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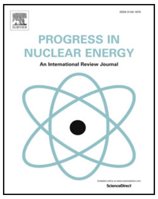

A novel multi-objective optimization method, imperialist competitive algorithm, for fuel loading pattern of nuclear reactors

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ABSTRACT

Imperialist Competitive Algorithm (ICA) has been successfully applied to the various optimization problems and has demonstrated great results in both the global optimal achievement and the convergence rate. In this work, the ICA has been applied to achieve the best fuel arrangement of the VVER-1000 reactor core during the cycle. Bushehr Nuclear Power Plant (BNPP) core optimal arrangement has been searched by considering the minimization of the power peaking factor, flattening of the radial neutron flux distribution and maximizing the effective multiplication factor (K_{eff}) of the core. Cross section and power distribution calculations have been performed by DRAGON-4 and CITATION codes, respectively. The algorithm implementation has been carried out in MATLAB framework for optimization of one-sixth (1/6) and one-twelfth (1/12) symmetry of the core. The results show that this method can be used as an efficient computational method for finding an optimized multi-objective loading pattern in a reactor core.

1. Introduction

Optimized core fuel loading pattern of a nuclear reactor is one of the most important issues in nuclear plant design that leads to the reduction in the economic cost and also raises the safety and burn-up levels for a desired period of time. Burn-up maximization, flattening of power distribution and minimization of power peaking with adequate safety margins are the main goals of optimization that should be considered in the optimization method by the fitness function. The optimization of core fuel loading pattern is an NP-Hard combinatorial type problem. By increasing the numbers of fuel assemblies (FA) in the reactor core, the complexity of these problems increases like a non-polynomial function. For example, in a PWR, there are n! fuel loading pattern for n FAs which shows that this problem is NP-Hard since the complexity of the problem increases as a non-polynomial function of the number of FAs. In recent years, the intelligent optimization algorithms which are inspired by nature such as Tabu Search (TS), Simulated Annealing (SA), Ant Colony Optimization (ACO), Population-Based Incremental Learning (PBIL), Genetic Algorithm (GA), Artificial Bee Colony (ABC), Particle Swarm Optimization (PSO), and Shuffled Frog Leaping (SFL) have been successfully applied to the different problems (Glover, 1986; Kirkpatrick, 1984; Socha and Dorigo, 2008; Gen and Cheng, 2000; Whitley, 1994; Kennedy, 2011; Fathian et al., 2007; Mirvakili et al., 2012). Some of these intelligence methods have been used in nuclear engineering to optimize fuel loading problem like GA (Do and Nguyen, 2007), PSO (Khoshahval et al., 2010), SA (Dueck and Scheuer, 1990) and ABC (Safarzadeh et al., 2011). Each one of the optimization methods has their own restrictions and can only reach to the near-optimum solutions, but they can't achieve overall optimum.

ICA as a new algorithm, which in its optimization process do not need the gradient of the function, can be used for solving continuous problems (Roshanaei et al., 2009). In another word, ICA and GA can be considered as the social counterpart of each other (Gen and Cheng, 2000). GA is based on the biological mutation of species, while ICA is based on the mathematical simulation of human social evolution. This method is successfully applied and used in some engineering applications. For instance, Banaei et al. (2015) have studied damping of oscillations using ICA in power system equipment.

In this paper, ICA has been used to solve In-Core fuel management of the VVER-1000 reactor. Bushehr VVER-1000 core is loaded by 163 hexagonal FAs. All types of FAs used in the core are modeled by DRAGON 4 (Marleau et al., 2016; Akbari-Jeyhouni et al., 2018) to achieve diffusion coefficient and group constant. Then, CITATION code (Zarifi et al., 2013; Fowler and Vondy, 1969) is utilized to simulate the

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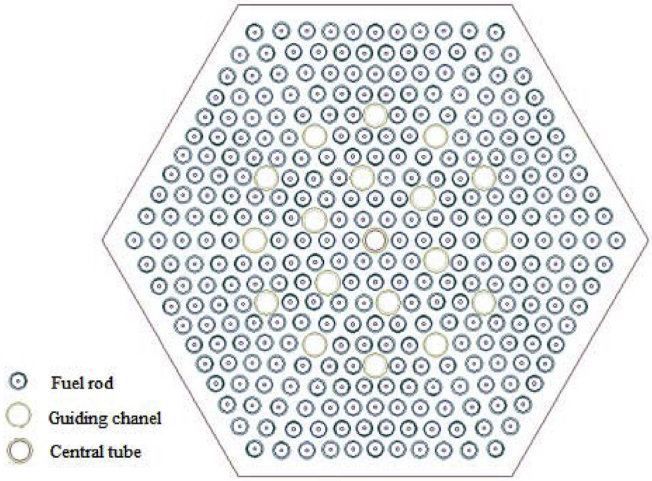

Fig. 1. The VVER-1000 fuel assembly model.

3D reactor core based on a hexagonal geometry. All calculations have been performed for the BNPP first core configuration and begin of the cycle (BOC). For each core configuration which is proposed by ICA, the objective function value is calculated according to the desired core parameters from neutronic calculations.

