

RESEARCH REACTOR POWER CONTROL SYSTEM DESIGN BY MATLAB/SIMULINK

DANE BAANG *, YONG SUK SUH, YOUNG KI KIM

*Instrumentation and Control Dept., Korea Atomic
Energy Research Institute, 111 Daedeok-daero,
Yuseong Gu, 305-353, Daejeon City,
Rep. of Korea*

KI HONG IM

*Samsung Electronics, Meatan 3-dong,
Yeongtong-gu, Suwon City, Rep. of Korea*

*Corresponding author: dibang@gmail.com

ABSTRACT

In this study it is presented that MATLAB/SIMULINK can be efficiently used for modeling and power control system design for research reactors. The presented power control system deals with various functions including reactivity control, signals processing, reactivity calculation, alarm request generation, etc., thus it is required to test all the software logic using proper model for reactor, control rods, and field instruments. In MATLAB/SIMULINK tool, point kinetics, thermal model, control absorber rod model, and other instrument models were developed based on reactor parameters and known properties of each component or system. The software for power control system was invented and linked to the model to test each function. From the simulation result it is shown that the power control performance and other functions of the system can be easily tested and analyzed in the proposed simulation structure.

1. Introduction

The simulation technique on the nuclear power plant has been well-studied for last several decades. The process of implementing the power plant simulator consists of modeling using design data and the parameter tuning based on actual operation data from the target plant. This approach is meaningful only for existing nuclear power plant with available operation data, but is not possible to apply this simulator development process to new reactor construction since parameter tuning using operation data is impossible in design stage. However, in a new reactor construction, a sort of simulator is still needed before reactor construction, especially for power control system design. The main functions of power control system are power control by moving control rods, signal processing for field instrument, communication with operator workstation, etc. Thus, this sort of software functions should be designed and tested in the simulation environment with proper models for reactor, control rods, sensors of field instruments prior to actual installation at site.

In this study we propose a simulator structure for research reactor. In this simulator, all software of power control system was implemented and the required feedback information for the system was generated from models for reactor, control rod sensors, and field instruments. Only simple dynamics for modeling was used in this simulator considering that the parameter tuning is not possible in the design stage. MATLAB/SIMULINK tool was used since it is one of the most widely-used engineering tool and proper for reducing development time for this study due to its user-friendly interface. For controller design, MRAC(Model-Reference Adaptive Control) scheme was used based on the result of Baang, et. al.[1]. For modeling, we used one group precursor-based point kinetic model and designed observer and adaptive control scheme to make the system output(neutron power) tracks the reference model output with proper robustness. Control performance was good even with reactivity feedback effects by fuel and coolant temperature, since the controller compares the reference model output and the system output, to tune the control parameters in online to minimize the plant-model error. The other functions of the power control systems were implemented as well in the simulator. Thus it is shown that the software design, development, testing can be easily

performed in the proposed simulator structure in the design stage.

2. Modeling and System Software Design

2.2 Reactor Model

The reactor model describes the behaviors of the neutron and precursors, decay heat by fission products, and fuel, coolant, and reflector temperatures by means of the well-known point kinetics and dynamics model. Rather than using the equations directly, all the variables were normalized into full power unit(FPU). The expression $\bar{(\cdot)}$ denotes the variables normalized by full-power value. For the derivation procedure and symbol definition, see [4] and the nomenclature of [1], respectively.

Neutron Point Kinetics:

$$\frac{d\bar{N}}{dt} = \frac{1}{\Lambda} [(\rho - \beta)\bar{N} + \beta\bar{C}], \quad \frac{d\bar{C}}{dt} = \lambda(\bar{N} - \bar{C}), \quad (1)$$

Fission Product Decay Heat and Reactor Power:

$$\frac{d\bar{W}_k}{dt} = \lambda_{wk}(\bar{N} - \bar{W}_k), \quad \bar{N}_R = \bar{N} - \sum_{k=1}^K \gamma_{wk}(\bar{N} - \bar{W}_k), \quad (2)$$

Thermal Power:

$$Q_C = \bar{N}_R Q_T \eta_C, \quad Q_R = \bar{N}_R Q_T (1 - \eta_C), \quad Q = Q_C + Q_R, \quad (3)$$

