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Optimization of power production through coordinated use of hydroelectric and conventional power units

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ABSTRACT

In the present work a methodology to tackle the problem of simultaneous utilization of hydroelectric and conventional power units with the goal of optimizing power production operations over the short term is presented. Most problem formulations found in the literature result in the development of nonlinear optimization programs, which are solved with stochastic methods. The methodology presented in this paper leads to the development of a convex mixed integer quadratic programming (MIQP) model, which is a special type of nonlinear model that enables reaching the global optimum solution in short computational time. The efficiency of the proposed approach is demonstrated by its application to a realistic power production system.

1. Introduction

Hydroelectric power is the most widely used form of renewable energy, accounting for 16% of global electricity consumption [1]. However, many hydroelectric projects prove themselves unable to perform as expected prior to construction mainly due to omissions in the design phase and dysfunctional management, while at the same time the need for improved efficiency in hydroelectric operation is stimulated from the reduction of available new installation locations, the need to moderate the ecological impact of existing projects, dynamic power prices and uncertainty in water supply [2,3]. One way to improve the efficiencies of hydroelectric plants is to schedule their operations together with thermal plants, i.e. determine simultaneously the actions and operation levels of hydroelectric and thermal power units with the goal to minimize the total cost of energy production [4]. Costs in this case arise mainly by the cost required to operate thermal power units, as the costs incurred by hydroelectric units are relatively low. At the same time, the specific technical attributes of the two kinds of units must be considered, so that the solutions generated reflect actual operation statuses and lead to realistic and thus immediately applicable operation plans.

Regarding the thermal power units, the cost of electricity production depends on the levels of produced energy and on the attributes of each power unit. Furthermore, there are functional parameters that affect the ability to respond to demand variations and are specific to each power unit. These are the maximum allowed step increase/decrease in production rates (ramp rate constraints) and the startup/shutdown costs of each unit.

The hydroelectric units are fed by water inflows which are first collected in a reservoir and then fed to the generator. In certain cases, network topology is rather complex, as the generator outlet flow is fed to another reservoir-generator system and in this way partially determines its water inflow. In that case, hydroelectric units are coupled, as the total production capacity of a unit, is affected by water outlet flows in upstream units.

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Nomenclature

Indices

i	thermal unit
h,k	hydroelectric unit
t	hour

Data or fixed parameters

$UpCost(i)$	startup cost of thermal unit i ($)
$DownCost(i)$	shutdown cost of thermal unit i ($)
$P_{\min}(i)$	minimum allowed energy production by thermal unit i in an hour (MWh)
$P_{\max}(i)$	maximum allowed energy production by thermal unit i in an hour (MWh)
$UpRate(i)$	upper limit of increase in power produced by thermal unit i (MWh/h)
$DownRate(i)$	lower limit of increase in power produced by thermal unit i (MWh/h)
$UpTime(i)$	minimum time in operation of thermal unit i once it is activated (h)
$DownTime(i)$	minimum time out of operation of thermal unit i once it is shut down (h)
$a(i)$, $b(i)$, $c(i)$	cost parameters of thermal unit i as a function of produced power ($a(i)$[€/h], $b(i)$[€/MWh], $c(i)$[€/MWh^2])
$Offpenalty(i)$	penalty cost for operation of thermal unit i in the transient state ($)
$Demand(t)$	energy demand during time period (hour) t (MWh)
$Reserve(t)$	energy in reserve, potentially available during time period t (MWh)
$PH_{\min}(h)$	minimum allowed energy production by hydropower unit h during 1 h (MWh)
$PH_{\max}(h)$	maximum allowed energy production by hydropower unit h during 1 h (MWh)
$VE_{in}(h)$	initial water levels in the reservoir prior to generator h (energy equivalent) (MWh)
$VE_{\min}(h)$	minimum water levels in the reservoir prior to generator h (energy equivalent) (MWh)
$VE_{\max}(h)$	maximum water levels in the reservoir prior to generator h (energy equivalent) (MWh)
$Inflow(h, t)$	water inflow to the reservoir of generator (energy equivalent) (MWh)
$Delay(k)$	transition delay from reservoir k to its downstream reservoir (h)
$Next(k)$	index of the downstream reservoir to reservoir k

Binary variables

$U(i, t)$	binary (0/1–off/on) variable indicating the operating condition of thermal unit i in period t

Positive variables

$CUp(i, t)$	auxiliary variable to calculate the startup cost of thermal unit i in period t ($)
$CDown(i, t)$	auxiliary variable to calculate the shutdown cost of thermal unit i in period t ($)
$P(i, t)$	energy produced by thermal unit i in period t (MWh)
$P_{off}(i, t)$	energy produced by thermal unit i in period t only when unit is in transient state (MWh)
$PH(h, t)$	energy produced by hydroelectric unit h in period t (MWh)
$VE(h, t)$	water levels in the reservoir prior to generator h in period t (energy equivalent) (MWh)

A problem inherent in hydrothermal power systems caused by operational characteristics, line overloading limits and water availability is congestion. This is studied in [5] where a novel congestion management strategy is proposed that is tested on two modified power system test cases for congestion management under line outages. The authors also study the effect of hydro units on the cost of energy production by solving the same problem using two configurations, one containing both hydro and thermal units and a second one using only the thermal units. In the latter case a cost increase of 13% is exhibited, thus demonstrating the benefits of hydro-thermal coordination.

The benefits of efficient hydrothermal scheduling have been identified and accepted by many researchers, leading to the development of a variety of methodologies in order to tackle the problem, while at the same time the suboptimal operation of many hydro plants pushes towards the development of tools that would increase efficiency [3,6–8]. A review of the application of optimization methods in short-term hydrothermal scheduling that includes Lagrangian relaxation and Benders decomposition-based methods, Mixed-integer programming, Dynamic programming, Evolutionary methods, Artificial intelligence and Interior-point methods is provided by [9]; a broader scope of methodologies that have been applied to this problem is covered in [10]. In most cases found in literature, the problem is not dealt with in its entirety, but due to the difficulty involved in reaching a solution it is broken into smaller subproblems [6,11]. Furthermore, in most cases the length of the scheduling horizon does not exceed 24 h, leaving only limited space for longer term planning decisions and proactive behavior.

A Mixed Integer Linear Programming (MILP) approach to the short-term hydrothermal scheduling problem is presented in [12], where a piecewise linear function for thermal unit cost is used. Based on a Nonlinear Programming (NLP) formulation, Evolutionary Programming (EP), classical Gradient Search (GS) and Simulated Annealing (SA) are