THE SPEED CONTROL OF DC SERIER WOUND MOTOR USING DSP (TMS320F240)

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ABSTRACT

In general, the electronic forklift driven by DC motor drive system is used in the industrial field. Classically, the DC motor is controlled by speed control using proportion control method, by output torque following the load on the plane like a manual operation. But in the industrial field, the electronic forklift is demanded the robust drive mode. Some cases of the mode, there are trouble in torque and speed control following slope capacity. The control is sensitive concerning with slope angle and output speed, various control method is studied for stability of speed control.

We apply speed controller for the self-tuning using DSP(TMS320F240) as main controller for high speed processor, embody dynamic characteristic of control compared the PI control to the fuzzy control.

1. INTRODUCTION

Adaptive control which adjusts gain of PID controller according to change in a system is used in order to control speed of an electric forklift car. Under this adaptive control, however, it is practically hard to make an efficient controller due to complication of algorithm and any other reason. Also variable structure control is applied as a nonlinear control but it might cause high frequency characteristics disregarding high speed modeling on a sliding surface.

In order to solve this problem a fuzzy controller under genetic algorithm with self-tuning is applied, which will perform high efficiency speed control. The efficiency of control algorithm is presented through an experiment and compared with the quality of PID controller.

2. METHODS

2.1 DC series wound motor in transfer function

DC series wound motor in an electric forklift needs huge force of traction, which steady-state speed is determined by friction and force of traction. And rated speed of the motor, the highest terminal voltage, is controlled in a uniform torque or current by regulating terminal voltage.

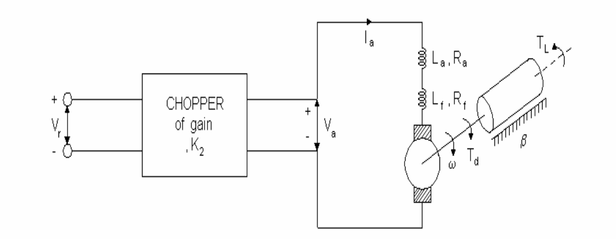


Fig. 1 Chopper-fed DC series motor drive

As Fig. 1 indicates, the terminal voltage is related with the standard voltage on chopper's linearity gain k_2. Supposing that kv, electro motive force coefficient is fixed regardless of armature (or field) current, the DC series wound motor equation for motor system including load is induced as a formula,

$$V_a = K_2 V_r \ , \ \ e_g = K_v i_a \omega$$

$$V_a = R_m i_a + L_m \frac{di_a}{dt} + e_g \tag{1}$$

$$T_d = K_t i_a^2$$

$$T_d = J\frac{d\omega}{dt} + B\omega + T_L \tag{2}$$

In the equation $T_d = k_{t*} i_a^2$, it is characteristic of variable-type non-linear, controller is designed on limited range of operation transforming the nonlinear system into the linearity system on the purpose of applying transfer function. So define system parameters at operating point as follows,

$$e_g = E_{go} + \Delta e_g \quad , \quad i_a = I_{ao} + \Delta i_a$$

$$v_a = V_{ao} + \Delta v_a \quad , \ T_d = T_{do} + \Delta T_d \tag{3}$$

$$\omega = \omega_o + \Delta\omega \quad , \ v_r = V_{ro} + \Delta v_r$$

$$T_L = T_{Lo} + \Delta T_L \tag{4}$$

Where, we can find that $\Delta i_a \ \Delta\omega$ are entirely small.

