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Modelling minimum pressure height in short-term hydropower production planning

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Abstract

When planning the production for certain hydropower plants, minimum pressure is one of the major critical points. Violation of the minimum pressure causes the power plant to automatically shut down, hence violating the obligations of the plant. Automatic pressure switches and pressure constraints are difficult to model in particular when embedded in a complex water way. This problem is expected to increase when retrofitting hydro installations with new parallel units and increased exploitation of inflow resources. From a scheduling point of view, however, such switches become hard to integrate in an optimal operation plan as the constraint depends on the system state. This paper introduces a novelty in short-term production planning, namely a solution for modelling minimum pressure height in regulated watercourses when optimizing the energy production of hydropower plants. This solution is integrated in the short-term hydropower scheduling tool SHOP. The tool finds an optimal strategy to run a power station with such minimum pressure restrictions and the state dependent topological couplings within the water system. We apply the model on a complex topology, the Sira-Kvina water system, where Norway's largest hydropower station *Tonstad Kraftstajon* is operationally subject to this rigorous pressure constraint. First, in order to illustrate the concepts of the model, we apply the model on a simplified water course including one reservoir. Next, the outcome and tests are demonstrated on the final model of two reservoirs whose respective outflows are joining together above the pressure gauge, as found in the Sira-Kvina water system.

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1. Introduction

Nomenclature

h_{rsv}/h_{creek}	Reservoir and creek level at period t [m].
$\Delta h/H_{min}/h_O/h_H$	Head loss / Minimum pressure height / Left reservoir level (here *Ousdalsvann*) / Right reservoir level (here *Homstølvann*) at period t [m].
$\alpha_1/\alpha_2/\alpha_O/\alpha_H$	Head loss coefficient for the tunnel above pressure gauge /above power plant / left above junction / right above junction [$\frac{s}{m^2}$].

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Nomenclature

$q_O/q_H/q_O^i/\ q_H^i$ Tunnel flow for left / right tunnel above junction / Segments for linearisation of q_O / q_H [$\frac{m^3}{s}$].
δ_O/δ_H Binary variable for direction of flow for left / right tunnel above junction at period t.
$Q_{max}/Q/\ q_{cr}$ Maximum discharge through tunnels above junction/ Linearised total discharge through power station / Inflow to creek intake [$\frac{m^3}{s}$].

1.1. Background

SHOP (Short-term Hydro Operation Planning) [1] is a decision support tool for short-term hydro scheduling. The general objective of the program is to utilize the available resources taking into account the physical and technical limitation of the water system. It maximizes the profit of the hydro power company within the given short-term period by exploiting the options for buying and selling in the spot market, while fulfilling firm load obligations. The planning horizon is flexible and can be between one week to 14 days and time resolution is typically one hour.

Being a model in operational use, SHOP has a high level of detail to assess the valuation of system wide capacity allocation as well as correct pricing of energy and cost of power reserves [2]. SHOP is a part of SINTEF Energy Research's state-of-the-art models for hydropower and hydro thermal scheduling and power markets developed over more than 40 years. This includes models that are widely used by players in the Nordic power market [3] which provides SINTEF Energy Research with a broad and thorough understanding of operation research and mathematical programming together with an excellent success rate of establishing new models in the energy sector, such as long-terms models [4], mid-term models [5], short-term models [6], risk management [7]and simulation models.

The SHOP program includes all the main components in hydro production systems including reservoirs, hydro units, discharge gates, junctions, and thermal units. A firm load profile and a day ahead market are also modelled. The reservoirs are the interconnecting elements of a given water course. A reservoir may connect to one or more power station and/or one or more discharge gates downstream. Two reservoirs may supply water to one power station via two interconnected tunnels, a so-called *junction*. In this respect, the pressure balance decides the distribution of water flow between the intake tunnels. The water flow in discharge gates is a decision variable in an optimisation problem and is dependent on the relation between the volume of hydro in reservoir and the water level of the reservoir (*head*).

Topologies of a water systems and power stations are the fundamental elements for the mathematical modelling of the optimization problem in SHOP. Topological couplings within the water system allow alternative strategies on how the water can be managed in each reservoir with respect to inflow, spillage, bypass, and plant discharge. The time couplings within the scheduling period define the water balance in each time step. On the other hand, this results in a large number of equations for each reservoir in every time step during the scheduling period. Some reservoirs can be connected to the power stations through multiple penstocks, with further connections to multiple generators. Friction occurs between the water and the walls in the tunnels and penstocks. Hence head loss is also a variable function that has to be included in the modelling. This can be a complicated task since the head loss is associated with static- and effective plant head.

Head optimization for hydro plants is modelled in SHOP. This is implemented based on optimum calculated energy equivalent resulted from power-discharge curves (PQ-curves). Hence, the PQ-curve is derived from calculations regarding head-loss and efficiency. PQ-curves are an important topic in the essence of short-term hydropower scheduling. In the short-term optimisation of hydro production, the relationship between discharge and production is non-linear and non-convex, depending on the number of units in operation. It gets more complicated since the tunnel and tailrace loss is dependent on the discharge of all units in the plant, while the penstock loss is only dependent on the connected units discharge. The method for handling non-linearities and state dependencies in SHOP is successive linear programming, where the reservoir and production trajectories of the solution of one (mixed integer) linear programming (MI)LP model are used as input to the next (MI)LP call in an iterative procedure. In SHOP, MILP is