The Design of PIDA Controller with Pre-Compensator

Kang Shin Chool*, Cho Yong Sung**

* Dept. of Computer Application Electricity, Namhae College, Namhae, Kyung Nam
** Dept. of Electronics Dong-A University, Hadan-dong, Saha-gu, 604-714, Busan Korea
Phone : 82-051-200-6733, FAX : 82-051-200-7703

Abstract

PID controller is applied mostly to two-order system. In third-order or higher- system, it's impossible to get high response quality because of having more zero point than the number of zero point being in the PID controller. To solve those, Jung & Dorf suggested a new type of PIDA controller and solved problen of a third-order system.. But, as the result of getting step response using PIDA controller, rising time is very quickly but wide overshoot is happened. Beside designing PIDA controller with using CDM(Coefficient Diagram Method) suggested by shunji manabe. But , In Performance standard, CDM decreases overshoot to desired but rising time is very slow. Therefore this paper suggest a PD-PIDA controller for low overshoot with PD type Pre-compensator. This paper applied designed PD-PIDA controller to position control of 3-Phase induction motor.

Ⅰ. Introduction

PID controller is applied mostly to two-order system. In third-order or higher- system, it's impossible to get high response quality because of having more zero point than the number of zero point being in the PID controller. To solve those, Jung & Dorf suggested a new type of PIDA controller and solved problen of a third-order system. That is, We can take desired PIDA controller, if designed characteristic equation and system transfer function containing controller is solved and they are considered as equl wanted PIDA controller can be designed. But, as the result of getting step response using PIDA controller, rising time is very quickly but wide overshoot is happened. Also, In case of designing PIDA controller using CDM mothod suggested by Shunji Manabe, CDM decreases overshoot that desired in response but rising time is very slow. And Mathematical definition of stability exponents (γ_i), equivalent exonents using in CDM is not precise because of that is empirical value. Therefore, this paper suggested PD-PIDA controller. That is, it is add PD controller for Pre-compensator to PIDA controller. PD-PIDA controller has performance that is fast response speed and decreses overshoot for change root loci of control system to safe form. And, using Jung&dorf, CDM PD-PIDA controller, This paper applied to position control of 3-Phase induction motor.

Ⅱ. Design of PIDA controller

1. Design of PIDA controller using CDM(Coefficient Diagram Method)

Controller designed by CDM has safety and strength to step response. Fig. 1. is fundamental block diagram of controller designed by CDM to SISO(Single-Input Single-Output). system transfer function for each block's polynomial is same to equation (1a), (1b)

$$G_D(s) = p_k s^k + p_{k-1} s^{k-1} + \cdots + p_0 \quad (1a)$$

$$G_N(s) = q_m s^m + q_{m-1} s^{m-1} + \cdots + q_0 \quad (1b)$$

Controller's polynomail is same to equation (2a), 2b).

$$C_D(s) = l_\lambda s^\lambda + l_{\lambda-1} s^{\lambda-1} + \cdots + l_0 \quad (2a)$$

$$C_N(s) = k_\lambda s^\lambda + k_{\lambda-1} s^{\lambda-1} + \cdots + k_0 \quad (2b)$$

$$C_0(s) = k_0 \quad (2c)$$

In equation (1) and (2), $G_D(s)$: a denominator system, $G_N(s)$: a numerator of system, : $C_D(s)$: a denominator of controller, $C_N(s)$: a numerator of controller.

Where, $\lambda < k$, $m < k$, $C_0(s)$ is selected k_0. Specific polynomial of control system is same to equation (3) shown Fig. 1.

$$\begin{aligned} P(s) &= C_D(s)\, G_D(s) + C_N(s)\, G_N(s) \\ &= a_n s^n + a_{n-1} s^{n-1} + \cdots + a_0 \\ &= \sum_{i=0}^{n} a_i s^i \end{aligned} \quad (3)$$

Where, $a_0, a_1, \cdots a_n$ is coefficients of sfecific polynomial. A safety exponent γ_i, equivalence time constant τ, and limit exponent of safety γ_i^*.

$$\gamma_i = \frac{a_i^2}{a_{i+1} \cdot a_{i-1}} \quad (4)$$

(only, where $i = n-1$)

$$\tau = \frac{a_1}{a_0} \quad (5)$$

$$\gamma_i^* = \frac{1}{\gamma_{i+1}} + \frac{1}{\gamma_{i-1}} \; : \; \gamma_0,\ \gamma_n = \infty \quad (6)$$

