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Cooperative game theory and last addition method in the allocation of firm energy rights

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HIGHLIGHTS

- We propose a faster method to compute core constraints for the firm energy problem.
- Cooperative game theory is applied together with a traditional allocation method.
- We propose an efficient way to allocate firm energy rights.
- Our proposed firm energy allocation framework is applied to real-sized instances.
- Benders has a slower performance than MILP to compute core constraints of the game.

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ABSTRACT

The firm energy rights of a hydro plant is a parameter used in some electricity markets to define the maximum amount of energy that a power plant can trade through contracts. In a centralized dispatch scheme, the coordinated operation of the hydro plants generates a synergetic gain in the system firm energy, in this setting, a question that often arises is how to fairly allocate this energy among each hydro plant. This work proposes a formulation to compute the firm energy rights of hydro plants using cooperative game theory and the last addition allocation method. The main goal is to integrate the interests of hydro agents with the needs of the regulatory agencies, searching in the core of the game for solutions that give the right incentives to the optimal system development. In order to make simulations of real instances possible, it is proposed a reformulation of the traditional mixed integer linear programming model that computes the core constraints, which induces a significant speed-up of the algorithm solution time. It is shown an application of the proposed methodology to a real instance representing the Brazilian electric power system.

Nomenclature

The main notation used throughout this paper is listed below. Subscripts k and ℓ are used to indicate the value of a parameter or variable at a specific stage k or ℓ.

Abbreviations

AE	assured energy
AFE	Allocation of firm energy. Represented by Eqs. (20)–(22)
APCP	Average production in the critical period. Represented by Eq. (11)
CGM	Cooperative game model. Represented by Eqs. (14)–(19)
FE	firm energy
FEMILP	algorithm that allocates firm energy rights using cooperative game theory and the last addition method. Presented in Fig. 1
LA	Last addition. Represented by Eq. (12)
LB	lower bound
MGFE(I_s)	model that computes the global firm energy associated with subset $I_s \subseteq I$. Represented by Eqs. (1)–(10)
MP	master problem
MP^R	reformulated master problem
MILP	mixed integer linear programming
SP	sub-problem

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SP^R	reformulated sub-problem
UB	upper bound
Indices and Sets	
$CP \subseteq T$	subset of months that define the critical period of the hydro power system inflow
$i \in I$	set of hydro power plants
$I_s \subseteq I$	subset of hydro power plants
$I_{LA}^i \subseteq I_s$	subset of all hydro plants in I excluding plant i
$m \in M_i$	set composed by hydro plants located immediately upstream of hydro plant i
$m \in \widehat{M}_i$	set composed by all hydro plants located upstream of hydro plant i
$t \in T$	set of monthly time stages
Functions	
$\phi_i(\cdot)$	4-th order polynomial to represent the reservoir head and volume of plant i
Deterministic parameters	
A_i^t	incremental water inflow in the river that supplies hydro plant i, at stage t, expressed in $[m^3/month]$
AE_i	individual assured energy of hydro plant i, expressed in average MW, or [MW·month]
$\widehat{FE}_i$	individual firm energy of hydro plant i, expressed in average MW, or [MW·month]
$\widehat{GFE}_{I_s}$	firm energy of the subset of hydro plants I_s, expressed in average MW, or [MW·month]
h_{eq}^i	equivalent net head of hydro plant i, expressed in [m]
HE	hydro power energy fraction of the system assured energy, expressed in average MW, or [MW·month]
HL_i	hydraulic losses at hydro plant i due to the water flow though pipelines, expressed in [m]
N_i^t	natural water inflow in the river that supplies hydro plant i, at stage t, expressed in $[m^3/month]$
N_{CP}	number of months in the critical period
NP	number of hydro plants in the subset I
$\overline{Q_i}$	maximum turbine outflow of plant i, expressed in $[m^3/month]$
$\overline{V_i}$	maximum storage volume of hydro plant i, expressed in $[m^3]$
$\underline{V_i}$	minimum storage volume of hydro plant i, expressed in $[m^3]$
$\widehat{Y}_i$	binary coefficient that defines if the plant i belongs to the subset I_s ($\widehat{Y}_i = 1$) or not ($\widehat{Y}_i = 0$)
$\overline{\theta_i}$	hydro plant i average tailrace level, expressed in [m]
ρ_{eq}^i	equivalent productivity of hydro plant i, expressed in$\left[\frac{MW\cdot month}{m^3/month}\right]$
ρ_{sp}^i	specific productivity of hydro plant i, expressed in$\left[\frac{MW\cdot month}{\frac{m^3}{month}\cdot m}\right]$
$\gamma_{k,i}$	k-th polynomial coefficient that represent reservoir head and volume of hydro plant i
Decision variables	
FE_i	individual firm energy of the hydro plant i, measured in average MW, or [MW·month]
GFE_{I_s}	firm energy of the subset of hydro plants I_s, measured in average MW, or [MW·month]
PG_i^t	average power generated by hydro plant i, at stage t, measured in average MW
Q_i^t	turbined outflow of hydro plant i, at stage t, expressed in $[m^3/month]$
S_i^t	water spillage outflow of hydro plant i, at stage t, expressed in $[m^3/month]$
V_i^t	available water volume stored in the reservoir of hydro plant i, at stage t, expressed in $[m^3]$
Y_i	binary variable that defines if the plant i belongs to the subset I_s ($Y_i = 1$) or not ($Y_i = 0$)
π^α	dual variable associated with each constraint ($\alpha = 0, \ldots, 4$) in the sub-problem

