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A Comparative Study on the Refueling Simulation Method for a CANDU Reactor

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1. Introduction

The Canada deuterium uranium (CANDU) reactor calculation is typically performed by the RFSP [1] code to obtain the power distribution upon a refueling. In order to assess the equilibrium behavior of the CANDU reactor, a few methods were suggested for a selection of the refueling channel. For example, an automatic refueling channel selection method (AUTOREFUEL) and a deterministic method (GENOVA) were developed, which were based on a reactor's operation experience and the generalized perturbation theory, respectively [2,3]. Both programs were designed to keep the zone controller unit (ZCU) water level within a reasonable range during a continuous refueling simulation. However, a global optimization of the refueling simulation, that includes constraints on the discharge burn-up, maximum channel power (MCP), maximum bundle power (MBP), channel power peaking factor (CPPF) and the ZCU water level, was not achieved. In this study, an evolutionary algorithm, which is indeed a hybrid method based on the genetic algorithm [4], the elitism strategy and the heuristic rules for a multi-cycle and multi-objective optimization of the refueling simulation has been developed for the CANDU reactor. This paper presents the optimization model of the genetic algorithm and compares the results with those obtained by other simulation methods.

2. Description of the Optimization Model

The multi-objective optimization maximizes the average discharge burnup, minimizes the MCP and minimizes the maximum change in the ZCU water levels. In this problem, the fitness function is written as a linear weighted sum of the objective functions as follows:

$$F(x) = \alpha\left(\frac{1}{(L - L_0 + 1)}\sum_{k=L_0}^{L}\frac{1}{N_k}\sum_{i=1}^{N_k}\frac{1}{M_i}\sum_{j=1}^{M_i}BU_{ij}\right) + \beta\left[MCP^0 - MCP\right] + \gamma\left[\Delta Z^0 - \Delta Z^{max}\right] \quad (1)$$

where x denotes the refueling pattern, α, β and γ are weighting factors, MCP^0 is an input coefficient that is chosen such that the MCP is always lower than MCP^0, ΔZ^0 is an input coefficient such that the maximum change in the ZCU level (ΔZ^{max}) is always lower than ΔZ^0, BU_{ij} is the discharge burnup of fuel bundle j in fuel channel i, M_i is the refueling scheme for channel i, N_k is the refueling rate for cycle k, L is the current cycle number and L_0 is the number of previous cycles.

The constraints include the discharge burnup, MCP, MBP, CPPF and the ZCU water level, which are very important from the view point of a reactor operation. The constraints define a feasible region and any point in that region is a feasible solution, which represents a feasible refueling pattern that satisfies all the constraints and it can be chosen for a practical refueling operation.

The decision variable vector is a refueling pattern, which is composed of a refueling rate and refueling channels. The refueling rate is the number of refueling channels per day. In the genetic algorithm, the decision variable vector is decoded into a binary string of numbers 0 and 1 and vice versa.

3. Selection Strategy for the Optimal Solution

The overall procedure of the optimal refueling channel selection by the genetic algorithm can be classified into four stages: the preparation of an initial population, selection of the best solution, a crossover and the mutation. At the beginning of the search process, a pool of candidate refueling channels is created for a single cycle under the condition that the reactor channel and bundle powers are kept below specified limiting values. Then an initial population is produced by randomly selecting refueling channels from the candidate pool.

Selection is a process that chooses the fittest individuals in the current generation to create a breeding pool for the next generation. An elitism strategy is incorporated into the genetic search by creating an archive that stores the best non-dominated solutions found during the search process. Any solution that is not dominated by others is regarded as a non-dominated solution. All the non-dominated solutions satisfying the archival conditions are considered to be stored in the archive. Besides the solutions selected from the archive, the new generation is composed of the solutions of the current population by the roulette wheel spin method. The number of archived solutions that enters the new generation is chosen as a quadrant of the population size.

Crossover is the most dominant operator in the genetic algorithm. With the crossover operation, the genetic algorithm can obtain more information and therefore the search space is extended. In this study, the crossover is performed by the one-point method which mixes parts of the two parent solutions in the breeding pool to create two off-springs. Then a mutation is performed to maintain the diversity of the population by randomly altering the value of a string position with a small probability.

A flexible terminating condition is used in this study to reduce the computing time. The search process for a single cycle terminates whenever a target solution, which satisfies all the target conditions, is found. The target conditions are composed of constraints that the solution of the problem is to attain. In case when a target solution is not found at the final generation, the non-dominated solution with the highest fitness value of the archive is chosen as the final solution of the problem.

4. Multi-cycle Algorithm

The multi-cycle optimization is carried out through a single cycle optimization. During a continuous refueling simulation, the average ZCU water level is used as an indicator of the excess reactivity that the reactor core needs to maintain the criticality. If the average ZCU water level drops to below the typical operating value, the excess reactivity should be provided by the fresh fuels. In this study, the average ZCU water level is maintained simply by adjusting the minimum or maximum limit of the refueling rate for the next cycle when the average ZCU water level in the current cycle is lower or higher than the specific values.

5. Simulation Results

A refueling simulation of a CANDU reactor loaded with the natural uranium fuel was performed for 250 full power days at the equilibrium state. The constraints and other parameters used for the optimal refueling simulation were determined based on the preliminary simulation results of a single cycle optimization. The maximum number of generations in this calculation is set to be 15 to limit the computing time for each single cycle. Investigation of the simulation results can be summarized as follows:

- The target condition on the average discharge burnup significantly affects the computing time. If a higher discharge burnup is required, the computing time increases.
- Loose constraints on the lower and upper limits of the ZCU water level can help to establish the refueling pattern with a higher value of a discharge burnup.

Table I summarizes the performance parameters of the simulation and it compares them with those obtained by other methods. The performance parameters of the four simulations are in general very close to each other. For the Wolsong nuclear power plant 3, the discharge burnup was obtained from the simulation, while the others are from the operation history in the year 2000. Note that the simulation by the generalized perturbation theory was specifically designed to satisfy the ZCU level of 0.2~0.8 while other parameters such as the MCP and MBP were free to increase. Therefore the MCP and MBP of the GENOVA were higher than those of the other simulations. The simulation results of the genetic algorithm are very close to those of the AUTOREFUEL simulation.

As can be seen in Table I, the multi-objective optimization by the genetic algorithm doesn't drastically improve a single performance parameter such as the discharge burnup under the current fuel management strategy, which adopts an 8-bundle shift refueling scheme with two different fueling core regions. Under this fixed fuel management strategy, it is very difficult to change either the axial and radial power distribution of the core. Conversely speaking, the quality of the refueling simulation by the genetic algorithm is not much different from that of the other methods including the operation data.

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Table I Comparison of Refueling Simulation Results

		Genetic Algorithm	AUTOREFUEL	GENOVA	Wolsong-3
Discharge burnup (MWh/kgU)		171	171	171	168
MCP (kW)	Maximum	7070	7082	7248	7109
	Average	6910	6891	6964	6958
	Minimum	6701	6734	6720	6846
MBP (kW)	Maximum	890	893	914	840
	Average	857	855	859	825
	Minimum	822	827	830	810
CPPF	Maximum	1.11	1.09	1.11	1.13
	Average	1.07	1.06	1.07	1.09
	Minimum	1.04	1.04	1.04	1.07
ZCU level	Maximum	0.84	0.90	0.74	0.80
	Average	0.47	0.50	0.51	0.44
	Minimum	0.15	0.25	0.23	0.19