유전자 알고리즘에 의해 최적화된 모델예측제어를 이용한 PWR 출력제어기

A Pressurized Water Reactor Power Controller Using Model Predictive Control Optimized by a Genetic Algorithm

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Abstract - In this work, a PWR reactor core dynamics is identified online by a recursive least squares method. Based on this identified reactor model consisting of the control rod position and the core average coolant temperature, the future average coolant temperature is predicted. A model predictive control method is applied to design an automatic controller for thermal power control in PWRs. The basic concept of the model predictive control is to solve an optimization problem for a finite future at current time and to implement as the current control input only the first optimal control input among the solutions of the finite time steps. At the next time step, the procedure to solve the optimization problem is then repeated. The objectives of the proposed model predictive controller are to minimize both the difference between the predicted core coolant temperature and the desired one, and the variation of the control rod positions. Also, the objectives are subject to maximum and minimum control rod positions and maximum control rod speed. Therefore, the genetic algorithm that is appropriate to accomplish multiple objectives is used to optimize the model predictive controller. A 3-dimensional nuclear reactor analysis code, MASTER that was developed by Korea Atomic Energy Research Institute (KAERI), is used to verify the proposed controller for a nuclear reactor. From results of numerical simulation to check the performance of the proposed controller at the 5%/min ramp increase or decrease of a desired load and its 10% step increase or decrease which are design requirements, it was found that the nuclear power level controlled by the proposed controller could track the desired power level very well.

Key Words: Genetic algorithm, model predictive control, nuclear reactor power control, recursive parameter estimation.

1. Introduction

Nuclear reactor power and temperature should be properly controlled to establish good operation performance and also to maximize the thermal efficiency of nuclear power plants. But power plants are highly complex, nonlinear, time-varying, and constrained systems. For example, the plant characteristics vary with operating power levels, and ageing effects in plant performance and changes in nuclear core reactivity with fuel burnup generally degrade system performance.

2. Model Predictive Controller

The model predictive control method solves an optimization problem for finite future time steps at current time and to implement the first optimal control input as the current control input. At the next time step, new values of the measured output are obtained, the control horizon is shifted forward by one step, and the same calculations are repeated. The purpose of taking new measurements at each time step is to compensate for unmeasured disturbances and model inaccuracy, both of which cause the measured system output to be different from the one predicted by the model. At every time instant, model predictive control requires the on-line solution of an optimization problem to compute optimal control inputs over a fixed number of future time instants, known as the time horizon. The basic idea of model predictive control is to calculate a sequence of future control signals in such a way that it minimizes a multistage cost function defined over a prediction horizon.

The associated performance index is the following quadratic function:

$$J = \frac{1}{2}\sum_{j=1}^{N} Q\left[\hat{y}(t+j\,|\,t) - w(t+j)\right]^2 + \frac{1}{2}\sum_{j=1}^{M} R\left[\Delta u(t+j-1)\right]^2$$

$$\text{subject to constraints} \begin{cases} \Delta u(t+j-1) = 0 \ \text{for} \ j > M, \\ u_{\min} \le u(t) \le u_{\max}, \\ -du_{\max} \le \Delta u(t) \le du_{\max}. \end{cases}$$

In this paper, a model predictive control method is applied to design an automatic controller for thermal power control in PWRs. The desired coolant average temperature is usually programmed according to the desired reactor

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power.

The process model is estimated recursively every time step to reflect time-varying conditions of the plant including fuel burnup, control rod movement and so on. The schematic block diagram of the model predictive controller is illustrated in Fig. 1.

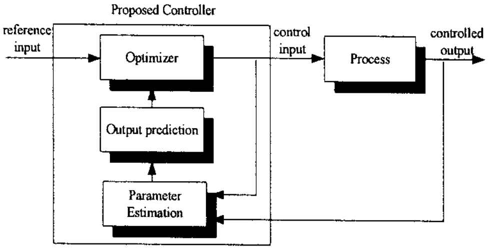


Fig. 1. Schematic block diagram of a proposed controller

3. Optimization of the Model Predictive Controller by a Genetic Algorithm (GA)

A genetic algorithm is used to minimize the objective function with multiple objectives. The genetic algorithm has been known to be proper in solving multiple objective functions. Compared to the conventional optimization methods that move from one point to another, genetic algorithms start from many points simultaneously climbing many peaks in parallel. Accordingly, genetic algorithms are less susceptible to being stuck at local minima compared to conventional search methods. In the genetic algorithm, the term *chromosome* refers to a candidate solution that minimizes a cost function. In this work, a chromosome consists of present and future control inputs.

As the generation proceeds, populations of chromosomes are iteratively altered by biological mechanisms inspired by natural evolution such as selection, crossover, and mutation. The genetic algorithms require a fitness function that assigns a score to each chromosome in the current population, and maximize the fitness function value. The fitness function evaluates the extent to which each candidate solution is suitable for specified objectives. The genetic algorithm starts with an initial population of chromosomes, which represent possible solutions of the optimization problem. The fitness function is computed for each chromosome. New generations are produced by the genetic operators that are known as selection, crossover and mutation. The algorithm stops after the maximum allowed time has elapsed.

A simplified genetic algorithm makes it possible to calculate the optimal control input in real time.

