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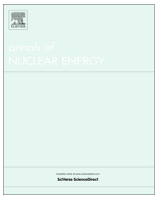

Hybrid particle swarm optimization algorithm and its application in nuclear engineering

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ABSTRACT

A hybrid particle swarm optimization algorithm with a feasibility-based rule for solving constrained optimization problems has been developed in this research. Firstly, the global optimal solution zone can be obtained through particle swarm optimization process, and then the refined search of the global optimal solution will be achieved through the modified Nelder–Mead simplex algorithm. Simulations based on two well-studied benchmark problems demonstrate the proposed algorithm will be an efficient alternative to solving constrained optimization problems. The vertical electrical heating pressurizer is one of the key components in reactor coolant system. The mathematical model of pressurizer has been established in steady state. The optimization design of pressurizer weight has been carried out through HPSO algorithm. The results show the pressurizer weight can be reduced by 16.92%. The thermal efficiencies of conventional PWR nuclear power plants are about 31–35% so far, which are much lower than fossil fueled plants based in a steam cycle as PWR. The thermal equilibrium mathematic model for nuclear power plant secondary loop has been established. An optimization case study has been conducted to improve the efficiency of the nuclear power plant with the proposed algorithm. The results show the thermal efficiency is improved by 0.5%.

1. Introduction

Many search and optimization problems in science and engineering involve a number of constraints which the optimal solution must satisfy. A constrained optimization problem is usually written as a nonlinear programming problem of the following type:

$$\text{Find } \vec{x} \text{ to minimize} f(\vec{x}) \tag{1}$$

$$\text{Subject to} \begin{cases} g_j(\vec{x}) \leqslant 0, & j = 1, \dots, J \\ h_k(\vec{x}) = 0, & k = 1, \dots, K \\ \vec{x_l} \leqslant \vec{x_i} \leqslant \vec{x_u}, & i = 1, \dots, n \end{cases} \tag{2}$$

In the above problem, there are n variables, J less-than-equal-to type inequality constraints, and K equality constraints. In a common practice, an equality constraint $h_k(\vec{x}) = 0$ can be replaced by a couple of inequality constraints $h_k(\vec{x}) \geqslant -\delta$ and $h_k(\vec{x}) \leqslant \delta$ (here δ is a small tolerant value). Therefore all constraints can be transformed to $N = J + 2K$ inequality constraints. We define $\vec{x}$ as a feasible solution if it satisfies all the constraints.

In recent years, PSO (Kennedy and Eberhart, 1995) is one of the most successful methods which can be used to find the global solutions of cost functions. The superior advantages make PSO widely used in nuclear power engineering design, such as PWR core loading pattern optimization (Yadav and Gupta, 2011; Abbassi et al., 2012; Khoshahval et al., 2011), PWR power distribution flattening (Jamalipour et al., 2013), and critical heat flux prediction (Jiang and Zhao, 2013).

In this research, a hybrid PSO is proposed to solve COPs. Motivated by Deb (2000), the feasibility-based rule is introduced into PSO, which gives an instruction on the determination of the best solution of the population $(\overrightarrow{gbest})$, the best historical solution of every particle $(\overrightarrow{pbest_i})$ and the sequence of the swarm. NM algorithm is applied to process the last several preserved best solutions of the swarm, which will help to improve the precision of the optimal solution. Simulation results based on two famous testing functions show that, HPSO is of great effectiveness, efficiency and robustness.

Pressurizers in PWRs play a fundamental role of protecting and controlling the change of system pressure. Nowadays, it tends to use high capacity pressurizers in RCS, which makes the pressurizers heavier and larger. Therefore, the design of pressurizers is going to be more complicated, and the transport and arrangement of such pressurizers are more difficult. Besides, for the nuclear power plants in submarine, or in aircraft carrier, it is promising the nuclear power plants and corresponding components are as compact as possible. Therefore, on the basis of satisfying the performance

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Nomenclature

Abbreviation

COPs	Constrained Optimization Problems
CVCS	Chemical and Volume Control System
HPSO	Hybrid Particle Swarm Optimization
HP	High-Pressure
LP	Low-Pressure
MSR	Moisture Separator Reheater
NM	modified Nelder–Mead simplex algorithm
NPP	Nuclear Power Plant
PWR	Pressurized Water Reactor
RCS	Reactor Coolant System
SG	Steam Generator

General symbols for pressurizer model

D_i	pressurizer inner diameter (m)
d	outer diameter of electric heating element (m)
h_{eh}	height of electric heating zone (m)
h_s	height of pressurizer cylinder shell (m)
l	length of electric heating element (m)
L	measurement range of water level instrument (m)
M_{s2}	condensate steam mass (kg)
N_{eh}	amount of electric heating element
R	boiloff coefficient
V_0	total water volume in primary loop (m^3)
$\overline{V_f}$	water volume when normal water level drop on the lowest water level (m^3)
x	ratio of loop hot segment water volume to V_0
W_{eh}	single electric heating element weight (kg)

