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Multi objective loading pattern optimization of PWRs with Fuzzy logic controller based Gravitational Search Algorithm

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HIGHLIGHTS

- Fuzzy logic controllers (FLC) is used to control the effective parameter of GSA.
- The Ackley and Shekel's Foxholes problems have been solved with FGSA.
- The membership functions are designed for Multi Objective LPOs.
- The MOLPO based on NTH goals in WWER440 and WWER1000 are presented.
- Results show the acceptable performance of FGSA for MOLPO problem.

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ABSTRACT

The multi objective Loading Pattern Optimization (LPO) is one of the most important concerns for the incore design of nuclear reactors. Hence, different techniques have been presented for optimization of incore patterns for nuclear reactors, this paper presents a new optimization technique, which uses Fuzzy Logic Controller (FLC) for solving multi-objective optimization problems. In this work, using the FLC, the gravity constant of the Gravitational Search Algorithm (GSA) is controlled to reach better optimization results and convergence rate. A well-designed loading pattern of fuel assemblies in a reactor core depends on Neutronics and Thermal-Hydraulics (NTH) aspects, simultaneously. In this way, for multi-objective optimization, the NTH parameters are included in the fitness function. Neutronic goals are focused on multiplication factor, power peaking factor, and power density and for TH, fuel temperature and critical heat flux are considered. In the present investigation, for evaluating the Fuzzy Gravitational Search Algorithm (FGSA), four cases have been studied. At the first step, to demonstrate the performance of proposed algorithm, the Ackley and Shekel Foxholes functions have been studied. In the next step, the FGSA algorithm with a multi-objective fitness function has been applied for two PWR reactors. For the NTH calculations, valid codes have been executed in searching iterations. The results reveal that convergence rate of the FGSA method is quite promising. Also, the FGSA improves the quality of multi objective LPO in average and could be accounted as a trustworthy method.

1. Introduction

The Loading Pattern Optimization (LPO) is a complex combinatorial optimization problem in nuclear fuel management field. Researchers have been focused on this problem with several methods in recent years. In PWRs, the fuel reloading pattern has a significant effect on both safety and economics. In PWRs, at the end of the cycle (EOC), about one-third of the burned fuel assemblies (FAs) will be replaced by new FAs. For next cycle, the new inserting batch and remaining FAs should be rearranged to give a pattern that meets safety constraints (Kim et al., 1993). The immensity of search space with regard to all effective parameters requires a massive amount of searching process with a classical method to find the optimum solution (Fadaei and Setayeshi, 2009). The complexity of FAs pattern optimization in PWRs clarifies the necessity of implementation of the new numerical methods across the meta-heuristic algorithms (Levine, 1986). The metaheuristic algorithms are beneficial for these kinds of engineering problems (Sadighi et al., 2002). Heuristic search algorithms have been inspired from nature for solving the physical problems. Several techniques such as: Performance Evaluation of PSO and GA Algorithms

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Nomenclature

a	temperature weight
t	iteration number
x, y	Cartesian coordinates
n	space dimension
r	distance between to agents
N	population of agents
N_{FA}	number of FAs
PPF_i	ith FA power peaking factor
T	maximum number of iterations
$Temp$	temperature (K)
K_b	set of agents with best fitness
$rand$	random generator function in [0, 1]
$b(t)$	best fitness at iteration t
$w(t)$	worst fitness at iteration t
$G(t)$	gravitational constant at iteration t
$m_i(t)$	mass of object i
x_i^d	dth position of ith agent search space
f_{ij}^d	force of agent i from agent j
$fit(t)$	fitness function value in iteration t
$r_{ij}(t)$	distance between object i and j at iteration t
$x_i^d(t)$	dth position of the agent i at iteration t
$v_i^d(t)$	dth velocity of the agent i at iteration t
$a_i^d(t)$	dth acceleration of the agent i at iteration t
$fit_i(t)$	fitness of ith agent at iteration t

Greek symbols

ε	constant
α	controlling constant in gravity constant

Subscripts

0	referenced value (initial)
i	index of agents
j	index of agents
min	minimum of value
max	maximum of value
ave	average of value

