Annals of Nuclear Energy 62 (2013) 86–102

Contents lists available at SciVerse ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Self-adaptive global best harmony search algorithm applied to reactor core fuel management optimization

N. Poursalehi [a,*], A. Zolfaghari [a], A. Minuchehr [a], K. Valavi [b]

[a] Department of Nuclear Engineering, Shahid Beheshti University, GC, P.O. Box 1983963113, Tehran, Iran
[b] Department of Nuclear Engineering, Science and Research Branch, Islamic Azad University, Punak, Tehran, Iran

ARTICLE INFO

Article history:
Received 9 July 2012
Received in revised form 2 June 2013
Accepted 6 June 2013
Available online 2 July 2013

Keywords:
Loading pattern optimization
Self-adaptive global best harmony search algorithm
Nodal expansion method
Rectangular and hexagonal geometries

ABSTRACT

The aim of this work is to apply the new developed optimization algorithm, Self-adaptive Global best Harmony Search (SGHS), for PWRs fuel management optimization. SGHS algorithm has some modifications in comparison with basic Harmony Search (HS) and Global-best Harmony Search (GHS) algorithms such as dynamically change of parameters. For the demonstration of SGHS ability to find an optimal configuration of fuel assemblies, basic Harmony Search (HS) and Global-best Harmony Search (GHS) algorithms also have been developed and investigated. For this purpose, Self-adaptive Global best Harmony Search Nodal Expansion package (SGHSNE) has been developed implementing HS, GHS and SGHS optimization algorithms for the fuel management operation of nuclear reactor cores. This package uses developed average current nodal expansion code which solves the multi group diffusion equation by employment of first and second orders of Nodal Expansion Method (NEM) for two dimensional, hexagonal and rectangular geometries, respectively, by one node per a FA. Loading pattern optimization was performed using SGHSNE package for some test cases to present the SGHS algorithm capability in converging to near optimal loading pattern. Results indicate that the convergence rate and reliability of the SGHS method are quite promising and practically, SGHS improves the quality of loading pattern optimization results relative to HS and GHS algorithms. As a result, it has the potential to be used in the other nuclear engineering optimization problems.

1. Introduction

The In-Core Fuel Management Optimization (ICFMO), also known as Loading Pattern Optimization (LPO) problem or nuclear reactor reload problem, is a classical problem in Nuclear Engineering. According to Levine (1987), the goal of the ICFMO is to determine the LPs for producing full power within adequate safety margins. An optimal nuclear reload design can be defined as a configuration which has the maximum cycle length for the given fuel inventory or uses the minimum amount of fissionable materials for the given cycle length while satisfying safety constraints such as limitation on power peaking factor. The main problem in the fuel assembly position determination is the large number of possible combinations for the fuel loading pattern in the core. In addition, the fact that this is a nonlinear and discrete problem creates complications in the use of conventional optimization techniques (Babazadeh et al., 2009).

The ICFMO is a real-world problem studied for more than four decades and several techniques have been used for its solution, such as optimization techniques and human expert knowledge. The ICFMO presents characteristics such as high-dimensionality, the large number of feasible solutions, disconnected feasible regions in the search space as well as the high computational cost of the evaluation function and lack of derivative information, which contribute to the challenge of the optimization of the ICFMO. The group of techniques used in the ICMFO over the years encompasses manual optimization, Mathematical Programming, Optimization Meta-heuristics and Knowledge-Based Systems. As a matter of fact, these approaches lead to three categories of computerized tools for decision support for the ICFMO: manual design packages, expert systems and optimization packages. Knowledge-Based Systems have also been applied to the ICFMO and one early use of logical rules for generating LPs may be seen in Naft and Sesonske (1972). Besides the important contributions of Mathematical Programming and Knowledge-Based Systems, Optimization Meta-heuristics have been successfully applied to the ICFMO. These algorithms also known as generic heuristic methods, (Taillard et al., 2001), have demonstrated an outstanding capability of dealing with complex search spaces, especially in the case of the ICFMO. Such Artificial Intelligence (AI) algorithms, besides the low coupling to the specificities of the problems, have some characteristics such as the memorization of solutions (or characteristics of solutions), which allows the

* Corresponding author. Fax: +98 21 29902546.
E-mail address: npsalehi@yahoo.com (N. Poursalehi).

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http://dx.doi.org/10.1016/j.anucene.2013.06.003

algorithm to retain intrinsic patterns of optimal or near-optimal solutions or, in other words, "inner" heuristics as described by Gendreau and Potvin (2005). As search methodologies, meta-heuristics may have in common: diversification, in order to explore different areas; mechanisms of intensification, in order to exploit specific areas of the search space; memory, in order to retain the best solutions; and tuning of parameters, (Siarry and Zbigniew, 2008).

Various meta-heuristics or computational intelligence approaches have been developed and implemented for reactor core fuel management optimizations. Through these techniques, direct search (Stout, 1973), variational techniques (Terney and Williamson, 1982), backward diffusion calculation (Chao et al., 1986), reverse depletion (Kim et al., 1987), Population-Based Incremental Learning (Baluja, 1994), linear programming (Stillman et al., 1989), simulated annealing (Smuc et al., 1994; Mahlers, 1994), Ant Colony algorithm for maximizing boron concentration (Machado and Schirru, 2002), genetic algorithms (Mohseni et al., 2008), harmony search algorithm (Poursalehi et al., 2013a), differential harmony search algorithm (Poursalehi et al., 2013b), discrete Particle Swarm Optimization (Babazadeh et al., 2009), continuous Particle Swarm Optimization (Meneses et al., 2009), artificial intelligence techniques like Artificial Neural Networks (ANN) (Sadighi et al., 2002), continuous firefly algorithm (Poursalehi et al., 2013c), discrete firefly algorithm (Poursalehi et al., 2013d), enhanced integer coded genetic algorithm (EICGA) (Norouzi et al., 2011), are the ones most commonly used in the core fuel management optimization.

