DESIGN OF DELAY-TOLERANT CONTROLLER FOR REMOTE CONTROL OF NUCLEAR REACTOR POWER

YOON JOON LEE* and MAN GYUN NA[1]
Department of Nuclear and Energy Engineering, Cheju National University,
Ara 1-dong, Cheju-City, 690-756, Korea
[1]Department of Nuclear Engineering, Chosun University
375 Seosuk-dong, Dong-gu, Gwangju 501-759, Korea
*Corresponding author. E-mail : leeyj@cheju.ac.kr

Received July 10, 2008
Accepted for Publication September 5, 2008

One of main concepts involved in regional small nuclear reactors is unmanned remote control. Internet-based virtual private networks provide environments for the remote monitoring and control of geographically-dispersed systems, and with the advances in communication technologies, the potential of networks for real time control and automation becomes enormous. However, networked control has some problems. The most critical is delay in signal transmission, which degrades system stability and performance. Therefore, a networked control system should be designed to account for delay. This paper proposes some design approaches for a delay-tolerant system that can guarantee predetermined stability margins and performance. To accomplish this, the reactor plant is modeled with consideration of uncertainties. With this model, three kinds of controllers are developed using different methods. The designed systems are compared with respect to stability and performance, and a second-order controller designed using the table lookup method was found to give the most satisfactory results.

KEYWORDS : Nuclear Reactor, Remote Control, Signal Delay, Table Lookup

1. INTRODUCTION

Recently, numerous studies have been performed in many countries on small and medium-sized nuclear reactors. The typical capacities of these reactors are about one-tenth those of existing commercial reactors, and are favorable for applications other than electricity generation, such as desalinization and local heating. Extending the concept of the small and medium-sized reactor one step further, we are developing a very small reactor for supplying energy to a residential complex. The prototype is the REX-10 [1], whose capacity is 10 MWt. For intrinsic safety, it employs a natural convection with a low operating pressure of 20 bars, and is installed in an underground pool-type containment vessel.

One of the main features introduced in regional small reactors is unmanned remote control. This is necessary to guarantee economic feasibility by decreasing operating costs. There are many ways of implementing remote control. All of these methods are based on communication technologies, and the most promising and practical technology is remote control by transmission control protocol/internet protocol (TCP/IP). The infrastructure related to TCP/IP has already been constructed, and is expected to develop continuously. Problems such as communication security are expected to be solved. In addition, since numerous application tools have been developed, it is very easy to establish specific goal-oriented environments [2]. Some applications of TCP/IP have already been developed for the remote control of simple systems (e.g. motor control) and show satisfactory operation [3].

There are some problems in the technology of remote control by communication. These include communication security, reliability of signal transmission, and transmission speed. Among these, the most critical is the delay of signal transmission, and communication deadlock between the site and an operator in a remote location. This delay or deadlock becomes an important issue in remote control, particularly when the system is concerned with safety.

The delay of signal flow has an adverse effect on system stability and performance. The stability margin decreases with an increase in delay time, and the system becomes unstable. There are usually signal delays in communication networks such as TCP/IP; hence, a control system is required to be robust under the situation of signal communication delay. The delays are due to hardware characteristics of networks such as routing and interface modules, and to software characteristics such as window size and protocol layers. In addition, the redundancy of the equipment may increase delay times [4].

The purpose of this paper is to describe the design of a nuclear power control system that can handle signal delays. To achieve this, a mathematical reactor model should be defined first. However, because the governing mechanisms of the reactor involve nuclear phenomena, material properties, and thermal-hydraulics, the model has a large degree of inevitable uncertainty. In addition, the dynamics of the reactor vary widely depending on factors such as operating conditions and core life, and it is very difficult to define a mathematically exact plant.

To account for modeling uncertainties, the reactor is described by a family of transfer functions. Then, three controllers are designed and compared to each other. The first is a proportional-integral (PI) controller using the extended frequency response (EFR) method. The second and third are a proportional (P) controller and a second-order controller, respectively, which are developed by the table lookup (TL) method. During the design, emphasis is placed on maximum permissible delay and overall system stability.

2. SYSTEM DESCRIPTION

The reactor dynamics are described by point kinetics equations with one group delayed neutrons. A singly lumped energy balance equation is incorporated to consider the moderator and fuel temperature feedback effects on reactivity. Even this simple description yields a fifth-order multi-input, multi-output (MIMO) system. The system matrices are functions of nuclear and thermal-hydraulic properties as well as of power level. In addition to the simplification and linearization of governing equations, the assumptions are made that the coolant inlet temperature and coolant flow rate are constant. Then, with specific nuclear and thermal-hydraulic properties, the MIMO reactor plant is reduced to a single-input, single-output (SISO) system described by the following linear state variable equations [5].

$$\dot{\boldsymbol{x}} = \boldsymbol{A}(P)\boldsymbol{x} + \boldsymbol{B}(P)u, \quad y = \boldsymbol{C}\boldsymbol{x} + \boldsymbol{D}u, \tag{1}$$

where P is the reactor power, y is the measured output of power, and u is the control input of rod speed.

