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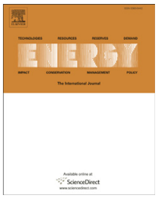

Coordinated operations of multiple-reservoir cascaded hydropower plants with cooperation benefit allocation

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ABSTRACT

The coordinated operations of multiple-reservoir cascaded hydropower plants provide opportunities to increase the benefits of the entire river system. However, it is very challenging to fairly allocate the incremental benefits of cooperation among all participant hydropower plants, which is critical to the implementation of operation polices in practice. A methodology that combines POA-DDDP–based multidimensional search algorithm(PDMSA) with game theory is proposed to address this challenge. The PDMSA is developed to determine optimal operation decisions and obtain the multi-yearly average revenue under all possible coalitions of plants. Thus, the cooperation benefit can be accurately calculated based on the differences of generation production revenue among various coalitions. The game-theoretic Shapley method is used to find the appropriate share of each cooperating plant from overall cooperation benefits. The cooperative core based on a set of necessary conditions helps select possibly stable allocation schemes, and their stability is evaluated by the propensity to disrupt(PTD). The proposed methodology is applied to a multiple-reservoir hydropower system on Lancang River, which is one of 14 large hydropower bases in China. This case shows that the method provides the most stable incremental allocation scheme by comparison with several commonly used methods.

1. Introduction

The pursuit of maximizing energy production or profit motivates cooperation among cascaded hydropower plants with different stakeholders. As is well-known, the coordinated operations of multiple-reservoir cascaded hydropower plants in one river provide opportunities to increase the benefits of the entire river system compared to the individual operation of each plant [1,2]. However, the incremental benefits are a system property. In other words, it is produced by the entire hydropower system not by any individual plant. This poses a great challenge for river system operators or managers: how to fairly and efficiently allocate the synergic benefits among cascaded hydropower plants?

The allocation of cooperation benefits is a thorny and common problem for many river hydropower systems, having a significant impact on the operation efficiency of hydropower systems. Especially in some rich-hydropower countries, it may affect the security of power grid operations because hydropower systems usually bear important responsibility for power supply and peak-shaving [3,4]. For instance, in the case of China whose hydropower capacity has reached 332 GW and ranks first in the world, many large river such as Lancang River, Jinsha River, Yalong River, Hongshui River, Dadu River, Yangtze River, etc., are multi-operator multi-reservoir cascaded hydropower systems [5–7]. In these river systems, the large storage and big installed capacity provide great potential for the coordination of operation policies among cascaded hydropower plants to increase cooperative generation production or overall gains. However, the optimal operational polices of cooperation is difficult to implement in real-world engineering. One of the major obstacles is lack of appropriate methods for determining reasonable share of each participant hydropower plant from the incremental benefits [8].

In recent years, such benefit/cost allocation problems in water resources and power systems have attracted the attention of researchers. There are firm-energy rights allocation among hydro plants [9], basin-wide cooperative water resources allocation [10], profit sharing from coordinated operations of hydro and wind

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Nomenclature

A. Acronyms

POA	progress optimality algorithm
DDDP	discrete differential dynamic programming
PDMSA	POA-DDDP–based multidimensional search algorithm
PTD	Propensity to disrupt
GS	group strategy

B. Indices

m	the index of hydropower plant
t	the index of time period
C	plant coalition

C. Constants

U	total number of upstream plants for hydropower plant m
M	total number of hydropower plants
M_C	the plant number in the given coalition C
T	total number of time period during the whole optimization horizon
Δ_t	the number of hours in time period t