Harmony Search (HS) is a new meta-heuristic algorithm developed by Geem et al. (2001), which is inspired by the natural musical performance process that occurs when a musician searches for a better state of harmony. In the HS algorithm, the solution vector is analogous to the harmony in music, and the local and global search schemes are analogous to musician's improvisations. In the optimization process, global optimum solution may be found by performing several iterations through different values of decision variables. In comparison to other meta-heuristics in the literature, the HS algorithm imposes fewer mathematical requirements and can be easily adapted for solving various kinds of engineering optimization problems, (Mahdavi et al., 2007). Furthermore, numerical comparisons demonstrated that the evolution in the HS algorithm was faster than genetic algorithms, (Lee and Geem, 2005; Mahdavi et al., 2007). HS may be viewed as a simple real-coded GA, since it incorporates many important features of GA like mutation, recombination, and selection. Therefore, the HS algorithm has captured much attention and has been successfully applied to solve a wide range of practical optimization problems, such as structural optimization, parameter estimation of the nonlinear Muskingum model, design optimization of water distribution networks, vehicle routing, combined heat and power economic dispatch, design of steel frames, and transport energy modeling (Lee and Geem, 2005). Recently, Poursalehi et al. (2013a) have exploited the basic Harmony Search (HS) algorithm for PWR loading pattern optimization. They concluded that the basic HS algorithm has the quite promising results and reliability for reactor core fuel management optimization. Their results presented that on the average the final band width of search fitness values is narrow and very close to optimal value along approximately 10,000 harmony vectors generating for KWU reactor test case, (Poursalehi et al., 2013a).

The HS algorithm is good at identifying the high performance regions of solution space within a reasonable time. But, it is not efficient in performing local search in numerical optimization applications, (Mahdavi et al., 2007). Thus, a few modified variants were developed for enhancing solution accuracy and convergence rate. Mahdavi et al. (2007) presented an Improved HS algorithm, denoted as IHS; by introducing a strategy to dynamically tune the key parameters, whereas Omran and Mahdavi (2008) proposed a Global best HS algorithm, denoted as GHS, by borrowing the concept from swarm intelligence. Their experiments revealed the fact that both improved variants could find better solutions when compared to the basic HS algorithm. Particularly, the GHS algorithm outperformed the IHS algorithm. Recently, Pan et al. (2010) has developed a Self-adaptive Global best Harmony Search (SGHS) algorithm for solving optimization problems. SGHS' computational experiments and comparison have shown that the proposed SGHS algorithm outperforms the existing basic HS and GHS algorithms when applied to optimize various benchmark global optimization problems, Pan et al. (2010). In the SGHS method, one of differences relative to basic HS and GHS is the dynamically change of HS parameters.

In this paper, we exploited the Self-adaptive Global best Harmony Search (SGHS) algorithm in the nuclear engineering field to optimize FAs arrangement of reactor core to satisfy an arbitrary objective function along constraints. For the performance evaluation of method, the flattening of FAs relative power for some PWRs including KWU, BIBLIS and VVER-440 test cases is considered as fitness function. For this purpose, we developed Self-adaptive Global best Harmony Search Nodal Expansion package (SGHSNE-2D) for 2D rectangular and hexagonal geometries to use in the fuel management operation of nuclear reactors core. In this package, a neutronic module is developed which solves the two dimensional-multi group diffusion equation using second order of Average Current Nodal Expansion Method (ACNEM), exploiting fourth degree flux expansion for rectangular geometries (Poursalehi et al., 2012, 2013e), and first order of ACNEM for hexagonal geometries, (Putney, 1984). The major score of this developed neutronic code is the coarse mesh calculation using one node per a FA which lessens the computational cost and time of core calculation operation. To demonstrate the SGHS algorithm merits, basic HS and GHS algorithms also developed and implemented in SGHSNE-2D and results have been compared. The improvement of SGHS results relative to basic HS and GHS algorithms have been found from the comparison of results.

The remainder of this paper is organized as follows: Sections 2 and 3 briefly outline basic HS, and GHS algorithms, respectively; Section 4 presents the proposed algorithm, i.e. SGHS and its validation against Shekel's Foxhole test case, Section 5 defines the fitness function definition for the fuel management operation and in Section 6 results are given and compared for three test cases and finally the paper is concluded in Section 7.

2. Basic harmony search optimization algorithm

Harmony Search (HS) algorithm, originated by Geem et al. (2001), is based on natural musical performance processes that occur when a musician searches for a better state of harmony. The resemblance, for example between jazz improvisation that seeks to find musically pleasing harmony and the optimization is that the optimum design process seeks to find the optimum solution as determined by the objective function. The pitch of each musical instrument determines the esthetic quality just as the objective function is determined by the set of values assigned to each design variable. Esthetic sound quality can be improved practice after practice just as objective function value can be improved iteration by iteration.

The analogy between improvisation and optimization is shown in Fig. 1. Each musician (double bassist, guitarist, and saxophonist) has some notes in their memories and they can correspond to each decision variable ($x1$, $x2$, and $x3$). The range of each music instrument (double bass = {Do, Re, Mi}; guitar = {Mi, Fa, Sol}; and saxophone = {La, Si, Do}) corresponds to each variable value ($x1$ = {1.2, 2.2, 3.1}; $x2$ = {3.2, 2.4, 1.8}; and $x3$ = {1.7, 2.8, 2.3}). If the double