The equation (2) from equation (1) can be linearization as follows.

$$\Delta v_a = K_2 \Delta v_r \quad \Delta e_g = K_v (I_{ao} \Delta\omega + \omega_o \Delta i_a) \qquad (5)$$

$$\Delta v_a = R_m i_a + L_m \frac{d(\Delta\omega)}{dt} + B\Delta e_g \qquad (6)$$

$$\Delta T_d = 2K_v I_{ao} \Delta I_a$$

$$\Delta T_d = J\frac{d(\Delta\omega)}{dt} + B\Delta\omega + \Delta T_L \qquad (7)$$

Which are written in the transform of Laplace space as follows.

$$\Delta V_a(s) = K_2 \Delta V_r(s) \qquad (8)$$

$$\Delta E_g(s) = K_v[I_{ao}\Delta\omega(s) + \omega_o \Delta I_a(s)] \qquad (9)$$

$$\Delta V_a(s) = R_m \Delta I_a(s) + sL_m \Delta I_a(s) + \Delta E_g(s) \qquad (10)$$

$$\Delta T_d(s) = 2K_v I_{ao} \Delta I_a(s) \qquad (11)$$

$$\Delta T_d(s) = sJ\Delta\omega(s) + B\Delta\omega(s) + \Delta T_L(s) \qquad (12)$$

Which mean that the change of either reference voltage or load torque is the change of speed block diagram for the change of reference voltage and load torque is drawn in Fig. 2 and Fig. 3.

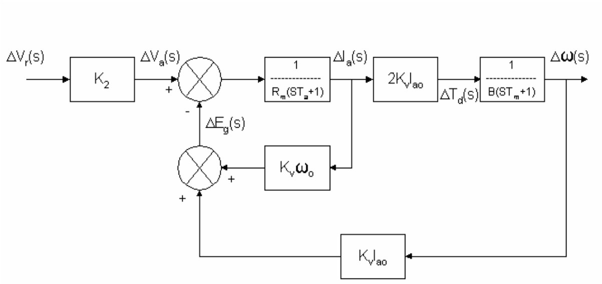


Fig. 2 Block diagram for reference voltage

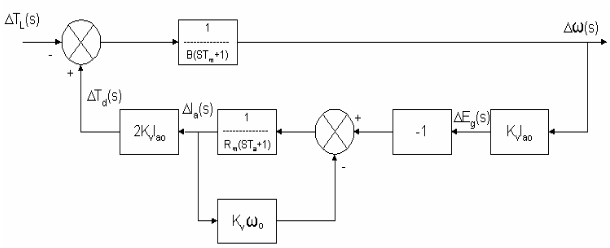
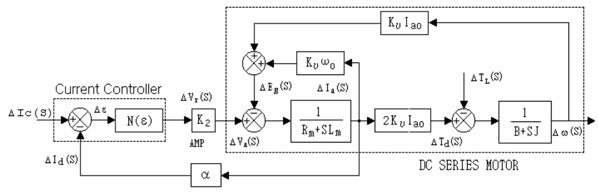


Fig. 3 Block diagram for load torque disturbances

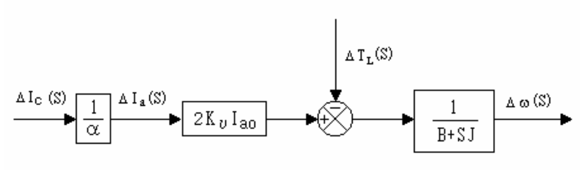
2.2 Current controller with closed transfer function

We can get the dynamic equation of an electric motor as Kirchhoff's voltage equation is applied to armature field system circuits and easily obtain the dynamic equation through Newton's dynamic laws that are applied to rotation machinery part as the electric and mechanical combined relation equation is applied to motor current and generation torque.

In section 2.1, current sensor is connected to power circuit to convert closed-loop system into closed-loop system, so the output of sensor is amplified in proportion to supply current of rotor by α-factor and generates error voltage ($\Delta\varepsilon$) comparing it with current ($\Delta I_c(s)$)



(a) Block diagram of DC series wound motor



(b) Simpled equation block diagram

Fig. 4 Closed-loop block diagram of DC series wound motor

(1) Let us solve that closed-loop step response (Δω(s)) caused change of reference current in the block diagram

$$\frac{\Delta\omega(s)}{\Delta I_c(s)} = \frac{N(\varepsilon)K_2 2K_v I_{ao}}{(R_m+sL_m)(B+sJ)+N(\varepsilon)K_2\alpha(B+sJ)+K_v\omega_o(B+sJ)+sK_v^2 I_{ao}^2}$$

