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Applying successive linear programming for stochastic short-term hydropower optimization

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ABSTRACT

We present a model for operational stochastic short-term hydropower scheduling, taking into account the uncertainty in future prices and inflow, and illustrate how the benefits of using a stochastic rather than a deterministic model can be quantified. The solution method is based on stochastic successive linear programming. The proposed method is tested against the solution of the true non-linear problem in a principal setting. We demonstrate that the applied methodology is a first-order approximation to a formal correct head-of-water optimization and achieve good results in tests. How the concept of stochastic successive linear programming has been implemented in a prototype software for operational short-term hydropower scheduling is also presented, and the model's ability is demonstrated through case studies from Norwegian power industry. From these studies, improvements occurred in terms of the objective function value and decreased risk of spill from reservoirs.

1. Introduction

In Norway, power supply has traditionally been almost 100% hydropower. Hydropower optimization is challenging, and the main reason is that decisions are coupled in time; the optimization problem includes state-variables such as reservoir levels and stochastic, climate dependent variables where the most important is inflow. Therefore, the full multi-dimensional optimization problem is decomposed into sub-problems. Typically a long-, a medium- and a short-term sub-problem is formulated, where each problem is solved by dedicated solution techniques [1], as illustrated in Fig. 1. This paper presents a model for the short-term optimization of hydropower based on stochastic successive linear programming and illustrates through case studies that the proposed methodology may give improved decision support to producers acting under price and inflow uncertainty, compared to using a deterministic model.

Models for short-term hydropower scheduling have typically focused on the constraints that are important to get feasible or close to feasible generation schedules for the period where the schedules are to be implemented. This period may be different for different systems, and in the Nordic region the watercourses are typically scheduled for the next operating day according to the daily clearing of the day-ahead market. The day-ahead market is the most important market place for power in the Nordic countries with 84% market share in 2013 [2]. Short-term scheduling must consider many constraints due to complex cascaded watercourses, concession rules, shared ownership, multipurpose use, etc., but also technical constraints like startup costs, generation ramping and various market constraints. In Scandinavia, uncertainty in variables such as inflow and market prices are handled by frequent reapplication of models with updated input parameters (also called rolling horizon), or by adding safety constraints that limit the characteristics of optimization models to produce too smart schedules for the hydropower system. The cost of such uncertainty imposed constraints is calculated from sensitivity analyses or based on specific and practical system experience. This works fine as long as some flexibility is available in the hydropower system or in the different markets. The sequential structure of power markets creates needs and opportunities for rescheduling. The volumes offered in the day-ahead spot market reflects expected production for each producer, but these volumes can be adjusted in the intra-day market, Elbas, as new information is revealed over time. In 2013, the total traded volume in the Elspot day-ahead market at Nord Pool was 349 TWh, while the volume traded on Elbas was 4.2 TWh [2]. Producers may also participate in the real-time balancing market for regulating power. In the regulating power market producers bid to sell additional power or buy back power from the market

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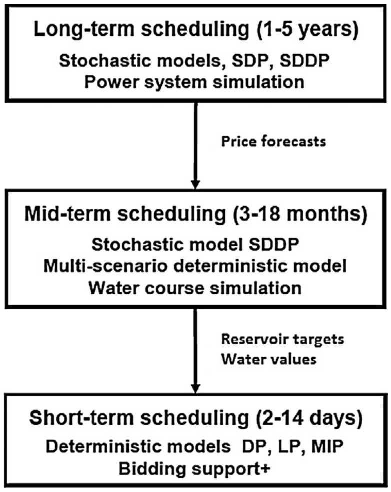

Fig. 1. Hydropower scheduling sub-problems.

in order to maintain the instantaneous balance between supply and demand. Fig. 2 gives an overview of bid and operating hours for the different markets under present organization of markets in Norway.

