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Implementation of the batch composition preserving genetic algorithm for burn up extension of a typical PWR

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ABSTRACT

Nuclear reactor core is the heart of a power plant producing power from fissile fuel fission. Refueling is needed periodically when it becomes impossible to maintain the reactor operating at nominal power as a result of fuel burn up. In PWR core reloading, attention is drawn to the configuration that meets safety requirements and minimizes energy cost. This paper focuses on finding the best core configuration for a typical two-loop, 300 MWe PWR satisfying the objectives of power peaking factor minimization to enhance safety of the reactor and maximization of multiplication factor to increase fuel burn up. Multi-objective optimization of the first core has been accomplished by implementing the batch composition preserving genetic algorithms (GA). Neutronic calculations and burn up analysis of the optimized loading patterns have been carried out using available reactor physics codes. It is found from this study that burn up of the optimized core has been extended by 48 effective full power days (EFPD's) while satisfying safety criterion by keeping power peaking factor below the reference value.

1. Introduction

Refueling is needed periodically when fuel is burnt-up and it is no more possible to maintain the reactor operating at nominal power. In PWR core reloading, attention is drawn to the reloading configuration that meets safety requirements and minimizes energy costs. It involves determination of parameters for initial core as well as subsequent reload cores to minimize fuel cost while satisfying safety restrictions. The important safety related factors include hot channel factor, power peaking factor, moderator temperature coefficient and maximum allowable fuel assembly burn up. The cost-related parameters are effective multiplication factor (k-eff) and cycle length. An optimal loading pattern (LP) should allow for a reasonably high k-eff without compromising integrity of the reactor core components.

Optimization of core reload of a nuclear PWR plant is a problem whose time complexity grows exponentially with the number of variables. Moreover, the problem is constrained and non-linear with a highly discontinuous and multi-modal search space.

In 1986, Hamasaki and Takeda (1986) used linear programing for fuel loading optimization. The sensitivities of various performance parameters to loading pattern changes were calculated with depletion perturbation theory (DPT). Cycle burn up maximization and flattening of power profile was achieved.

Kropaczek and Turinsky (1991) developed a computational code FORMOSA (Fuel Optimization for Reloads – Multiple Objectives by Simulated Annealing). This code was used for in-core fuel management. Later on, Mahlers (1995) made some modifications in the FORMOSA code. He used simulated annealing and successive linear programming for optimization of the core reload pattern. Although application of the successive linear programming for searching the best fuel reload pattern provided high quality of solution obtained, however, it increased computational cost of the algorithm.

Babazadeh et al. (2009) used particle swarm optimization (PSO) technique to solve LP optimization for VVER nuclear power. A multi-objective optimization with linear fitness function was performed and better results were achieved as compared to reference LP. Likewise, Liu and Cai (2012) reported that a better LP for Daya Bay Nuclear Power Plant was achieved as compared to the reference loading pattern by using multi-objective improved pivot particle swarm optimization.

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Recently, Zameer et al. (2014) performed a comparative study of core reload optimization based on simulated annealing and genetic algorithm. They developed a hybrid technique of core reload pattern optimization for a typical PWR. It was found from their study that simulated annealing either exhibited premature convergence or failed to converge to global minimum depending upon the annealing temperature. They proposed a batch composition preserving genetic algorithm with novel crossover and mutation operators. Its performance was better than simulated annealing for larger population size.

This paper focuses on finding the best core configuration of a typical two-loop, 300 MWe PWR satisfying the objectives of power peaking factor minimization to enhance safety of the reactor and maximization of the multiplication factor to increase fuel burn up. The multi-objective optimization of the first core has been accomplished by implementing the batch composition preserving genetic algorithms (GA). Neutronic calculations and burn up analysis of loading patterns have been carried out using available reactor physics codes. It is found from this study that burn up of the optimized core has been extended by 48 effective full power days (EFPD's) while satisfying safety criterion by keeping power peaking factor below the reference value.

