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Time-Optimal Power Control for KMRR Using Reactivity Constraint Method

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반응도 제한법에 의한 KMRR의 시간 최적 출력 제어

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Abstract

For automatic power control of KMRR, a new method, Reactivity Constraint Method, is applied for time optimal control. This method limits the net reactivity to the amount that can be offset by instantaneous control rod action. The reactivity to be constrained for the constant reactor period should be obtained by the dynamic period equation. A new formulation of the dynamic period equation for 2-point kinetics model is presented. A methematical controller model was applied to the plant simulator, KMRSIM to test this control law. The performance test showed that reactivity constraint approach is also a reliable means for reactor power change control.

요 약

한국형 다목적 연구로(KMRR)의 출력 자동제어를 위하여 새로운 제어이론으로 등장한 반응도 제한법을 시간 최적제어에 적용하여 보았다. 반응도 제한법은 원자로내의 반응도가 제어봉의 움직임으로 상쇄될 수 있는 반응도보다 항상 작도록 제한하여 준다. 이 방법을 시간 최적제어에 이용하기 위해서는 일정한 원자로주기를 유지하도록 하는 반응도 값을 Dynamic Period Equation으로 얻어야 한다. 따라서 2점 동특성 방정식에 의한 Dynamic Period Equation이 새로 유도되었다. 이 제어법을 시험하기 위해 수학적 모델로 구성된 제어모델을 원자로 모의 전산코드인 KMRSIM에 적용하여 보았다. 반응도제한법도 출력의 시간 최적제어에서 신뢰할만한 결과를 보여줌을 알았다.

I. INTRODUCTION

Automatic power control option has not been accepted in nuclear industry because of safety issues even though coming situation might need its various benefits. However, existing computer and control technology raised the level of confidence in automatic control. In Korea, nuclear reactor power control has been chosen for

KMRR(Korea Multi-Purpose Research Reactor)[1], [2]. This reactor was designed to be controlled by a P-I-D control limiting a reactor period to the minimum limit. Optimal control gains were applied to both the lograte of power change and the power level difference from the target power in order to find the control rod movement speed.

A new control method using the reactivity constraint approach was introduced by the M.I.T. group and showed good performance in a few research reactors [3], [4], [5]. This method calculated a control rod speed required for the desired reactor period using a mathematical model so called dynamic period equations. The performance of this control method was shown to be excellent. Automatic power level control was done fast without overshoot [8], [9]. However, reactor power change should be limited within a certain limit because of reactor safety. It is required, therefore, to design a controller which keeps the maximum allowed change-rate using the reactivity constraint approach. The purpose of this work was to apply this reactivity constraint approach for KMRR, to verify the controllability and to extend the applied scope of that.

II. KMRR and KMRSIM

KMRR is the name of the open-tank-in-pool type reactor of 30 MWth for material test and radio-isotope production. Reactor was designed to be fueled by 20% enriched uranium-aluminum-silicon fuel which is cooled by ordinary water. The primary coolant system consists of main coolant path flow and additional by-pass flow for safety concern. Figure 1 shows the brief scheme of KMRR primary coolant system. A large amount of D_2O reflector wrapping the compact core was designed to increase the neutron economy. Therefore, the photoneutron effect occurring in reflector should not be ignored for power level monitoring, Since this reactor has been under construction, a computer program KMRSIM was developed as a simulator [2].

