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Pattern optimization of PWR reactor using hybrid parallel Artificial Bee Colony

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ABSTRACT

In this paper, we propose a core reloading of pressurized water reactors technique based on a hybrid Artificial Bee Colony (ABC) algorithm. Our approach integrates the merits of both ABC algorithm and Particle Swarm Optimization (PSO). The neighborhood search scheme of the algorithm is improved by location of personally encountered the most flowers and location of highest concentration of flowers explored by the intact swarm. The probability of selecting food sources by onlooker in the proposed algorithm is enhanced through using roulette-wheel mechanism. To address the drawback of most optimization algorithms, this method has been parallelized, so that the runtimes may be greatly reduced by using a multiprocessor computer cluster. The proposed optimization method is applied to the cycle length maximization of a VVER-1000 core. Simulation results show that the proposed ABC method could have the advantages of original ABC, and is capable of producing low cost, fast, and reasonably accurate solutions.

1. Introduction

Reactor core fuel management is a dominant procedure which leads to economic and safe operation of nuclear power plants (NPPs). This complicated and vital chore is constituted of fuel assembly design, including burnable poison and enrichment distributions, the operational strategy and placements of the fresh and burned bundles within the core (Levine, 1987). In-core fuel management is done on fuel utilization, in order to reduce the fuel costs and the volume of nuclear waste, and safety operational procedures concerns to satisfying required operational and safety constraints (Maldonado, 2005). The issue is a complex and combinatorial problem and the most challenging areas in optimization because of the large number of possible solution, such as loading pattern (LP) of fresh and used fuel assemblies (FAs), its orientations and placement of burnable poison. In this optimization problem, there would be $n!$ possible solution for n FAs, without considering the placement of burnable poison and orientations of these FAs which indeed increases more the complexity of the problem. Furthermore, these LPs are not feasible solutions in accordance with safety constraints, causing the feasible regions to be disconnected (Stevens, 1995).

Several algorithms have been developed and successfully applied to optimize reactor core loading problem such as Dynamic Programming (Wall and Fenech, 1965), direct search (Stout, 1973), Variational Techniques (Terney and Williamson, 1982), Backward Diffusion Calculation (Chao et al., 1986), Reverse Depletion (Downar and Kim, 1986; Kim et al., 1987), Linear Programming (Stillman et al., 1989), Simulated Annealing (Stevens, 1995), Ant Colony algorithm (Schirru et al., 2006), Safarzadeh et al. (2011) applied ABC algorithm to power flattening of PWR reactor, continuous Genetic Algorithm (GA) introduced for flatting power distribution (Zolfaghari et al., 2009; Norouzi et al., 2011), discrete PSO (Babazadeh et al., 2009), continuous PSO (Khoshahval et al., 2010), Mohseni et al. used GA in multi-objective optimization of lowering power peaking factor, maximization of the effective multiplication factor (Mohseni et al., 2008), Cellular Automata for maximizing initial excess reactivity and minimizing power peaking factor (Fadaei and Setayeshi, 2009), Perturbation Theory (Stacey, 1974; Hosseini and Vosoughi, 2012), ArtificialIntelligence techniques like Artificial Neural Networks (ANNs) (Sadighi et al., 2002), and combination of fuzzy logic and ANN (Kim et al., 1993) are the ones most commonly used in core fuel management. A further study based on hybrid algorithms was performed (Stevens, 1995; Erdog and Geçkinli, 2003; Fadaei et al., 2009). The hybrid algorithm was developed to combine the strengths of three algorithms: direct search for local improvement, liberated search through simulated, and search bias through relational heuristics.

ABC recently proposed as a biological-inspired optimization algorithm which mimics the foraging behavior of honey bee swarm (Karaboga, 2005). The performance of ABC had already been compared with other search optimization techniques such as genetic and particle swarm intelligence algorithms (Safarzadeh et al.,

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2011). The comparison results showed that ABC can find a better solution, and is more effective than mentioned optimization techniques. However, some deficiencies are found at utilizing the existing knowledge to look for better solutions and convergence speed in ABC. Therefore, modified ABCs had been introduced to improve the performances of original ABC. Zhu and Kwong proposed an improved ABC algorithm by incorporating the information of global best solution into the solution search equation, called gbest-guided ABC, to improve the exploitation (Zhu and Kwong, 2010). In I-ABC algorithm, inertia weight and acceleration coefficient was proposed to modify the search process of original ABC (Li et al., 2012).

In this paper, we propose a high-efficiency ABC method to further improve the performance of the original ABC algorithm. This hybrid optimization integrates the merits of both ABC algorithm and PSO method. In this algorithm, the neighborhood search scheme is improved by location of individually encountered the most flowers and location of utmost concentration of flowers revealed by the entire swarm. Therefore, each bee adjusts its flying according to the flying experiences of both itself and its companions using equations of position and velocity. Furthermore, the probability of selecting food sources by onlooker is enhanced through using roulette-wheel mechanism. We used parallel computation to further improve the algorithm's performance. The proposed technique is applied to cycle length maximization along reducing maximum power peaking factor, of a VVER-1000 core as a test case, as the most important objective functions in the fuel LP optimization problems. Although other objective functions can be taken into account.