The behavior of the markets is expected to become much more volatile due to the transition toward more renewable power production in the energy systems. The European Union Renewable Energy Directive 2009/28/EC [3], that was implemented in 2010, define binding targets for 20% renewable contribution to total energy demand by 2020. From January 2012 a joint certificate system was implemented in the Nordic market to ensure development of 26.4 TWh of new renewable energy toward 2020 [4]. To reach European and Nordic targets, intermittent production such as wind- and solar power will play a major role. As a consequence of the increased variability of inter-nordic balancing and regulating power and new cables that are planned from the Nordic system to the rest of Europe, Nordic power prices may also become more volatile in the future. Hydropower producers might then have to use more of the capacity toward the intra-day market or the balancing markets. To optimize production in the future, hydropower utilities must therefore schedule the watercourses in such a way that obligations in several different markets can be honored. The challenge is to maintain flexibility for fast changes in generation levels without increased spillage or efficiency loss, and to decide what part of the capacity to use in what market. This task calls for an explicit representation of the uncertainty of price and resource availability. Continued operation with multiple re-runs or manual rules for maintaining system flexibility is difficult when the boundary conditions are constantly changing, in which case the safety limits should become an integrated part of the operational decisions.

1.1. Short-term hydropower scheduling

The challenge of short-term planning is to handle non-linear and non-convex elements together with state-dependencies. Nonlinearities are present almost everywhere in hydropower modeling, in efficiency curves, reservoir curves, losses and so on. Examples of non-convex elements are minimum generation and spill descriptions. State-dependency also occur several places; water flow through gates and hydraulic connections [5], but regarding overall hydropower efficiency the state-dependency in turbine curves are the most important. Efficiency of hydro turbines depends on head and head depends on reservoirs levels but also discharge dependent losses above and sometimes below the turbine. The head, or pressure height, the coming hour(s) depends on the decision that the operator is making this particular hour. This makes it impossible to build an exact efficiency curve for the turbines for coming hours and in a two-week perspective errors might be large. Different techniques are in use for handling this issue. One method is to apply successive linear programming (SLP) [1,6,7]. This method is implemented in SHOP (Short-term Hydro Optimization Program) [7], which is applied by most large producers in Scandinavia. A large effort has been put into the development of this general hydro-scheduling model so that it includes many details important for Scandinavian watercourses.

Another approach is found in [8]. There the non-linear three-dimensional relationship between the head, the water discharged and the power generated is handled by discretization of a family of non-linear curves. This leads to a mixed-integer linear model that

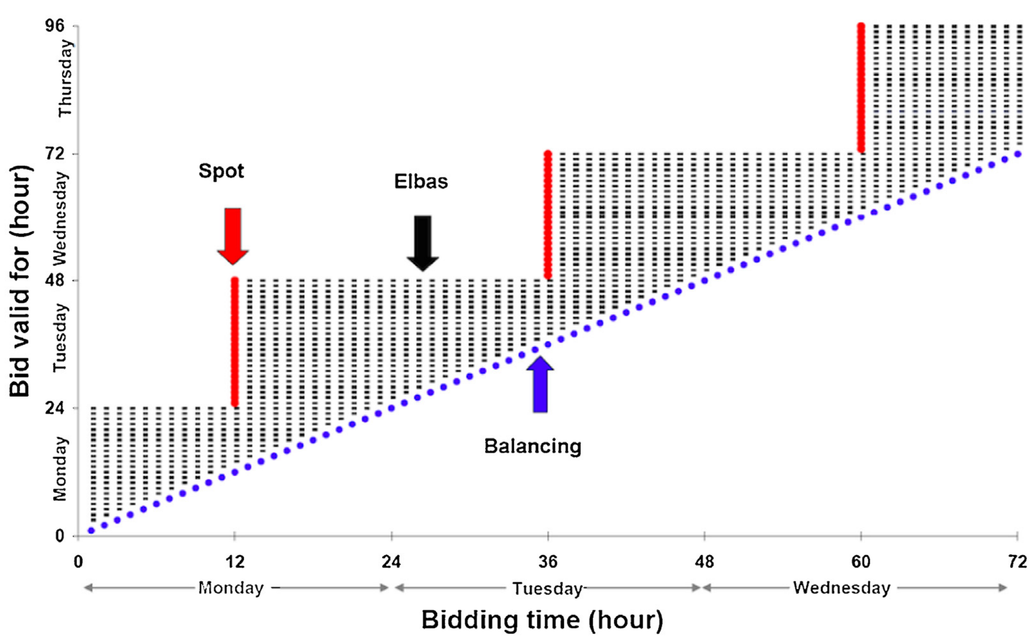

Fig. 2. Hydropower dispatch in the Nordic markets.