According to final value theorem

$$\lim_{s\to o}\frac{\Delta\omega(s)}{\Delta I_c(s)} = \frac{N(\varepsilon)K_2 2K_v I_{ao}}{(R_m B + N(\varepsilon)K_2\alpha B + K_v\omega_o B)}$$

(2) Speed change in normal operating-Δω(s)

$$\lim_{s\to o}\frac{\Delta\omega(s)}{\Delta T_L(s)} = \frac{R + K_2 N(\varepsilon)\alpha + K_v\omega_o}{B(R_m + K_2 N(\varepsilon) + K_v\omega_o) + 2K_v^2 I_{ao}^2}$$

$$\frac{\Delta\omega(s)}{\Delta T_L(s)} = \frac{(R_m+sL_m)+K_2N(\varepsilon)\alpha+K_v\omega_o}{(B+Js)[(R_m+sL_m)+K_2N(\varepsilon)\alpha+K_v\omega_o]+2K_v^2 I_{ao}^2}$$

3. THE SPEED CONTROL OF DC SERIES WOUND MOTOR USING DSP (TMS320F240).

3.1 Configuration of total hardware.

We use the PI current controller for internal loop to control DC series wound motor as Fig. 12.

Configuration of hardware system shows in the Fig.13.

The internal loop is consisting of current controller, PWM, motor driver circuit and current sensor. The external loop is consist of speed controller, DC series wound motor, tachometer which is used as speed sensor.

As the Fig. 14, The speed controller changes current commend every 5 [msec]. Setups about interrupt, PWM follow the one of PI current controller.

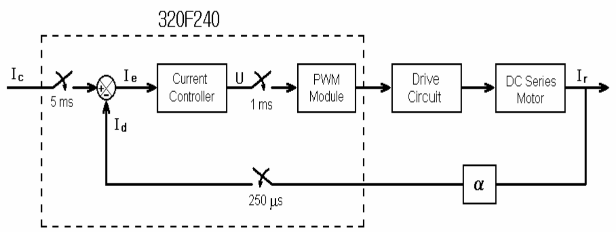


Fig. 5 Total hardware diagram for current control of real system

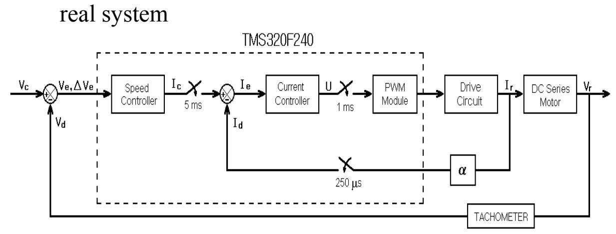


Fig. 6 Total hardware diagram for speed control of DC series wound motor

3.2 The speed control using PI controller.

(1) The architecture of controller.

It is possible to control speed with the PI controller substituting speed controller to PI controller in the Fig 14. The input value of speed control is the gap between reference speed command and feedback value from the tachometer. Out put value is current command from current controller which is internal loop. The equation used in the PI controller is equation(15).

$$u = k_P \times e + k_I \times \int e \; dt$$
$$= k_P \times e + k_I \times \sum e \cdot \Delta t \quad (15)$$

