Educations on scheduling head-dependent hydro plants under competitive energy market

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Abstract

The paper presents an educational approach for teaching on the optimal management of the water available in hydro plants to convert into electric energy. We combine management knowledge of head-dependent hydro plants with computer simulation methods, based on linear and non-linear network programming, on the assessment of accurate short-term decisions for the hydroelectric energy in light of market conditions. Optimal exploitation of hydro resources for undergraduate power engineering education is important for preparing the future engineers to address the problem on nowadays competitive energy market.

1. Introduction

As the traditional monopolistic scenery for the electric energy makes way to a competitive energy market, an improved scheduling is crucial for generating companies to face competitiveness. In this new competitive environment, a generating company with hydroelectric facilities faces the optimal trade-off problem of how to make the present profit by the management of the water available for power generation without compromising future potential profit.

This problem is known as hydro scheduling. In the short-term, hydro scheduling, STHS, is concerned with the operation during a time horizon of one to seven days, usually discretized in hourly intervals. The problem is treated as a deterministic one. Where the problem includes stochastic quantities, such as inflows to reservoirs or energy prices, the corresponding forecasts are used [1].

Modern computers make linear network programming algorithms widely used for hydro scheduling [2-6]. These algorithms accommodate easily constraints such as the water balance equation and hydro plants limits of operation. In addition, linear network programming algorithms lead to extremely efficient codes, which are commercially available.

Head-dependent hydro plants, due to a non-linear power generation function of water discharge and head, are not proper modelled by linear methods. A non-linear network programming approach is justified for improving the results in hydro plants where the head greatly depends on the storage [7-8].

The optimal exploitation of hydro resources, maximizing the profit of the generating company from selling electric energy, also responds to climate change contributing to reduce fossil fuels energy dependency [9].
In this paper we present an educational approach of conceptually teaching the hydro scheduling problem in the light of market conditions. The approach is based on a computer support and is illustrated by a case study, designed for teaching power engineers in this indubitably important issue to achieve a superiority judgment in the management of head-dependent cascaded hydro plants.

2. Problem formulation

The STHS problem is stated as to find out the water discharges, $q_{ik}$, the water storages, $v_{ik}$, and the water spillages, $s_{ik}$, for each reservoir, $i = 1, \ldots, I$, at each scheduling time periods, $k = 1, \ldots, K$, over the time horizon considered, that optimise a performance criterion subject to the operational and physical constraints. Normally, the water storages at the end of the time horizon, $v_{ik}$, are valued for future operation use.

In the STHS problem under consideration the performance criterion, the objective function, is a measure of the benefit obtained by the conversion of potential energy of the water available in the reservoirs into electric energy. The maximum of this objective function, satisfying all physical and operational constraints, is a blend of the benefit of the hydroelectric power generation due to discharges throughout the time horizon and the future benefit of the water left at the last period. Equation (1) shows our objective function blending these two benefits. The objective function is composed of two terms. The first term expresses the economic value of the future use of the water stored in the reservoirs at the last period, $\Psi_1$. This term is considered if no final water storage requirement is specified as a constraint. The last term represents the profit with the hydro chain during the short-term time horizon, where $\pi_k$ is the forecasted energy price at period $k$ and $p_{ik}$ is the power generation of plant $i$ during period $k$. In mathematical programming the STHS problem can be formulated as to maximize

$$J = \sum_{i=1}^{I} \Psi_1 (v_{ik}) + \sum_{i=1}^{I} \sum_{k=1}^{K} \pi_k p_{ik} \tag{1}$$

Subject to:

Water conservation equation for each reservoir.

$$v_{ik} = v_{i,k-1} + a_{ik} - q_{ik} - s_{ik} + q_{i-1,k} + s_{i-1,k} \tag{2}$$

Power generation equation.

$$p_{ik} = q_{ik} (\alpha_i h_{ik} + \eta_{io}) \tag{3}$$

Head equation.

$$h_{ik} = l_{ik} - l_{i+1,k}, \quad i = 1, \ldots, I, \quad k = 1, \ldots, K \tag{4}$$

Water storage constraints.