(Khoshahval et al., 2011), Combination of Cellular Automata and Simulated Annealing (Fadaei et al., 2009), Harmony Search Algorithms (Aghaie et al., 2013a; Nazari et al., 2013), Advanced Genetic Algorithm in a single job and Parallel Integer Coded GA with multi jobs (Aghaie et al., 2013b; Norouzi et al., 2013), Bat Algorithm (Kashi et al., 2014), Biogeography Based Algorithm (Khoshahval et al., 2014) and Optimization by Enhanced PSO with Novel Mutation Operator (Mortezazadeh et al., 2015) are presented for fuel management in recent years. A heuristic algorithm typically finds an acceptable solution to an optimization problem by heuristic search in space, there is no guarantee to find the best solution in absolute. It could find best or improved solution from that educated (Nazari et al., 2013). The GSA is based on the natural law of gravity and the motion of mass with interactions (Mahmoudi et al., 2016). The GSA algorithm uses the classic Newtonian directions in physics and its searcher agents are based on the collection of masses with their interactions. In this paper, using Fuzzy Gravitational Search Algorithm, a new method has been developed for multi objective LPO. Fuzzy Logic Controller (FLC) is used to control the parameter of Gravitational Search Algorithm to increase convergence rate and to ensure finding an optimum solution. Increasing convergence rate and guarantee of finding the approximate optimum solution are important issues in metaheuristic algorithms. There are common methods to establish the trade-off between the exploration and exploitation of the algorithm by controlling the effective parameter (Rashedi et al., 2009; Saeidi-Khabisi and Rashedi, 2012). Hence, due to the simplicity, flexibility, and intelligibility of FLC, it is a convenient method for controlling the parameters of the optimization algorithm.

In this work, at first step for evaluating the FGSA, it is compared with GSA in Ackley and Shekel Foxholes function problems. The Ackley and Shekel Foxholes functions are well-known optimization problems utilized for comparing the performance of the FGSA in searching and its convergence rate. To obtain best reactor core configuration, a fitness function that satisfies the goals and relates NTH constraints is prepared. The NTH goals in multi objective optimization are to maximize (K_{eff}, CHF) and minimizing (PPFs and fuel temperatures) with flattening of power density. For multi-objective LPO of WWER440 and WWER1000, the FGSA is coupled with NTH codes. For NTH calculations, the PARCS and COBRA-EN are applied, respectively. In this study, a program is developed in MATLAB to optimizing core fuel loading pattern using GSA and FGSA.

2. Fuzzy Gravitational Search algorithm

2.1. The GSA

The GSA is an optimization method that has been utilized in many engineering optimization problems (Rashedi et al., 2009). The GSA is based on the law of Newtonian Gravity in classical physics. In all over the universe, every particle attracts each other with the gravitational force. The force is proportional to the product of their masses and gravitational constant in numerator and square of the distance between them in denominator (Aghaie and Mahmoudi, 2016). In this algorithm, all the entities can be viewed as objects with masses. These objects attract each other by the gravity force and it makes all of them move towards the heavier masses. This force is a vector for conversion of objects information and the objects with better finesses are heavier.

The GSA follows an algorithm according to the sequence of Fig. 1. The position vector, X_i, contains the agents (masses) data. All of the forces acting each mass, f_{ij}^d, could be calculated with regard to its mass, position (or distance) and gravitational constant. The mass, distance and gravitational constant for each agent could be calculated with Eqs. (13), respectively.

$$m_i(t) = \frac{fit_i(t)}{\sum_{i=1}^{N} fit_i(t)} \tag{1}$$

$$r_{ij}(t) = (x_i^1 - x_j^1)^2 + \ldots + (x_i^d - x_j^d)^2 + \ldots + (x_i^n - x_j^n)^2 \tag{2}$$

$$G(t) = G_0 e^{-\alpha \frac{t}{T}} \tag{3}$$

Newton's second law of motion presents acceleration of the agents, $F = ma$. The net of forces that affected *ith* agent at iteration t, $F_i^d(t)$, dividing by $m_i(t)$, presents its acceleration, $a_i^d(t)$. New position and velocity of agents in each dimension could be found with calculated acceleration (Fig. 1). In this way, the GSA could present the heavier mass or the best fitness during iterations in the search space.

In this paper, a FLC is designed to control the convergence speed of a GSA in LPO. It is obvious that the acceleration of the agents depends on α in G (Eq. (3)). The FLC tries to a modification in population diversity and approach progress with controlling α.