A GENETIC ALGORITHM TO SEARCH FOR THE OPTIMAL LOADING PATTERNS OF A RESEARCH REACTOR

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1. Introduction

Recent research works related to the reactor in-core fuel management problem have achieved a perspective progress, which has resulted in a lot of methods being discovered for solving the problem. One of them, which can work efficiently to search for solutions which optimize several objectives while satisfying many conditions, is a genetic algorithm (GA). However, most of the work has focused on power reactors [1, 2] while a very few were concerned with research reactors. In this paper we tried to apply the GA to search for optimal fuel loading patterns (LP) which maximize the effective multiplication factor (k_{eff}) and minimize the power peaking factor (PPF) while satisfying the operational and safety constraints of a research reactor.

2. Formulation of the multi-objective fuel reload optimization problem for research reactors

The multi-objective fuel reload optimization problem for research reactors can be formulated such as finding the optimal fuel LPs which maximize k_{eff} and minimize PPF. Then the objective function is written as

$$F = \alpha(k_{eff} - 1) + \beta(PPF - PPF_{max}) \quad (1)$$

And the constraints are

$$k_{min} \le k_{eff} \le k_{max}, \quad (2)$$

$$PPF \le PPF_{max}, \quad (3)$$

$$BU \le BU_{max}, \quad (4)$$

$$N_{FS} \le N_{max}, \quad (5)$$

where k_{min} and k_{max} are the limits of k_{eff}, PPF_{max} is the maximum value of PPF, α and β are the weighting factors for k_{eff} and PPF, respectively, BU_{max} is the maximum fuel burn-up, N_{FS} is the number of fuel shuffles of an LP issued from the core configuration at EOC, and N_{max} is the maximum number of fuel shuffles.

The last constraint requires a reduction of the number of fuel shuffles in a refueling scheme. This arises from the operational practice at research reactors where automatic refueling machines are seldom equipped, so reactor managers prefer simple refueling schemes with a limited number of fuel shuffles. This requirement also helps to improve the reactor safety because of a reduction of the fuel handling during the refueling process. However this constraint is not easily satisfied in an automatic search.

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3. Method for searching optimal fuel LPs

In general, GAs work with three genetic operators – a selection, a crossover and a mutation. The selection carries better solutions into the next generation based on their fitness values. The crossover mixes parts of two parent solutions to create two different off-springs. Finally, the mutation makes some small random changes in the solutions, maintaining a diversity of the population to prevent a premature convergence to local optima.

A GA combined with an elitism strategy (ES) and a suitable coding procedure is used in this study. To preserve the best solutions during the search process, we used an ES by creating an archive that contains non-dominated solutions. Every solution in the archive is directly transferred to a breeding pool for the next generation. In our problem, a solution X with PPF_1 and k_{eff1} is dominated by a solution Y with PPF_2 and k_{eff2} if $PPF_2 < PPF_1$ and $k_{eff2} > k_{eff1}$. Any solution that is not dominated by others is regarded as a non-dominated solution.

In this study a coding procedure for a GA implementation is based on a one-dimensional chromosome as described below.

- Consider a reactor core consisting of N positions for a fuel loading and the total number of fuel bundles (FBs) loaded into the core is also equal to N.
- At first, assume a *base* LP by replacing the discharge FBs by fresh FBs. An FB in the *base* LP is then assigned with the same number as the core position into which it is loaded.
- **Encoding**: an LP is encoded into a chromosome of length N_{max} which is a string of N_{max} integer numbers (i_1, i_2, ..., i_{Nmax}), where N_{max} is the maximum number of fixed core positions for a fuel shuffling and i_k = {1, ..., N} is the FB number. The fixed core positions are the ones loaded with fresh FBs in the *base* LP. The position of gene i_k in the chromosome defines a fixed core position pos(k) into which FB i_k is loaded.
- **Decoding**: the chromosome (i_1, i_2, ..., i_{Nmax}) can be decoded into an LP by the following steps: i) Make a *transition* LP from the *base* LP by exchanging FB i_1 and the FB at position pos(1). ii) Create the next *transition* LP based on the current *transition* LP by exchanging FB i_2 and the FB at position pos(2). iii) Repeat step 2 until the final exchange between FB i_{Nmax} and the FB in position pos(N_{max}) is accomplished. iv) The final *transition* LP is only the LP corresponding to the chromosome (i_1, i_2, ..., i_{Nmax}).

