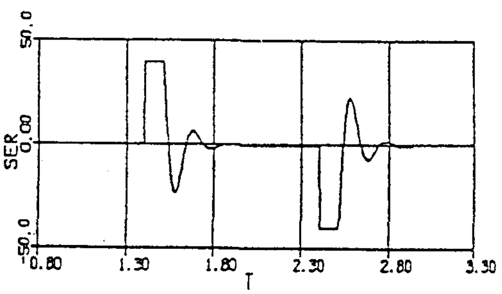
Fig. 5. Block diagram of vector control system with proposed speed controller.

Table 5. The induction machine parameters.

ranted voltage	220V
rated current	8A
Rs	1.26Ω
Rr	1.28Ω
Ls	109mH
Lr	109mH
M	106mH
J	0.02kgm²

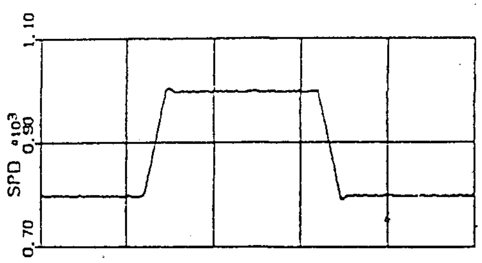


(a) Actual speed[200 rpm/div]

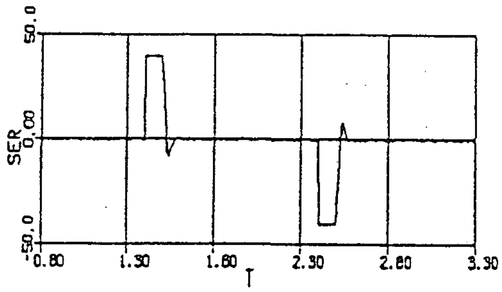


(b) Speed error [50 rpm/div]

Fig. 6. Speed response of PI controller.



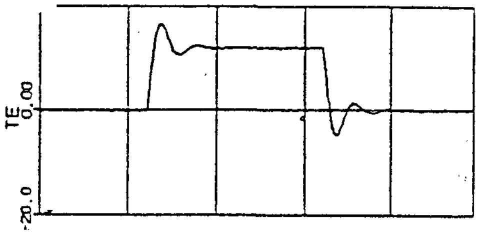
(a) Actual speed[200 rpm/div]



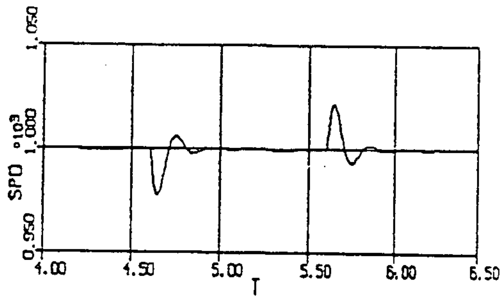
(b) Speed error [50 rpm/div]

Fig. 7. Speed response of proposed controller.

In these results, obviously, the transient response of proposed system is substantially better than that of PI controllers. As we have applied an initial equivalent inertia J in the control law, the damping ratio in the PI controller is reduced and settling time is longer than that of proposed controller.



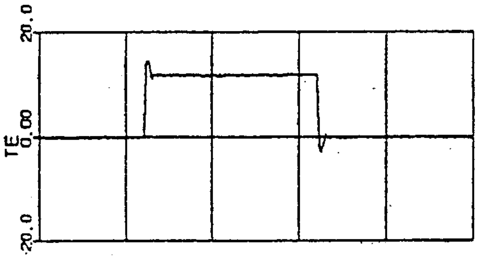
(a) Motor torque [20 Nm/div]



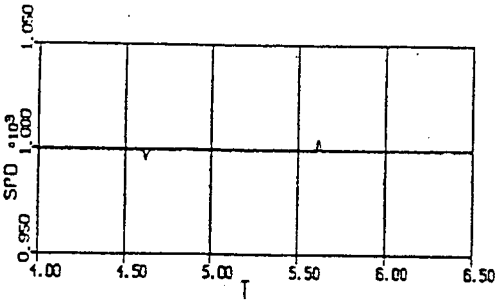
(b) Speed error [50 rpm/div]

Fig. 8. Torque response of PI controller.

Fig. 8 shows the step response of load torque with PI controller. Step response of load torque from 0 to 10Nm, and 10Nm to 0 is applied. Fig. 8(a) shows the developed motor torque and Fig. 8(b) shows speed error. Fig. 9 shows the similar simulation result with proposed controller. Also in these results, we can easily see the better results in the proposed controller.



(a) Motor torque [20 Nm/div]

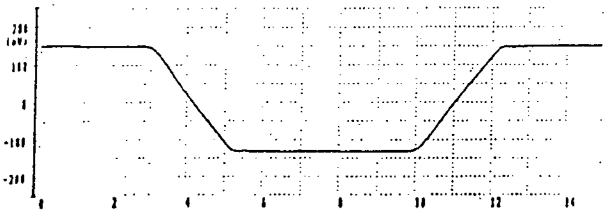


(b) Speed error [50 rpm/div].

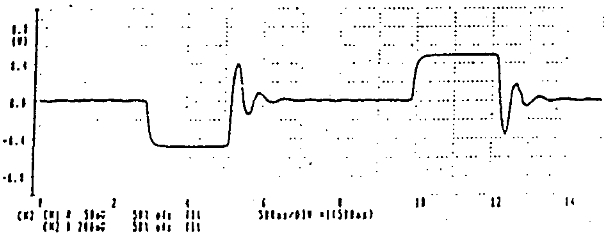
Fig. 8. Torque response of proposed controller.

