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Pareto-dominance based adaptive multi-objective optimization for hydrothermal coordinated scheduling with environmental emission

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ABSTRACT

Since hydrothermal optimal operation has been a headache in the energy and electricity field due to its coupled and complex non-convex characteristics, this paper proposes an adaptive second mutation based multi-objective differential evolution (ASMMODE) for hydrothermal coordinated scheduling problems, optimal assignments of hydro output and thermal output are taken to reduce thermal cost and environment pollution simultaneously. Firstly, an adaptive second mutation mechanism is proposed to enhance population diversity to avoid premature problem, and entropy density based distribution control strategy is improved to properly control the diversity distribution of obtained Pareto front, which can provide proper candidate optimal scheme for decision-makers. Followed by taking consideration of complex and coupled constraints, coordinated constraint handling technique is proposed to proper handle system load balance, which can coordinate hydro output and thermal output in each time period. Furthermore, those above improvements are testified on benchmark problems and hydrothermal system, according to comparisons and analysis on statistical results, it reveals that the proposed optimization method can be a viable way for solving hydrothermal optimization problems.

1. Introduction

Hydrothermal scheduling plays an important role in economic optimal operation of power system, its main goal is to minimize the fuel cost of thermal units with properly controlling the output of hydropower plant and thermal units. The representative methods include lagrangian method [1], evolutionary programming technique [2], neural network methodology [3,4], fuzzy satisfaction maximizing decision approach [5], goal-attainment method [6,7] and evolutionary algorithm [8]. However, due to the increase concern over emission pollutants, traditional economic operation pattern of hydrothermal system cannot satisfy the requirements of environmental protection. Switching to low emission fuel can be a good choice to reduce emissions, but it only can be considered as a long-term option due to its high price and scarcity of low emission fuel. Therefore, a new strategy of hydrothermal economic emission optimal operation is becoming more desirable as it can consider fuel cost and emission issue simultaneously, and emission rate of thermal units is taken into consideration in the economic dispatch of hydrothermal system [9]. Generally, emission rate is considered as an additional constraint or another objective by many research groups [10,11], while emission pollutions cannot be restricted at the certain degree as more and more the requirements are continual increasing rapidly needed. Some scholars have proposed economic operation model with considering environmental problems, which takes fuel cost and environmental emission as two objectives, and obtains some success with optimization theory or intelligent algorithm [12–15].

Generally, there are two directions for solving this hydrothermal scheduling problem. The first direction is to convert the multiple objective optimization problem into single objective optimization problem. Ela develops DE to solve economic dispatch problem with treating emission as a constraint, and achieves reduction of overall dispatching problem [12]. Basu solves this problem by converting them into single-optimization problem with interactive fuzzy method, and some satisfactory results have been obtained [13]. Mandal obtains different results with differential evolution by weighting all those objectives [14]. Chao utilizes ε-constraint technique to optimize the economic emission dispatch problem, and obtains some success [15]. However, all above methods are actually single-objective optimization methods, they have several limitations for optimizing hydrothermal operation problem, which has been clearly demonstrated in literature [16].

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Nomenclature

a_i, b_i, c_i, d_i, e_i the cost coefficients of the i-th thermal unit
P_{sit} the output of the i-th thermal unit at t-th time period
$P_{si\min}$ the minimum output of the i-th thermal unit
N_s the number of thermal units
T the total time period
$\alpha_i, \beta_i, \gamma_i, \eta_i, \sigma_i$ the emission coefficients of the i-th thermal unit
P_{Dt} system load at t-th time period
P_{hjt} the output of the j-th hydro plant at the t-th time period
N_h the number of hydro plants
P_{Lt} the output loss at the t-th time period
$C_{1j}, C_{2j}, C_{3j}, C_{4j}, C_{5j}, C_{6j}$ output coefficients of the j-th hydro plant
B_{ik}, B_{0i}, B_{00} the coefficients of transmission loss
V_{hit} the reservoir storage of the i-th hydro plant at t-th time period
I_{it} the incoming water of the i-th hydro plant at t-th time period
S_{it} the spillage water of the i-th hydro plant at t-th time period
Q_{hit} the water discharge of the i-th hydro plant at the t-th time period
${\tau_i}^k$ the time delay of the k-th upstream hydro plant of the i-th hydro plant
N_i the number of upstream hydro plants of the i-th hydro plant
$P_{hi\min}, P_{hi\max}$ the minimum and maximum output of the i-th hydro plant
$P_{sj\min}, P_{sj\max}$ the minimum and maximum output of the j-th thermal unit
$V_{hi\min}, V_{hi\max}$ the minimum and maximum storage of the i-th hydro plant
$Q_{hi\min}, Q_{hi\max}$ the minimum and maximum water discharge of the i-th hydro plant
$V_{i,begin}, V_{i,end}$ the initial storage and final storage of the i-th hydro plant