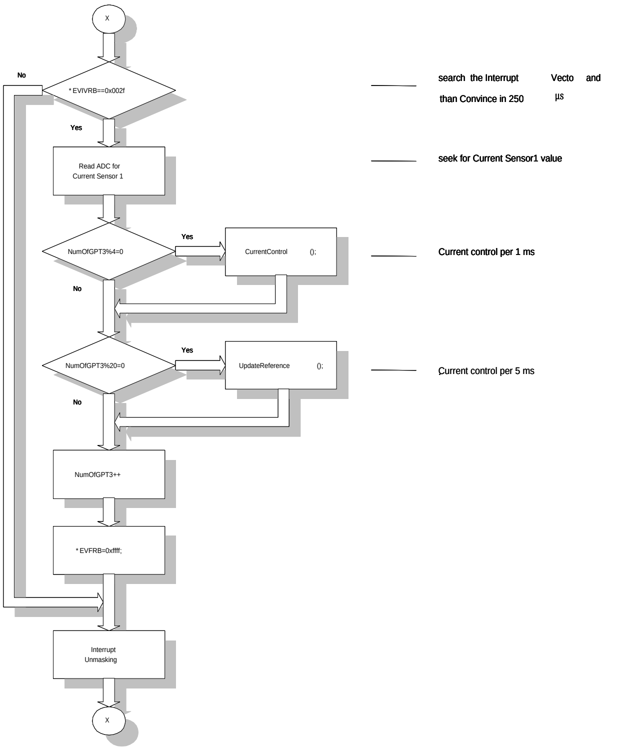


Fig. 7 Flow chart of 250[μs] interrupt subprogram

It is possible to remove the noise from the tachometer, current sensor and potentiometer by taking five simple moving mean value using speed information every 5ms, current every 1ms and pedal every 1ms.

The moving mean method correspond with digital low pass filter and represented equation (16). If weight is uniform, it can be simple movement mean method.

$$y(i) = \frac{1}{w}\sum_{j=-m}^{0} \omega(j) x(i+j) \quad (16)$$

(2) The control of PI speed controller gain

At the graph of test results, the speed response of the top side is that 1[V] shows 500[rpm] and the current of the low side means that 1[V] shows 100[A].

The current scale of downward oscilloscope channel 2 means that 100[mV] represents 1V/div. It shows the load of the weight of electric forklift car body concerning that Load becomes 100[A] and the 160[A] Load shows the load of weights of electric forklift car body and something loaded.

a) Response in changing a proportional gain

At Fig.15, the response is showed as K_p changes when speed command value K_I, K_p, are equal to 1500[rpm], 1, 100[A] respectively.

b) Response in changing an integral gain

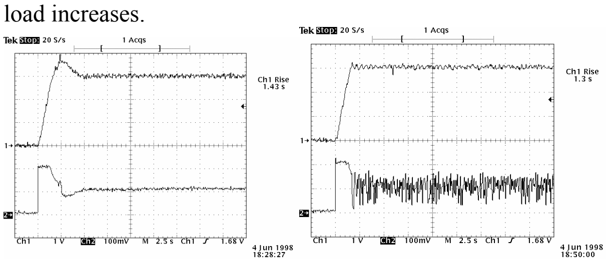
Fig.16 shows response of changing K_I when speed command value is 1500[rpm], K_p is 5.0 and Load is 100[A].

(3) Result of Test

When load's being kept at 100[A], Fig.17 shows the response of changing reference speed at $K_p = 5.0$, $K_I = 0.5$

Due to such limits, the wrong response appears like steady-state error and asymptotic slope increases with keeping the load in 160[A]. After increasing the limits of current maximum to 300[A], Fig.18 represents the response in changing reference speed at $K_p = 5.0$, $K_I = 0.5$ According to characteristic curve 160[A] is limited around 1500[rpm] and the response at 2000[rpm], 2500[rpm] appears about 1500[rpm].

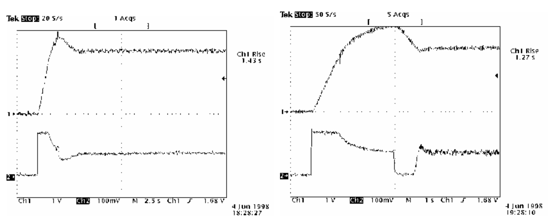
Fig. 19 represents that response characteristic is adapted to the change of speed and Fig. 20 shows that the response is worse as load increases.