From above equation, standard value of safety exponent

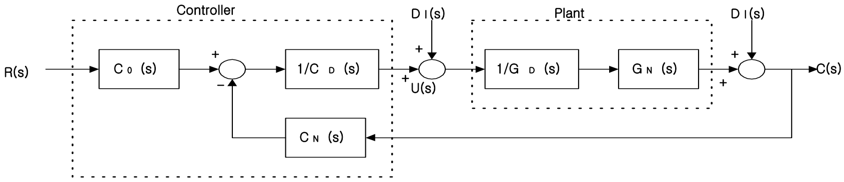

Fig. 1. CDM standard block diagram for the SISO system

and equivalence time constant is selected,

$$t_s = 2.5\tau \sim 3\tau \quad (7)$$

$$\gamma_{n-1} = \cdots = \gamma_3 = \gamma_2 = 2, \ \gamma_1 = 2.5 \quad (8)$$

Customary Transfer function of PIDA controller $C(s)$ is same to eqation (9).

$$C(s) = K_P + \frac{K_I}{s} + K_D s + K_A s^2 \quad (9)$$

$$C(s) = \frac{k_3 s^3 + k_2 s^2 + k_1 s + k_0}{s} \quad (10)$$

where,

$k_3 = K, \ k_2 = K(a+b+z), \ k_1 = K[(a+b)z + ab],$

$k_0 = K(abz)$

Comparing equation (2a) with (2b), we ca get coefficient of controller $C_D(s)$, $l_3 = l_2 = l_0 = 0$, $l_1 = 1$. Thus, $C_D(s) = s$ and , coefficient of $C_N(s)$ is equl to the other.

2. Design of PIDA using Jung & Dorf method

PIDA controller suggested by Jung & Dorf that is existing PODA controller add acceleration is expressed as

$$C(s) = K_P + \frac{K_I}{s} + K_D s + K_A s^2 \quad (11)$$

Writing simply that is PIDA controller added zero point and is expressed as,

$$C(s) = K\frac{(s+a)(s+b)(s+z)}{s(s+d)(s+e)} \quad (12)$$

Where $a, b, z \ll d, e$ two PIDA controller pole (d, e) far from zero point is excluded in the design for stability. For this, desired system performance standard is determinded as the following. A system perpomance standard satisfying output response is overshoot(P.O), peak time(T_p), settling time(T_s), steady state error(e_{ss}), error constant(K_p, K_v), a ratio of disturbance of output $\left(\left|\frac{Y(s)}{D(s)}\right|\right)$ and etc. Because performance standard desired in each system is difference, but generally its required small overshoot , quick response and perpormance standard without steady state error. About determining system response velocity and overshoot damping(ζ)and natural frequency(ω_n) following equation is

$$\zeta = \sqrt{\frac{\left\{\ln\frac{L}{100}\right)}{\pi^2 + \left(\ln\frac{L}{100}\right)}} \quad (13)$$

$$\frac{4}{T_s} \le \zeta\omega_n \quad (14)$$

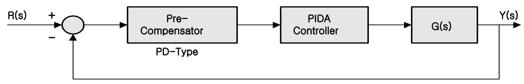

Fig. 2. The Block Diagram with PD-PIDA

T_s: desired steady state time value, L: percent overshoot

From equation (13) and (14), calculating $\zeta, \ \omega_n$ dominatnt root place and domain at the s-plane can be got. Dominant roots $q, \ \hat{q}$ is as

$$q, \ \hat{q} = \zeta\omega_n \pm j\omega_n\sqrt{1-\zeta^2} \quad (15)$$

3. Design of PIDA controller using PD type Pre-compensator

In this paper, we designed PIDA controller using Pre-compesator. That stisfied standard Performance of control system and has fast response chacteristic ,safety strength. Using Jung & Dorf method for mathmatical definition, we designed PD-PIDA controller with Pre-compensator for reduce overshoot. Fig. 2 is block diagram of PD-PIDA controller that suggested in this paper. Performance of PD compensator in PD-PIDA controller purposed that change root loci of control system. That is, adding PD type compensator to get safety response in design method of desired PIDA controller, and chage position of root loci to safe position. Therefore, using Jung & Dorf method, it reduced overshoot that happened when used Jung & Dorf PIDA controller with Precompensator in front of controller shown Fig. 2.