Primary Cooling System:

$$M_{FE} C_{FE} \frac{dT_{FE}}{dt} = \eta_F Q_C - H_F (T_F - T_C), \quad M_C C_C \frac{dT_C}{dt} = (1 - \eta_F) Q_C + H_F (T_F - T_C) - W_C C_C (T_{CO} - T_{CI}), \quad (4)$$

Reactivity Feedback:

$$\rho_F = \alpha_F [T_F(t) - T_{F0}], \quad \rho_C = \alpha_C [T_C(t) - T_{C0}]. \quad (5)$$

2.3 Controller design

One of the commonly used adaptive control methods is MRAC(Model Reference Adaptive Control) and this scheme for linear system is composed of four parts: a plant with known structure and unknown parameters, a designer-defined reference model for compactly specifying the desired output of the control system, a feedback control law containing adjustable parameters, and an adaptation mechanism for updating the adjustable parameters. The key concept is to tune the controller parameter such that the plant output converges to reference model output[7]. In our case, the reactor point kinetics about \bar{N} is nonlinear due to the term $\rho\bar{N}/\Lambda$ which is a multiplication of the input and the output. In order to resolve this problem, we define the control input as $u = \rho\bar{N}$ considering that \bar{N} is directly measurable from fission chamber and positive during the whole control process. Thus, using (1) we obtain the linear kinetics w.r.t. u .

$$\frac{d\bar{N}}{dt} = \frac{1}{\Lambda} [-\beta\bar{N} + \beta\bar{C}] + \frac{u}{\Lambda}, \quad \frac{d\bar{C}}{dt} = \lambda(\bar{N} - \bar{C}), \quad (6)$$

and the transfer-function as

$$\bar{N}(s) = \frac{(1/\Lambda)(s + \lambda)}{s^2 + (\lambda + \beta/\Lambda)s} u(s) := T_p(s)u(s), \quad (7)$$

where the reactor parameters Λ, β, λ are unknown. The next step is to define a reference model so that output of the reactor model (1)-(5) tracks the reference model output.

The stable reference model with DC gain equal to 1 is chosen as

$$\bar{N}_r(s) = \frac{0.25(s+1)}{s^2 + s + 0.25} r(s) := T_r(s)r(s), \quad (8)$$

where $\bar{N}_r(s)$ and $r(s)$ denote the reference model output and the power demand(PDM), respectively.

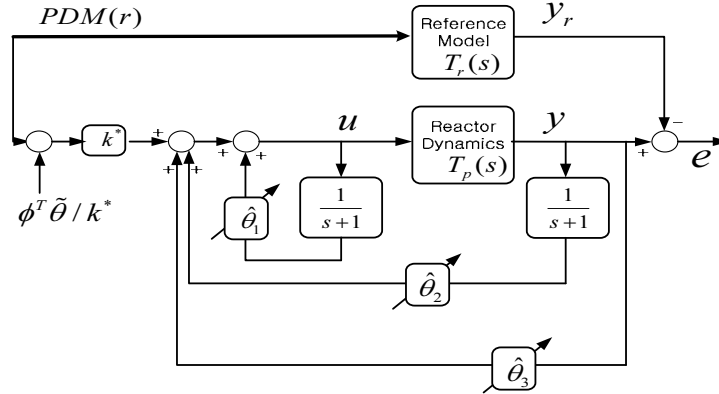


Fig 1. MRAC block diagram

The control u is defined as follows and it uses only the measurable signals and the parameters updated by adjusting mechanism.

$$u(t) = \phi^T \hat{\theta} = \phi^T \theta^* + \phi^T \tilde{\theta}, \quad (9)$$

where $\phi := [r, \omega_1, \omega_2, y]^T$, $\hat{\theta} := [\hat{k}, \hat{\theta}_1, \hat{\theta}_2, \hat{\theta}_3]^T$, $\tilde{\theta} := \hat{\theta} - \theta^*$, and ω_1, ω_2 are the filter outputs. $\hat{\theta}$ denotes the estimated value of θ^* .

As demonstrated in Fig. 1, two filters were used for $u(t)$ and y with the reference model zero ($s = -1$) as their poles. It can be easily shown that, if the filters have properly-designed parameters (θ^*) by using known plant parameters, then the plant output converges to model output for the ideal control $u^*(t) = \phi^T \theta^*$.