The moderator temperature coefficient α_c, fuel temperature coefficient α_f, and the fuel gap heat transfer coefficient h_g strongly affect the system matrices of $\boldsymbol{A}$ and $\boldsymbol{B}$. For example, the fuel gap heat transfer coefficient has a wide range of 2,500 to 11,000 $w/m^{2\circ}K$ [6]. The reactivity feedback temperature coefficients depend on factors such as boron concentration, reactor lifetime, fuel temperature, and rod position. For Kori Unit 2, the moderator temperature coefficient has a value of $\alpha_c \in$

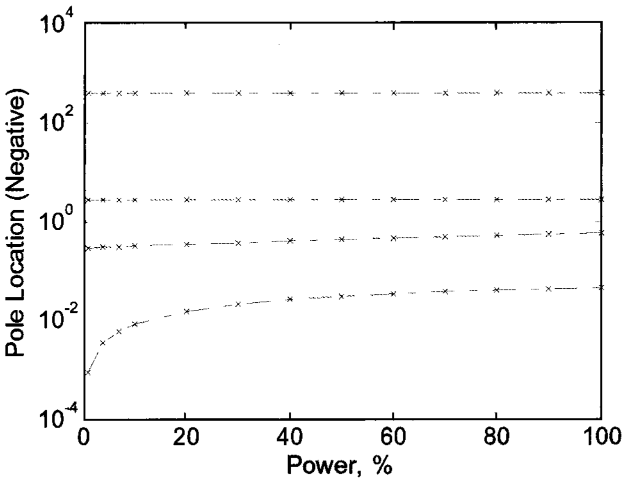

Fig. 1. Pole Locations of Reactor Plant by Power Level

($-57pcm/^\circ K$ $13.5pcm/^\circ K$) and fuel temperature feedback reactivity coefficient has a value of $\alpha_f \in (-4.7pcm/^\circ K$ $-2.8pcm/^\circ K)$.

Two reactor models are defined. The optimistic reactor, which has the largest stability, is determined to be the plant whose parameters are P = 100%, $\alpha_f = -4.7pcm/^\circ K$, $\alpha_c = -57pcm/^\circ K$, $h_g = 11{,}000w/m^{2\circ}K$; the pessimistic plant parameters are $P \approx 0\%$, $\alpha_f = -2.8pcm/^\circ K$, $\alpha_c = 13.5pcm/^\circ K$, and $h_g = 2{,}000w/m^{2\circ}K$. Each model in the s domain is:

$$G_{opt} = \frac{228.5s^3 + 683.9s^2 + 177.3s + 9.8}{s^5 + 406.2s^4 + 1496s^3 + 1443s^2 + 93.4s}, \tag{2}$$

$$G_{pes} = \frac{228.5s^3 + 726s^2 + 259.7s + 16.1}{s^5 + 406.4s^4 + 1253s^3 + 364.3s^2 + 0.316s}. \tag{3}$$

Then, the family of reactor models is described by

$$\tilde{G}(s) = \frac{\tilde{a}_0 s^3 + \tilde{a}_1 s^2 + \tilde{a}_2 s + \tilde{a}_3}{\tilde{b}_0 s^5 + \tilde{b}_1 s^4 + \tilde{b}_2 s^3 + \tilde{b}_3 s^2 + \tilde{b}_4 s + \tilde{b}_5}, \tag{4}$$

where $\tilde{a}_0 \in (228.5, 228.5)$, $\tilde{a}_1 \in (683.9, 726)$, $\cdots$, $\tilde{b}_0 \in (1,1)$ $\tilde{b}_1 \in (406.2, 406.4)$, $\cdots$.

Under normal operation, the reactor is assumed to have the values of $(\alpha_f \ \alpha_c \ h_g) \approx (-3.7 \ \ 0 \ \ 4{,}850)$. Then, the plant is dependent on power only. Figure 1 shows the pole locations of the plant by power level. The reactor plant has one pole on the origin, which plays the role of an integrator. As the power decreases, the poles become smaller. Particularly, the governing pole approaches the origin. This makes the reactor plant more unstable, and, accordingly, it is more difficult to control reactor the plant as the power decreases.

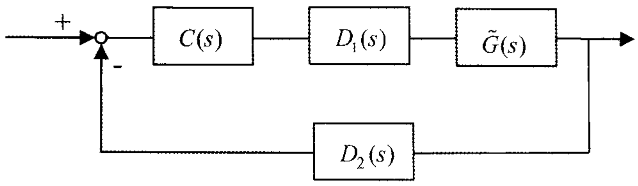

Fig. 2. Overall Block Diagram of the Power Control System

Figure 2 is the overall block diagram of the power control system. The system is comprised of the perturbed reactor plant, $\tilde{G}(s)$, delays of $D_1(s)$ on feedforward loop, $D_2(s)$ on feedback loop, and controller $C(s)$.