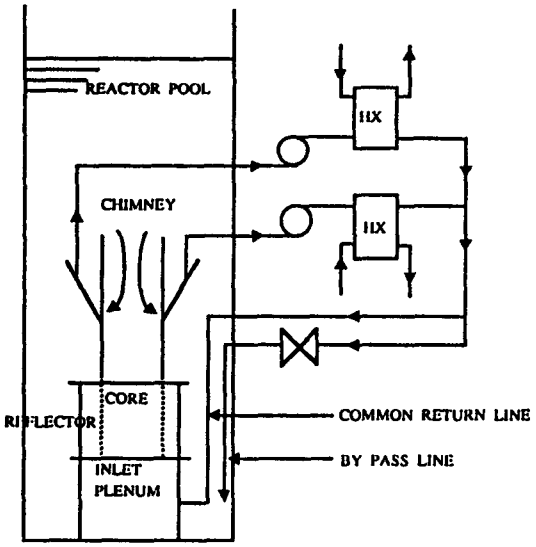

Figure 1. KMRR Primary Coolant Pathes

KMRSIM adopted 2-point kinetics model for monitoring the neutron flux at both core and reflector. Also, KMRSIM includes fuel and coolant temperature feedback model and xenon reactivity model. Lumped parameter model was used for heat transfer calculation for primary coolant system. Detailed description for KMRSIM is founded in reference [6]. Total 35 non-linear differential equations including 9 neutron kinetics equations, 2 xenon & iodine decay equations, one fuel to coolant heat transfer equation and the other energy transfer equations for coolant system were solved by Runge-Kutta Method. In this work, numerical schemes are revised for the fast simulation capability by replacing with theta-weighting scheme. Figure 2. showed the same calculation results of two method. For this 100 second transient, it took 423 seconds for Runge-Kutta method to simulate using a time step size of 0.2 second. However, theta-weighting method spent only 44 seconds under the same condition. This improvement provide the capability of real time

control for KMRR.

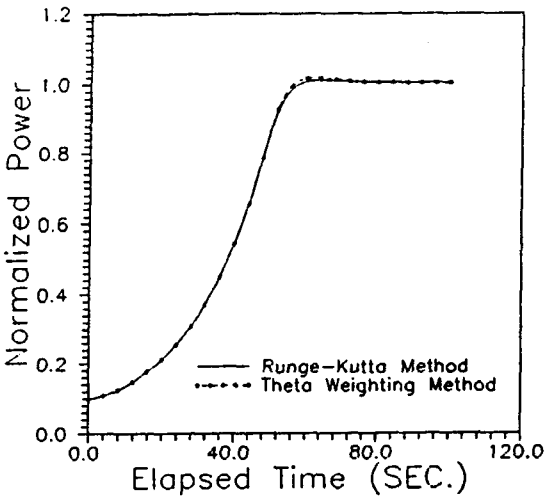

Figure 2. Comparison of Calculation Results using 2 Kinds of Numerical Schemes

Table 1. Kinetics Parameters Used in KMRSIM (Calculated by HEXKIN Code)

Neutron Generation Time(sec)	1.40504E-4

Group	Yield Fraction	Decay Constant(sec.)
1	2.4757E-4	0.012708
2	1.4133E-3	0.031677
3	1.2484E-3	0.11585
4	2.6898E-3	0.31248
5	8.6412E-4	1.4012
6	1.8127E-4	3.8823

	Yield Fraction	Decay Constant(sec.)
Iodine	0.056	2.87E-5
Xenon	0.003	2.09E-5
Photoneutron	8.525E-4	0.1829

	Reactivity Feedback Coefficient
α_f	-0.01223E-3(Fuel Temp.)
α_c	-0.0932E-3(Moderator Temp.)
α_x	-0.03435(Xenon Density)

One out of four control rods was designed to be chosen automatically to maneuver one by one responding the rod movement signal. All kinetics parameters for 2-point kinetics model were calculated by HEXKIN code [6]. Calculation result was tabled below.

In order to ensure safety of KMRR, following operational requirements should be applied.

* The neutron power should not be overshoot during power increase.
* The lograte never becomes higher than 5%sec of the present power.
* the reactivity increase rate of the controller never becomes higher than 0.33mksec

From the third condition, the maximum control rod steps could be calculated by the rod worth table. The time-optimal control law in this study is very different from traditional Pontryagin approaches. The physical condition. i.e. rod movement steps are solved to follow the optimal trajectory that corresponds to the system along the most limiting constraint, i.e. the minimum 20 second reactor period[4].

III. CONTROL THEORY

3.1 Control logic of KMRSIM

The controller developed in KAERI [1] used typical P-I-D control law. It employed the difference between a detected lograte and a present power change demand to obtain the error signal for calculating the control rod steps. Principal concept is summarized below;

$$Y_1=\left[G_1 \log \frac{P_d}{N(t)}\right|_{\pm 1} - G_2 \frac{1}{N(t)} \frac{dN(t)}{dt}\Big]_{\pm 1} \quad (1)$$

where P_d is a target power level

$N(t)$ is a power level at time t

Y_1 is an error signal corresponding to rod movement step numbers

G_1, G_2 are control gains

First term in Eq(1) represents the deviation of

power level from the target value, and the second term shows the stiffness of power change rate. At initial stage of power transient, first term is dominant whereas second term is quite small, and therefore control rod is withdrawn in the maximum speed. As time goes on, first term starts to decrease, however second term increases more and more. In the mid stage, both terms offset each other. So Y_1 almost nearly zero. In later stage, second term is prevailed for rod movement signal so that the rate of power change should be slowed down as control rod was inserted into reactor core. Figure 3 shows power change from 0.1 to 1.0 by KAERI's control method.

