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Application of Genetic Algorithm methodologies in fuel bundle burnup optimization of Pressurized Heavy Water Reactor

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HIGHLIGHTS

- We study and compare Genetic Algorithms (GA) in the fuel bundle burnup optimization of an Indian Pressurized Heavy Water Reactor (PHWR) of 220 MWe.
- Two Genetic Algorithm methodologies namely, Penalty Functions based GA and Multi Objective GA are considered.
- For the selected problem, Multi Objective GA performs better than Penalty Functions based GA.
- In the present study, Multi Objective GA outperforms Penalty Functions based GA in convergence speed and better diversity in solutions.

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ABSTRACT

The work carried out as a part of application and comparison of GA techniques in nuclear reactor environment is presented in the study. The nuclear fuel management optimization problem selected for the study aims at arriving appropriate reference discharge burnup values for the two burnup zones of 220 MWe Pressurized Heavy Water Reactor (PHWR) core. Two Genetic Algorithm methodologies namely, Penalty Functions based GA and Multi Objective GA are applied in this study. The study reveals, for the selected problem of PHWR fuel bundle burnup optimization, Multi Objective GA is more suitable than Penalty Functions based GA in the two aspects considered: by way of producing diverse feasible solutions and the convergence speed being better, i.e. it is capable of generating more number of feasible solutions, from earlier generations. It is observed that for the selected problem, the Multi Objective GA is 25.0% faster than Penalty Functions based GA with respect to CPU time, for generating 80% of the population with feasible solutions. When average computational time of fixed generations are considered, Penalty Functions based GA is 44.5% faster than Multi Objective GA. In the overall performance, the convergence speed of Multi Objective GA surpasses the computational time advantage of Penalty Functions based GA. The ability of Multi Objective GA in producing more diverse feasible solutions is a desired feature of the problem selected, that helps the reactor operator in getting more choices when deciding the appropriate discharge burnups of the core zones.

1. Introduction

The Pressurized Heavy Water Reactors (PHWRs) play an important role in the Indian nuclear power program. PHWR is characterized by the use of natural uranium dioxide as fuel, heavy water as moderator and heavy water at high pressure/temperature in a separate circuit as coolant. The reactor consists of a low-pressure horizontal reactor vessel (‘calandria’) containing the moderator at near ambient pressure and temperature. The fuel bundle burnup optimization of PHWR involves finding the optimum average discharge burnup of fuel bundles within the reactor core which gives the maximum fuel economy, while ensuring that operational and safety related constraints are always satisfied. In the present study, the reactor core considered is of two burnup zones. The aim of optimization is to find appropriate reference discharge burnup values for the two zones in order to obtain the optimum average discharge burnup for the total core. The zones reference discharge burnups obtained from the optimization can be used as the reference in

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selecting channels for refueling. The present study is based on 220 MWe Indian PHWR and that type forms the highest number of nuclear power plants operating in India. Nuclear Power Corporation of India Limited (NPCIL) reports that there are fourteen 220 MWe PHWR plants under operation in India (NPCIL, 2014). The aim of the present work is to apply and study the suitability of two flavors of the evolutionary optimization algorithm namely Genetic Algorithm (GA) in deriving burnup reference values for the two zones, which give maximum average discharge burnup of the total core without violating various operational and safety aspects of the reactor.

Genetic Algorithm (GA) is an optimization tool based on Darwinian Theory of biological evolution. The method was developed by John Holland (Holland, 1975) and later popularized by one of his students, David Goldberg, who successfully applied to various practical engineering problems (Goldberg, 1989). GA has several advantages over the traditional optimization techniques. While calculus based optimization techniques depend on the derivative information of the objective functions, GA based techniques do not have this dependency. Furthermore, they are more efficient than enumerative schemes and random search algorithms, as they do not require evaluation of a very large number of points in the search space. These advantages brought GA as a suitable and efficient tool in nuclear fuel management applications (Poon and Parks, 1993).

The remaining part of the paper is organized as follows: a brief description about nuclear fuel management and the optimization techniques applied in the field is given in Section 2. The overall procedure of GA, as applied to nuclear fuel management problems is included in Section 3. The neutronics simulation code used in the present work is described in Section 4. The features of the optimization of fuel bundle for PHWR and the mathematical model formulation is given in Section 5. The two GA based methodologies applicable for the selected problem is formulated in Section 6. Section 7 gives GA related implementation details of the present work. Section 8 comprises the results followed by the conclusion of the study in Section 9.

