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Stochastic optimization model for the weekly scheduling of a hydropower system in day-ahead and secondary regulation reserve markets

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ABSTRACT

Hydropower stands out for its fast response ability and flexible operation, playing a predominant role in the provision of regulation reserves. As hydro power is an energy-constrained generation technology, it needs to be protected against any possible deployment of the scheduled reserves. However, the few models that formulate a detailed hourly co-optimization of energy and regulation reserves, neglect infeasibilities that could be derived from the requested reserves in real-time. As the regulation reserve market is becoming increasingly important, hydro producers can no longer neglect such effect. This paper presents a stochastic optimization model to find the optimal hourly schedule of a set of hydraulically coupled hydropower plants to obtain the weekly operation that simultaneously maximizes the expected profit in both energy and regulation reserves markets. The model is formulated for a price-taker agent, and it considers a very detailed representation of the system including minimum–maximum water flows, net head dependency, and fractional water travel time. The main contribution is that the obtained solution protects a multi-reservoir system against risk of water and storage unavailability due to the uncertainty in real-time use of regulation-up and down reserves, respectively, and that the reserves deem the net head dependency. The paper presents a realistic case study where the proposed formulation has been tested successfully with real data from the Spanish electricity market.

1. Introduction

The increasing penetration level of renewable energy sources in many power systems is changing the pattern of energy and ancillary services prices in electricity markets [1]. In this framework, hydro generation companies need to update their models and scheduling tools in order to maximize their expected profit taking advantage of the price spread that can be observed between the energy and reserve prices in real markets (especially in periods with a substantial share of wind power in the generation mix).

Hydropower units are more flexible than low variable cost technologies such as nuclear and coal thermal plants, as they can change their generation from the minimum to maximum capacity in just few seconds. In addition to this, hydropower generation involves lower variable costs comparing to flexible thermal technologies such as open gas cycle units. Therefore, the hydropower technology plays an important role in the provision of the secondary regulation service in many systems all around the world.

The management of a hydrosystem in both the long-term and short-term is not an easy task. A hydropower producer must decide the hourly operation of reservoirs in order to optimize its participation in competitive electricity markets. In the literature, short-term hydropower scheduling problem has been treated widely. However, only some few works have formulated a co-optimization model from the perspective of a hydro producer who tries to maximize the expected profit in both the day-ahead electricity market and the secondary regulation reserve market.

In [2], a deterministic short-term model (24 hourly periods) for a hydro system participating in day-ahead electricity market, spinning reserve market and regulation market is described. With similar features than [2], the model presented in [3] introduces stochasticity in market prices, treating water inflows as a deterministic input data. It is important to highlight that spinning reserves (10S) and non-spinning reserves (10N) calculated by [3] are not

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Nomenclature

Some sets, subsets, parameters and variables are also shown graphically in Fig. 1.

Sets and indexes

G, g set and index of hydropower units. One hydropower plant can be made of several units (turbines)
J, j set and index of water arcs
K, k set and index of discrete generation curves for each net head considered in the approximation
N, n set and index of nodes of the hydro system: reservoirs (e), hydropower plants (c) and natural water inflows (i)
P, p set and index of time periods, running from 1 to P
W, w set and index of uncertainty scenarios
N', P', W' alias of previously defined sets

Subsets

$BG(g)$ set of hydropower units allowed to participate in the secondary regulation reserver market
$C(n)$ sets of nodes which are hydropower plant, formed by at least one hydropower unit
$CG(n)$ unit or set of units which belong to node $n \in C(n)$
$Dq(n)$ set of arcs of water discharged flow which begin in node n
$Ds(n)$ set of arcs of water spilled flow which begin in node n
$E(n)$ set of nodes which are reservoirs
$EG(g)$ reservoir associated to hydropower unit g
$I(n)$ set of nodes representing water inflow locations which are not placed in a reservoir
$PG(g)$ set of hydropower units which are pumped storage units
$UPC(n)$ reservoir or set of reservoirs from which the units in node $n \in C(n)$ receive water flow directly
$Uq(n)$ set of arcs of water discharged flow which finish in node n
$Us(n)$ set of arcs of water spilled flow which finish in node n