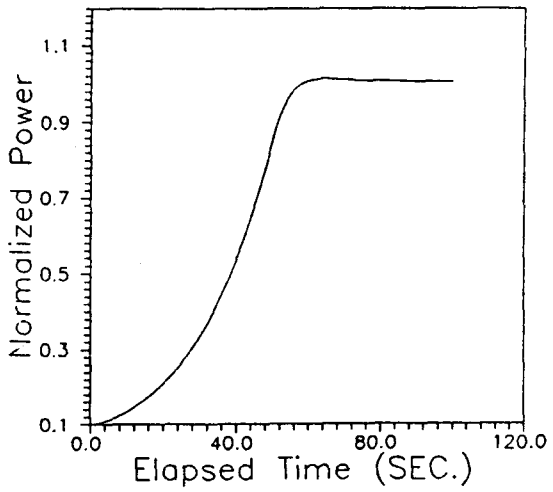

Figure 3. Power Change by KAERI's Control

3.2 Reactivity Constraint Method

A reactor period can be derived from the point kinetics equation

$$\tau(t)=\frac{\beta-\rho(t)}{\rho(t)+\lambda e(t)\rho(t)+\Sigma\beta i(\lambda i-\lambda e(t))} \quad (2)$$

This equation was derived by J.A. Bernard and A.F. Henry[3] and named as dynamic period equation. $\lambda'_e(t)$ is the effective decay constant which is weighted with delayed neutron precursor concentraions.

$$\lambda'_e(t)=\frac{\Sigma\lambda^2_i C_i}{\Sigma\lambda_i C_i} \quad (3)$$

$\lambda'_e(t)\ \rho(t)$ has an effect of total delayed neutron concentration and $\Sigma\ \beta i(\lambda i-\lambda'_e(t))$ has an effect of precursor concentration distribution among delayed neutron groups. Because delayed neutron population is not a function of reactivity but a function of power history and also it is not observable $\dot{\rho}(t)$ and $\rho(t)$ are the only active parameters to be measured.

In a reactor power control, a rapid reactivity insertion(either in positive or negative) is needed for an initial period of transient. As power level changes in a certain fashion, control rod is not required to move that much. The most significant key action is to reverse the reactivity insertion to compensate delayed reactivity response and finally to level off the power change near the target power level. This unobservable reactivity compensation can be predicted by the dynamic period equation by making the denominator of Eq.(2) zero. If the maximum available reactivity change rate from control rod is greater than the other terms in the denominator, control mechanism could offset the reactivity induced from delayed neutrons. That is, the following condition should be met;

$$|\dot{\rho}_c| = \dot{\rho}_f+\lambda'_e(t)\rho(t)+\Sigma\beta_i(\lambda_i-\lambda_e'(t)) \quad (4)$$

where $\dot{\rho}_f$ is the reactivity change rate that comes from thermal hydraulic feedback effects and the symbol $|\dot{\rho}_c|$ denotes the maximum available rate of reactivity change that could be obtained by reversing the control rod movement. This constraint limiting the control rod movement is called Absolute Reactivity Constraint. Physical meaning for this condition is that it should be possible to level reactor power at any time during a transient. This constraint is quite conservative because the net reactivity in core satisfying this constraint condition is rather small. Therefore it takes long to

reach to the desired power.

In case of power rise, although there exists reactivity beyond the amount specified by the absolute constraint we may have enough time to remove this excess reactivity before the overshoot. The available time before reaching to the target power level can be calculated by the following definition.

$$T_{aval} = \tau(t) \ln\left[\frac{Pd}{P(t)}\right] \quad (5)$$

where P(t) is the power level at time t,

P_d is the desired power level and,

$\tau(t)$ is the dynamic period.

If there were enough available time, ramp rate can be raised by insertion of more reactivity beyond absolute reactivity. However, we should have capability to turn the present reactivity back to the absolute reactivity constraint. The time interval required to restore the absolute constraint is defined as the required time.

$$T_{req} = \frac{\rho_{net}(t) - \rho_a(t)}{|\dot{\rho}_c|} \quad (6)$$

where $\rho_{net}(t)$ is reactivity present in core at time t, and $\rho_a(t)$ is the reactivity satisfying the absolute reactivity constraint. If the required time is greater than the available time, there is no enough time to compensate the power rise speed with the control rod movement. Therefore it is necessary to control with net reactivity lest T_{req} should exceed T_{aval}.

$$Treg. \leq Taval \quad (7)$$

By keeping this constraint; T_{aval} could be kept longer than the time interval to be spent, that is, net reactivity is guaranteed to be eliminated during transient before overshoot or undershoot. This reactivity constraint condition is called Sufficient Reactivity Constraint. Once a power level reaches to the target level, available time becomes to zero. At the moment of reaching to the target power, therefore, the reactivity due to the delayed neutrons is always kept less than the available maximum reactivity attainable by control rod mechanism.