$$v_{i}^{\min} \leq v_{ik} \leq v_{i}^{\max} \quad i = 1, \ldots, I, \quad k = 1, \ldots, K \tag{5}$$

Water discharge constraints.

$$0 \leq q_{ik} \leq q_{i}^{\max} \quad i = 1, \ldots, I, \quad k = 1, \ldots, K \tag{6}$$

Water spillage constraints.

$$s_{ik} \geq 0, \quad i = 1, \ldots, I, \quad k = 1, \ldots, K \tag{7}$$

The optimal value of the objective function given by (1) is subject to constraints of two kinds: equality constraints and inequality constraints or simple bounds on the variables. Equation (2) is the water conservation equation for each reservoir and assumes that the water discharge from any upstream reservoir flows directly into the succeeding downstream reservoir with no time lag, where $v_{ik}$ is the water storage of reservoir $i$ at end of period $k$, $a_{ik}$ the natural inflow to reservoir $i$ during the period $k$, $q_{ik}$ the water discharge of plant $i$ during the period $k$, and $s_{ik}$ the water spillage by reservoir $i$ during the period $k$. Although the water travel times or the water time-delays between cascaded reservoirs have not been considered, these can be easily taken into account if necessary. Equation (3) gives the power generation, $p_{ik}$, considered a
function of water discharge and of the head, \( h_{ik} \). Equation (4) gives the head as a
difference between the water levels in the
upstream reservoir, \( l_{i,k} \), and the
downstream reservoir, \( l_{i+1,k} \), depending on
the water storages in the respectively
reservoirs. Equations (5) and (6) are lower
and upper bounds for the water storage and
the water discharge. Here for each reservoir
\( i \), \( v_{i}^{\text{max}} \) is the maximum storage, \( v_{i}^{\text{min}} \) the
minimum storage, \( q_{i}^{\text{max}} \) the maximum
discharge. In (7) only a null lower bound is
considered for water spillage. The rest of the
data, \( \alpha, \eta, \beta, l_{0} \) are parameter for the
head-dependent hydro plants.

3. Case study

The short-term hydro scheduling problem
is guided by the energy prices forecasted for
the time horizon.

The goal is to maximize the profit of the
generating company from selling electric
energy in the energy market. We consider
the optimal schedule for three cascaded
hydro plants in the energy market, during a
time horizon of 168 hours.

The initial and the final water storages
are 80% of the maximum storage for each
reservoir.

The number of the variables for the
problem, defining the size of the problem,
can be determined as three times the
number of reservoirs multiplied by the
number of scheduling time periods. For the
case study used in this paper, the problem
size is \( 3 \times 3 \times 168 \) therefore exists 1512
variables.

Normally, water spillage by the reservoirs
occurs when without it the water storage
exceeds its upper bound, so spilling is
necessary to avoid damage. The case study
is shortage of water scenery so no spillage
was necessary.

Figure 1. Short-term schedule for the LP and NLP approach.
There is only natural inflows, ‘a₁’, on the first reservoir in this case study. For the first reservoir, Figure 1., the linear programming results show that the water discharge starts immediately with the price increase. The discharge changes from a null value quickly to the maximum value. While the non-linear programming results show that the discharge is postponed in order to reach a proper head. The discharge over the horizon is the same; it is equal to the total inflow during the week. Table 1 shows a comparison between the linear and non-linear programming results.

Table 1. Linear and non-linear results.

<table>
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<tr>
<th>Method</th>
<th>Average [MWh]</th>
<th>Profit [€]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LNP</td>
<td>19091</td>
<td>592295</td>
</tr>
<tr>
<td>NLNP</td>
<td>20121</td>
<td>626447</td>
</tr>
</tbody>
</table>

Therefore, with non-linear programming we have a 5.8% increase on total profit.

4. Conclusion

This paper deals with an educational approach for instruction on management of hydro plants in power systems engineering, considering head-dependency in the short-term schedule of the plants. Reservoirs should operate at a proper level of storage to benefit power generation efficiency, giving a higher profit. The students with the help of an optimisation solver can easily program this approach and put together several conclusions, regarding a better management of the water available in the reservoirs.

References