(a) $K_I = 0.1$ (b) $K_I = 4.0$

($K_I = 1$, load 100[A], reference speed 1500[rpm])

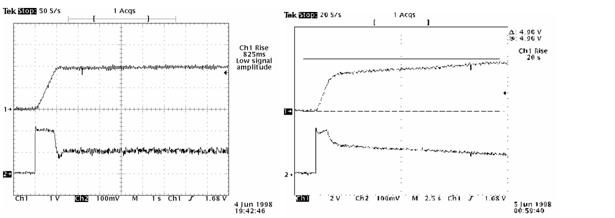
Fig. 8 Experiment results 1 of PI speed controller



(a) $K_I = 0.1$ (b) $K_I = 4.0$

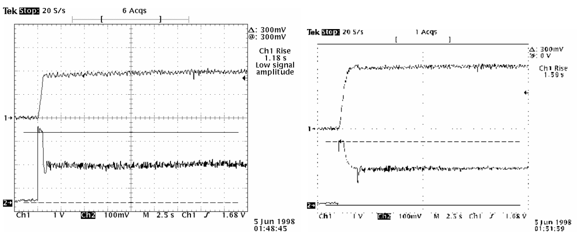
($K_I = 1$, load 100[A], reference speed 1500[rpm])

Fig. 9 Experiment results 2 of PI speed controller

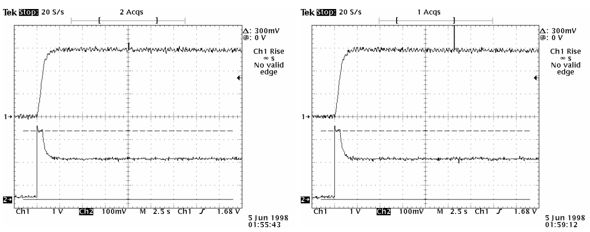


(a) Reference speed 1000[rpm](b) Reference speed 2500[rpm]

Fig. 10 Experiment results of PI speed controller
when load 100[A] (max. 200[A])

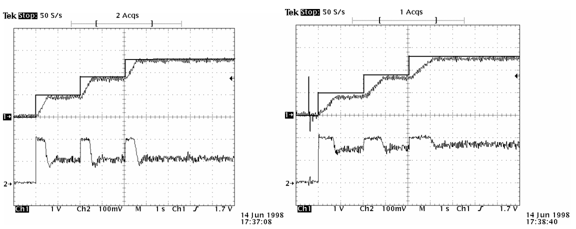


(a) Reference speed 1000[rpm](b) Reference speed 1500[rpm]



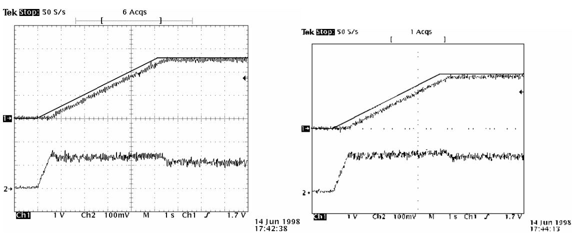
(c) Reference speed 2000[rpm](d) Reference speed 2500[rpm]

Fig. 11 Experiment results of PI speed controller
when load 160[A] (max. 300[A])



(a) Load 100[A] (b) Load 160[A]

Fig. 12 Response of regular order step input
(500[rpm], 900[rpm], 1300[rpm])



(a) Load 100[A] (b) Load 160[A]

Fig. 13 Response of ramp input
(500[rpm], 900[rpm], 1300[rpm])

3.3 Speed control using fussy controller

3.3.1 Configuration of controller

We constitute the fussy controller from speed controller in Fig. 13 for speed control. Inputs of fussy controller become the reference command value, the error and the change ratio of the feedback speed value from tachometer, so output has the command value of reference current of current controller like initial loop.