The transfer function of the overall system is:

$$H(s)=\frac{D_1(s)C(s)\tilde{G}(s)}{1+D_1(s)D_2(s)C(s)\tilde{G}(s)}. \tag{5}$$

The location of the delay has no effect on system stability [7]. Rather, the sum of delay times, d_1+d_2, has an effect on the stability. The effects of delay on system stability are investigated using Nyquist diagrams. With a perturbed plant and a fixed controller of:

$$\tilde{G}(s)=\frac{P_1(s)}{P_2(s)},\ C(s)=\frac{F_1(s)}{F_2(s)}, \tag{6}$$

the characteristic equation of the closed loop system is:

$$\Delta(s)=P_1(s)F_1(s)+P_2(s)F_2(s). \tag{7}$$

Eight Kharitonov vertex equations are obtained from the segment polynomials of $P_l(s)$ and $P_2(s)$ [8]. They are:

$$K_m^1(s)=q_0^- s^0+q_1^+ s^1+q_2^+ s^2+q_3^- s^3+q_0^- s^4+\ldots,$$

$$K_m^2(s)=q_0^- s^0+q_1^- s^1+q_2^+ s^2+q_3^+ s^3+q_0^- s^4+\ldots$$

$$K_m^3(s)=q_0^+ s^0+q_1^+ s^1+q_2^- s^2+q_3^- s^3+q_0^+ s^4+\ldots,$$

$$K_m^1(s)=q_0^+ s^0+q_1^- s^1+q_2^- s^2+q_3^+ s^3+q_0^+ s^4+\ldots,$$

for $P_m(s)=\sum_0^n[q_i^-,\ q_i^+]s^i$, where $m=1, 2$.

The extremal subset, $\boldsymbol{P}_E^l(s)$, $l=1, 2$, consists of:

$$\boldsymbol{P}_E^l(s)=\frac{\lambda_l K_l^j+(1-\lambda_l)K_l^k}{K_2^i},\ \boldsymbol{P}_E^2(s)=\frac{K_l^i}{\lambda_m K_2^j+(1-\lambda_m)K_2^k}, \tag{8}$$

where $\lambda\in(0, 1)$, $l=1, 2, 3, 4$, $m=1, 2, 3, 4$, $i=1, 2$ and $[j, k]=[1, 2], [1, 3], [2, 4], [3,4]$.

Then, the characteristic equation of the perturbed system is:

$$\Delta_E(s)=\boldsymbol{P}_E^1(s)F_1(s)+\boldsymbol{P}_E^2(s)F_2(s). \tag{9}$$

With $d_1+d_2\equiv d=0$ and with $C(s)=1$, the Nyquist diagram of the system (Eq.9) is described as shown in Fig. 3.

With the presence of delays, the characteristic equation of the system is :

$$\Delta_E(s)=\boldsymbol{P}_E^1(s)d_{11}(s)d_{21}(s)+\boldsymbol{P}_E^2(s)d_{21}(s)d_{22}(s), \tag{10}$$

where $D_1(s)=d_{11}(s)/d_{12}(s)$, and $D_2(s)=d_{21}(s)/d_{22}(s)$.

The stability margin decreases as d increases, and with the critical delay of 1.6 sec, one of the perturbed models becomes unstable as shown in Fig. 4.

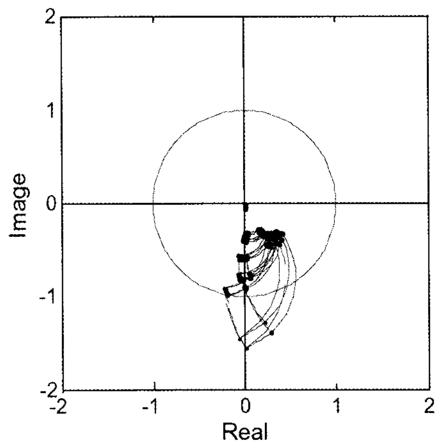

Fig. 3. Nyquist Diagrams of the Perturbed Reactor Plants Without Delay, $C(s)=1$

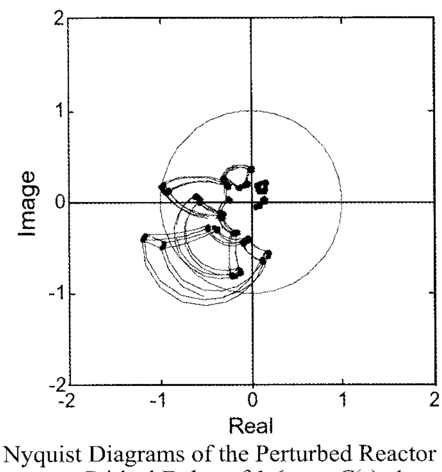

Fig. 4. Nyquist Diagrams of the Perturbed Reactor Plants with Critical Delay of 1.6 sec, $C(s)=1$

3. DESIGN OF CONTROLLERS

With a proper controller, a system becomes more delay-tolerant. There are many ways to design a controller, ranging from the classical proportional-integral-differential (PID) controller to various modern control technologies. The majority of control systems in industry are of PID design. However, in some cases, a high-order controller gives better system characteristics.

