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Multi-objective optimization of hydrothermal energy system considering economic and environmental aspects

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ABSTRACT

Along with continuous global warming, the environmental problems, besides the economic objective, are expected to play more and more important role in the operation of hydrothermal power system. In this paper, the short-term multi-objective economic environmental hydrothermal scheduling (MEEHS) model is developed to analyze the operating approach of MEEHS problem, which simultaneously optimize energy cost as well as the pollutant emission effects. Meanwhile, transmission line losses among generation units, valve-point loading effects of thermal units and water transport delay between hydraulic connected reservoirs are taken into consideration in the problem formulation. In order to solve MEEHS problem, a new multi-objective cultural algorithm based on particle swarm optimization (MOCA-PSO) is presented in way of combining the cultural algorithm framework with particle swarm optimization (PSO) to carry though the evolution of population space. Furthermore, an effective constrain handling method is proposed to handle the operational constraints of MEEHS problem. The proposed method is applied to a hydrothermal power system consisting of four hydro plants and three thermal units for the case studies. Compared with several previous methods, the simulation solutions of MOCA-PSO with smaller fuel cost and lower emission effects proves that it can be an alternative method to deal with MEEHS problems. The obtained results demonstrate that the change of optimization objective leads to the shift of optimal operation schedules. Finally, the scheduling results of MEEHS problem offer enough choices to the decision makers. Thus, the operation with better performance of environment is achieved by more energy system cost.

1. Introduction

In recent years, the short-term economic hydrothermal scheduling (SEHS) is recognized as one of the most significant problems in the interconnected electric system operation. The purpose of this problem is to find the optimal results of the water discharge rates of the hydro stations and power output of the thermal units so as to minimize the total production cost while subjecting to a series of hydraulic and thermal constrains. Compared with the thermal units, the operational cost of the hydro plant is insignificance because of the regenerative resource they use. Therefore, the objective of minimizing the hydrothermal system cost reduces to minimize the total fuel cost of the thermal units while satisfying various constrains over the optimal horizon. In the past few decades, researchers have applied many methods to deal with this problem, such as linear and non-linear programming [1,2], dynamic programming [3,4], progressive optimality algorithm [5], artificial neural networks [6], genetic algorithm [7,8], evolution algorithm [9,10], differential evolution algorithm [11,12], particle swarm optimization [13–15], and cultural algorithm [16]. These strategies have achieved various degrees of success in solving this single-objective optimal problem. As the public have paid much attention to the atmospheric environment, especially when the passage of the clean air act amendments was published in 1990 [17], the traditional economic optimization cannot satisfy the requirement of reducing the harmful effects of the gaseous emission caused by fossil fuel. Therefore, the conventional economic hydrothermal optimal scheduling needs to be modified and the multi-objective economic environmental hydrothermal scheduling which adds the emission effects of the atmospheric pollution as the other objective becomes more and more desirable.

The short-term multi-objective economic environmental hydrothermal scheduling (MEEHS) problem is a multi-objective optimization problem which optimize the two competing objectives, the minimum fuel cost and the minimum emission effect, simultaneously. Compared with the traditional economic emission dispatch, this model takes the hydraulic connected hydro plants into account. In recent years, many different methods have been adopted to solve this problem. Such as goal-attainment method [18], real code genetic algorithm [19], differential evolution algorithm with price penalty factor [20], improved genetic algorithm

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with evolutionary direction operator [21], and self-organizing hierarchical particle swarm optimization technique [22]. These strategies attempted to transform the multi-objective problem into a single one by constrained or weighted methods. Although the transformation can reduce the difficulty of solving MEEHS problems, some shortcomings still exist: only one solution can be obtained in a run while the Pareto optimal front needs a serve of solutions; since the objective formulation of the MEEHS problem is non-convex, the method mentioned above may fail to find the true Pareto optimal front. Therefore, a more effective approach is necessary to deal with this multi-objective and non-convex optimization problem.

In order to deal with this multi-objective, non-linear and constrained problem, an innovative method, multi-objective optimization algorithm, is usually needed. Multi-objective Evolutionary algorithms (MOEAs) are modern heuristic searching methods for dealing with multi-objective problems. For their fast convergence and population-based characteristic, many MOEAs, such as multi-objective genetic algorithm [23,24], multi-objective evolutionary algorithm [25,26], multi-objective differential evolution [27,28], multi-objective particle swarm optimization [29–31], have been applied to solve complex multi-objective problem and get a set of solutions efficiently. Among these methods, NSGA-II proposed by Deb and Pratap [23] and SPEA2 proposed by Zitzler et al. [25] are the most famous strategies. However, the problem of premature convergence caused by sharply decrease of the population diversity still exist in these current algorithms. Therefore, it takes on a big range of significance to develop novel efficient techniques to solve the multi-objective problems precisely.