General symbols for nuclear power plant model

$G_{t,s}$	total consumption steam flow rate of turbine (kg/s)
$G_{es,i}$	extract steam flow rate at the *i* extract point of turbine (kg/s)
G_{roh}	drain water flow rate (kg/s)
G_{seh}	extract steam flow rate (kg/s)
G_{fw}	feed water flow rate (kg/s)
G_{spw}	drain water flow rate of MSR (kg/s)
h_{fh}	steam enthalpy of SG (kJ/kg)
h'_s	saturated water enthalpy corresponding to the secondary pressure of SG (kJ/kg)
h_{fw}	feed water enthalpy (kJ/kg)
h_0	steam enthalpy of turbine inlet (kJ/kg)
h_z	steam enthalpy of turbine outlet (kJ/kg)
$h_{es,i}$	extract steam enthalpy at the *i* extract point of turbine (kJ/kg)
h_{seh}	extract steam enthalpy (kJ/kg)
h_{roh}	drain water enthalpy (kJ/kg)
h_{spw}	drain water enthalpy of MSR (kJ/kg)
$N_{t,h}$	internal power of HP turbine (kW)
$N_{t,l}$	internal power of LP turbine (kW)
N_e	NPP effective power (kW)
$p_{e,l}$	LP turbine exhaust steam pressure (MPa)
Q_R	reactor thermal power (kW)

Greek symbols

Δp	pressure change (MPa)
δ_u	thickness of pressurizer upper head (m)
δ_l	thickness of pressurizer lower head (m)
δ_s	thickness of pressurizer cylinder shell (m)
ε	measurement accuracy of water level instrument
η_1	energy utilization coefficient of primary loop
η_k	efficiency of heater
θ	maximum rolling angle
ξ_d	pollution exhaust ratio of SG
$\rho_{g,p}$	saturation steam density corresponding to the operation pressure (kg/m^3)
$\rho_{g,\max}$	steam density corresponding to the top pressure (kg/m^3)
ρ_u	density of pressurizer upper head (kg/m^3)
ρ_l	density of pressurizer lower head (kg/m^3)
ρ_s	density of pressurizer cylinder shell (kg/m^3)
v_{av0}	coolant specific volume at full power (m^3/kg)
v_h	coolant specific volume of hot segment at full power (m^3/kg)
v_c	coolant specific volume of cool segment at full power (m^3/kg)
v_B	coolant specific volume at pressurizer bottom (m^3/kg)
$v_{av-\Delta t}$	coolant specific volume when the corresponding temperature is $t_{av} - \Delta t$ (m^3/kg)
$v_{av+\Delta t}$	coolant specific volume when the corresponding temperature is $t_{av} + \Delta t$ (m^3/kg)
v_{av}	coolant specific volume when the corresponding temperature is t_{av} (m^3/kg)
v_{av1}	coolant specific volume when the corresponding temperature is t_{av1} (m^3/kg)
v_{av2}	coolant specific volume when the corresponding temperature is t_{av2} (m^3/kg)

requirements and safety constraints, it is necessary and meaningful to introduce optimization techniques into the preliminary design of the pressurizer in order to cut down the weight through finding the optimum combination of design parameters.

Xu (1987) selected pressurizer inner diameter, sprayer water flow rate, reactor inlet coolant temperature, reactor outlet coolant temperature and reactor pressure as the independent variables to optimize pressurizer weight and structure size. He et al. (2010a) optimized pressurizer volume through the self-developed complex-genetic algorithm, and the influence on the volume of primary loop operating parameters was also analyzed.

Pressurized water reactor is the main reactor category that is under operation all over the world. Heat generated in the reactor core is transferred to the secondary side by mean of two, three or four steam generators. The SGs subsequently transfer heat to the main steam system. PWRs have excellent service records and it is expected that unremitting work will permit the PWR station to continue its operation for an additional 30 years period. Within this framework, it has been considered important to study different avenues that can permit the efficiency of the plant to be increased; thus, this paper also concerns the optimization of the thermal efficiency of PWR nuclear power plant.

The paper is organized as follows. This section presents the objective, the motivation and the methodology of the work. In Section 2, the HPSO algorithm is proposed and explained in detail. Simulation and comparisons are presented. Section 3 describes the mathematical model of pressurizer and the optimization of pressurizer weight. Section 4 presents the optimization of the thermal efficiency of nuclear power plant. Finally, we end the paper with some conclusions and future work in Section 5.