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A continuous compact model for cascaded hydro-power generation and preventive maintenance scheduling

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ABSTRACT

This paper proposes a new nonlinear model for cascaded hydro-power generation and preventive maintenance scheduling. The reservoir level and the maintenance scheduling are optimized, simultaneously, to minimize the thermal generation complement and to maximize the future water value. To achieve better accuracy, the productivity was modeled considering the head effect. Since the model considers individualized plants, the water flow balance must be taken into account. By means of a transformation, this constraint can be modeled only with the reservoir volume. Also, by means of a simple nonlinear transformation, the maintenance scheduling was modeled as continuous variable, instead of the usual binary models. The maintenance start date is a continuous variable, so, it allows the maintenance to begin within the time period. These simplifications altogether define a compact continuous nonconvex problem. The proposed model was successfully solved by a Differential Evolution (DE) algorithm in Brazilian cascades.

Introduction

Hydro-power systems are present in many countries and, frequently, these systems have various hydroelectric power plants installed in the same river basin in order to take advantage of the natural hydro-power potential. This set of plants, interconnected by the natural water flows in the river and its tributaries, is defined as a cascaded hydro-power system. For example, the James Bay Project in Canada is composed by eight plants installed in the La Grande river basin with a capacity of 15,240 MW. In Brazil, there are fifteen plants in the Grande river basin with a capacity of 7619 MW. In order to obtain an economical and reliable system operational policy, the operator should define the most appropriate way to manage the water resources in the cascade. For this reason, the model should include the main characteristics of each power plant, such as the power generation efficiency, the water flow conservation equation, the environmental restrictions and preventive maintenance scheduling.

The system planning aims to meet the demand with the maximum participation of hydro generation due to low costs and low environmental impacts. So, the thermal/nuclear generation could be considered a complement, which should be minimized. Besides the operation costs, another important goal is to reduce future risks associated with the reservoirs control and future inflows. Thus, the planning also aims to value the water stored in the reservoirs at the end of the horizon, maximizing the power reserve in the system.

The availability of generation units (turbines) is essential to control the reservoir and generation. For example, in the Brazilian system, the operator can be penalized due to planned outages (maintenance) if these outages significantly reduce the generation availability. In this context, the maintenance scheduling should be considered in the generation scheduling. The maintenance is expected to occur in certain periods of the horizon, e.g. due to technical criterion or sector regulation, but it can be refined to improve the system planning.

Most articles on cascade optimization did not address the scheduling of preventive maintenance. Furthermore, a recurrent approach is to represent the hydroelectric system by equivalent reservoirs and not as a cascade. This consideration is used, for instance, in the dual dynamic programming model used for the Brazilian hydro-power planning [1]. On the other hand, mathematical programming approaches with individualized power plants were presented. Gagnon et al. [2] formulated the problem through (nonconvex) nonlinear programming in order to minimize the

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power deficit. The model contains only storage variables, while the water discharge and spill variables are implicit. Due the non-convexity, generally associated with the power plant generation function, the metaheuristics have also been explored. One of the first works with metaheuristics was Leite and Carneiro [3]. They developed a genetic algorithm with local search to minimize the thermal complement. Just the storage variables are used to represent the individuals in the algorithm. Whereas Zhang et al. [4] developed a multi-elite guide particle swarm algorithm using only the discharge variables. Both representation strategies were used in the generation scheduling literature, as shown in the "Variables" column at Table 1, in order to reduce the dimension and improve the constraint handling techniques. The "Objective" column abbreviations stand for: minimization of thermal complement (Thermal), minimization of power deficit (Deficit), maximization of hydro-power generation (Generation), maximization of the benefits of water use (Water) and minimization of the thermal emissions (Emission).

