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Optimal self-scheduling of hydro producer in the electricity market

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ABSTRACT

This paper proposes an efficient method to solve the profit-based optimal self-scheduling of a hydroelectric company in the pool-based day-ahead electricity market by integrating cultural algorithm (CA) with feasible sequential quadratic programming (SQP). The proposed method is developed in such a way that CA is applied as a based level search, which can give a good direction to the optimal global region, and a local search SQP is used as a fine-tuning to determine the optimal solution at the final. Finally, optimal self-scheduling of hydro company with several cascaded hydro plants along a river basin is used to illustrate the effectiveness of the proposed method. Results from the proposed method are compared with those obtained by other optimization methods in terms of solution precision. It is shown that the proposed method is capable of yielding higher quality solutions.

1. Introduction

Throughout the world, the electricity industry is currently undergoing significant restructuring towards deregulation and competition. Deregulation and restructuring of electric power system have created a competitive open market environment. This paper considers a day-ahead electricity market for energy based on a pool. In this market framework, the task of generation scheduling is left to power producers themselves in order for them to make dispatch decisions to maximize their own benefits. The traditional short-term hydro-generation scheduling problem, whose goal was usually to maximize the total power generation, is no longer suitable in the new competitive environment for electric energy. In the electricity market, hydro producers face new challenging problems with the ultimate goal of maximizing their profits. One of those problems consists of determining, in the short-term (up to 24 h), the optimal self-scheduling of plants belonging to the hydro company so that the profit from selling energy is maximized without regard to the power balance in the system. This problem is referred to as self-scheduling. A pure hydro-generation company has to elaborate a daily operation scheduling of its hydro resources in order to assess the available energy that could be offered in the day-ahead market, and it is the problem addressed in this paper.

Recently, several contributions handling the problem of self-scheduling for thermal plant have been available in the Ref. [1,2]. But there is seldom contribution dealing with the self-scheduling of hydro producer [3]. Comparing with the thermal plants, cascaded plants of hydro company have some specific features: (i) spatial–temporal coupling among reservoirs and (ii) for each plant, nonlinear and non-convex relationships among the power output, water discharge, the net hydraulic head of reservoir and the water transport delay time. These properties make self-scheduling of hydro company is a large-scale, dynamic, nonlinear and non-convex constrained optimization problem and it is difficult to be solved.

In this paper, we present a self-scheduling technique for the purpose of a hydro company owning several plants cascaded along a river basin to optimize its profit in a day-ahead electricity market for energy based on a pool. The hydro company is taken as a price-taker in the market, which means that its generation bids are not expected to influence the market price. In other words, it does not have market power, i.e., its schedule does not alter the hourly market clearing prices. Thus, market uncertainty is limited to the expected prices for the next 24 h. Therefore, market price can be considered an external stochastic variable and modeled via scenarios. It can be estimated using some forecasting methods (such as regression model, ARIMA, GARCH, input/output hidden Markov model, neural networks) using relevant historical data [4–9]. The purpose of this paper is to provide the hydro company that can be considered as a price-taker with a short-term self-scheduling tool to achieve maximum profit from selling energy in the day-ahead market while considering various constraints. In our optimal self-scheduling model, the objective of the hydro producer is to maximize the expected value of profit, assuming a certain given risk level. In order to be protected against the worse prices scenarios, a minimum profit constraint is introduced in the model as a risk-aversion criterion. Therefore, a precise modeling of risk is embedded in the considered maximum profit problem. The profit maximization problem faced by the hydro producer is therefore a

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risk-constrained self-scheduling problem that is formulated as nonlinear constrained optimization problem. Our optimization model has two main features: first, the model considers simultaneously a predetermined number of price scenarios weighted with their corresponding probabilities; second, a risk-aversion criterion is introduced in order to ensure at least a minimum profit.

Regarding the solution technique, the optimization methods for traditional short-term hydro scheduling problem can be applied to solve the profit-based self-scheduling of a hydro company in the day-ahead market. These methods mainly include dynamic programming [10], network flow [11], linear and nonlinear programming [12], Lagrangian relaxation [13], artificial intelligent methods [14–20], etc. But these methods have one or another drawback such as dimensionality difficulties, large memory requirement or an inability to handle nonlinear characteristics, premature phenomena and trapping into local optimum, taking too much computation time. Therefore, improving current optimization techniques and exploring new methods to solve this problem have great significance.

In recent years, a new optimization method known as cultural algorithm (CA) proposed by Reynolds has become a candidate for optimization applications due to its flexibility and efficiency. CA is a technique that incorporates domain knowledge obtained during the evolutionary process as to make the search process more efficient. It has been successfully applied to solve optimization problems [21]. Although CA seems to be good method to solve optimization problem, sometimes the solutions obtained from CA are just near global optimum ones. Therefore, hybrid method combining probabilistic method and deterministic method found to be effective in solving complex optimization problem. In this paper, a novel hybrid method is proposed to solve the profit-based optimal self-scheduling of a hydro company in the day-ahead market by integrating the cultural algorithm (CA) with the feasible sequential quadratic programming (SQP), which the CA is applied to obtain a near global solution; once the CA terminates its procedure, the SQP will be applied to obtain final optimal solution. Finally, an example demonstrates the effectiveness of the proposed method.

