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Improved decomposition–coordination and discrete differential dynamic programming for optimization of large-scale hydropower system

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ABSTRACT

With the construction of major hydro plants, more and more large-scale hydropower systems are taking shape gradually, which brings up a challenge to optimize these systems. Optimization of large-scale hydropower system (OLHS), which is to determine water discharges or water levels of overall hydro plants for maximizing total power generation when subjecting to lots of constrains, is a high dimensional, nonlinear and coupling complex problem. In order to solve the OLHS problem effectively, an improved decomposition–coordination and discrete differential dynamic programming (IDC–DDDP) method is proposed in this paper. A strategy that initial solution is generated randomly is adopted to reduce generation time. Meanwhile, a relative coefficient based on maximum output capacity is proposed for more power generation. Moreover, an adaptive bias corridor technology is proposed to enhance convergence speed. The proposed method is applied to long-term optimal dispatches of large-scale hydropower system (LHS) in the Yangtze River basin. Compared to other methods, IDC–DDDP has competitive performances in not only total power generation but also convergence speed, which provides a new method to solve the OLHS problem.

1. Introduction

Hydropower is a kind of renewable and clean energy when compared with traditional fossil fuel, which leads to widespread construction of hydro plants in many countries. As constructed hydro plants are put into operation, the optimization of these hydro plants becomes a challenge to researchers and operators. The optimization of large-scale hydropower system (OLHS) [1–6] is to determine water discharges or water levels of overall hydro plants for maximizing optimal objective while considering various constrains, including hydraulic connection, water balance equation, water level and water discharge limits et al. Due to these coupled constrains and system scale, OLHS is a high dimensional, nonlinear and coupling complex problem [7–9].

In order to solve the OLHS problem, lots of methods have been proposed and discussed by researchers in the past decades, including linear programming (LP) [10,11], non-linear programming (NLP) [2,12], dynamic programming (DP) [13–15], progressive optimal algorithms (POA) [16–18] and dynamic programming successive approximation (DPSA) [19,20]. Besides these mathematical programming methods, kinds of heuristic algorithms have been proposed, such as genetic algorithm (GA) [21,22], ant colony optimization (ACO) [23,24], differential evolution (DE) [25,26] and particle swarm optimization (PSO) [27–29]. These mathematical programming methods and heuristic algorithms have received various degrees of success in OLHS. However, because of hydraulic connection and water balance equation, the operational state of current hydro plant influences other hydro plants and future periods. Moreover, kinds of limits aggravate the complexity of OLHS. These characteristics lead to high dimension, nonlinearity and complexity. LP is not suitable for OLHS because hydropower system is nonlinear. NLP has problems that it cannot handle non-convexity and the convergence efficiency is bad [9]. DP is a widely used method, while it suffers from "curse of dimensionality" in OLHS. POA hardly finds feasible initial solution of complex system, and it is easily trapped in local optimum when system scale is huge [17]. DPSA has the similar drawbacks with POA when it is applied to OLHS. Due to huge optimizing space of OLHS, heuristic algorithms will hardly obtain optimal solution while trapped in local optimum [5,28].

Decomposition–coordination (DC), also called "two level" algorithm, has been widely utilized in OLHS [30–32] and other complex system optimizations [33–36]. It divides the complex system into

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some non-coupling subsystems and coordinates them to realize optimization. By decomposing and decoupling, the complexity of original system is reduced sharply. Meanwhile, the subsystems' coordination realizes overall optimization of the complex system. Discrete differential dynamic programming (DDDP) is an improved DP method to solve "curse of dimensionality", and it has achieved a certain degree of success in OLHS [37–41]. It splits the searching space of large-scale hydropower system (LHS) into some small searching spaces for reducing calculation. Due to incremental search mechanism, DDDP will hardly obtain optimal solution if the searching space is too huge [42]. On the contrary, DC is a good method to overcome drawbacks of DDDP by combining them because of the powerful globe optimization capacity. Therefore, an improved DC and DDDP method (IDC–DDDP) is proposed to solve the OLHS problem in this paper. It combines DC and DDDP, with DC for overall optimization and DDDP for local optimization. Meanwhile, some improvement strategies are proposed to overcome drawbacks of DC and DDDP. A stochastic strategy is adopted to reduce generation time of initial solution. An adaptive bias corridor technology is proposed to improve convergence speed of DDDP. Moreover, a relative coefficient based on maximum output capacity is proposed to enhance optimization of DC. Finally, the proposed novel method is applied to long-term optimal dispatches of LHS in the Yangtze River basin. Compared with other methods, IDC–DDDP has competitive performances in optimal objective and convergence speed.