Ⅲ. Simulation Result

We compare each simulation result to PIDA controller with Pre-compensator suggested this paper, Jung&Dorf method and PIDA controller designed by CDM method. Desired performance standard about designed controller is determined as the following and we did simulation about AC induction Motor. $t_s \le 2$sec, $P.O = 5\%$

Fig. 3 is block diagram of position control of 3-phase induction motor system. Transfer function of induction motor is same to equation (16).

$$G(s) = \theta_d\frac{(s)}{\theta(s)} = \frac{K_I K_t}{s(Js^2 + (f + K_P K_t)s + K_I K_t)} \quad (16)$$

Where, $K_P, \ K_I$: Gain of PI controller, K_t : Constant of

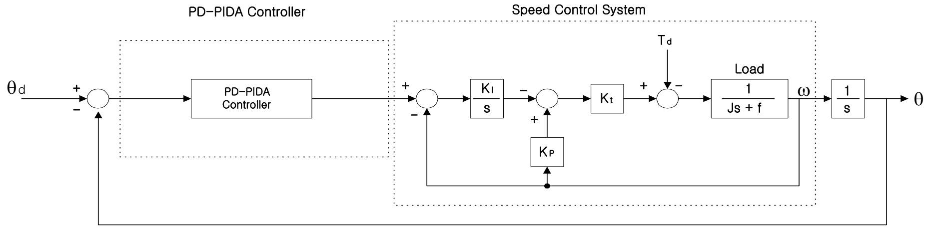

Fig. 3. 3-Phase Induction motor with a PD-PIDA controller

Motor Coefficient value is

$J=0.305,\ f=0.2725,\ K_P=14.0242,\ \ K_t=0.5443$

Thus, in equation (16), transfer function of induction motor is same to equation (17).

$$G(s)=\frac{168.0436}{s(s^2+25.921s+168.0436)} \qquad (17)$$

Using equation (17), we designed PD-PIDA controller suggested this paper, Jung&Dorf method and PIDA controller designed by CDM method. And examined the result.

1. Simulation of 3-phase induction motor using Jung & Dorf method

For simulate 3-phase induction using Jung&Dorf method, deremined standard of performance, percent overshoot = 5%, settling time = 1 sec. And we get following damping and natural frequency, etc.

$\zeta = 0.7244,\ \omega_n = 2.7618,\ r=28,\ R=2$

Form of PIDA controller is

$$\begin{aligned}\Delta(s) &= a_4s^4+a_3s^3+a_2s^2+a_1s+a_0\\ &= s^4+34s^3+183.6229s^2+452.6881s+426.8845\end{aligned}$$

$$\begin{aligned}PIDA_c(s) &= \frac{K_As^3+K_Ds^2+K_Ps+K_I}{s}\\ &= \frac{8.079s^3+78.0387s^2+573.1331s+3499.7648}{s}\end{aligned}$$

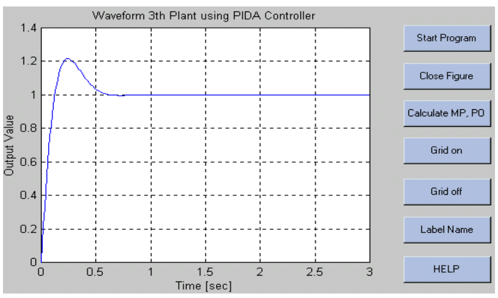

Fig. 4. Step response of 3-Phase Induction Motor using Jung &Dorf (When R=2, r= 28)

In result of Fig.4 used Jung&Dorf method, it has many overshoot, that can't desired 5% percent overshoot. But it satisfied standard performance of settling time.

2. Simulation of 3-phase inductio motor using CDM

We examined response of 3-phase induction motor by CDM. Used parameter is

$t_s = 1,\ \ \tau = t_s/3 = 0.3333,\ \gamma_1 = 2.5,\ \gamma_2 = 2,\ \gamma_3 = 2.5$

$\gamma_1^* = 0.5,\ \gamma_2^* = 0.8,\ \gamma_3^* = 0.5$

$$\begin{aligned}\Delta(s) &= a_4s^4+a_3s^3+a_2s^2+a_1s+a_0\\ &= s^4+37.5s^3+562.5s^2+4219s+12660\end{aligned}$$

$$\begin{aligned}PIDA_c(s) &= \frac{K_As^3+K_Ds^2+K_Ps+K_I}{s}\\ &= \frac{0.0689s^3+2.347s^2+25.11s+75.32}{s}\end{aligned}$$