3.3.2 Speed control of fussy controller of using tuned belonging function

As we consider the condition used for fussy controller fussy rule uses the value in Table 1 based on phase plane and belonging function uses the value in Table 2 tuned by a genetic algorithm. Because all the belonging functions in Table 2 are normalized, we need scale values, so let's speed error scale, error change rate and output go to 0.5, 1.0 and 2.5 respectively. Here, speed error and error change rate mean 500rpm when they are 1.0 and output means 100[A] when it is 1.0.

Table 1 Table of 49 control rules

e / Δe	NB	NM	NS	ZO	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZO
NM	NB	NB	NB	NM	NS	ZO	PS
NS	NB	NB	NM	NS	ZO	PS	PM
ZO	NB	NM	NS	ZO	PS	PM	PB
PS	NM	NS	ZO	PS	PM	PB	PB
PM	NS	ZO	PS	PM	PB	PB	PB
PB	ZO	PS	PM	PB	PB	PB	PB

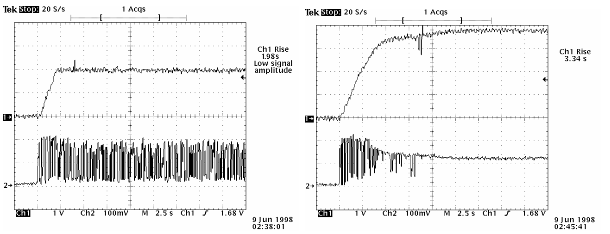
Language Value
NB : Negative big, PS : Positive small
NM : Negative medium,PU : Positive medium
NS : Negative small, PB : Positive big

Table 2 Belonging function of tuning fuzzy controller

Kind	NB	NM	NS	ZO	PS	PM	PB
e	-1.00	-0.42	-0.08	0.00	0.03	0.21	1.00
Δe	-1.00	-0.61	-0.25	0.00	0.31	0.74	1.00
u	-1.00	-0.62	-0.35	0.00	0.32	0.57	1.00

(1) Test when load 100[A]
a) Classification fussy controller

The result is showed in Fig. 21 when fussy controller with self-tuning belonging function is executed by a genetic algorithm and load is 100[A]. Here, the speed information is the value from five moving mean method every 5[ms] and we get error and error rate by using that. As the response, steady-state error doesn't occur at reference speed of 1000rpm and the asymptotic slope to steady state reaches zero.
But steady state error occurs at 2000 [rpm] because output fuzzy scale doesn't match.

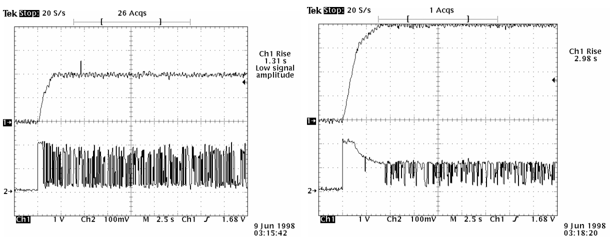


(a) Reference speed 1000[rpm](b) Reference speed 2000[rpm]

Fig. 14 Outputs of basic fuzzy controller (load 100[A])

b) The fuzzy controller using fuzzy singleton.

The fuzzy singleton generates ON-OFF signal not like general fuzzy group. The Fig 22(a) shows that the quick response becomes slow because of using the Fuzzy controller from the transition response. The Fig 22(b) represent that the quick response time is improved comparing with existing Fuzzy controller and steady-state error, asymptotic slope disappear.

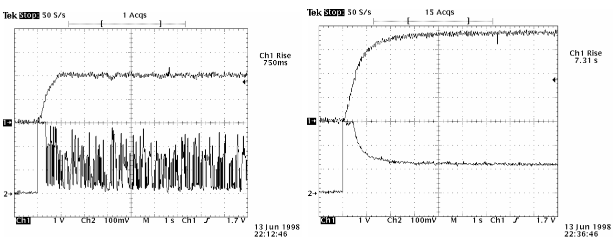


(a) Reference speed 1000[rpm](b) Reference speed 2000[rpm]

Fig. 15 Fuzzy controller output using fuzzy singleton (load 100[A])

c) Fuzzy controller using individual moving mean method.