The second direction is to optimize those objectives simultaneously while treating these objectives equally. Many researches have been focus on the efficient multi-objective evolutionary algorithm (MOEA) due to its population based methodology and independence of problem representation, which easily tackles with complicated multi-objective optimization problem and obtains a set of non-dominated schemes no matter whether it is non-convex or the optimal Pareto front is disconnected. The most representative algorithms include non-dominated sorting genetic algorithm (NSGA-II) [17], enhanced strength Pareto evolutionary algorithm (SPEA-II) [18], multi-objective particle swarm optimization (MOPSO) [19,20], and multi-objective differential evolution (MODE) [21–23]. Though these MOEAs can obtain the optima for properly solving hydrothermal scheduling problem, they may also fall into local optima at certain degree, which can cause the premature problem. This paper proposes an adaptive second mutation based multi-objective differential evolution for avoiding premature problem, the improved mutation operator is imbedded into the differential evolution (DE).

DE is taken as a simple yet powerful population-based evolutionary algorithm with less parameters, and has been popularly used in the practical engineering application [24]. Since DE has less parameter but is efficient for solving optimization problems especially for those involve non-smooth objective functions as it does not require derivative information [10], some scholars develop DE to solve multi-objective optimization problems. The classical multi-objective evolutionary methods based on DE include Pareto differential evolution (PDE) [23], Pareto differential evolution approach (PDEA) [25], differential evolution for multi-objective optimization (DEMO) and adaptive differential evolution algorithm (ADEA) [22]. However, these DE based multi-objective optimization methods suffer from premature problems at different degrees, and exploration of new computational technique is needed to avoid premature problem. With consideration of above problems, the main rationales of the proposed method can be presented as follows: (1) an adaptive second mutation mechanism is proposed to increase population diversity, and avoid premature problem. (2) Density entropy based diversity control strategy is improved to enhance diversity distribution of Pareto front, which can provide convenience for decision-making. (3) Coordinated constraint-handling technique is proposed to tackle with system load balance with considering transmission loss, hydropower plant and thermal units are coordinated to adjust the constraint violation.

This paper presents the problem formulation in Section 2, basic definitions about multi-objective optimization is introduced in Section 3, an adaptive second mutation based multi-objective differential evolution is described in Section 4, the coordinated constraint-handling method and total measurement of the algorithm is introduced in Sections 5 and 6, and simulations and case studies are presented with results and analysis in Sections 7 and 8.

2. Problem formulation

The hydrothermal operation model mainly consists of two objectives: Nitric oxide emission and fuel cost, and it also satisfies system load balance, water balance and some basic constraint requirements [26–29].

2.1. Objectives

(1) Fuel cost

For a given hydrothermal system, the economic objective is mainly described by the total fuel cost of thermal units during the whole time period. Generally, fuel cost can be defined as the quadratic function of thermal output, but it cannot precisely describe the relationship between thermal output and fuel cost. Here, valve point effect of fuel cost is properly taken into consideration, it can be expressed by the sum of quadratic and sinusoidal function. The total fuel cost can be presented as follows [30]:

$$f_1 = \sum_{t=1}^{T}\sum_{i=1}^{N_s}\{a_i + b_i * P_{sit} + c_i * {P_{sit}}^2 + |d_i * \sin[e_i * (P_{si\min} - P_{sit})]|\} \quad (1)$$

(2) Nitric oxide emission

The emission objective is mainly described as total emission rate of all the thermal units during the whole time period, and the amount of emission pollutant resulted from the fossil-fired thermal unit is based on the output of each thermal unit. Among those emission pollutant, Nitric oxide is taken as the main effect of emission pollutant, its emission generated of each thermal unit at each time period can be generally expressed as the sum of a quadratic and exponential function. Therefore, emission rate of hydrothermal system can be presented as follows [30]:

$$f_2 = \sum_{t=1}^{T}\sum_{i=1}^{N_s}[\alpha_i + \beta_i * P_{sit} + \gamma_i * {P_{sit}}^2 + \eta_i * \exp(\delta_i * P_{sit})] \quad (2)$$