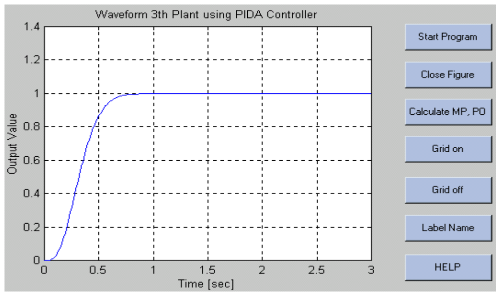

Fig. 5. Step response of 3-Phase Induction Motor using CDM (When $t_s = 1$)

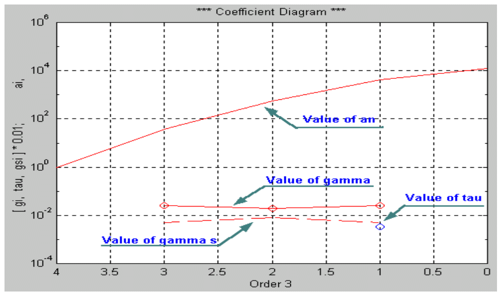

Fig. 6. Coefficient Diagram of 3-Phase Induction Motor of CDM (When $t_s = 1$)

Fig.5 is shown step response. In simulation result, it has less overshoot than Jung&Dorf method. But it' settling time is late. Fig. 6 is shown Coefficient diagram of CDM.

3. simulation of 3-phase induction motor using PD-PIDA controller

Using PD-PIDA controller suggested this paper, Fig. 7 is shown simulation result of unit step response about 3-phase induction motor. From the above result of simulation about JUng&Dorf method and CDM, response is fast and less overshoot then each controller. And found the performance is exellent. Used coefficient of simulation is

$\zeta = 0.7244,\ \omega_n = 2.7618,\ K_P = 1.2,$

$K_D = 0.3, \ r = 28, \ R=2$

$$\Delta(s) = a_4 s^4 + a_3 s^3 + a_2 s^2 + a_1 s + a_0$$
$$= s^4 + 34 s^3 + 183.6229 s^2 + 452.6881 s + 426.8845$$

$$PIDA_c(s) = \frac{K_A s^3 + K_D s^2 + K_P s + K_I}{s}$$
$$= \frac{8.079 s^3 + 78.0387 s^2 + 573.1331 s + 3499.7648}{s}$$

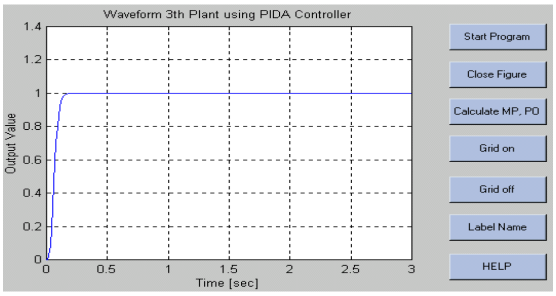

Fig. 7. Step response of 3-Phase Induction Motor using PD-PIDA (When $K_P = 1.2, \ K_D = 0.3$)

Talble 1. is comparig result of PD-PIDA controller suggested this paper with Jung&Dorf and CDM, that design and applied to 3-phase induction motor about peak time, maximum overshoot, and percent overshoot value.

Table 1. Comparision of JungDorf, CDM and PD-PIDA Controller

Induction Motor	t_p [sec]	M_p	P.O [%]
Jung&Dorf	0.18	1.21	21.38
CDM	1.47	1.01	0.948
PD-PIDA	0.4	1.0462	4.615

Ⅳ. Experiment and Result

1. Experimental instrument

This paper compare and estimate comtrollers suggested by using 3-phase induction motor and encoder. Fig 8. is shown instrument for experiment. Coefficient of PIDA get by simulation. And observed response changing coefficient a little.

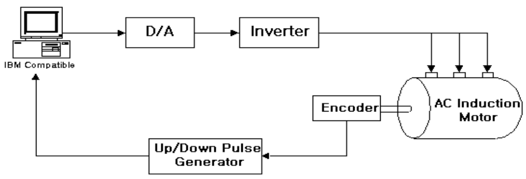

Fig. 8. The Block Diagram of Experiment

We used 2000[pulse/circle] encoder for detecte position of induction motor. 16bit/up counter used by position detector. PC load pulse value that desired position to the counter. and compare with input pulse that according to turning direction of motor. And, this deviation count value used to reference signal of the controller. therefore, it identified up or down pulse though direction discriminator from feedback pluse by encoder. when it input to PC, if forward rotation, count down, and reverse turn, count up, rotate until 0. Fig 9. is shown direction distinction circuit.