Since plant parameter θ^* is not known, the actual control $u(t)$ has the structure of the ideal control $\phi^T \theta^*$ with the additive external signal $\phi^T \tilde{\theta} / k^*$. This concept is represented in (10) and Fig. 1, where k^* is the ratio of model-plant parameter $k^* = 0.25 / (1 / \Lambda) = 0.25\Lambda (> 0)$. Since

$$y(t) = T_r(s)r + T_r(s)\phi^T \tilde{\theta} / k^*, \quad (10)$$

holds, the output error between the plant and the model is obtained as $e(t) = y(t) - y_r(t) = T_r(s)[\phi^T \tilde{\theta} / k^*]$.

Since $T_r(s)$ is stable (more precisely, strictly positive real) and can be neglected for adaptive law, we first calculate the gradient of $e^2(t)$ w.r.t. $\hat{\theta}$ to the direction of diminishing $e^2(t)$.

$$-\frac{\gamma}{2} \frac{\partial e^2}{\partial \hat{\theta}} = -\gamma e \frac{\partial e}{\partial \hat{\theta}} = -\gamma e(t) \frac{\partial [\phi^T (\hat{\theta} - \theta^*) / k^*]}{\partial \hat{\theta}}, \quad (11)$$

and obtain the parameter update law as

$$\dot{\hat{\theta}} = -\gamma \text{sgn}(\Lambda) \phi e = -\gamma \phi e, \quad (12)$$

where $\gamma \in R^{1+}$ is a design parameter. Note that the sign of k^* was used instead of its value. Theoretically, it is possible to prove that $e(t) \rightarrow 0$ as $t \rightarrow \infty$ in our design. Proof is omitted here and referred to [7].

2.4 Implementation of Other Functions of the System

The other functions of the control system consist of the followings.

-Two Control Modes(MANUAL and AUTO)

User can move control rods manually in MANUAL control mode, while the proposed control logic moves the rods in AUTO mode.

-Communication with Operator Computer

Operator's input was implemented by switch object.

-Reactivity Calculation

Reactivity calculator was implemented based on [2].

-Signal Processing for Field Signals

Signals from all field instruments was gathered and converted by engineering conversion.

-Alarm Generation

Alarm signal generation was implemented when accidental condition is met.

3. Results

3.1 Overall Structure

The simulator developed in MATLAB/SIMULINK consists of the following blocks, which has its own sub-blocks. Basically the control system block includes the system software logic and the other blocks are for generating feedback signals for the control system block. Thus, using this simulation structure, it is possible to develop and test all the functions of power control system in advance of building new research reactor.