In this paper, we proposed a novel multi-objective cultural algorithm based on particle swarm optimization to determine the optimal operating strategy of MEEHS problem. Cultural algorithm (CA) is a novel optimization method framework proposed by Reynolds in 1994 [32]. The computational model maintains the elite information from the evolving population so as to make use of this useful knowledge to enhance the adaptability of the individuals and improve the evolution speed. In recent years, cultural algorithm has been used in dealing with single-objective problems successfully [33–36]. Therefore, the proposed method combines the particle swarm optimization [37] with the cultural algorithm to implement the population space evolution and three kinds of knowledge structures in the belief space are redefined according to the feathers of the multi-objective problems. Furthermore, an efficient constraints handling method is proposed to deal with the complicated constraints of the MEEHS problems. Finally, the proposed MOCA-PSO is applied to a hydrothermal power system consisted of four hydro plants and three thermal units and the trade-off relationship between economic and environmental performances is analyzed.

The paper is organized as follows: Section 2 introduces the belief concept of multi-objective problem as well as the formulation of short-term multi-objective economic environmental hydrothermal scheduling. In Section 3, we describe the proposed method MOCA-PSO in details. Section 4 presents the practical solution methodology of the MOCA-PSO for solving MEEHS problem. In Section 5, the proposed method is applied to a hydrothermal power system and compared the results of case studies with current studies. Section 6 concludes the paper followed by acknowledgements.

2. Problem formulation

2.1. Concept of multi-objective optimization problem

Compared with the single-objective problems, there are many multi-objective optimization problems in the real world, which require simultaneous optimization of several objectives that are almost non-commensurable and competing with each other. Generally, a multi-objective optimization subjected to a number of equality and inequality constraints can be formulated as follows:

$$\begin{aligned}
&\min y = f(x) = \left(f_1(x), f_2(x), \ldots, f_{N_{obj}}(x)\right) \\
&s.t. g_i(x) = 0, i = 1, 2, \ldots \mathrm{Num}_g \\
&h_i(x) \leqslant 0, j = 1, 2, \ldots, \mathrm{Num}_h \\
&x = (x_1, x_2, \ldots, x_D) \in R^D, = (y_1, y_2, \ldots, y_{N_{obj}}) \in R^{N_{obj}}
\end{aligned} \tag{11}$$

where N_{obj} is the dimension of objective space and $f_i(x)$ is the ith objective of the optimal problem; Num_g and Num_h are respectively the numbers of equality and inequality constraints; x is a D-dimensional decision vector which stands for a solution of the problem.

Mathematically, the definition of Pareto optimal solution can be described like this: In a minimum optimization problem, a solution $x_1 \in R^D$ dominates another solution $x_2 \in R^D$ only if:

$$\begin{aligned}
&\{\forall i \in [1, 2, \ldots, N_{obj}] : f_i(x_1) \leqslant f_i(x_2)\} \cap \{\exists j \in [1, 2, \ldots, N_{obj}] \\
&\quad : f_j(x_1) < f_j(x_2)\}
\end{aligned} \tag{12}$$

If the solution cannot be dominated by other solutions of the solution domain, it will be called non-dominated or Pareto optimal solution. Meanwhile, a series of all non-dominated solutions can be indicated as Pareto optimal front.

2.2. Mathematical formulation of the MEEHS model

The MEEHS model aims at providing decision support to planners for selecting the operating level of various hydro plants and thermal generation units throughout the planning period.

2.2.1. Objectives functions

The MEEHS model considers two objective functions, the total energy cost and the environmental impact. The environmental impact objective function is trying to capture the increasing awareness of environmental externalities resulting from energy generation. Meanwhile, transmission line losses among generation units, valve-point loading effects of thermal units and water transport delay between hydraulic connected reservoirs are considered in the problem formulation.

2.2.2.1. Economy objective. The fuel cost function of each thermal plant considering valve-point effect is described as a sum of a quadratic and a sinusoidal function. In practical hydrothermal generation system, the fuel losses will increase sharply when stream admission valve starts to open. This increased part can be described as a sinusoidal function. So the total cost of the hydrothermal real power system can be presented as follows [38]:

$$\begin{aligned}
\min\ f_1 = \min \sum_{t=1}^{T}\sum_{i=1}^{N_s}&[a_i + b_i \cdot P^s_{i,t} + c_i \cdot (P^s_{i,t})^2 \\
&+ |d_i \cdot \sin(e_i \cdot (P^s_{i,\min} - P^s_{i,t}))|]
\end{aligned} \tag{1}$$

where the $P^s_{i,t}$ is the output power of the ith thermal plant at tth schedule period, $P^s_{i,\min}$ is the lower generation limit for the ith thermal plant, N_s is the number of thermal plant, t and T are the period index and total periods over the schedule horizon, a_i, b_i, c_i, d_i, e_i are the cost curve coefficients of the ith thermal plant.

2.2.2.2. Emission objective. Compared with hydropower plants, the major atmospheric pollution is produced by thermal generation units, which is constituted mainly by sulfur oxide (SO_x) and nitrogen oxides (NO_x). In this paper, nitrogen oxides (NO_x) emission is selected as the index for environment evaluating. The amount of