IV. CONTROL SYSTEM STRUCTURE

4.1 Derivation of Dynamic Period Equation based on 2-Point Kinetics

In order to predict the reactor period of KMRR, it is required to use the dynamic period equation based on the two point kinetics. Therefore, new formulation including photo-neutron effect in reflector was derived. It started from 2-point kinetics equations, one for core and the other for reflector and then they were normalized with steady state values. Detailed derivation procedure can be found in reference [8].

$$\frac{d}{dt}N_c(t) = \frac{\rho(t) - \beta - \gamma}{A}N_c(t) + \Sigma \lambda_i C_i(t) + \frac{\alpha_{cr}}{A}N_r(t - \tau_{cr}) \quad (8)$$

$$\frac{d}{dt}C_i(t) = \frac{\beta_i}{A}N_c(t) - \lambda_i C_i(t) \qquad i = 1, \ldots, 6 \quad (9)$$

$$\frac{d}{dt}N_r(t) = -\frac{\gamma + \alpha_{rc}}{A\Omega}N_r(t) + \lambda_d D(t) + \frac{\alpha_{rc}}{A}N_c(t - \tau_{rc}) \quad (10)$$

$$\frac{d}{dt}D(t) = \frac{\gamma}{A}N_c(t) - \lambda_d D(t) \quad (11)$$

where

$N_c(t)$	: normalized neutron density at the core to the stady state value
$C_i(t)$	: normalized i-th group delayed neutron precursor density
$N_r(t)$	: normalized neutron density at the reflector
$D(t)$	: normalized photo-neutron precursor density
A	: prompt neutron life time
λ_i, λ_d	: decay constant of precursors for delayed neutron and photoneutron
β_i γ	: yield fraction of precursors for each
α_{rc}, α_{cr}	: cross coupling coefficients between core and reflector

τ_{rc}, τ_{cr} : time lag for neutron transfer between two region

Ω : steady state neutron density ratio of reflector to core

Differentiating Eq. (8),

$$\dot{\omega}(t)N_c(t)+\omega^2(t)N_c(t) = \frac{\dot{\rho}}{A}N_c+\frac{\rho-\beta-\gamma}{A}\omega(t)N_c(t) + \Sigma\lambda_i\dot{C}_i(t)+\frac{\alpha_{cr}}{A}\dot{N}_r(t-\tau_{cr}) \quad (12)$$

where $\omega(t)$ is the inverse period at time t. Substituting Eq.(9) into this,

$$\dot{\omega}(t)N_c(t)+\omega^2(t)N_c(t)=\frac{\dot{\rho}}{A}N_c + \frac{\rho-\beta-\gamma}{A}\omega(t)N_c(t)+\Sigma\lambda_i\beta_i\frac{N_c}{A} - \Sigma\lambda^2_iC_i+\frac{\alpha_{cr}}{A}\dot{N}_r(t-\tau_{cr}). \quad (13)$$

Now, precursor concentration is eliminated by the definition of $\lambda'_e(t)$ in equation(3). Rearranging Eq.(8) for $\Sigma\ \lambda iCi$ and substituting into Eq.(3),

$$\Sigma\ \lambda_i^2C_i=\lambda'_e(t)\ [\omega(t)N_c-\frac{\rho-\beta-\gamma}{A}N_c -\frac{\alpha_{cr}}{A}Nr(t-\tau_{cr})] \quad (14)$$

Now, we can eliminate $\Sigma\ \lambda^2_iC_i$ in Eq.(13).

$$\dot{\omega}(t)Nc(t)+\omega^2(t)Nc(t)=\frac{\dot{\rho}}{A}N_c + \frac{\rho-\beta-\gamma}{A}\omega(t)N_c(t)+\Sigma\lambda_i\beta_i\frac{N_c}{A} + \frac{\alpha_{cr}}{A}\dot{N}_r(t-\tau_{cr})-\lambda'_e(t)[\omega(t)Nc-\frac{\rho-\beta-\gamma}{A} Nr(t-\tau_{cr})] \quad (15)$$

Differenting Eq.(10) and then substituting Eq.(11) into this, we have another combining equation.