Three different controllers are designed in this study. The first is a PI controller designed using the extended frequency response (EFR) method [9], [10]. The second is a simple P controller obtained by the table lookup (TL) method. The third is a second-order controller designed using the TL method. It is a usual practice to consider the system stability and performance as design specifications. But since the control rod movement is critical for nuclear safety, it is considered also in controller design.

3.1 Proportional-Integral Controller by Extended Frequency Response Method

In the extended frequency response method, the system is mapped into the extended frequency domain by the relation $s = -m\omega + j\omega$. Then, the plant is described by $G(m,\omega)$ instead of $G(\omega)$ in the conventional frequency domain. The value m can be regarded as a design specification. For the case of impulse response of the second system, the fading factor is found to be

$$\Psi = 1 - e^{-2\pi m} = 1 - \frac{A_2}{A_1}, \qquad (11)$$

where A_1 and A_2 are the amplitudes of the first peak and the second peak, respectively.

The PI controller is $C(s) = K_P + \frac{K_I}{s} = K_P + \frac{K_P}{T_I s}$, or

$$C(m,\omega) = K_P + \frac{K_I}{-m\omega + j\omega} \qquad (12)$$

From the characteristic equation of $1+G(m,\omega)C(m,\omega)=0$, $Re[G(m,\omega)C(m,\omega)]=-1$ and $Im[G(m,\omega)C(m,\omega)]=0$. By letting $Re[G(m,\omega)]=R_\mu(m,\omega)$ and $Im[G(m,\omega)]=I_\mu(m,\omega)$, K_P and K_I are found to be

$$K_P(m,\omega) = \frac{-R_\mu(m,\omega) - mI_\mu(m,\omega)}{R_\mu(m,\omega)^2 + I_\mu(m,\omega)^2} \qquad (13)$$

$$K_I(m,\omega) = \frac{-\omega(1+m^2)I_\mu(m,\omega)}{R_\mu(m,\omega)^2 + I_\mu(m,\omega)^2} \qquad (14)$$

In Eqs.(13) and (14), ω is the critical frequency at which K_P or K_I is maximum.

Among the family of perturbed plants $\tilde{G}(s)$, G_{pes} of Eq.(3) is used for the basis of controller design to preserve conservativeness. Figure 5 shows K_P and K_I for different value of m. As shown in the figure, K_I increases monotonically; hence, the critical frequency is obtained from $dK_P/d\omega = 0$.

Figure 6 describes the relationship between PI gains and critical delay with m=0.5. Critical delay means the longest delay time that can be permitted to keep the system stable, including the marginal stability. The critical delay time grows longer as reactor power increases. This is because the reactor at a high power level has increased stability margins.

The simulations of the designed system are presented in Fig. 7. Two cases, m=0.366 and m=0.5, are tried for a power increase from 40% to 50%. For m=0.366, the PI coefficients are calculated to be K_P = 0.359 and K_I = 0.148, and for m = 0.5, the PI coefficients are K_P = 0.538 and K_I = 0.217.

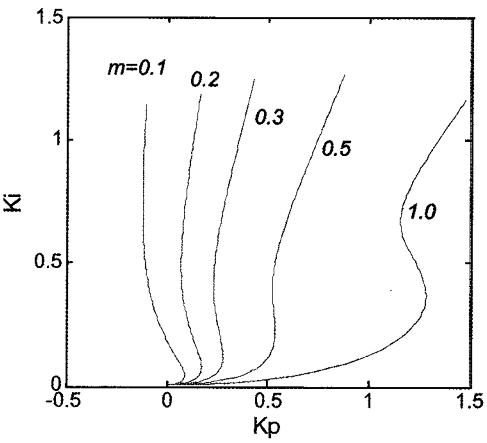

Fig. 5. Proportional Gain (K_P) and Integral Gain (K_I) for Different Values of m