IV. Experimental Results

The hardware structure we used consists of a DSP card and some other fast devices. Almost every part of controller is processed in the DSP with 100μsec control time. Speed sampling is performed at every 1 msec. The main switching device in this experiment is IGBT.



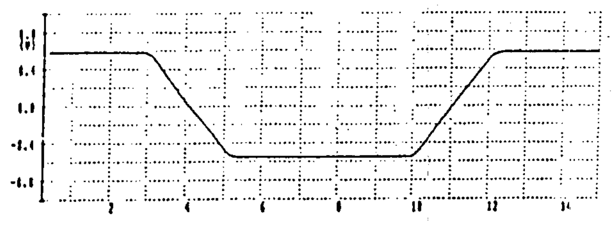
(a) Actul speed [400 rpm/div]



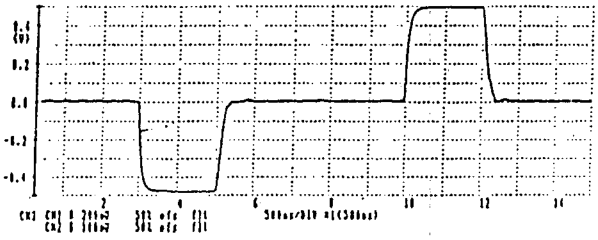
(b) Speed error [10 rpm/div]

Fig. 10. Speed response of PI controller.

Fig. 10 and 11 show the experimental results of speed response with PI controller and proposed fuzzy controller respectively. In these experiments, the speed command is 1000 rpm to - 1000rpm and vice versa. Fig. 10(a) and 11(a) show the actual speed, and Fig. 10(b) and Fig. 11(b) show speed error waveform. Rising time is almost the same in these cases, but overshoot is 21.9 rpm in a PI controller, 4.2 rpm in proposed controller. Therefore, we know that proposed controller has better response than that of PI controller.

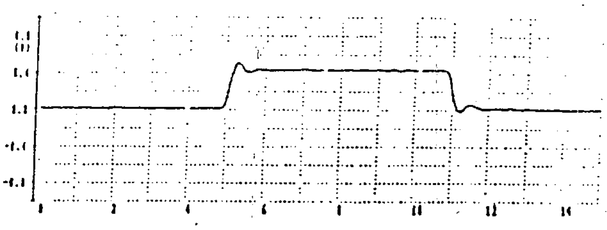


(a) Actul speed [400 rpm/div]

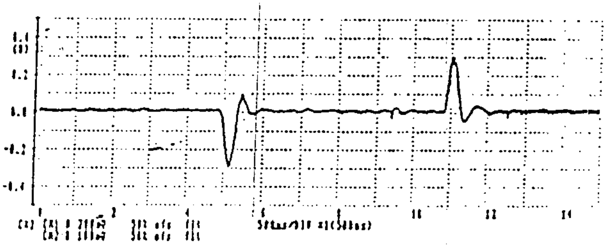


(b) Speed error [10 rpm/div]

Fig. 11. Speed response of proposed controller.



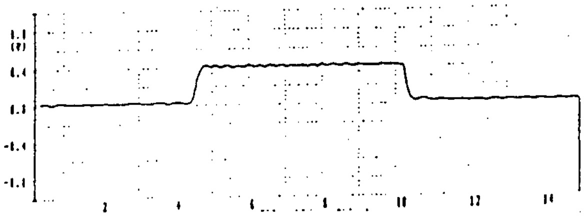
(a) Motor torque [5 Nm/div]



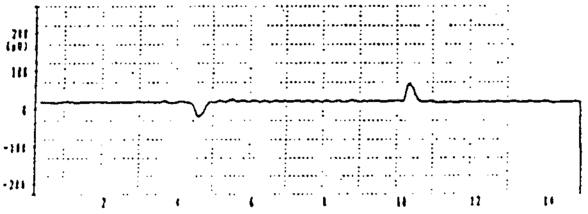
(b) Speed error [5 rpm/div]

Fig. 12. Torque response of PI controller.

Fig. 12 shows the experimental result of torque response with PI controller. Fig. 12(a) shows torque current while Fig. 12(b) shows speed error waveform. In this experiment, applied torque is approximately 10Nm. The same experiment was performed with fuzzy controller. Fig. 13 shows the result. In this experiment, overshoot of speed is 15.9 rpm in a PI controller, 10 rpm in proposed controller. Therefore, we can see better response also.



(a) motor torque [5 Nm/div]



(b) speed error [5 rpm/div]

Fig. 13. Torque response of proposed controller.

V. Conclusion

In this paper, the speed controller of induction motor based on fuzzy algorithm with hierarchical structure is proposed. Fuzzy controller does the fuzzification with fuzzy singleton, the exponential-quantization and the simplified product-sum method of the type of mixture. Therefore we can obtain the desirable control characteristics. Specially, by using the fuzzy controller with hierarchical structure which can abridges or magnifies a range of input variable according to the magnitude of error, steady state error the weak point of the fuzzy controller can be considerably reduced. For the changes in load torque and/or load inertia moment, the simulation results reveal that the proposed fuzzy controller is more robust than the conventional PI controller. And the proposed controller can be easily implemented in a DSP controller. The simple and robust speed controller using fuzzy algorithm has been realized.

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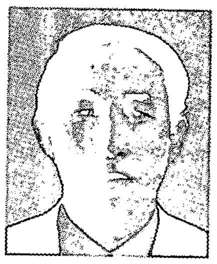

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