What follows is an explanation of material and method in Section 2. Description of the reference reactor is given in sub-section 2.1. Details of the simulation codes used are given in sub-section 2.2. The methodology adopted is elaborated in sub-section 2.3. Section 3 deals with results and discussion. Results of core optimization are presented in Section 3.1 whereas burn up analysis is presented in sub-section 3.2. Concluding remarks are given in Section 4.

2. Materials and methods

This section deals with description of the reference reactor, brief introduction of the computational codes used and methodology adopted in this work. The detail is given in the subsequent subsections.

2.1. Description of the reference reactor

The Chasma Nuclear Power Plant Unit-1 (CHASNUPP-1) is selected as the reference reactor for this study. It is a two loop, 300 MWe pressurized water reactor. The core is nearly a square cylinder with equivalent diameter of 248.6 cm and core active height of 290 cm. The design specifications of the CHASNUPP-1 reactor are given in Table 1 (Chashma Nuclear Power Plant, 1989).

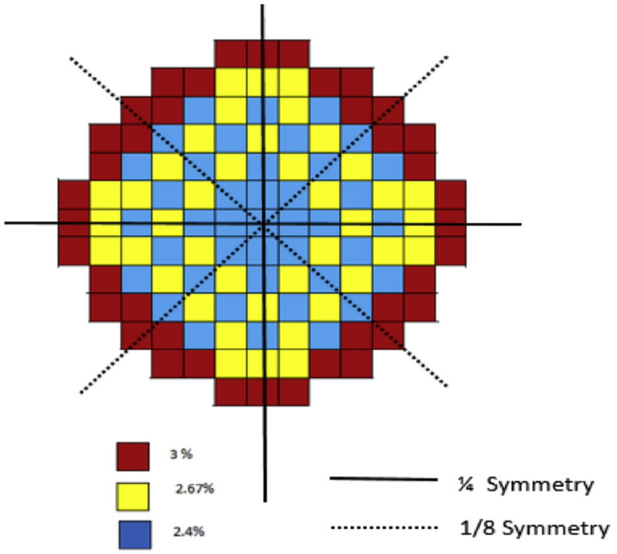

Fig. 1. 2D cross-sectional view of CHASNUPP-I core showing different enrichment zones.

Fig. 1 shows a two-dimensional cross-sectional view of the standard core configuration. It consists of 121 fuel assemblies (FA) with three enrichment zones of 2.4, 2.67 and 3.0 wt%. Each FA is comprised of 15 × 15 channel array with 204 fuel pins, 20 control rod guide tubes and a central instrumentation thimble tube. The core has eight-fold symmetry. Effective multiplication factor (k-eff) of standard core in cold clean conditions is 1.29 (Chashma Nuclear Power Plant, 1989).

The standard core has an out-in scattered loading pattern. The fresh fuel assemblies are placed at outer periphery whereas once and twice burnt fuel assemblies are arranged in a checker board pattern in interior region.

2.2. Simulation codes

Detailed neutronic calculations and burn up analysis have been carried out using available reactor physics codes. WDIMSD/4 (Deen and Woodruff, 1995) has been used for macroscopic group-constants generation whereas PRIDE (Ahmad, 2012a) has been used for core modeling. Burn up Analysis has been carried out using the FICS (Ahmad, 2012b) code. Description of these codes is given below:

Table 1
Design data of the Chashma Nuclear Power Plant Unit_I (CHASNUPP-I) (Chashma Nuclear Power Plant, 1989).

Parameter	Unit	Value
Reactor nominal thermal power	MW	1000
Number of fuel assemblies	–	121
Core active length	mm	2900
Equivalent core diameter	mm	2486
Uranium mass in first loading	ton	35.92
Number of fuel assembly having enrichment 2.4/2.67/3.0 $^{w}/_{o}$	–	41/40/40
Average power density	kW/dm^3	73.5
Fuel material	–	UO_2
Clad material	–	Zr-4
Moderator	–	Light water
Fuel pellet diameter	mm	8.43
Clad outer diameter	mm	10
Clad thickness	mm	0.785
Fuel rod centerline pitch	mm	13.3
Number of fuel rods per assembly	–	204
Number of control rod guide thimbles per assembly	–	20