1. Introduction

Renewable energy sources are currently playing a key role in the energy matrix of many countries around the world [1]. In 2016, the renewable energy production represented approximately 24% of the total electricity generated worldwide [2]. This amount is likely to increase in the next few years/decades as the investments in solar, wind and other renewable sources are ramping up. Another important renewable energy source is hydro power, which is considered by many as a conventional form of electricity production [3]. Nowadays, hydro power alone represents the largest share in renewable energy production, e.g. in 2016 hydro power alone corresponded to 67% of the total renewable electricity production [2].

In hydroelectric generating systems the optimal operation of the hydro power plants depends on the wise use of the water available at the reservoirs. Upstream hydro plants have to coordinate their operation with downstream plants in order to minimize spillages and maximize the total electricity production [4]. Sometimes the optimal operation of a hydro power system is even more complex and involves coordination of plants that are not connected hydrologically and that are owned by different agents.

In some countries, with predominance of hydro generation, such as Brazil [5], Canada [6], and Norway [7], the coordination of the hydro power generation [8] is an essential task related to the security of supply and the power system stability [9]. In this work, we consider a centralized coordination of energy resources, where a synergetic energy gain is achieved by the optimal dispatch of a set of hydro power plants. As a result from the optimization process, the total energy production for the system composed by the set of hydro plants is obtained. However, due to the synergetic energy gains obtained from the coordinated operation, it is necessary to properly allocate each hydro plant share from the total system production. In this context, the problem of firm energy (FE) rights allocation [10,11], and its associated models are the key to find satisfactory answers.

For example, in Brazil, where a centralized dispatch of energy sources is performed, the total hydro-thermal energy production that a system can guarantee for a safe and reliable operation is determined according to a procedure similar to the one described in [12]. This energy measure is known as assured energy (AE) and represents a hypothetical amount of energy that the system is capable of generate under a determined level of supply risk. After dividing the system AE into a hydro power energy fraction (HE) and a thermal energy fraction, the individual assured energy (AE_i) is determined according to the firm energy rights allocation method, that basically uses an individual firm energy variable (FE_i) to divide the HE among each hydro plant of the system (this procedure will be described in detail in the Section 2). The larger is the FE_i, the bigger will be the portion of the HE allocated to the plant and its AE_i. The AE_i works as ballast for energy sales in the electricity market, this way, if a particular hydro plant has more AE_i, it can sell more energy in the market and achieve larger profits.

For hydro power systems operating in a centralized dispatch scheme, it is possible to attribute a desirable property in the allocation models called fairness. The concept of fairness was first proposed by Von Neumann [13] and was recently applied in the FE computation [11]. According to the cooperative game theory, an allocation is fair, if and only if, none of its participants have interest in leaving the grand coalition to form sub-coalitions. In other words, the benefit of