This paper is organized as follows. Section 2 provides the mathematical formulation of the self-scheduling of a hydro producer in the day-ahead market. Section 3 introduces cultural algorithm briefly. Section 4 describes differential evolution. Section 5 presents the improved cultural algorithm. Section 6 outlines the feasible sequential quadratic programming. Section 7 proposes solution technique using hybrid CA and SQP for self-scheduling of a hydro producer. Section 8 gives the numerical example. Section 9 draws the conclusions. Finally, acknowledgements are given.

2. Problem formulations

2.1. Objective function and constraints

In a competitive electricity market, the main objective is to maximize the expected profit of the hydro company from selling energy in the day-ahead electric market, satisfying all physical and operational constraints. The objective function takes into account all the price scenarios at once and weighted by its occurrence probability.

$$\text{Maximize} : J = \sum_{k=1}^{L}\sum_{t=1}^{T}\left\{\rho_k \cdot \pi_k^t \cdot \sum_{i=1}^{N}(P_i^t \cdot \Delta t)\right\} \tag{1}$$

where ρ_k is the probability of the price scenario k; π_k^t is the price of the scenario k at the hour t; P_i^t is the power generation of hydro plant i at time interval t; N is number of hydro plants; Δt is time interval; T is total time horizon.

Subject to the following constraints:

- Minimum revenue constraint

In order to be protected against the worse prices scenarios, the risk aversion of the hydro company can be modeled by the following set of constraints where minimum revenue $B_{\min}$ is required for every price scenario k.

$$\sum_{t=1}^{T}\left\{\pi_k^t \cdot \sum_{i=1}^{N}(P_i^t \cdot \Delta t)\right\} \geqslant B_{\min} \quad k = 1, 2, \ldots, L \tag{2}$$

- Hydro plant power generation limits

$$P_i^{\min} \leqslant P_i^t \leqslant P_i^{\max} \quad i = 1, 2 \ldots N;\ t = 1, 2 \ldots T \tag{3}$$

- Hydro plant discharge limits

$$Q_i^{\min} \leqslant Q_i^t \leqslant Q_i^{\max} \quad i = 1, 2 \ldots N;\ t = 1, 2 \ldots T \tag{4}$$

- Reservoir storage volumes limits

$$V_i^{\min} \leqslant V_i^t \leqslant V_i^{\max} \quad i = 1, 2 \ldots N;\ t = 1, 2 \ldots T \tag{5}$$

- Initial and terminal reservoir storage volumes

$$V_i^0 = V_i^B, \quad V_i^T = V_i^E \quad i = 1, 2 \ldots N \tag{6}$$

- Water dynamic balance equation

$$V_i^t = V_i^{t-1} + M \cdot \left\{I_i^t - Q_i^t - S_i^t + \sum_{m=1}^{N_u}\left[Q_m^{t-\tau_{m,i}} + S_m^{t-\tau_{m,i}}\right]\right\} \quad i = 1, 2 \ldots N;\ t = 1, 2 \ldots T \tag{7}$$

where L is number of total price scenarios; $B_{\min}$ is minimum revenue; $P_i^{\min}$ is minimum power generation of hydro plant i; $P_i^{\max}$ is maximum power generation of hydro plant i; V_i^t is water volume storage of reservoir i at the end of time interval t; $V_i^{\min}$ is minimum water storage volume of reservoir i; $V_i^{\max}$ is maximum water storage volume of reservoir i; Q_i^t is water discharge of hydro plant i at time interval t; $Q_i^{\min}$ is minimum water discharge of hydro plant i; $Q_i^{\max}$ is maximum water discharge of hydro plant i; V_i^B is initial storage volume of reservoir i; V_i^E is final storage volume of reservoir i at the end of horizon; S_i^t is water spillage of hydro plant i at time interval t; I_i^t is natural inflow into reservoir i at time interval t; Nu is number of upstream hydro plants directly above plant i; $\tau_{m,i}$ is water transport delay time from reservoir m to i; M is conversion factor.

2.2. Hydropower generation characteristics

The power generated from a hydro plant is related to the reservoir characteristics as well as the water discharge. A number of models have been used to represent this relationship. In general, the hydro generator power output is a function of the water discharge through the turbine and the net head. Since the net head is a function of volume of stored water, hydropower generation can be written in terms of turbine discharge rate and storage, and a frequently used expression is [14]:

$$P_i^t = C_{1i} \cdot (V_i^t)^2 + C_{2i} \cdot (Q_i^t)^2 + C_{3i} \cdot V_i^t \cdot Q_i^t + C_{4i} \cdot V_i^t + C_{5i} \cdot Q_i^t + C_{6i} \quad i = 1, 2, \ldots, N;\ t = 1, 2, \ldots, T \tag{8}$$