D. Variables

$c_{m,t}$	the average price of electricity of plant m in period t
A_m	the output coefficient of plant m
$H_{m,t}$	net water head of plant m in period t
$V_{m,t}$	storage volumes of the reservoir m in period t
$Q_{m,t}$	inflow into reservoir m in period t
$q_{m,t}$	turbine discharge of hydropower plant m in period t
$Ql_{m,t}$	spill flow of reservoir m in period t
$S_{m,t}$	total discharge of reservoir m in period t, and $S_{m,t} = q_{m,t} + Ql_{m,t}$
$Qn_{m,t}$	natural inflow into reservoir m in period t
$QT^{u}_{m,t}$	delay flow from the upstream reservoir u into reservoir m in period t with time delays
$Z_{m,T}, Z'_{m,T}$	final forebay level and specified forebay level target of reservoir m in stopping period T
$\overline{q}_{m,t}$	maximum turbine discharge of hydropower plant m in period t
$\underline{S}_{m,t}$	minimum discharge of reservoir m in period t
$Z_{m,t}, \overline{Z}_{m,t}, \underline{Z}_{m,t}$	forebay level of reservoir m in period t, and maximum and minimum forebay levels
$p_{m,t}$	average generation of plant m in period t, and $p_{m,t} = A_m \times q_{m,t} \times H_{m,t}$
$\overline{p}_{m,t}, \underline{p}_{m,t}$	maximum and minimum generation of plant m in period t
$\Omega(C)$	the set of plants in the coalition C
x_m	sharing benefit of each plant
$v(C)$	total benefit of coalition C
$v(i)$	generation benefit of plant I under the non-cooperative mode

power [11], benefit allocation of cooperation among reservoirs [12], and transmission service cost allocation among network users [13,14], etc. A few engineering methods and mathematical theories have been suggested to address these problems. The allocation method by average production originates from the real demands [9]. In this method, the share of each plant from the total benefits is in proportion to its average generation production. This allocation is intuitively fair but it neglects the contributions of large reservoirs without turbines to inflow regulation. Even though all reservoirs are installed with turbines, the different storages, generation capacities, local inflows, geographical location, and other characteristics make it difficult to accurately reflect the contribution of each reservoir or plant. Similar engineering methods according to installed capacity or firm generation are also confronted with the same problems [15]. In fact, the discussed problem is a representative example of allocating benefits among a coalition of agents that cooperate. Game Theory provides an effective tool to analyze the interaction of different agents in competitive markets, and especially the cooperative game theory can accurately reflect and solve such a problem [16,17]. The theory exhibits good ability in guaranteeing the fairness, efficiency and stability of benefit allocation. It is capable of finding satisfactory allocation results with highest acceptance potential. Under the mechanism of game theory, various allocation methods have been applied to the benefit/cost allocation problems, such as Nash-Harsanyi model [18], Incremental Allocation [9], Shapley Value [19,20], and others [21]. The Nash-Harsanyi model, proposed by Harsanyi in 1959, tries to maximize the product of incremental benefits of all members in the grand coalition. The Incremental Allocation method takes advantage of the difference of total benefits with and without one member in the grand coalition to determine the obtainable profit. Obviously, this method is dependent on the entry order. The Shapley's method was developed by Shapley in 1953 and commonly used. This method determines the profit share of each member by the weighted additional benefits resulting from the gain of the member to all the possible coalitions. In this way, the impact of different entry orders into the coalitions is eliminated. The extensive literature reviews on allocation methods can refer to [21]. In summary, these cooperative allocation methods are based on different notions of fairness [12]. Which method should be selected usually depends on the considered water resource management system.

While applying the cooperative game theory to allocation of cooperation benefits for multiple-reservoir cascaded hydropower plants, the monthly operational decisions in different coalitions of plants over several decades need to be calculated. The purpose is to identify the role of each hydropower plant in a given coalition and exactly quantify the cooperation benefits. This may be another challenge. To overcome the above challenges, a complete methodology that can cope with the hydropower optimization, allocation of cooperation benefits and fairness evaluation is needed. Therefore, this study proposes a method by combining POA-DDDP–based multidimensional search algorithm(PDMSA) with cooperative game theory. The PDMSA is developed to determine optimal operation decisions, and obtain the multi-yearly average revenue under all possible coalitions. Thus, we can accurately calculate the cooperation benefit based on the differences of generation production benefits among various plant coalitions. The game-theoretic Shapley method is used to find the appropriate share of each cooperating hydropower plant from overall cooperation benefits. The stability analysis method can select all potential stable allocation schemes using a group of conditions. These conditions form the core of the cooperative game. In any a stable scheme, the benefit of each hydropower plant from grand coalition should be bigger than that from non-cooperation. Moreover, the overall benefit of some hydropower plants from partial coalitions