$$\dot{\omega}(t)N_r(t)+\omega^2(t)N_r=\frac{\alpha_{cr}}{A}\omega(t)N_c(t-\tau_{cr}) -\frac{1}{\Omega A}(\gamma+\alpha_{cr})\omega(t)N_r+\lambda_d[\frac{\gamma}{A}N_c-\lambda_dD] \quad (16)$$

In Eq.(10), solving for λ_dD and introducing to Eq.(16), we have

$$\frac{N_r}{N_c}= \frac{\alpha_{cr}\omega+\lambda_d\gamma+\lambda_d\alpha_{rc}}{A[\dot{\omega}+\omega^2+\lambda_d\omega]+[(\gamma+\alpha_{rc})(\omega+\lambda_d)]/\Omega} \quad (17)$$

Substituting this into Eq.(12),

$$\tau(t)= \frac{\beta+\gamma-\rho}{\dot{\rho}+\Sigma\beta_i(\lambda_i-\lambda'_e)+\lambda'e(\rho-\gamma)+\Omega\alpha_{cr}(\lambda'_e+\omega)R}$$

where $R=\frac{\alpha_{cr\omega}+\lambda_d(\omega+\alpha_{rc})}{(\omega+\lambda_d)(\gamma+\alpha_{rc})}$ (18)

Eq.(18) is the dynamic period equation for 2-point kinetics model. Although there exists some extraneous terms comparing with Eq.(2), denoting the photo-neutron effects, they should not have contributed very much. Therefore, Eq.(18) also could be applied for reactivity constraint method theory. Figure 4 shows the result of the calculated period for two kinds of kinetics model.

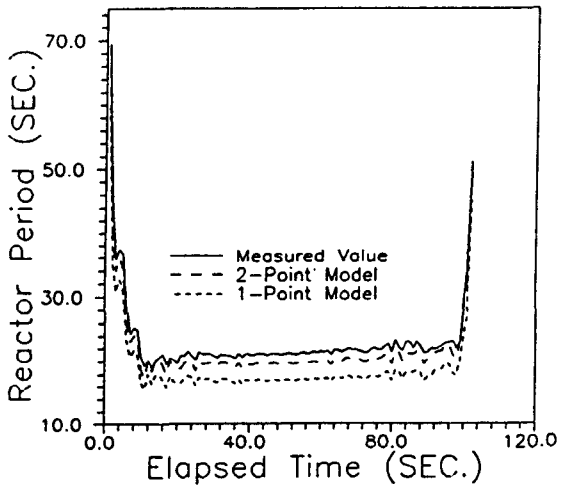

Figure 4. Detected and Calculated period using Two Kinds of Kinetics Model(1,2-Point)

It was apparent that dynamic period equation for 2-point kinetics model could calculate more correctly.

4.2 Observer and Control System Structure

In order to control the reactor power using reactivity constraint method, it was required much information for such as neutron power level, $\lambda'_e(t)$, $\rho_c(t)$, $\tau(t)$ and $\rho_c(t)$. These parameters could be calculated from present power level and control rod position. They could be evaluated through the mathematical model, here named as observer. Delayed neutron precursor concentration is dependent on the power history. Equation (9) is integrated with an assumption that power should change linearly for a short time step period.

$$C_i^{n+1}=C_i^n e^{-\lambda_i\Delta t}+\frac{\beta_i}{A}N^{n+1}\left\{\frac{1}{\lambda_i}-\frac{1}{\lambda_i^2\Delta t}(1-e^{-\lambda_i\Delta t})\right\}+\frac{\beta_i}{A}N^n\left\{\frac{1}{\lambda_i^2\Delta t}(1-e^{-\lambda_i\Delta t})-\frac{1}{\lambda_i}e^{-\lambda_i\Delta t}\right\} \quad (19)$$

More detailed information is appended at referance 8. A calculation procedure in the observer is shown in figure 5. All parameters obtained there transferred into a controller. System structure, schematically shown in figure 6, consisted of plant(KMRSIM), controller and observer. In a controller, the amount of reactivity to be satisfied to the sufficient reactivity condition, "T_{req} should be never excess T_{aval}," was calculated. Then it would be converted to required rod movement step numbers.

4.3 Time-Optimal Control Law

As mentained in chapter II, control objective in this study is to follow the most limiting constraint of minimum reactor period limitation, 20 sec. By keeping this constnat period, reactor power can be raised as fast as possible. The dynamic period equation derived in (18) gives the reactivity change rate for any dynamic period.