Parameters

$\delta^t_{w,k,g,p}$ generating energy coefficient in curve k of unit g in period p and scenario w (MW/h m^3/h)
$\lambda EM_{w,p}$, $\lambda SM_{w,p}$ day-ahead electricity market price (€/MWh) and secondary regulation reserve market price (€/MW) in period p and scenario w
$\tau^{q/s}_{p',p,j}$ percentage of water discharged/spilled flow from upstream of arc j in period p' reaching downstream of arc j in period p due to time delays
$\mathcal{F}^{up}$ maximum percentage of the offered secondary regulation-up reserve requested by TSO in real time
$\mathcal{F}^{dw}$ maximum percentage of the offered secondary regulation-down reserve requested by TSO in real time
l_p time lenght of period p (h)
M a big number, 10^6
$NI_{w,n,p}$ natural inflow (or outflow in case it takes a negative value) at node n, in scenario w and period p (h m^3/h)
OP_g maximum start-up and shutdown maneuvers per day in hydropower unit g
$\bar{p}_g, \bar{q}_g$ maximum technical generation (MW) and water flow (h m^3/h) of unit g
$\bar{p}^b_g, \bar{q}^b_g$ maximum technical consumption (MW) and pumped water flow (h m^3/h) of unit $g \in PG$
$\bar{p}_{w,k,g,p}, \underline{p}_{w,k,g,p}$ maximum and minimum hydropower generation in curve k of unit g in period p and scenario w (MW)
$\bar{q}_n, \underline{q}_n$ maximum and minimum total water flow through node n due to design characteristics (h m^3/h)
$\bar{q}_{w,k,g,p}, \underline{q}_{w,k,g,p}$ maximum and minimum water flow in curve k of unit g in period p and scenario w (h m^3/h)
$\bar{rf}_{n,p}$, $\underline{rf}_{n,p}$ maximum and minimum water discharged and/or spilled flow obligations imposed by water authorities in node n which is a reservoir or a run-of-the-river hydropower plant (h m^3/h)
TD_g minimum down time (h)
TU_g minimum up time (h)
$\bar{v}_n, \underline{v}_n$ maximum and minimum technical water storage limits of node n which is a reservoir $e(n)$ due to design characteristics (h m^3)
$\bar{v}_{n,p}$, $\underline{v}_{n,p}$ maximum and minimum water storage limit imposed by water authorities in node n which is a reservoir $e(n)$ and period p (h m^3)
vf_n target water volume of node n which is a reservoir $e(n)$ (h m^3)
$VUP_{w,n,p}, VDW_{w,n,p}$ maximum and minimum water volume in node $n \in E(n)$ to calculate hydropower generation curves (h m^3)
$VM_{w,n,p}$ mean value of $VUP_{w,n,p}$ and $VDW_{w,n,p}$ (h m^3)
ρ_w probability of scenario w

Positive variables

$aux\_b_{w,g,p}$ auxiliary variable to obtain a linear expresion of the head-dependent secondary regulation-down reserve (MW)
$b^{up}_{w,g,p}$, $b^{dw}_{w,g,p}$ secondary regulation-up and down reserve in hydropower unit g (MW)
$hg_{w,g,p}$ hydropower generation in unit g (MW)
$hg^+_{w,g,p}$, $hg^-_{w,g,p}$ power generation and consumption in pumped storage hydropower unit $g \in$ PG (MW)
$q_{w,g,p}$ water discharged flow in hydropower unit g (h m^3/h)
$q^+_{w,g,p}$, $q^-_{w,g,p}$ water discharged and pumped water flow in pumped storage hydropower unit $g \in PG$ (h m^3/h)
$q_{w,j,p}$ water discharged flow through arc j (h m^3/h)
$qs_{w,g,p}$ water discharged flow in a hydropower unit g above its minimum technical limit (h m^3/h)
$s_{w,j,p}$ water spilled flow through arc j (h m^3/h)
$v_{w,n,p}$ water storage volume (h m^3)
$y_{w,g,p}$ start-up decision (start-up=1/other=0)
$z_{w,g,p}$ shut-down decision (shut-down=1/other=0)

Binary variables

$d_{w,e,p}$ auxiliary binary variable used for the discretization of the hydropower generation curve in reservoir e
$ub_{w,g,p}$ state of hydropower unit g for pumping mode (On=1/Off=0)
$ut_{w,g,p}$ state of hydropower unit g for generating mode (On=1/Off=0)