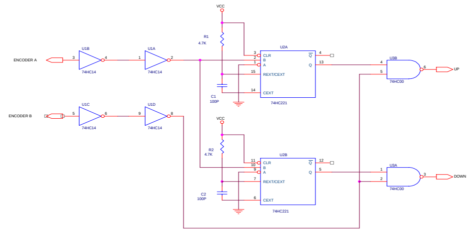

Fig. 9. Up/Down Pulse Generator

Also, IGBT that is used in an experiment is 600V 100A's IGBT module use of FairChild corp,SM2G100US60. Specification of induction motor that is used in an experiment is same to table 2.

Table 2. Specification of 3-Phase Induction Motor

Model	91DG3-90FP
Output [W]	90 [W]
Poles [P]	4 P
Rated Voltage [V]	220 [V]
Rated Current [A]	0.8 [A]
Inertia (J)	0.305 kg- m^2
Coefficient of friction (f)	0.2725 N-m/rad/sec
Constant of motor (Kt)	0.5443 N-m/A

Fig 10. and Fig 11 is shown external picture and experimental circutit of induction motor use in paper.

Fig. 10. 3-Phase Induction Motor

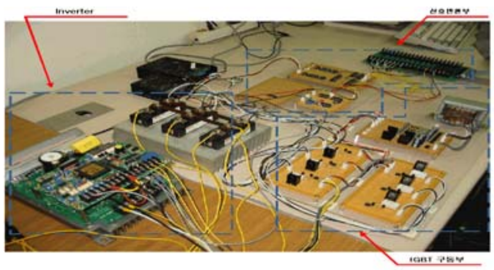

Fig. 11. Hardware apparatus used in this experiment

2. Result of experiment

Used coefficients of each controller(Jung&Dorf, CDM, PD-PIDA) in experiment is simulation value for 3-phase induction motor. Transfer target position of induction motor is 180 °. That established 1000 pulse.

(1) Jung & Dorf

Using Jung&Dorf method, express position control result of 3-phase induction motor. For examine whether value that get through simulation is most suitable in actuality control system, Coefficient value applied coefficient value that is get in simulation and value that regulate giving change of ± 10% in the coefficient value in an experiment. Result that experiment in coefficient value that get through simulation regulate by -10% is same to figure 12.

$K_P = 515.82,\ K_I = 3149.79,\ K_D = 70.23,\ K_A = 7.28$

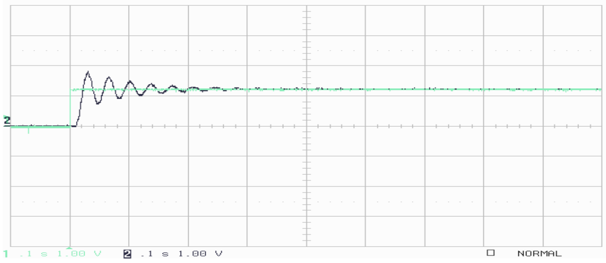

Fig. 12. Step response of Jung&Dorf (Deviation -10%)

Through simulation, experiment result of case that apply coefficient value that get just as it is is same to figure 13.

$K_P\ =\ 573,\ K_I\ =\ 3500,\ K_D\ =\ 78,\ K_A\ =\ 8$

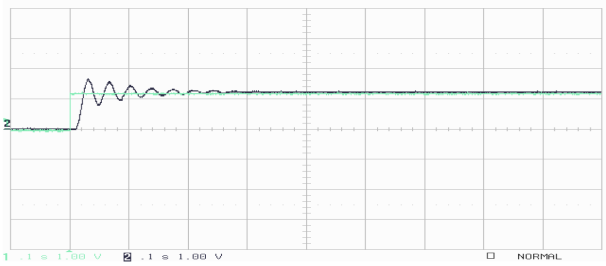

Fig. 13. Step response of Jung&Dorf (Deviation 0%)

Result that experiment in coefficient value that get through simulation regulate by +10% is same to figure 14.