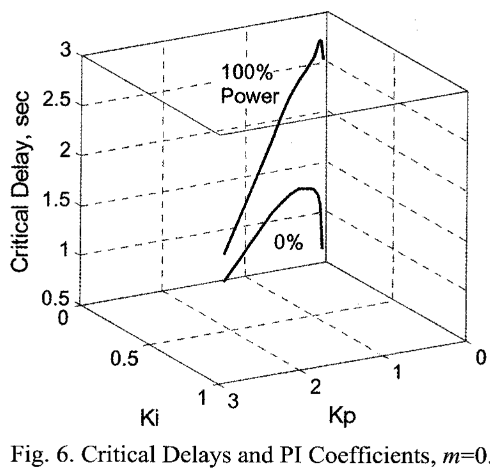

Fig. 6. Critical Delays and PI Coefficients, m=0.5

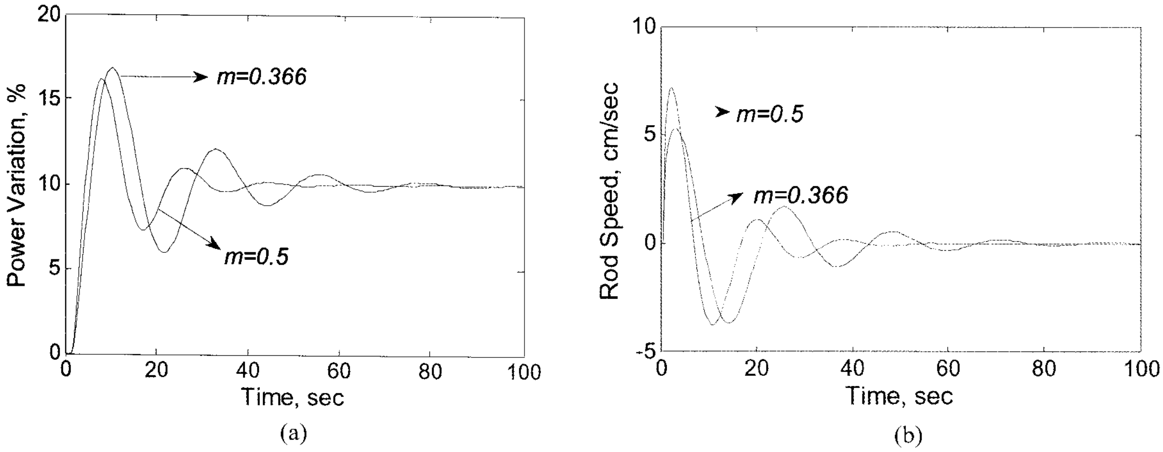

Fig. 7. (a)Power Transient with EFR PI (b)Control Rod Speed with EFR PI

The critical delays are 1.962 sec and 2.01 sec for m values of 0.366 and 0.5, respectively. In simulation, a delay of 1 sec is applied to both cases. As expected, the higher value of m yields the more desirable output, but at the expense of larger control input.

3.2 Proportional Controller by Table Lookup

The design procedure explained previously does not take into account stability margins during the design, and the designed system does not ensure the desired stability margins. To guarantee a specified margin for all power levels, and to guarantee delays that are less than the critical value, a table that relates power levels, gains, and critical delays was developed.

As described in Fig. 8, the plant is defined for a specific level of power. The system stability margins are then calculated for gain values ranging from 0.1 to 1, and the critical delays that guarantee a phase margin of at least 30 degrees are obtained.

The table obtained by this procedure has the form of *Lookup_Table (Power, Kp, Critical_Delay)*, as shown in Fig. 9. The critical delay time becomes longer for higher power and for a lower K_P value, that is, for a more stable plant, because it has a larger phase margin.

With this table, gain can be determined for a given power and system delay. The function of K_P = *kp_by_power_delay*(*Lookup_Table, Power, Delay*), in which interpolations are employed, was developed. For example, when the reactor power is 40% and a delay of 3 sec acts on the system, the gain that can maintain a stability margin of 30 degrees is obtained from Kp = *kp_by_power_delay* (*Lookup_Table, 40, 3*), and is found to be $K_P = 0.4015$.

Figure 10 shows the results of simulation for a step increase in power from 40% to 50%, which is the same as for the PI controller by EFR. However, the delay is assumed to be 3 sec instead of 1 sec. The Bode diagram, which is not given here, shows that the phase margin is