The rest of this paper is organized as follows: Section 2 introduces the long-term optimization model of LHS. The improvement strategies of IDC–DDDP are presented in Section 3, following by brief descriptions of DC and DDDP. In Section 4, IDC–DDDP is applied to optimal dispatches of LHS in the Yangtze River basin, and the optimal results are analyzed. Finally, conclusions followed by acknowledgements are summarized in Section 5.

2. Optimization model

The long-term optimal dispatch is to maximize the total power generation of LHS over the whole operation periods, while subjecting to kinds of equality and inequality constrains. In general, the objective and constrains of long-term OLHS are expressed as follows:

2.1. Objective function

$$\text{obj} = \max \sum_{i=1}^{M}\sum_{j=1}^{T} N_{ij}\Delta t \quad N_{ij} = A_i H_{ij} q_{ij} \tag{1}$$

where obj is the total power generation of LHS over the whole operation periods; M is the number of hydro plants; T is the whole periods; A_i is output coefficient of the i-th hydro plant; Δt is interval of scheduling term; N_{ij}, H_{ij} and q_{ij} denote output, water head and water discharge through hydro-turbine of the i-th hydro plant in the j-th period, respectively. Moreover, H_{ij} equals upstream water level minus downstream water level by formula (7); q_{ij} can be obtained by formula (8).

2.2. Constrains

In the process of long-term optimal dispatch, various complex equality and inequality constrains, such as water level, output and hydraulic connection, should be taken into account for restricting the total power generation optimization. The constraints of LHS are described as follows:

(1) Water level constrains

$$Z_{ij,\min} \le Z_{ij} \le Z_{ij,\max} \tag{2}$$

where Z_{ij} presents operation water level of the i-th hydro plant in the j-th period; $Z_{ij,\min}$ and $Z_{ij,\max}$ are lower and upper water level limits of the i-th hydro plant in the j-th period, respectively.

(2) Water discharge constrains

$$Q_{ij,\min} \le Q_{ij} \le Q_{ij,\max} \tag{3}$$

where Q_{ij} presents water discharge of the i-th hydro plant in the j-th period; $Q_{ij,\min}$ and $Q_{ij,\max}$ are minimum and maximum water discharge limits of the i-th hydro plant in the j-th period, respectively.

(3) Output constrains

$$N_{ij,\min} \le N_{ij} \le N_{ij,\max} \tag{4}$$

where N_{ij} presents output of the i-th hydro plant in the j-th period; $N_{ij,\min}$ and $N_{ij,\max}$ are minimum and maximum output limits of the i-th hydro plant in the j-th period, respectively.

(4) Hydraulic connection

$$I_{ij} = \sum_{l\in\Omega_i} Q_{lj} + B_{ij} \tag{5}$$

where I_{ij} and B_{ij} are inflow and local inflow of the i-th hydro plant in the j-th period, respectively; Q_{lj} is water discharge of the l-th hydro plant in the j-th period; Ω_i is upper hydro plants set of the i-th plant.

(5) Water balance equation

$$V_{ij+1} = V_{ij} + [I_{ij} - Q_{ij}]\Delta t \tag{6}$$

where V_{ij} is storage of the i-th hydro plant in the j-th period; I_{ij} and Q_{ij} are inflow and water discharge of the i-th hydro plant in the j-th period, respectively; Δt is interval of scheduling term.

(6) Water head equation

$$H_{ij} = (Z_{ij} + Z_{ij+1})/2 - f_{i,zd}(Q_{ij}) \tag{7}$$

where $f_{i,zd}$ is relation function between water discharge and downstream water level of the i-th hydro plant. By formula (7), water head can be calculated with the known water discharge and upstream water level.

(7) Water spillage equation

$$q_{ij} + S_{ij} = Q_{ij} \tag{8}$$

where S_{ij} is water spillage of the i-th hydro plant in the j-th period. If water discharge Q_{ij} is less than the discharge capacity of hydro-turbine, $S_{ij} = 0$ and $q_{ij} = Q_{ij}$. Otherwise, q_{ij} equals the discharge capacity of hydro-turbine and S_{ij} equals the surplus water.

(8) Initial and terminal water level

$$Z_{i0} = Z_{i\text{begin}} \text{ and } Z_{iT} = Z_{i\text{end}} \tag{9}$$

where $Z_{i\text{begin}}$ and $Z_{i\text{end}}$ are initial water level and terminal water level of the i-th hydro plant, respectively.

3. Strategies of IDC–DDDP

To solve the OLHS problem efficiently, an improved hybrid method named IDC–DDDP which combines DC and DDDP is proposed in this section. DC is a method that decomposes a complex system into weakly coupled subsystems and coordinates them. DDDP is a method for subsystem optimization. Meanwhile, some