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Automatic multi-cycle reload design of pressurized water reactor using particle swarm optimization algorithm and local search

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ABSTRACT

An automatic multi-cycle core reload design tool, which searches the fresh fuel assembly composition, is developed using particle swarm optimization and local search. The local search uses heuristic rules to change the current search result a little so that the result can be improved. The composition of the fresh fuel assemblies should provide the required cycle energy and satisfy the constraints, such as the hot zero power moderator temperature coefficient and the hot channel factor. Instead of designing loading pattern for each FA composition during search process, two fixed loading patterns are used to calculate the core status and the better fitness function value is used in the search process. The fitness function contains terms which reflect the design objectives such as cycle energy, constraints, and fuel cost. The results show that the developed tool can achieve the desire objective.

1. Introduction

When a nuclear power plant needs to reload its fuel core, the fuel cost is an important concern. In order to reduce the fuel cost, several factors must be considered, such as batch size, enrichment and fuel utilization. The batch size, i.e., the number of adopted fresh fuel assemblies (FAs), will directly affect the fuel manufacture cost and the final disposal cost. The enrichment will also influence the manufacture cost and the fuel utilization depends on the discharge exposure value. In addition to the aforementioned economic considerations, the required cycle energy and the safety constraints, such as the hot zero power moderator temperature coefficient (MTC) and hot channel factor, $F_{\Delta H}$, must be fulfilled.

In a pressurized water reactor (PWR), the reloaded core contains the fresh FAs, once-burned FAs, and twice-burned FAs; this means that the utilization of the FAs of the current cycle has an impact on the following cycles, i.e., there is coupling between successive reloaded cycles. From an optimization point of view, sequential single-cycle optimization may not result in global optimal results. Therefore, the multi-cycle reload design over the planning horizon is necessary if the minimum multi-cycle fuel cost is requested.

To date, few researches have studied this task. Yamamoto et al. (1997) developed an integrated software tool to automate the scoping analysis and to improve the fuel cycle cost. The multi-cycle analysis module performed multi-cycle loading pattern (LP) optimization, in which the fuel inventory was adjusted. Yamamoto et al. (2004) carried out simultaneous successive optimizations for the two cycles of a PWR. The adopted algorithm by Yamamoto et al. was simulated annealing. The results showed that sequential single-cycle optimization effectively reproduces the optimization results generated by the simultaneous optimization if the proper objective functions are chosen. Studsvik's code (Kropaczek, 2011) COPERNICUS, which utilizes the simulated annealing algorithm, performs optimization over a multi-cycle planning horizon. The calculated results include batch size, LP, etc. The particle swarm optimization (PSO) has been applied to PWR loading pattern design (Babazadeh et al., 2009; Meneses et al., 2009; Menese et al., 2010; Khoshahval et al., 2010), boiling water reactor (BWR) lattice design (Lin and Lin, 2012b), BWR control rod pattern design (Wang and Lin, 2013), and nuclear engineering problems (Waintraub et al., 2009).

In Taiwan, the electricity generation of a nuclear power plant unit is about three percent of the total electricity generation. Therefore, to shutdown the nuclear reactor and to perform plant maintenance and core reload should be scheduled much early. When fuel procurement is processed, it consists of three cycles with different cycle length. To minimize the fuel cost, the multi-cycle reload design had better be considered. In this study, the automatic multi-cycle reload design tool is developed using particle swarm optimization (PSO) and local search, i.e., the fresh fuel assembly (FA) composition of each cycle is automatically generated. The fresh FA composition contains the number of each FA type for each cycle. During the search procedure, two fixed LPs are adopted to evaluate the core status, i.e., the FA composition

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performance, to save the computation time. The LPs of the final adopted FA composition will be designed using a detailed LP design tool to guarantee the safety constraints are fulfilled. The core simulation was performed using a SIMULTE-3 code (Studsvik Scandpower, 2007), which is a two-group 3-dimensional nodal code for the analysis of both boiling water reactor and PWR, using an HP 3000 workstation.

2. Particle swarm optimization

The PSO algorithm (Engelbrecht, 2005) is a stochastic optimization algorithm which uses a swarm of particles and each particle provides a possible solution which is denoted by the particle position value. The movement to the next position is indicated by the velocity. The velocity is determined according to the current velocity, the individual particle's information, and the information of other particles such as neighbor particles, or the global best particle. To enhance the algorithm performance, there are many variations which can be found in the referred book (Engelbrecht, 2005). In this study, we adopted the basic PSO algorithm and the velocity includes the individual's and the global best particle's information. The adopted velocity equation is as follow:

$$v_{ij}(t+1) = w \times v_{ij}(t) + c_1 \times r_{1j} \times [pbest_{ij} - x_{ij}(t)] + c_2 \times r_{2j} \times [gbest_j - x_{ij}(t)] \quad (1)$$

The position updated is as:

$$x_{ij}(t+1) = x_{ij}(t) + v_{ij}(t+1) \quad (2)$$

where $v_{ij}(t)$ is the velocity of particle i in dimension j at iteration t, $x_{ij}(t)$ is the position of particle i in dimension j at iteration t, dimension j is the jth variable of the problem, c_1 and c_2 are positive constants to scale those two terms, respectively, r_{1j} and r_{2j} are random values in the range [0, 1], $pbest_{ij}$ is the best solution of particle i in dimension j, $gbest_j$ is the best solution of all particles in dimension j, and w is the weighting factor, which is as follows:

$$w = 0.9 - \frac{0.5}{t_{\max}} \times t \quad (3)$$

where $t_{\max}$ is the maximum number of iterations, and t is the current iteration number. Eq. (3) serves to reduce the influence of the previous velocity during the iteration proceeds.

