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Sizing of a pumped storage power plant in S. Miguel, Azores, using stochastic optimization

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ABSTRACT

A pumped storage power plant is being planned in the island of S. Miguel, Azores, as a way to accommodate an increasing share of renewable generation. With that purpose, an optimal schedule program of the whole system is simulated considering a moving window in a receding horizon, in which the operational rules established by the island's system operator are implemented. Given the stochastic nature of renewable sources and loads, this schedule has to be framed as a stochastic optimization problem with interrelated decision variables. The uncertainty originates from forecasting errors that are superimposed on simulated time series of load and wind generation, and this uncertainty is simulated as stochastic, normally distributed vectors of growing variance. The adequacy of the pumped storage power plant is assessed through statistical measures on lost load, lost reserve, and lost wind.

1. Introduction

Electric power systems must increasingly cope with a large share of generation from renewable sources, as policy makers push for the adoption of renewable generation as part of a more diverse and cleaner generation portfolio that can address a growing energy consumption. As a consequence, the accommodation in electric power systems of an increasing installed capacity in renewable generation is a problem that has received much attention in recent years [1]. This problem becomes more acute in isolated systems, with a small-area footprint, as is the case of islands.

Wind parks have been installed in S. Miguel, Azores, as part of this policy that calls for more participation of renewable energy sources in electricity generation. Also, a pumped storage power plant that feeds from a very large natural reservoir is being planned with the aim of improving the complementarity between intermittent wind generation and thermal diesel generation. With that purpose in mind, the pumped storage power plant – also called pondage plant, because the upper reservoir has no significant inflows – will be used to shift renewable generation from low-demand periods to high-demand periods, while decreasing the usage of expensive thermal generation which is based on diesel engines.

In order to test the proposed solution, an energy adequacy framework was built with the purpose of sizing the reservoir, the pumps, and the turbines of the pumped storage power plant, and also to assess the necessity to perform load following using the hydro turbines and pumps. In this framework, the optimal chronological scheduling of the generation system was simulated for long periods, while applying the same operational rules as the island's system operator. This scheduling problem is framed in a stochastic optimization model [2], where the main drivers for uncertainty are the stochastic wind generation and the stochastic load. In essence, the stochastic scheduling model is a stochastic version of the unit commitment problem [3], in this case using a mixed-integer linear (MILP) formulation [4]. Many techniques exist for the unit commitment problem [5]. Priority list, dynamic programming, and Lagrange relaxation are some of them. In any case, MILP is a powerful and simple formulation for the unit commitment problem that allows straightforward coding to use general purpose, industry-grade solvers.

Literature that addresses the scheduling of hydro and wind generation has been developed [6–9]. However, our framework presents some distinct features:

- the scheduling model described in this paper is used as a planning tool; the example given here illustrates how this tool can be used to solve a specific generation planning problem, which in this

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Nomenclature

Indices and sets:
$t, t^*, T, \mathcal{T}$ positive time instant, negative time instant, number of positive time instants, and set of positive time instants
$\mathcal{T}^{NR}$ set of time instants of non-recourse variables
n or m; $\mathcal{N}$ thermal turbination or pumping unit; set of units
$\mathcal{N}^G, \mathcal{N}^T, \mathcal{N}^P$ set of thermal units, set of turbines, and set of pumps
s or r; $\mathcal{S}$ scenario; set of scenarios
$l, L, \mathcal{L}$ segment of peicewise linear heat rate, number of segments, and set of segments; set of points is $\mathcal{L} \cup \{L+1\}$

Variables:
$u^{ON}_{n,t,s}, u^{SU}_{n,t,s}, u^{SD}_{n,t,s}$ unit on/off, start-up, and shut-down (binary)
$z^{SEG}_{n,t,s,l}, s^{SEG}_{n,t,s,l}$ active (binary) and fraction of ([0,1]) piecewise linear heat rate segment
$x_{n,t,s}$ thermal unit, turbine, or pump power output (≥ 0) [MW]
$spr_{t,s}, rvl_{t,s}$ spinning reserve (≥ 0) [MW] and reservoir level (≥ 0) [MWh]
$ll_{t,s}, lr_{t,s}$ lost load and lost spinning reserve (≥ 0) [MW]
$lg_{t,s}, lw_{t,s}$ lost geothermal power and lost wind power (≥ 0) [MW]