We get speed error and error rate from five moving mean value every 5 [msec] using fuzzy singleton. Individual means taking five moving mean every 5 [msec] from the speed information and error rate every 1 ms. The speed error can be taken from the moving mean of speed information. As the response, quick response improves much at the reference speed 1000 [rpm] but the steady-state error occurs at 2000 [rpm]. Because of not matching output fuzzy scale as the fig 23(a).



(a) Reference speed 1000[rpm](b) Reference speed 2000[rpm]

Fig. 16 Outputs of fuzzy controller using individual moving mean method (load 100[A])

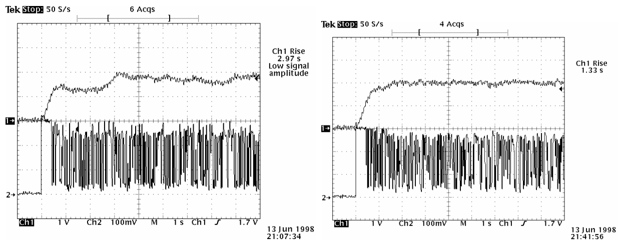
(2) The response following output scales at 160[A] load.

In this part, it shows response from other kind of digital filter after take all of fuzzy singleton.

We examine reference speed 1000 [rpm] following characteristic curve of motor because load is 160[A]. As a result, speed response doesn't follow reference speed command when the output scale is 2.5 and steady-state error disappear as scale increase. But the respect of quick response, it is worse over the specific scale value.

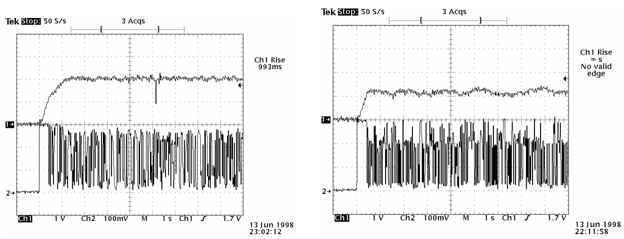
The Fig 24 shows response of changing scale when the load is 160[A], the Fuzzy controller is standard and the reference speed is 1000 [rpm].

The Fig. 25 shows the response of changing scale using fuzzy controller with individual mean method when the load is 160[A], the reference speed is 1000 [rpm].



(a) Output scale = 2.5 (b) Output scale = 7.0

Fig. 17 Outputs of basic fuzzy controller (load 160[A], reference speed 1000[rpm])



(a)Output scale = 2.5 (b) Output scale = 7.0

Fig. 18 Outputs of fuzzy controller using individual moving mean method (load 160[A], reference speed 1000[rpm])

3.3.3 Result of the test

A steady-state error was not generated if a clause in some degree is satisfied in fuzzy controller.

Fig. 26 shows quick responses of an each fuzzy controller at load 100[A], different reference speed. So responses using individual moving method shows very good. But, fuzzy controller using individual moving method was not converged because out put scale is small in the response of 2000[rpm].

Fig. 27 shows quick responses of each fuzzy controller at load 160[A], reference speed 1000[rpm] in variable out put scale. Generally quick responses improved if fuzzy out put scale increased. But, quick responses declined over the mean level. Generally fuzzy controller using individual moving method shows good quick responses. As you can see when steady-state error is generated because of high load, fuzzy membership function or fuzzy regulations are not adjusted, it shows that control is possible by revision out put scale only.

Fig. 28 shows quick responses of fuzzy controller using individual moving method when load is defined 100[A], reference speed is changed and load is increased 160[A], reference speed is changed. Fuzzy controller is not generated steady-state error be estimation performance about reference speed, changing of load but quick responses is changed.