$K_P = 630.45,\ K_I = 3849.74,\ K_D = 85.84,\ K_A = 8.9$

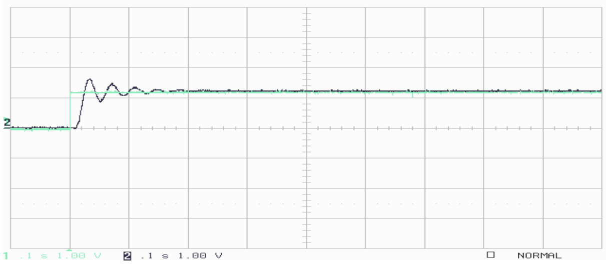

Fig. 14. Step response of Jung&Dorf (Deviation +10%)

(2) CDM

Using CDM method, coefficient value gets through simulation too. From PIDA coefficient though following safety exponent, Fig 15. is shown result of experiment.

$\gamma_1\ =\ 2.5,\ \gamma_2\ =\ 2.0,\ \gamma_3\ =\ 2.5$

$K_P = 25,\ K_I = 75,\ K_D = 2.4,\ K_A = 0.07$

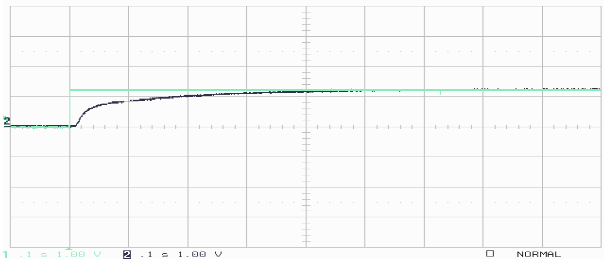

Fig. 15. Step response of CDM (γ is low)

From PIDA coefficient though following safety exponent, Fig 16. is shown result of experiment.

$\gamma_1\ =\ \gamma_2\ =\ \gamma_3\ =\ 2.5$

$K_P = 39.23,\ K_I = 117.68,\ K_D = 4.23,\ K_A = 0.13$

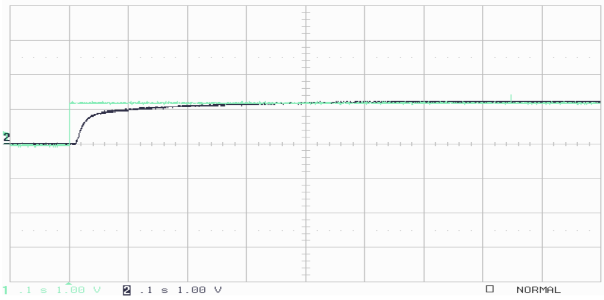

Fig. 16. Step response of CDM (γ is under certain conditions)

(3) PD-PIDA Controller

In design PD-PIDA controller, a coefficient of PIDA controller used value designed Jung&Dorf method. But, In case of using Jung&Dorf PIDA controller, because it has overshoot in initial, we can reduce overshoot by PD compensator. Therefore, experiment is look at result chaging coefficient ofPIDA and coefficient of PD compensator. Adjustment range of PD coefficient value regulates and experimented by ± 10% via cost that is get in simulation as PIDA coefficient value. Result that experiment in coefficient value that get through simulation regulate by -10% is same to Fig 17.

$K_P\ =\ 1.08,\ K_D\ =\ 0.27$

$K_P = 515.82,\ K_I = 3149.79,\ K_D = 70.23,\ K_A = 7.28$

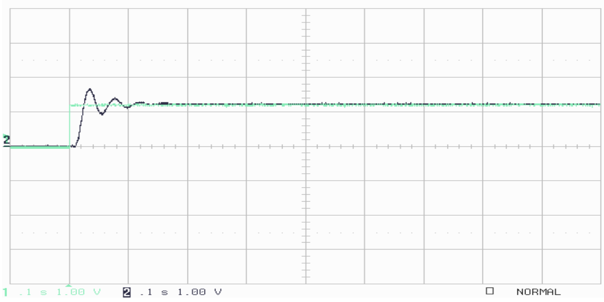

Fig. 17. Step response of PD-PIDA (Deviation -10%)

Through simulation, experiment result of case that apply coefficient value that get just as it is is same to figure 18.