Parameters:
$\Delta t, \Pi_s$ time step [h] and probability of scenario s ([0,1])
M^{ll}, M^{lr} penalties for lost load and lost spinning reserve [€/MWh]
M^{lg}, M^{lw}, M^{fl} penalties for lost geothermal power, lost wind power and final reservoir level [€/MWh]
F^p_n, SU^{cost}_n fuel price [€/MJ] and start-up cost [€/h]
$x^{\max}_n, x^{\min}_n$ maximum and minimum output [MW]
$rvl^{\max}_n, rvl^{\min}_n$ maximum and minimum reservoir level [MWh]
RVL^0 reservoir level in the beginning of the planning window [MWh]
FRC_L fraction of load ([0,1])
RU_n, RD_n ramp-up and ramp-down rates [MW/h]
SUT_n, SDT_n start-up and shut-down times
UPT_n, DWT_n minimum up- and minimum down-time
η_T, η_P turbine electrical-to-mechanical conversion efficiency and pump mechanical-to-electrical conversion efficiency

Tabulated parameters:
$U^{0,ON}(n, t^*)$ unit on/off before planning window (binary)
$U^{0,SU}(n, t^*)$ unit start-up before planning window (binary)
$U^{0,SD}(n, t^*)$ unit shut-down before planning window (binary)
$X^0(n, t^*)$ power output before planning window (≥ 0) [MW]
$hr^X(n, l), hr^Y(n, l)$ piecewise linear heat rate abscissas [MW] and ordinates [MJ/h]
$Ld(t, s)$ load [MW]
$Wd(t, s), Gt(t)$ wind and geothermal generation [MW]
$N^{G,ON}$ minimum number of online thermal units

case is the sizing of a pumped storage power plant, located in an isolated system that is very sensitive to the stochasticity of both wind and load;

- the scheduling problem is framed for a receding horizon, where many time-dependent constraints must also take into consideration past decisions; the decision variables are assumed to be stochastic and interrelated and, therefore, the problem is solved using a direct approach as opposed to a multi-stage approach [2,8]; moreover, all constraints (especially the start-up and shut-down logic for the thermal units) are presented with great detail – as opposed to using a simplified logic [7] –, and past and future decisions are separated in the decision vector;
- the forecast errors associated with load and wind generation are simulated as uncertainty cones of correlated time series (or trajectories), with growing variance that is adjusted to the forecast error variance determined (computed) by the system operator; instead of using scenario trees [6,7,9], the scenarios arise from those forecast error trajectories that are superimposed on the simulated stochastic realizations for load and wind generation;

In the scheduling problem defined in this work, the objective function is the cost of running the thermal units. Some slack (state) variables that are included in the problem and penalized in the objective function allow some of the (otherwise hard) constraints to be relaxed, such as the energy balance. These variables are, in increasing order of importance, lost wind (or wind spillage), lost (or tripped) geothermal generation, lost (or unsatisfied) spinning reserve, and lost (or unsatisfied) load. Loss expectations are extracted from these variables once the problem is solved for a specified period.

2. Stochastic scheduling model

The sizing of the pumped storage power plant depends upon the scheduling problem, whose constraints are defined by the system operator. It is this sizing that will determine whether it is possible to operate the system or not, under varying conditions and forecasting uncertainty. The scheduling problem is solved in a receding horizon; as such, the state of the scheduling problem includes past decisions taken in previous time instants. Usually this class of problems is written for positive time only, as if in the presence of a single decision planning window – as opposed to a rolling window – and the details are left to the implementation. The option taken here is to write the scheduling problem with all the details, including the buffers of past decisions, which take into account the non-recourse variables of previously run schedules.

In (1)–(6) the objective function of the scheduling problem is formulated along with the first set of constraints, using the variables defined in the nomenclature. The objective function implements the objective of the system operator, which is to minimize the expenditure in fuel burned by the diesel generators with respect to decision variables (thermal units' start-up, shut-down, and output level given by the piecewise linear heat rate variables; turbines and pumps' turn-on, turn-off and output level. Besides the fuel expenditure, the objective function given in (1) includes the cost for start-up and also the penalizations associated with the slack variables denoting lost load, lost spinning reserve, lost geothermal generation, and lost wind. A penalization for not leaving the reservoir, by the end of the planning window, at the same level as in the beginning of the planning window, is also included in the objective function. In the absence of reservoir inflows and also of a hierarchically higher schedule program, this penalization is used to bring the reservoir level close to its initial value by the end of the planning period.

The model uses stepwise linear costs for the thermal units. Therefore, the objective function in (1) describes the costs in terms of their stepwise linear heat-rate ordinates, their active heat rate linear segments, and their fractions of the heat rate linear segments. Similarly, constraint (2) expresses the power output of the thermal units in terms of their stepwise linear heat rate abscissas, their active heat rate linear segments, and their fractions of the heat rate