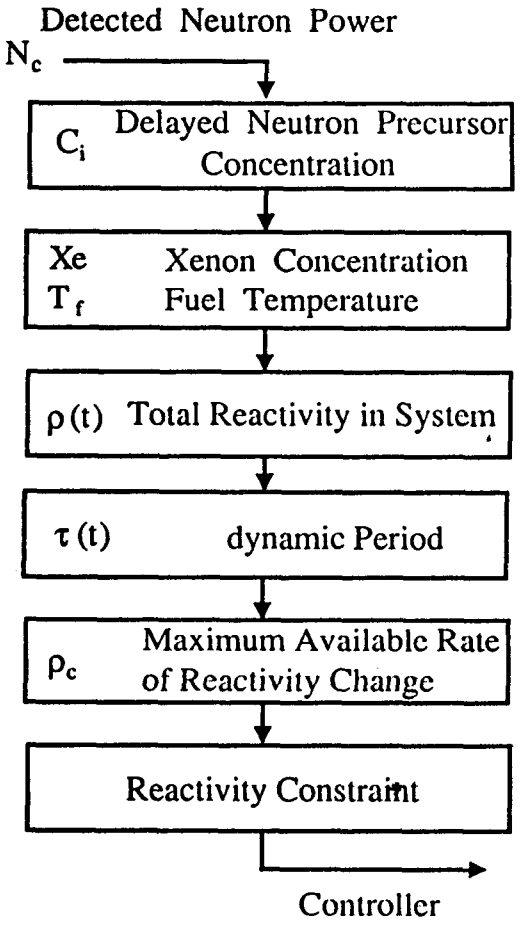

Figure 5. Calculation procedure in Observer.

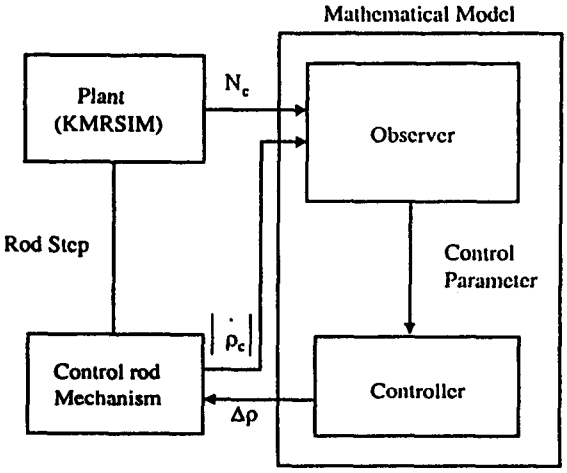

Figure 6. System Structure.

$$\dot{\rho}(t) = \omega(\beta + \gamma - \rho) - \beta_i(\lambda_i - \lambda'_e) - \lambda'_e(\rho - \gamma) - \Omega\,\alpha_{cr}(\lambda'_e + \omega)\frac{\alpha_{cr}\omega + \lambda_d\omega + \lambda_d\alpha_{rc}}{(\omega + \lambda_d)(\gamma + \alpha_{rc})} \quad (20)$$

where ω is the inverse period to be kept up. When power level change is required. control rod starts to move to make reactor period decrease. At this time, controller in the mathematical plant model calculates the optimal reactivity change rate to make reactor period to be allowed minimum value. In early stage of transient, however, control rod speed was limited by the mechanical speed limit ; therefore, rod is removed at its full speed. Thereafter, required rod speed for the minimum period was continuously calculated and reactor power would increase with the constant period. As the power increase, T_{aval} would decrease but T_{req} would increase. Once the T_{req} met with T_{aval}, $\dot{\rho}(t)$ should be constrained by the sufficient reactivity constraint lest T_{req} should exceed T_{aval}. After reaching to the target power, reactivity compensation would be kept to offset the delayed neutron by using absolute reactivity constraint.

V. CONTROL RESULTS

Figure 7. shows results of power control from 0.001 to 1.0 of rated power by using three control logics as following : reactivity constraint approach, KAERI's control logic, and time optimal control. In case of reactivity constraint approach(RCA), approaching speed was much faster than the other control logics ; however, this control logic ignored the operational safety limit of minimum reactor period. Therefore this method enabled the power change rate as fast as possible even though it might not be practical. Time optimal control under the RCA had almost the same performance with the P–I–D control because reactor period limitation is fairly large for KMRR.

However, new method had more robust capability to prevent transient from overshooting. Figure 8 showed the change mode of three terms in the denominator of equation (2). As the sum of three came back to zero ; that is, period became infinite again, power rise due to delayed neutrons could be terminated by control rod reactivity compensation.