Some papers have treated the preventive maintenance scheduling, especially in thermal power systems. One of the pioneering articles was Christiaanse and Palmer [16] which considers a single plant and heuristics-based solution. Canto [17] presented a mixed integer linear model to minimize the maintenance cost. A Bender's decomposition procedure was applied to integrated generation and transmission maintenance scheduling in hydro-thermal system [18]. A mixed integer program is also presented to a hydro-thermal system [19]. The simulation model to hydro-thermal systems proposed by Baslis et al. [20] considered the preventive maintenance scheduling on the hydro system modeling. Whereas Gjorgiev et al. [21] improved the short-term combined economical-environmental dispatch in a hydro-thermal system considering the availability of the generating units. Usually the formulation becomes combinatorial and the reservoir control is relegated to the background in theses cases.

However, this paper presents an integrated model to operational planning of a cascaded hydro-power system and preventive maintenance scheduling. The formulation is:

- compact, only storage variables are explicit;
- continuous, allows maintenance start during a time period;
- linearly constrained, only inequalities;
- nonconvex, water head factor and water discharge evaluation, and
- multiobjective, minimizes the thermal complement and maximizes the future water value.

These characteristics are well exploited by metaheuristics, i.e. evolutionary algorithms, as demonstrated by computational tests with Brazilian cascades.

Table 1
Generation scheduling literature review.

Paper	Objective	Method	Variables
[3]	Thermal	Genetic algorithm	Volume
[4]	Deficit	Particle Swarm	Discharge
[5]	Generation	Artificial Bee Colony	Volume
[6]	Water	Particle Swarm	Volume, discharge
[7]	Thermal	Genetic algorithm	Discharge
[8]	Thermal	Clonal algorithm	Discharge
[9]	Thermal	Clonal algorithm	Discharge
[10]	Thermal	Chemical Reaction	Discharge
[11]	Thermal	Artificial Bee Colony	Discharge
[12]	Thermal, Emission	Artificial Bee Colony	Discharge
[13]	Thermal, Emission	Gravitational search	Discharge
[14]	Thermal, Emission	Swarm optimization	Discharge
[15]	Thermal, Emission	Swarm optimization	discharge

Problem definition

Notation

Sets

$\mathbb{W}_j$	maintenance j start time window
Ω_i	immediate upstream plants for plant i
Λ_i	plant i, if it has reservoir, and all upstream plants with reservoir
Ψ_i	plant i and all upstream plants

Variables

$v_{i,t}$	plant i reservoir volume at period t
$q_{i,t}$	plant i water discharge at period t
$s_{i,t}$	plant i water spill at period t
z_j	maintenance j start time
$g_{i,t}$	hydro-power generation
p_t	thermal power generation at period t

Parameters

M	number of maintenances
N	number of plants
T	number of time periods
β	constant to convert volume to flow rate (e.g. h m^3 to m^3/s)
d_t	power demand at period t
r_j	maintenance j duration
$\underline{v}_i$	reservoir volume lower bound at plant i
$\overline{v}_i$	reservoir volume upper bound at plant i
$\underline{Q}_{it}$	environmental limit to discharged plus spilled flow at plant i
$\overline{Q}_{it}$	preventive flooding limit to discharged plus spilled flow at plant i
$\overline{q}_i$	discharge upper bound at plant i
γ_{it}	plant i natural inflow at period t
μ_{ji}	discharge reduction factor in plant i due to the maintenance j
w_i	reservoir i weight
$o()$	output to height function
$h()$	volume to height function
ε	penstocks head loss
κ	producibility coefficient

Objectives

Thermal complement

The objective is to minimize the thermal complement

$$\min \sum_{t=1}^{T} a + bp_t + cp_t^2, \tag{1}$$

where p is the thermal power generation, a, b, c are the power generation cost coefficients of thermal plant. For more details on the equivalent thermal cost function for hydrothermal generation planning see [22].

The load balance equation is expressed as follows

$$p_t + \sum_{i=1}^{N} g_{i,t} = d_t, \quad \forall t, \tag{2}$$

where d_t is the power demand and $g_{i,t}$ is the hydro-power generation. So, the thermal complement is calculated as