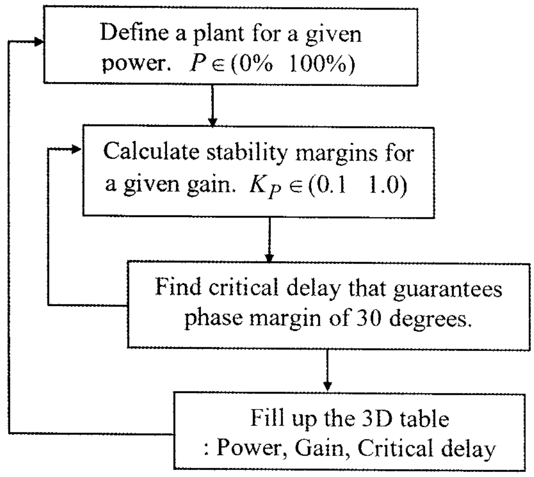

Fig. 8. Procedure of Preparing the Table for P Controller

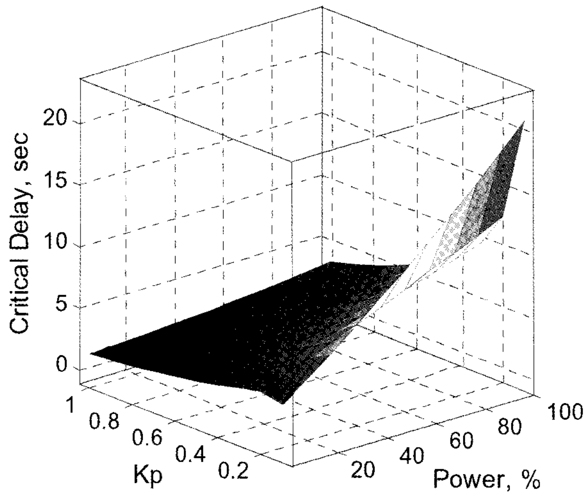

Fig. 9. Three-Dimensional View of the Table for P Controller

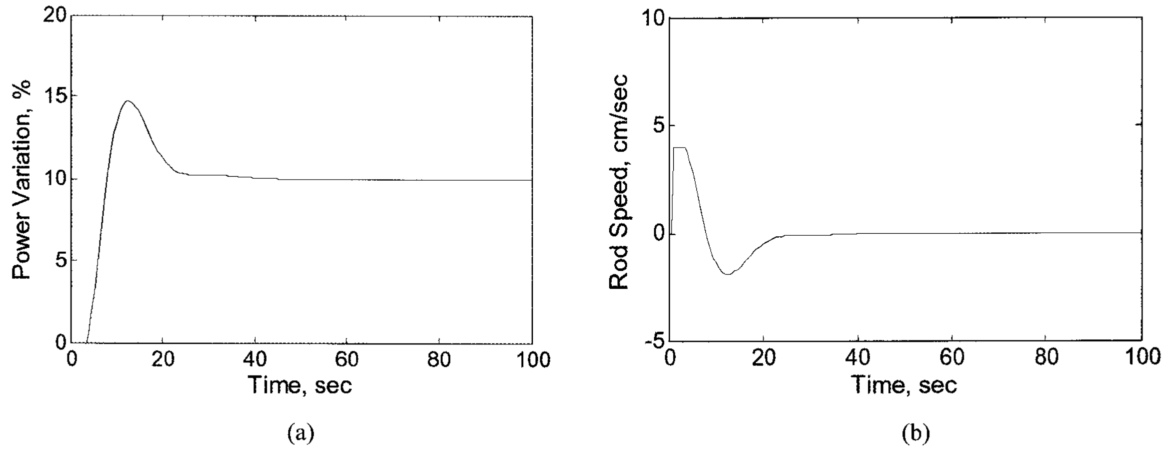

Fig. 10. (a)Power Transient with P Controller by Table Lookup (b)Control Rod Speed with P Controller by Table Lookup

65 degrees. The system gives the improved output found in Fig. 10(a), as compared to that found in Fig. 7(a), although the delay is three times larger. The control input shown in Fig. 10(b) settles down earlier without sustaining oscillations. In addition, peak values of both the output and the control input are smaller than those shown in Figs. 7(a) and 7(b). However, the rate of change in control rod speed, that is, the acceleration, is very large, which means that a large rod-driving motor torque is necessary. This is not desirable with respect to the integrity of control rod drive mechanism (CRDM) or to other nuclear safety problems.

3.3 Second-Order Controller by Table Lookup

A second-order controller was designed by table lookup. First, a second-order controller was determined by a standard classic design procedure for the perturbed plant without a delay. For a perturbed plant, the values of $P\in(70\%, 100\%)$ are considered. The rationale of these bounded values of power is to improve the performance. That is, if the design is made at low power, a larger stability could be obtained, but at the expense of the performance degradation. The Bode diagrams of the perturbed plant, obtained using the Kharitinov vertex equations of Eqs. (8) and (9), are shown in Fig. 11.

It should be noted that the Bode diagrams of the perturbed plant are somewhat conservative. This means that the envelope in the plot is, in general, not that of the specific member of the polynomial family. In other words, there is no system in the family that generates the entire boundary of the envelope.

With the aid of Bode diagrams, the controller is designed by the routine classic design procedure. In determining the controller, the lower boundary of the phase envelope is matched with the upper boundary of the gain envelope. Considering the desirable margins, the controller is determined to be:

$$C(s)=\frac{8.7s+1}{50s^2+15s+1}\ . \tag{15}$$

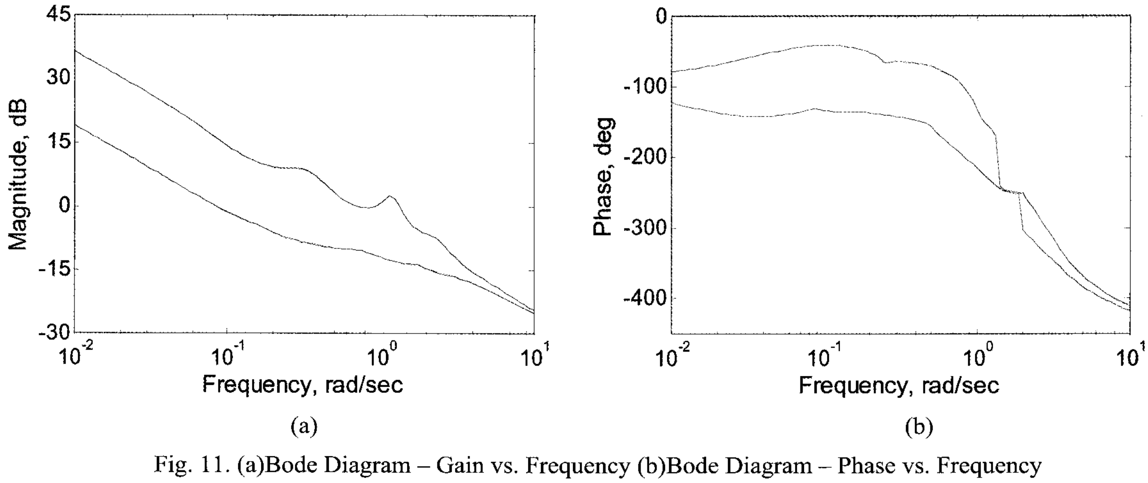

Fig. 11. (a)Bode Diagram – Gain vs. Frequency (b)Bode Diagram – Phase vs. Frequency

The Nyquist diagrams for $\tilde{G}(s)C(s)$, described in Fig. 12, show that the system with the designed controller has sufficient stability margins.