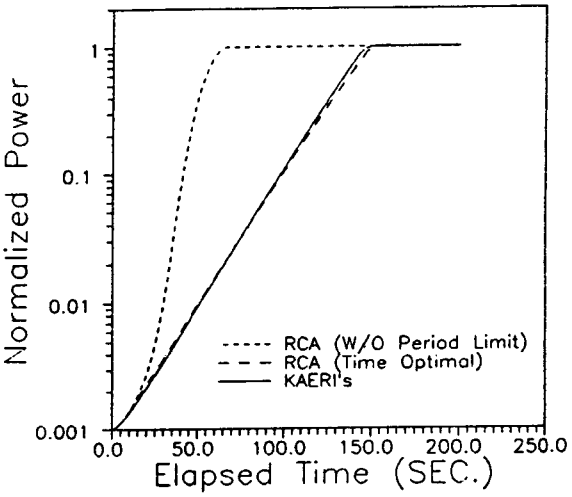

Figure 7. Power Change Control from 0.001 to 1.0 by Using Three Control Logics

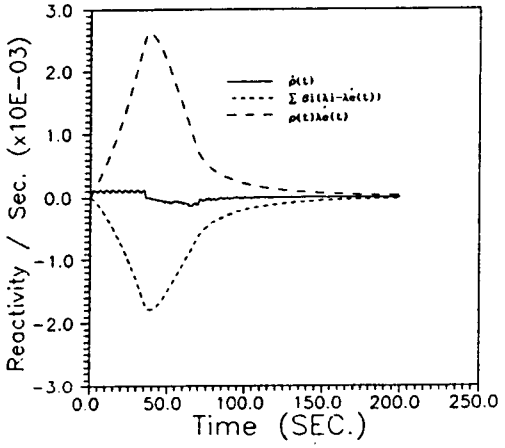

Figure 8. Component Terms of Dynamic Period Eq. for Fig. 7 Reactivity Constraint Approach

Figure 9 through 11 showed the power change transient from 0.01 of rated power to 1.0 under the time optimal control law. Allowed minimum period for KMRR was successfully kept constant

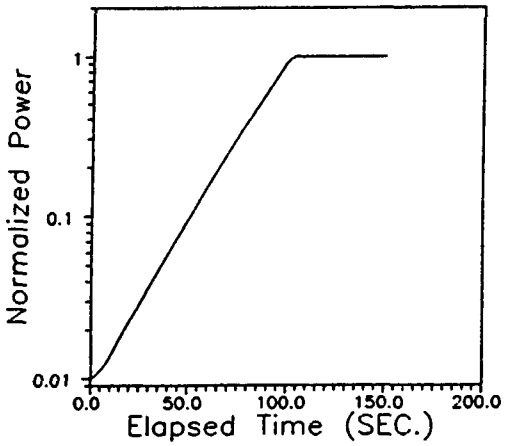

Figure 9. Power Change from 0.01 to 1.0 by Time Optimal Control

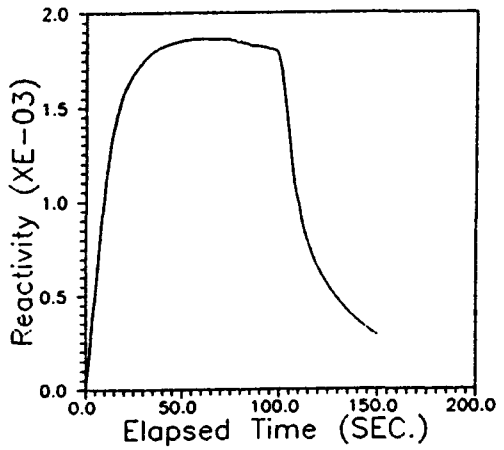

Figure 10. Reactivity Change for Power Change from 0.01 to 1.0 by Time Optimal Control

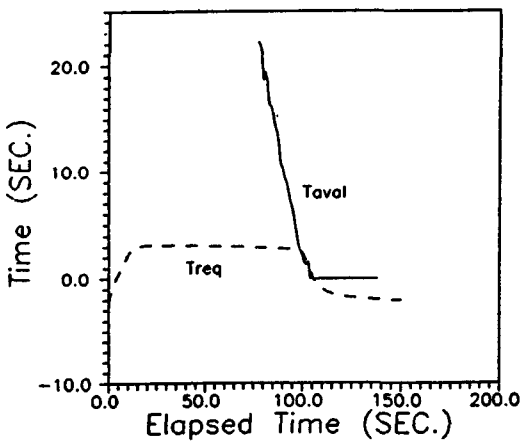

Figure 11. Change of Treq and Taval for Power Change from 0.01 to 1.0 by Time Optimal Control