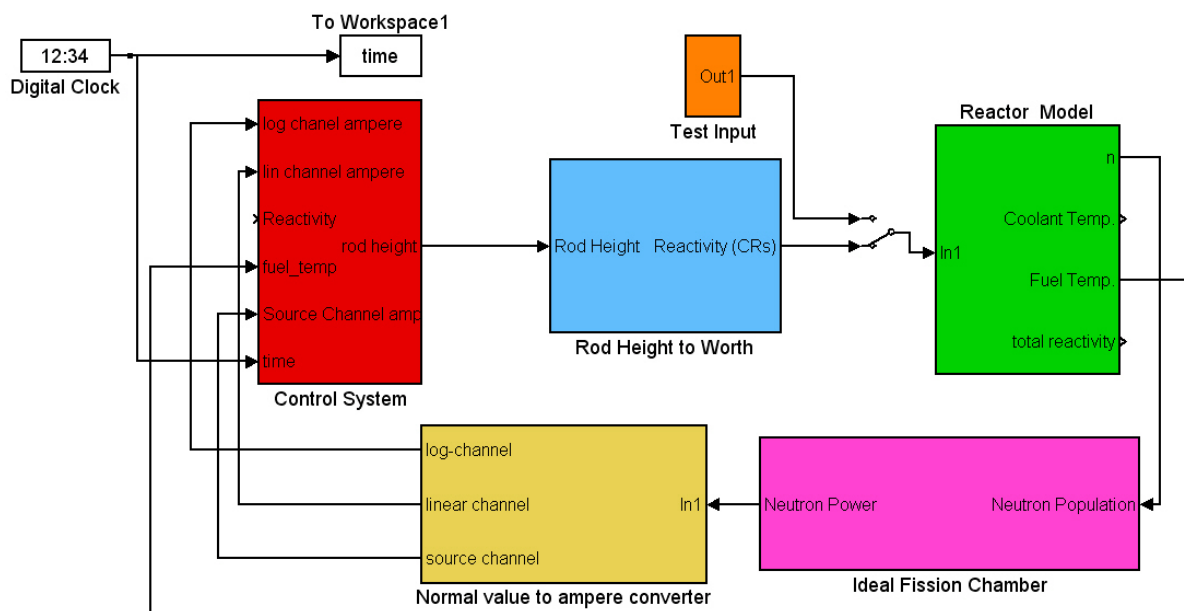


Fig 2. Simulator Structure

[Control System Block]

This block includes software of the power control system written in script form(.m file), data logger, and control rod model. The control rod model outputs position of the control rod, and outputs of limit switches(up/down). Values of the process variables handled by the system can be checked as well in the data logger window inside this block. This logger window displays over 300 number of variables that the system handles.

[Rod Height to Worth Block]

This block generates reactivity based on the current position of the control rods, and the reactivity worth curve.

[Reactor Model Block]

This block includes the reactor model presented in 2.2.

[Ideal Fission Chamber Block and Normal Value to Ampere Converter Block]

These blocks include ideal fission chamber that converts neutron population into real hard-wired current(ampere) signals.

3.2 Result Plot Window

Result of each simulation can be checked by an independent windows that indicates the position of control rods(blue: carrier, red: rod) in animation, current power in Linear/Log scale, and graph for reactor power, fuel temperature, reactivity(calculated and actual value), and Log-rate(Time change range of power).

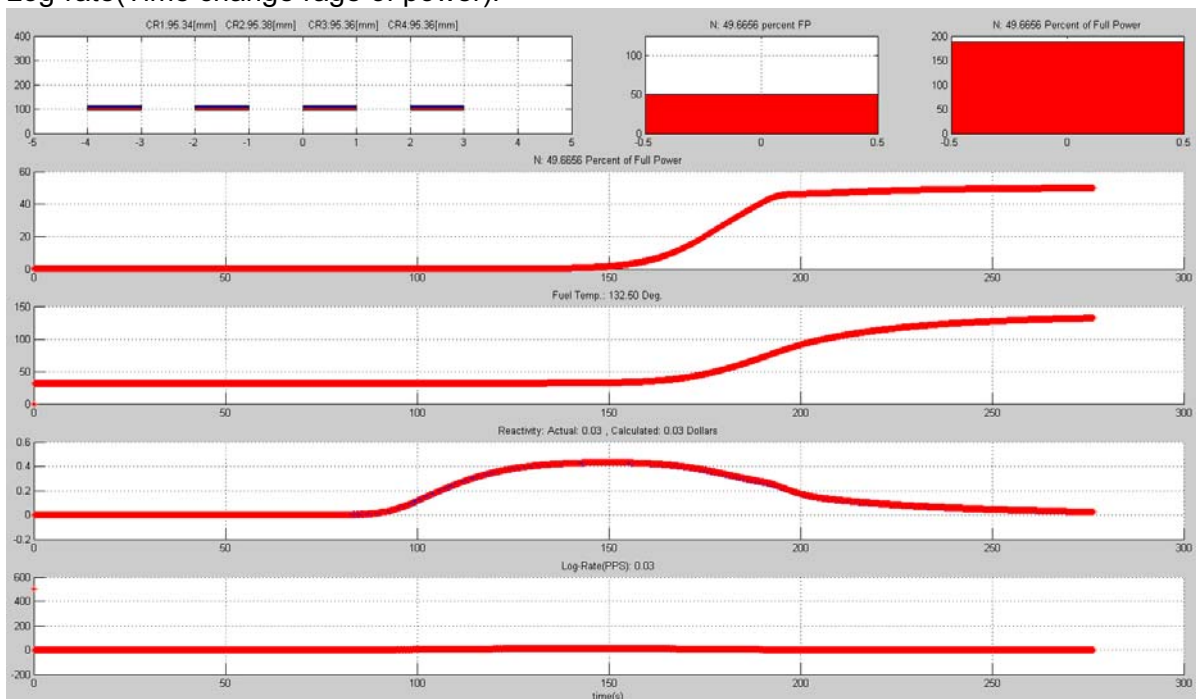


Fig 3. Result Plot Window

3.3 Control Performance

The reactor model and the proposed MRAC((9) and (12)) were implemented and simulated using MATLAB/SIMULINK. The considered case is the powering-up from 20% FP(Full Power) to 100% FP during 300sec. and, then powering-down from 100% FP to 50% FP. The result is given in Fig.4.