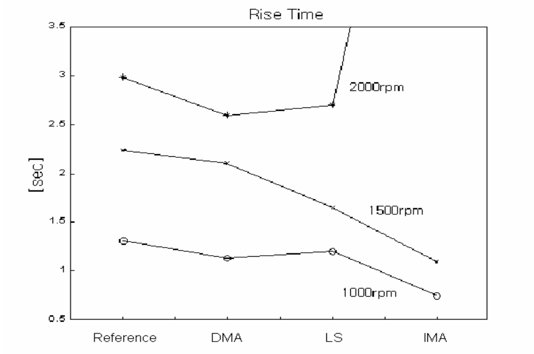


Fig. 19 Quick response each reference speed (load 100[A])

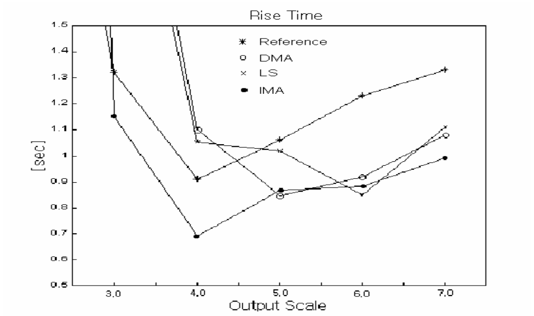
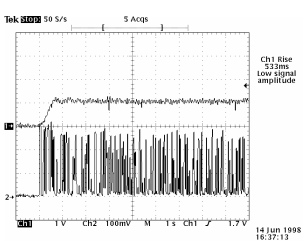
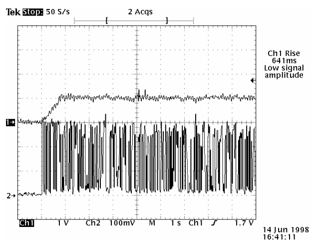


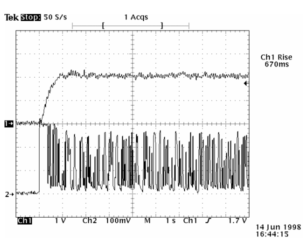
Fig. 20 Quick response each output scale
(load 160[A], reference speed 1000[rpm])



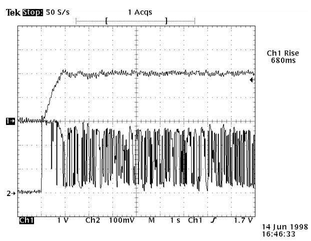
(a) load 100[A], reference speed 500[rpm]



(b) load 160[A], reference speed 500[rpm]



(c) load 100[A], reference speed 1000[rpm]



(d) load 160[A], reference speed 1000[rpm]

Fig. 21 Responses of fuzzy controller using individual moving method

4. RESULT

First seeing responses characteristics of PI controller, Fig. 19 shows that PI controller is not adapted speed changing and load increasing too, if load is increased steady-state error is more increased. Fig. 20 shows that quick response is worse, as the load is more increased.

When load changes, fussy controller didn't need tuned belonging function to be recontrolled and met with the change of the load only as controlling output scale.

Fussy controller influences the change rate of error as noise exists in speed feedback, so current ripple occurs. In this paper, we apply the simple moving mean method and the individual moving mean method to decrease the effect of the noise. The result shows that the individual moving mean method is most effective performance. We need more study of the PI type fuzzy controller to decrease current ripple occurring at the fuzzy controller.

Table 3 is comparison of PI controller response (Fig. 17(a), Fig. 18(a)) when reference speed is 1000[rpm], the load is 100[A], 160[A] and response of fuzzy controller (Fig. 28(c), Fig. 28(d)) using individual moving method. It shows fuzzy controller is better quick response and characteristics of steady-state than PI controller.

Table 3 Result comparison of PI control and fuzzy (reference speed 1000[rpm])

Controller / Function	PI controller		Fuzzy controller	
	100 [A]	160 [A]	100 [A]	160 [A]
Rising time(sec)	0.825	1.18	0.670	0.680
steady State error(rpm)	20	50	0	0
asymptotic slope rate(rpm/sec)	0	3.63	0	0

5. REFERENCE

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