$K_P = 1.2,\ K_D = 0.3$

$K_P = 573,\ K_I = 3500,\ K_D = 78,\ K_A = 8$

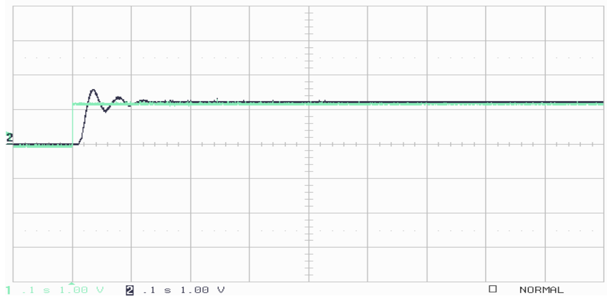

Fig. 18. Step response of PD-PIDA (Deviation 0%)

Result that experiment in coefficient value that get through simulation regulate by +10% is same to figure 19.

$K_P = 1.32,\ K_D = 0.33$

$K_P = 630.45,\ K_I = 3849.74,\ K_D = 85.84,\ K_A = 8.9$

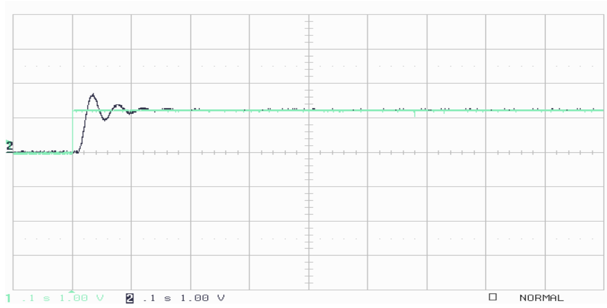

Fig. 19. Step response of PD-PIDA (Deviation +10%)

V. Conclusions

For apply PIDA controller to position control of 3-phase induction motor, this paper get coefficient by each design method. That is, get coefficient of PIDA by apply to 3-phase induction motor modeling equation. And, performance is confirmed by simulation. We can found the performance of PD-PIDA controller seggsted in this paper as result of simulation. And as giving change by -10%, -10% to confirm if is PIDA coefficient value this appropriate coefficient value that is get through simulation, regulate and apply in position control of 3-phase induction motor and verified result. As a result, characteristic of PD-PIDA cotroller suggested is exellent about overshoot and settling time. Also, Changing of characteristic of PD-PIDA controller is less about changing of coefficient. Thus, In spite of coefficient value isn't optimize. it can have safety contol characteristic. However, there is problem that must flow many trial and errors serving to establish coefficient value of PD type compensator. Therefor, research task at future is studing and getting Optimized coefficient of PD type compensator. And, more excellent performance is expected.

References

1. J. G. Ziegler and N. B. Nichols, "Optimum settings for automatic controllers", Trans. ASME, vol. 64, pp. 759-768, 1942.

2. E. J. Davison, "A Method for Simplifying Linear Dynamic Systems", IEEE Trans. Automatic Control, vol. AC-11, pp.93-101, JAN 1966.

3. P. N. Paraskevopoulos, "On the design of PID output feedback controllers for linear multi-variable systems", IEEE Trans. on Industrial Electronics and Control Instrumentation, vol. IECI-27, pp. 16-18, Feb, 1980.

4. K. Ogata, Modern Control Engineering, 2nd edition, Prentice Hall, 1990.

5. C. C. Hang, K. J. Äström, and W. K. Ho, "Refinements of the Ziegler-Nichols tuning formula, "Proc. IEE, Pt.D., vol. 138, pp. 111-118, 1991.

6. R. C. Dorf and D. R. Miller, "A method for enhanced PID controller design", Journal of Robotics and Automation, vol. 6, pp. 41-47, 1991.

7. R. C. Dorf and R. H. Bishop, Modern Control Systems, 7th edition, Addison Wesley, 1995.

8. R. C. Dorf, S. Jung, J. Dawes, and L. Ng, "An s-plane analytic technique for lead-lag controller design", Proc. of American Control Conference, pp. 2227-2228, Seattle, June, 1995.

9. Seul Jung and Richard C. Dorf, "Analytic PIDA Controller Design Technique for A Third Order System", Proc. of 35th, Conference on Decision and Control, Kobe, Japan, 1996, pp. 2513-2518

10 T. Iwasaki and A. Morita, “Fuzzy auto- tuning for PID controller with model classification." in Proc. NAFIPS '90 Toronto, Canada, June 6-8, 1990, pp. 90-93.

11 J. H. Kim, J. H. Park, and S. W. Lee, "Control of Systems with Deadzones usings PD Controllers with Fuzzy Precompensation", proc, of the IEEE Conf. Intelligent Control, pp.451-456 1993 August.