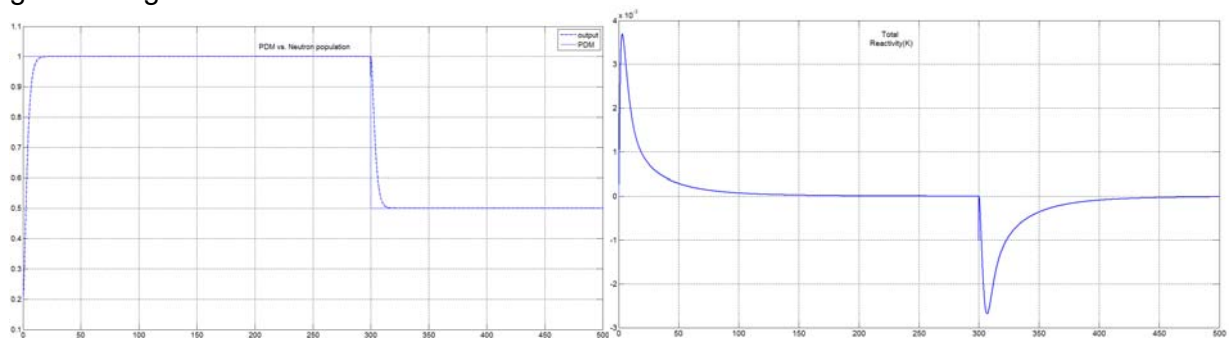


Fig 4. Normalized Neutron Power and PDM(left), Total Reactivity(K, right)

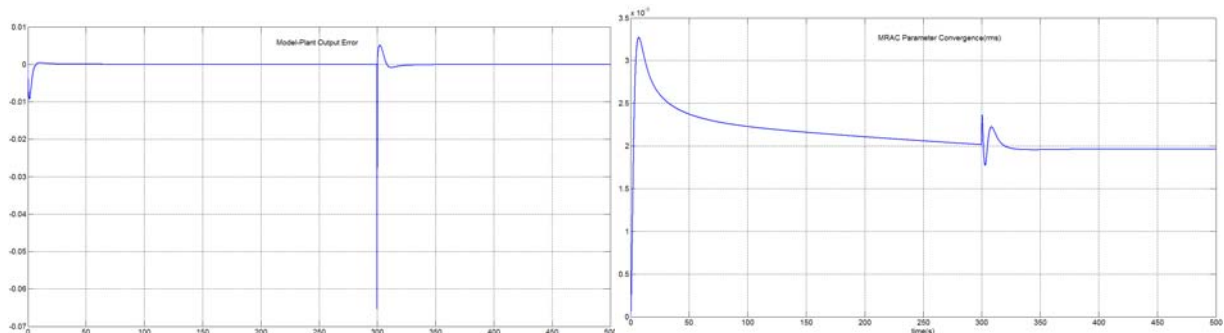


Fig 5. Normalized Error between Reference Model and Reactor Plant(left), MRAC Parameter Convergence in RMS(right)

Fig. 5 shows that, even for the reactivity feedback effect (5), the proposed MRAC performs reactor power control properly with converging adaptive parameter $\hat{\theta}$. The rising time was very short(10s), which is possible since no upper-limitation on the control rod speed was considered in this simulation. Total Reactivity also converges to zero that denotes the reactor goes into steady-state. The error between the reference model output and the reactor output becomes relatively large at the moment of sudden change of PDM at 300sec., but eventually converges to zero quickly.

4 Conclusion

It is shown that MATLAB/SIMULINK tool can be effectively used for developing a proper simulator structure for power control system design in early design stage. All software logic of the system can be invented, analyzed, and tested in the proposed simulation structure, prior to actual installation at site, which makes it possible to enhance the software performance and integrity as well as to reduce development and testing period. It was also shown that MRAC scheme can be successfully applied to a research reactor power control.

5. References

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