To evaluate the fitness function, neutronic code CITATION is used to obtain power density distribution of FAs in reactor core (Fowler, 1999) which solves the finite difference diffusion equation. In addition, to generate group constants (FAs cross sections) WIMS-D5 is used which deals with one-dimensional transport equation (Winfrith, 1985).

The paper is organized as follows: the ABC algorithm is reviewed in Section 2. The proposed ABC algorithms are described in Section 3. Section 4 illustrates application of the proposed algorithm in fuel management. The simulation results of theses algorithms are shown in Section 5. Finally, conclusion remarks are presented in section 6.

2. ABC algorithm

The ABC algorithm is inspired by the foraging behavior of bees. The method was proposed by Karaboga (2005) and further developed by Basturk and Karaboga (2006) and Akay and Karaboga (2012). This technique is very straightforward, robust and population-based on stochastic optimization algorithm.

A honey bee colony consists of forager bees which can be classified into three categories as employed, onlooker and scout bees. Half of the colony consists of the employed bees, and another half consists of the onlookers. All bees that are exploiting a food source at the same time are known as employed. The employed bees bring loads of nectar from the food sources to the hive and may share the information about food sources with those bees that are waiting in the hive and called onlookers. The onlookers start to search the food source based on the received information. An onlooker chooses a food source according to the probability proportional to the quality of that food source. The onlookers go around the food source to find a better one. When a food source has been abandoned by bees, the abandoned employed bee would become a scout. Whenever a scout or onlooker finds a food source, the bee becomes employed bee. The flowchart of the ABC algorithm is depicted in Fig. 1. The position of a food source corresponds to a possible solution to the optimization problem, and the nectar amount of each food source represents their quality (fitness) of the associated solution.

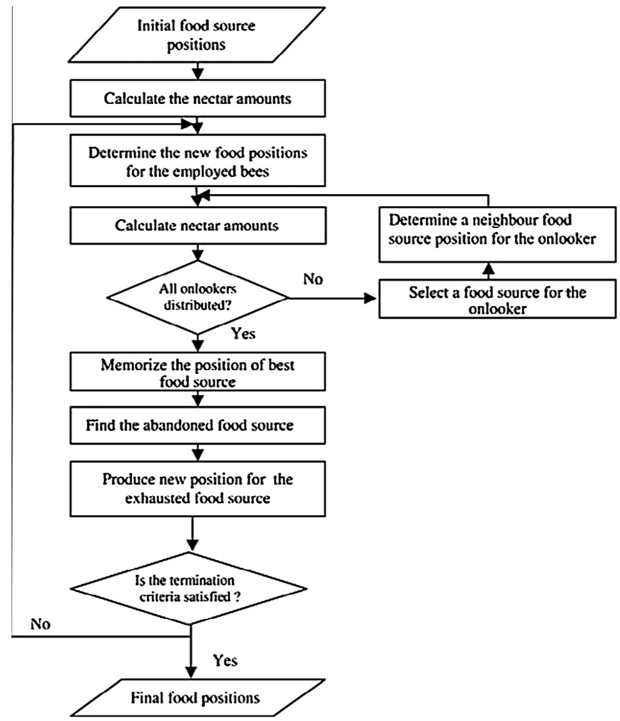

Fig. 1. Chart of the ABC algorithm (Karaboga, 2009).

In the first place of this algorithm, Initial population would be generated as a randomly distributed. Every solution has a dimension of the number of optimization parameters. After the initialization, the population of solutions is subject to repeated cycles. An employed bee could produce a modification on the solution. If x_{ij}^t be the position of the food source for j parameter of ith employed bee, then the neighborhood, x_{ij}^{t+1}, at the next iteration can be generated as (Akay and Karaboga, 2012):

$$x_{ij}^{t+1} = x_{ij}^t + \varphi_{ij}(x_{ij}^{t+1} - x_{kj}^t) \tag{1}$$

where k is a random integer number between 1 and number of employed bees and φ_{ij} is uniformly distributed real random number within the range $[-1,1]$. j is a randomly chosen number between 1 and dimension of problem.

If the fitness value of the new one is better than that of the previous one, the employed bee would memorize the new position and forget the previous one. Otherwise it keeps the position of the previous one in its memory. When all employed bees complete the search process, they will share the information about fitness amounts and positions of food sources with onlookers. An onlooker evaluates the nectar information which is owned by all employed bees, and then chooses a food source with a probability which is related to the nectar amount. The probability that ith food source is selected by an onlooker is proportional to the nectar amount of food source and defined as:

$$p_i = \frac{f(x_i)}{\sum_{k=1}^{N_e} f(x_k)} \tag{2}$$

$$p_i = \frac{\sum_{k=1}^{N_e}(1/f(x_k))}{f(x_i)} \tag{3}$$

where Eq. (2) is for maximization problems while Eq. (3) is for minimization ones. $f(x_i)$ is the fitness of ith food source and N_e is the