4. Results and discussion

Illustrative calculations were carried out for a research reactor TRIGA MARK II located in Dalat, Vietnam. The reactor is loaded with Russian FBs type VVR-M2 with a 36% ^{235}U enrichment. The reactor core is surrounded by a graphite reflector and consists of a 121-cell hexagonal lattice of FBs, controls rods, beryllium rods, irradiation channels and some beryllium blocks.

The reactor was loaded with Russian fresh fuel and brought to a first criticality in 1983. After an operation of about 11000 hrs at a nominal power of 500 kW, the reactor was reloaded for the first time in 1994. At that time, all the 89 existing FBs in the core were unchanged; only 11 beryllium rods at the core periphery were replaced by fresh FBs. This core configuration defines the *base* LP.

Reactor calculations in this study were performed by a 3-D finite difference multi-group diffusion theory code CITATION [3]. The neutron cross sections for use in CITATION were generated by using WIMSD-5B [4]. After a preliminary investigation on the change in the individual objective under various values of α and β in Eq. (1), we obtained the fitness function as given in Eq. (6) to ensure that the fitness value was positive and assumed that the search process maximizes k_{eff} and minimizes PPF simultaneously:

$$F = 1000\,(k_{eff} - 1.) + 100\,(PPF - 1.375) \quad (6)$$

GA calculations were performed with the population size of 50, by progressing then through 60 generations. Calculations with crossover probability of 0.5, and mutation probability of 0.001 gave good results. Results from a GA run are presented in Figs. 1, 2 and 3. The archive consists of the 12 best LPs, which have a k_{eff} higher than 1.062 (k_{min}) and a PPF smaller than 1.375 (PPF_{max}). An LP with the best qualities according to the given objectives has k_{eff} = 1.0640 and PPF = 1.368, better than that of the practical fuel LP with k_{eff} = 1.0604 and PPF = 1.370. The gain in k_{eff} from 1.0604 to 1.0643 allows the reactor to operate for about 1500 hrs longer at a nominal power. This optimal LP is actually a low-leakage LP because the fresh FBs are loaded into the inner positions of the reactor core.

5. Conclusion

A GA which includes three genetic operators working on chromosomes encoded by a specific procedure combined with ES can successfully search for the optimal fuel LPs that maximize k_{eff} and minimize PPF while satisfying a stringent constraint on the limited number of fuel shuffles for a research reactor type TRIGA MARK II. The optimal LPs all lead to a very simple reloading scheme which satisfies an ultimate practical desire of research reactor managers. It is also worth noting that the archive contains a lot of best LPs for a future analysis.

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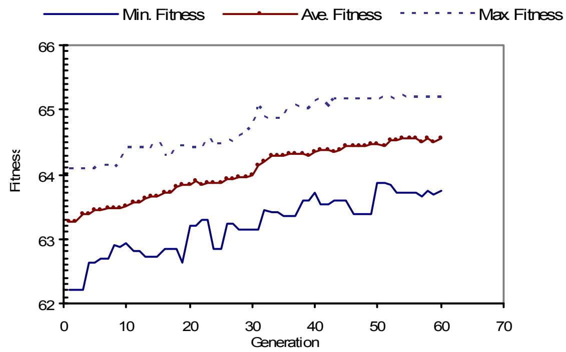

Fig. 1 Change in the population fitness

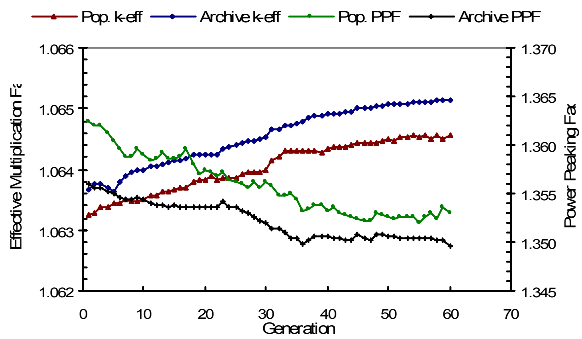

Fig. 2 Change in the average k_{eff} and power peaking factor of the population and the archive

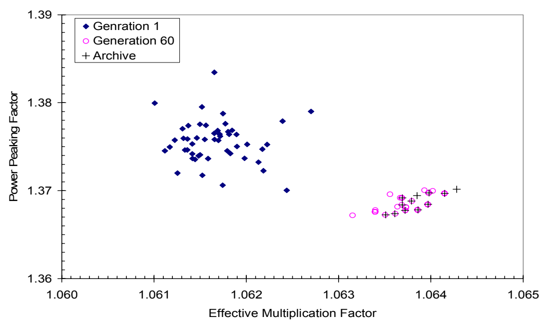

Fig. 3 Distribution of the LPs in a k_{eff}-PPF diagram