The controller described by Eq.(15) is designed with the reactor of $P \in (70\%, 100\%)$, and with the assumption of no delay. However, in reality, the powers are different from the design-based values, and delays act on the system. To consider these factors, the controller of Eq.(15) is rewritten as:

$$C(s) = \beta \cdot \frac{8.7s+1}{50s^2+15s+1}, \qquad (16)$$

and the values of β that guarantee a specified stability margin of at least 30 degrees for a given power and delay were found to prepare the table. Of course, each coefficient of the controller could be determined for a given power and delay. Then, five coefficients of Eq.(15) would need to be manipulated, which would be very involved and impractical.

The procedure of table preparation is described in Fig. 13, which is quite similar to Fig. 8, and some contents of the table are shown in Fig. 14.

In the preceding table, the critical delay of '*NaN*' indicates that with the given power and β, a margin of 30 degrees cannot be guaranteed. The entire contents of the table are described by the three-dimensional graph as shown in Fig. 15.

Similar to the P controller by table lookup described in Section 3.2, the function of [*beta*] = *Beta_by_Power_Delay* (*Power, Delay*) was derived. For example, with reactor power of 40% and a delay of 3 sec, β is found to be 0.139.

Figure 16 shows the system responses when the power is step-increased from an initial power of 40% to 50%, and the delay is 3 sec. Compared to Fig. 10(a), the power transient does not show improvement, and a small

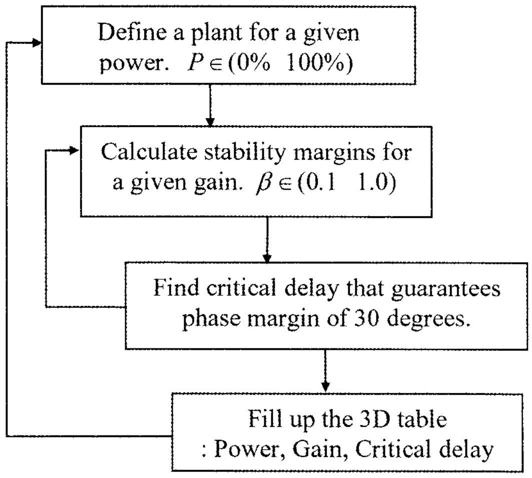

Fig. 13. Procedure of Preparing the Table for Second-Order Controller

Power (%)	β	Critical Delay (sec)
:	:	:
:		
20	:	:
20	0.36	0.1419
20	0.40	0.0849
20	:	NaN
:	:	:
100	:	:
100	0.40	3.7223
100	0.45	3.3631