4. Application to Nuclear Reactor Power Control

The developed power controller was applied to a 3-dimensional reactor model (MASTER code). MASTER (Multipurpose Analyzer for Static and Transient Effects of Reactor) developed by KAERI is a nuclear analysis and design code which can simulate the Pressurized Water Reactor (PWR) and Boiling Water Reactor (BWR) cores in 3-dimensional geometry. MASTER was designed to have a variety of capabilities such as static nuclear reactor core design, transient nuclear reactor core analysis and operation support. The MASTER code is written in FORTRAN and the proposed control algorithm in MATLAB. Visual C++ is in charge of the variable transfer between the MASTER code and the control algorithm.

The power level is controlled by only the regulating control rod banks, R5, R4, R3, R2, and R1 and the boric acid concentration is not changed for short period of a few hours when the depletion of nuclear fuel is insignificant.

Figure 3 shows its simulation result. The desired power is 70% initially and increases to 90% by ramp from 0.13hr and decreases to 80% by ramp from 1.20hr. Also, it increases from 80% to 90% by step at 2.25hr and decreases from 90% to 80% by step at 3.23hr. Figures 3(a) and 3(b) shows the responses of nuclear power level and average coolant temperature. It is shown that the average coolant temperature and the power level follow their desired values very well.

In addition, a conventional proportional-integral (PI) controller was designed to compare the performances for the power level response with the proposed model predictive controller optimized by GA. The existing PI controller has worse performance than the proposed model predictive controller.

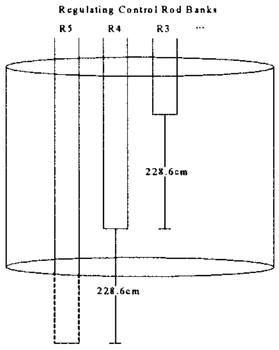
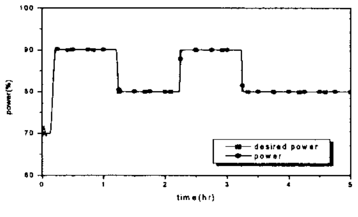
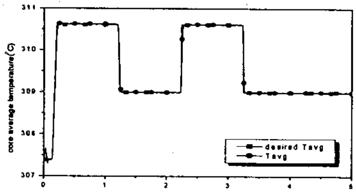


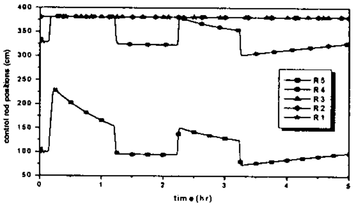
Fig. 2. Overlapped positions of the regulating control rod banks.



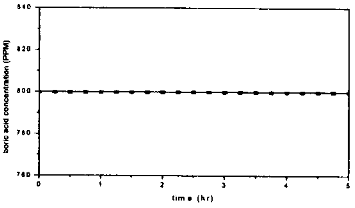
(a) power level



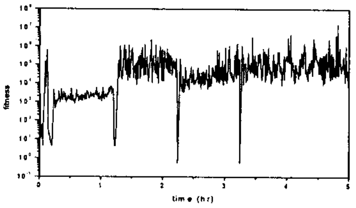
(b) average coolant temperature



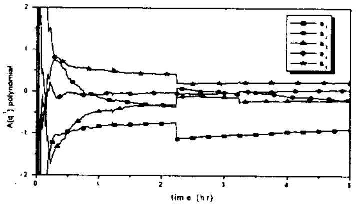
(c) regulating control rod bank position



(d) boric acid concentration

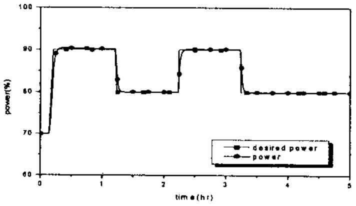


(e) best fitness value of the genetic algorithm

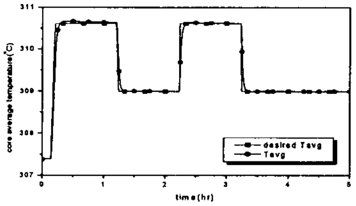


(f) $A(q^{-1})$ polynomial

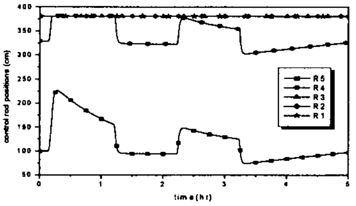
Fig.3. Power control performance by the proposed controller.



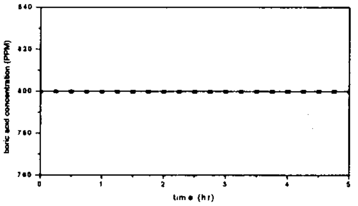
(a) power level



(b) average coolant temperature



(c) regulating control rod bank position



(d) boric acid concentration

Fig. 4. Power level control performance by an existing PI controller.

5. Conclusion

In this work, the developed controller has been applied to YGN-3 which was modeled by the MASTER code. And a controller design model used for designing the model predictive controller is estimated every time step by applying a recursive parameter estimation algorithm to reflect the time-varying condition. It was known that the proposed controller controls the control rod position so that the average coolant temperature tracks very well its setpoint change according to load and also the reactor power tracks the demand load very well. From these numerical simulation results, the performances of the proposed controller for the 5%/min ramp increase or decrease of a desired load and its 10% step increase or decrease which are design requirements are proved to be satisfactory.

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