2. Nuclear fuel management techniques and Genetic Algorithms

The study about PHWR fuel bundle burnup optimization presented here comes under the in-core nuclear fuel management. In-core nuclear fuel management deals with the arrangement of fresh and partially burned fuel assemblies and reactivity control mechanisms within the core that optimizes the performance of the reactor over operating cycles, while ensuring operational and safety related constraints always being satisfied (Poon and Parks, 1993). In-core fuel management and optimization is a classical nuclear engineering problem, which has been studied for more than four decades and several techniques have been employed for solving them (Turinsky, 1999; Turinsky et al., 2005). Genetic Algorithm (GA) is one among the major global optimization techniques, used in the field of in-core fuel management and optimization. Apart from Genetic Algorithms, there are other global optimization techniques applied in the in-core nuclear fuel management. Some of them are listed as, Simulated Annealing (Kropaczek and Turinsky, 1991), Tabu Search (Lin et al., 1998; Castillo et al., 2004), Ant Colony Optimization (ACO) (Ortiz et al., 2007; Lin and Lin, 2012), Ant-Q Optimization (Machado and Schirru, 2002), Particle Swarm Optimization (PSO) (Meneses et al., 2009; Waintraub et al., 2009), Artificial Bee Colony Optimization (ABCO) (Oliveira and Schirru, 2011; Safarzadeh et al., 2011), Harmony Search Algorithm (HSA) (Poursalehi et al., 2013a) and Continuous Firefly Algorithm (CFA) (Poursalehi et al., 2013b). The above listed techniques come under the category of nature inspired intelligent algorithms. There are other types of optimization techniques also applied like Mixed Integer Programming (Kim and Kim, 1997), Estimation Distribution Algorithm (EDA) (Jiang et al., 2006; Mishra et al., 2009), and Particle Collision Algorithm (PCA) (Sacco et al., 2006).

The survey carried out reveals that many of the GA applications in the field of in-core nuclear fuel management were applied for Light Water Reactors (i.e. for Pressurized Water Reactors and Boiling Water Reactors; Jayalal et al., 2014). For example, GA is applied for optimization of Pressurized Water Reactors core loading pattern and burnable poison (Alim et al., 2008; Chapot et al., 1999; DeChaine and Feltus, 1995, 1996; Haibach and Feltus, 1997; Hongchun, 2001; Khoshahval et al., 2011; Khoshahval and Fadaei, 2012; Norouzi et al., 2011; Pereira et al., 1999; Poon and Parks, 1993; Rafiei Karahroudi et al., 2013; Yamamoto, 1997; Yamamoto and Hashimoto, 2002; Yilmaz et al., 2006). Similarly, for Boiling Water Reactors, GA is applied for loading pattern optimization and control rod positioning (Kobayashi and Aiyoshi, 2001, 2002, 2003; Martin-del-Campo et al., 2001, 2009; Ortiz and Requena, 2004). There are a few studies related to Pressurized Heavy Water Reactor in-core fuel management. Quang Do et al. (2006) and Huo and Xie (2005) have applied GA for online refueling of PHWR. Mishra et al. (2009) considered special case of optimization of thorium loading in fresh core of PHWR and applied GA.

It can be seen from the survey carried out, that there are two major methodologies in formulating nuclear fuel optimization model for GA (Jayalal et al., 2014). The two methodologies being: Penalty Functions based Genetic Algorithms (referred to as Penalty Functions based GA in the rest of the paper) and Multi Objective Genetic Algorithms (referred to as Multi Objective GA in the rest of the paper). These two approaches are further explained in Section 6. A brief description of the previous studies reported in the literature, regarding nuclear fuel management optimization problems using different methodologies of GA are given next. Penalty Functions based GA is applied in fuel management of Pressurized Water Reactors by DeChaine and Feltus (1995), Yamamoto (1997), Pereira et al. (1999), Yilmaz et al. (2006), Alim et al. (2008), Khoshahval et al. (2011), Norouzi et al. (2011), Khoshahval and Fadaei (2012) and Rafiei Karahroudi et al. (2013). Similarly, Penalty Functions based GA is applied for Boiling Water Reactors by Martin-del-Campo et al. (2001, 2009) and Ortiz and Requena (2004). Similar works for PHWRs are done by Huo and Xie (2005) and Mishra et al. (2009). The early applications of Multi Objective GA in the nuclear fuel management were for Pressurized Water Reactor by Parks (1996) and later by Pereira (2004). Fuel management optimization for Boiling Water Reactor's by Multi Objective GA was carried out by Kobayashi and Aiyoshi (2001, 2002, 2003). Quang Do et al. (2006) applied the same concept for online refueling simulation of PHWR. There were some initiatives to apply Multi Objective GA in Fast Breeder Reactors also (Toshinsky et al., 1999, 2000).

In the present study, we are applying the concepts of Penalty Functions based GA and Multi Objective GA separately, to find their suitability in the selected fuel bundle burnup optimization problem of PHWR. Before going into the details of the implementation of these GA based methodologies, a brief description about the overall GA procedure, applicable for both Penalty Functions based GA and Multi Objective GA methodologies is given in the next section.

3. Genetic Algorithm in nuclear fuel management: overall procedure

The first step in applying GA to reactor fuel optimization is to determine the representation method which is suitable for the algorithm. As part of GA representation, a candidate solution (in the present study, burnup values of inner and outer zones) is encoded as a digital chromosome which has enough information to reproduce the original solution. While being executed, GA generate a