3. Application to multi-cycle reload design

3.1. Fitness function

The multi-cycle reload design problem is formulated as a combinatorial optimization problem, in which the desired objectives are included in the fitness function. The design task is to obtain the fresh FA composition so that the desired cycle energy and safety constraints are satisfied. There are five FA types to be chosen in this study. The optimized variables are the number of each FA type used. The value of the position, i.e., x, of Eq. (2), is used to determine the FA composition. To evaluate the goodness of the solution, the fitness function is as follows:

$$Fitness = W_{Boron} \times \sum_{i=1}^{4}(Boron_i - 10) + W_{MTC} \times \sum_{i=1}^{4}(MTC_i - \overline{MTC}) + W_{F\Delta H} \times \sum_{i=1}^{4}(F_{\Delta Hi} - \overline{F_{\Delta H}}) + W_{ER} \times \sum_{i=1}^{4} N_{ERi} + W_{Tot} \times \sum_{i=1}^{4}(N_{Fi} - \overline{N}_{Fi}) \quad (4)$$

where $Boron_i$ is the calculated boron concentration at the end of the required cycle length of the ith cycle, MTC_i the calculated moderator temperature coefficient of the ith cycle, $F_{\Delta Hi}$ the calculated hot channel factor of the ith cycle, $\overline{MTC}$, $\overline{F_{\Delta H}}$ the temporary limit value of MTC and $F_{\Delta H}$ during the search process, respectively, N_{ERi} the number of fresh FAs with lower enrichment of the ith cycle, N_{Fi} the total number of fresh FAs of the ith cycle, $\overline{N}_{Fi}$ the minimum total FA number required for the ith cycle, The Ws are the weighting factors, defined below.

$$W_{Boron} = \begin{cases} 1.5 & Boron > 10 \\ -15 & Boron \leqslant 10 \end{cases} \quad (5)$$

$$W_{MTC} = \begin{cases} 200 & MTC > \overline{MTC} \\ 0 & MTC \leqslant \overline{MTC} \end{cases} \quad (6)$$

$$W_{F_{\Delta H}} = \begin{cases} 300 & F_{\Delta H} > \overline{F}_{\Delta H} \\ 0 & F_{\Delta H} \leqslant \overline{F}_{\Delta H} \end{cases} \quad (7)$$

$$W_{ER} = -0.3 \quad (8)$$

$$W_{Tot} = 5 \quad (9)$$

The first term of Eq. (4) is the penalty of the cycle length shortage. Note that the weighting factor W_{ER} is negative so that the first term will be positive if boron concentration is smaller than 10. The extra 10 ppm boron concentration is reserved to account for the compensation of LP adjustment which is carried out during the final detailed LP design. The satisfactory LP design may place the higher reactivity FA near the core periphery, compared to the fixed LP used during search procedure, to reduce the value of MTC and $F_{\Delta H}$. The second and third terms of Eq. (4) serve to meet safety constraints. The adoption of the last two terms is to reduce the fuel cost, i.e., FA with lower enrichment have lower cost and the less total fresh FA numbers have lower final disposal cost.

Since a complete four cycle LP design by our developed automatic program (Lin and Lin, 2012a) takes about 4 days, an alternative method should be used to evaluate the performance of the FA composition. According to our experience, if the FA composition is proper, the fresh FAs are placed at the certain positions, and the burned FAs are arranged in some way, then the core status may deviate from that of the well designed LP a little, i.e., MTC and $F_{\Delta H}$ may be a few amount different, which can be accepted for the search purpose. If the FA composition is not proper, the calculated core status should be very worse and the fitness function value will be very large. For example, if the adopted number of the integrated fuel burnable absorber (IFBA) rods is too few, MTC may be large because the boron concentration is large at the beginning of cycle (BOC) and $F_{\Delta H}$ may be large because the local power of the fresh FA may be large. If the number of the IFBA rods is too many, the boron concentration at the end of cycle (EOC) may be too small because the reactivity is absorbed by the IFBA rods. In this study, two fixed LPs are adopted to calculate the core status because these two LP are the most possible LP to accommodate the fresh FAs and the more fixed LP adopted needs more core calculation. During the search process, the better result of these two LP is used to evaluate the performance of this FA composition. When the calculated MTC and $F_{\Delta H}$ are close to the certain value, i.e., $\overline{MTC}$ and $\overline{F}_{\Delta H}$ of Eq. (4), respectively, this FA composition will be proper because these two parameters can be improved to fulfill the design limit after detailed LP design. Otherwise, the satisfactory LP cannot be obtained. However, the satisfactory LP design will lose little reactivity, which means a positive boron concentration at EOC should be reserved to compensate for the violation of the calculated MTC and $F_{\Delta H}$ at this stage. As for $\overline{MTC}$ and $\overline{F}_{\Delta H}$, their value can be larger than the design limit to terminate the search process earlier, but they should be proper. That the too large value