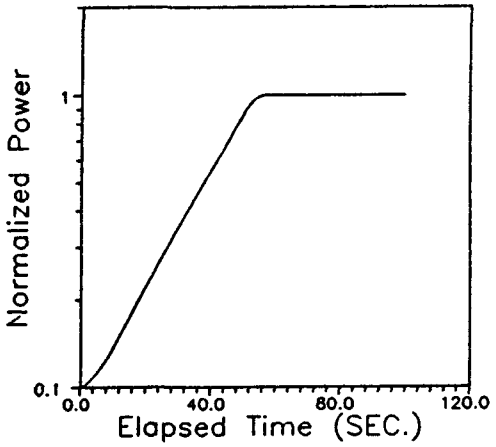

Figure 12. Power Change from 0.1 to 1.0 by Time Optimal Control

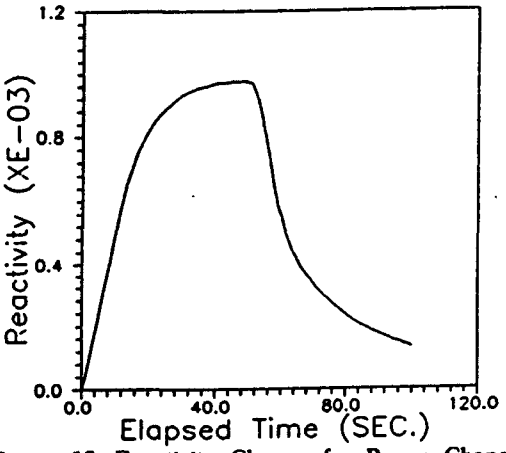

Figure 13. Reactivity Change for Power Change from 0.1 to 1.0 by Time Optimal Control

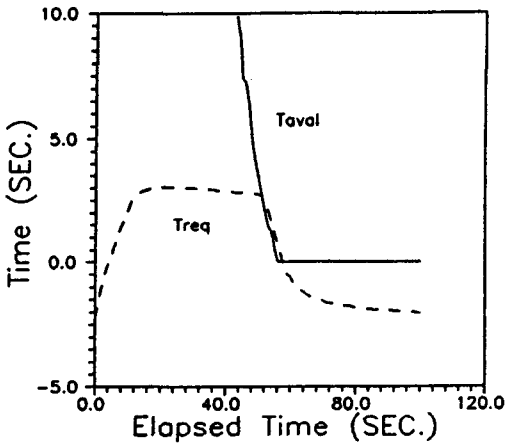

Figure 14. Change of Treq and Taval for Power Change from 0.1 to by Time Optimal Control

for a long period of time. Control performance was very reliable without sluggishness and overshoot. As shown in Figure 10, reactivity insertion rate was slowed down after 22 second because it was subjected to the minimum reactor period limit. Thereafter, as shown in Figure 11, T_{req} became almost constant because no more reactivity insertion was given. As time went on, while T_{req} remained constant, T_{aval} decreased. They met with each other at about 145 second. Then was required to control with net reactivity which lest T_{req} should exceed T_{aval} so that reverse motion of the control rod should be commenced.

Figure 12 through 14 showed results of power change control from 0.1 of rated power to 1.0 where thermal-hydraulic feedback was not negligible.

VI. CONCLUSION

A new dynamic period equation based on the 2-point kinetics was derived and applied successfully for time optimal control. A simulation code KMRSIM was improved in its calculation speed by utilizing theta-weighting numerical scheme. Therefore reactor power control was done in a real time even though it might be done only in software.

The mathematical model which monitors the reactor kinetic parameters was shown to work for the control using reactivity constraint approach. This model can be easily implemented as a computer controller which would process a power level signal and a rod position signal.

Although the performance results was quite similar between a KAERI's control method and a reactivity constraint approach, they differ each other in signal processing demand. In KAERI's control, one of the major signals used for rod maneuvering control is the detected lograte of neutron flux which could cause signal noise problem. The noise may be serious when time derivative is changing due to corrective control action. In time-optimal-control based on reactivity constraint method, dynamic period could be calculated in real-time from the only measured signal, the power level. Extending this merit, power projection in several seconds can be predicted, and it is possible to adjust the power level at any time, because the instantaneous reactor period can be regulated as a function of reactivity. This characteristic would give strong advantage for reactors which has very short reactor period limit, such as space reactors.

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