2. Material and method

2.1. Reactor core description

Bushehr Nuclear Power Plant (BNPP) is a VVER-1000 (V-446) type reactor that has one-sixth symmetric shape and hexagonal configuration. Figs. 1 and 2 depict fuel assembly and core model of the BNPP.

The core contains six types of FAs and each FA besides than 311 fuel pins consists of 20 guide channels, which are filled with light water, burnable absorber rods (BAR) or control rods. Characteristics of each type of FAs, which are used in the first loading of VVER-1000, are presented in Table 1. Some parameters of BNPP are demonstrated in Table 2 (AEOI, 2003; Vahman et al., 2016).

Table 1
Various FAs in the first core of VVER-1000 reactor (AEOI, 2010).

FA Type	Quantity of FA	Enrichment U-235	Fuel rod type 1	Fuel rod type 2	Quantity of BAR in FA	Boron content g/cc
16	54	1.6	311	–	–	–
24	31	2.4	311	–	–	–
36	36	3.62	245 (3.7%)	66 (3.3%)	–	–
24B20	6	2.4	311	–	18	0.020
24B36	30	2.4	311	–	18	0.036
36B36	6	3.62	245 (3.7%)	66 (3.3%)	18	0.036

Table 2
Specifications of the Bushehr NPP core.

Parameter	Value
Thermal power (MW)	3120
Coolant (pressure (MPa)/temperature (°C))	15.7 ± 0.3/321 ± 5.0
Coolant inlet temperature (°C)	291 ± 2.5
FA (form/number/pitch (mm))	Hexagonal/163/236
Fuel pin (arrangement/number in an FA/pitch (mm))	Triangle/311/12.75
Fuel (material/meat diameter (mm)/effective height (cm))	UO2/7.57/353
Cladding (material/thickness (mm))	Alloy Zr + 1% Nb/0.765
Mass of the fuel in the pin (kg)	1.575
Control rod (material/number)	B4C + (Dy2O3_TiO2)/85 × 18

2.2. Calculations of the neutronic parameters

Due to safety requirements, some constraints have been considered, which are described herein. One of these constraints is that the FAs of 1.6% enriched UO_2 not placed exactly besides the FAs with 3.6% enrichment. Furthermore, the number of each type of FAs must be equal to the number of FAs of core designer represented in Table 1. Another constraint is the maximum value of the power peaking factor (PPF) for FAs, which should not be greater than 1.35. Furthermore, due to the economic reasons, the core should be considered symmetric. In this paper, one-twelfth and one-sixth core symmetries are considered, and the results are compared to each other. These constraints are considered in MATLAB m-file code to generate random reactor core configuration for initial population of ICA. In this work DRAGON-4 (Marleau et al., 2016) code is applied to produce group constants and neutron macroscopic cross sections for the FAs. DRAGON code has a good capability in the homogenization of nuclear cross section and properties, and also this code includes transport equivalence calculations for the neutronic assessment of an FA (Marleau et al., 2016). Moreover, CITATION (Fowler and Vondy, 1969) code is applied to calculate the PPF of each assembly, thermal and fast neutron fluxes and the effective multiplication factor (K_{eff}) of the core.

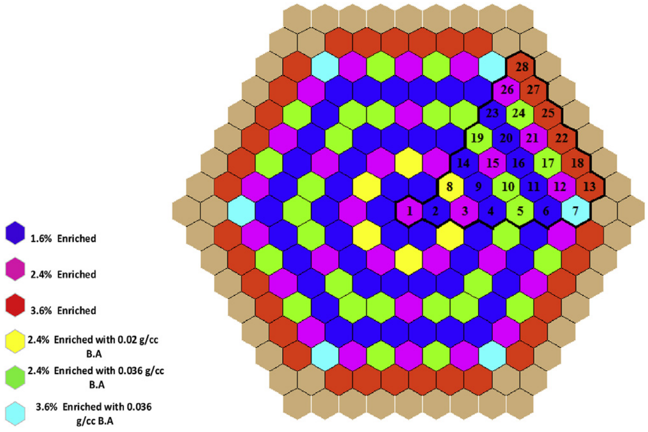

Fig. 2. The BNPP core configuration and one-sixth symmetry FAs No.

Cross sections for reflectors around the core and FAs are calculated according to the power history of Bushehr reactor (AEOI, 2010; Faghihi et al., 2016) by DRAGON-4 code and used in CITATION code for neutronic calculation of core parameters. The power history diagram for the first cycle of Bushehr reactor has been shown in Fig. 3. According to the history diagram of Bushehr reactor power, after 100th working day, power in the reactor remains constant, so all calculations have been performed up to this day.

2.3. Using ICA for core fuel loading pattern optimization

In the past centuries, developing countries competed extensively to overcome the different resources of less-developed countries. In this competition, each imperialist tried to have more development in different aspects to be able to compete with other imperialists and colonize more other countries. This idea has been used as the basis of the ICA. This algorithm is based on the different steps, including: forming empires by generating countries, assimilation and revolution of colonies and exchange positions between imperialists and colonies.

As demonstrated in Fig. 4, countries (generated random initial populations) will be divided into the different imperialists and colonies (according to their power that depends upon the problem) and together