Fig. 14. Table Contents of Second-Order Controller

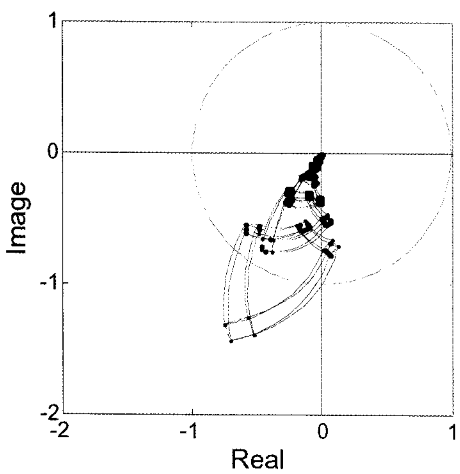

Fig. 12. Nyquist Diagrams of $\tilde{G}(s)C(s)$

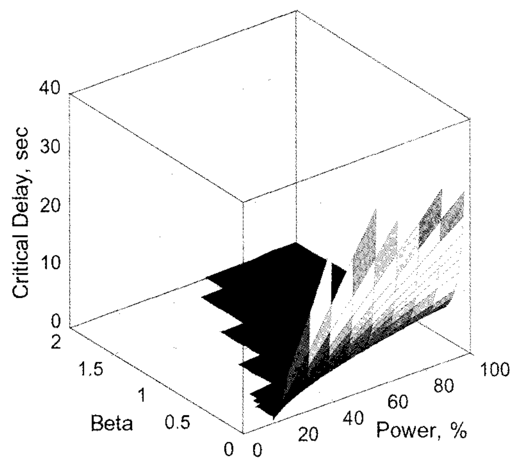

Fig. 15. Three-Dimensional View of the Table for the Second-Order Controller

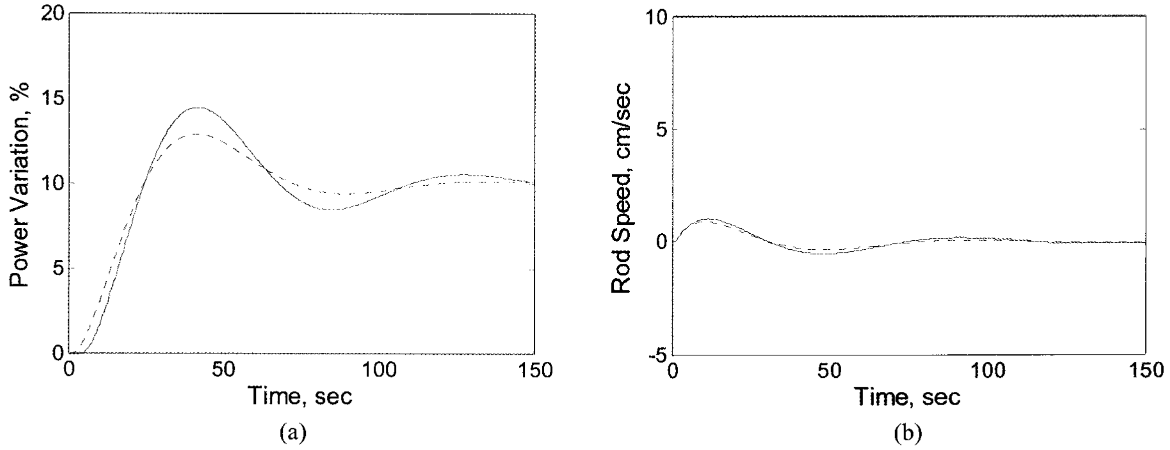

Fig. 16. (a)Power Transient with Second-Order Controller by Table Lookup (b)Control Rod Speed with Second-Order Controller by Table Lookup

fluctuation is sustained. However, the control rod speed improved significantly. The maximum speed is about 1 cm/sec, which is much less than the speed set forth in the Safety Analysis Reports (SARs). Furthermore, control rod acceleration is much smaller than that of the P controller system described in Fig. 10(b). Hence, with much a smaller control input, the system can achieve almost the same transient responses.

In addition, the designed system is tolerant of delays. The dotted lines in the figures are for the case of no-delay. There is not a large difference between the cases of with-delay and without-delay. This indicates the robustness of the designed controller of Eq.(16), and shows that the system has delay-tolerant characteristics.

4. SUMMARY

With the spread of communication networks, remote control using the internet is being widely used. It is expected that remote control will be applied to small nuclear reactors in the future. However, since control would be accomplished through communication networks, a delay in communication or signal flow is a critical problem for the stability and performance of the system, and thus it is important to design a system that is robust against delay

An exact description of the plant is a prerequisite for control system design. However, the governing mechanisms of a reactor have a large degree of uncertainty. In addition, the dynamics of a reactor vary widely depending on factors such as operating conditions and core life, and it is very difficult to define a mathematically exact plant. To account for modeling uncertainties, a reactor is described by a family of transfer functions.

With these uncertain models in mind, three controllers were designed. The first is a PI controller designed by the EFR method. The second and the third are a simple proportional controller and a second-order controller designed by the table lookup (TL) method. The concept of the TL method is to calculate the gains of a controller for various conditions of powers and delays in advance, and use the suitable value for the controller setting corresponding to a specific level of power and delay. Among the controllers designed so far, the second-order controller designed by TL gives the most satisfactory results. In particular, the control input shows desirable responses, which is critical for nuclear reactor operation.

REFERENCES

[1] "Study on Small Scale Reactor based Multi-purpose Regional Energy System," KESRI, R-2005-B-100 (2006)

[2] S. W. Lee et al., "Field Bus Monitoring by TCP/IP," KACC, pp. 684-687 (1998)

[3] "Remote Monitoring System of High Pressure Pumps of Thermal Power Plants," *Edited by Electric Tech.(Japan)*, **42**, 1-2, Feb. 2003

[4] M. James, *TCP/IP Networking : Architecture, Administration and Programming*, Prentice-Hall, (1998)

[5] Y. J. Lee, M. G. Na, "Robust Controller Design of Nuclear Power Reactor by Parametric Method," *J. of KNS*, **34**(5), 436-444 (2002)

[6] *Final Safety Analysis Report of Kori Unit 2*, 2nd ed., Korea Electric Power Corp. (1989)

[7] Y. J. Lee, M. G. Na, "Effects of Signal Delay on Remote Control of Nuclear Reactor," in *Procd. IWRES*, Seoul, Jan. 2007

[8] S. P. Bhattacharyya et al., Robust Control, The Parametric Approach, Prentice Hall (1995)

[9] V. V. Volgin, O. C. Kharitonova, "The Selection of Robust Tuning of PID Regulating Algorithms," in *Procd. Control 2003*, MPEI, Moscow, Oct. 2003

[10] Y. J. Lee, M. G. Na, "Robust Controller Design for the Nuclear Reactor by Extended Frequency Response Method," *Nucl. Eng. Tech.*, **38**(6), 551-560 (2006)