POWER GENERATION EFFICIENCY IMPROVEMENT IN CASCADED AND HEAD-DEPENDENT RESERVOIRS

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Abstract – This paper is on the problem of short-term hydro scheduling (STHS), particularly concerning cascaded and head-dependent reservoirs. We propose an efficient method, based on nonlinear programming (NLP), for power generation efficiency improvement. This method considers hydroelectric power generation as a function of water discharge and also of the head. The proposed method provides higher profit for the generating company (GENCO), at a negligible extra computational effort, in comparison with classical optimisation methods based on linear programming (LP) that ignore head dependence.

Keywords: Hydro scheduling, Head dependence, Nonlinear programming

1 INTRODUCTION

In a competitive electricity market, the optimal management of the water available in the reservoirs for power generation, without affecting future operation use, represents a major advantage for generating companies (GENCOs). The goal is to maximize the value of total hydroelectric generation throughout the time horizon considered, satisfying all hydraulic constraints, and consequently to maximize the profit of the GENCO from selling energy. This problem is known as hydro scheduling.

Short-term hydro scheduling (SHTS) 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 [1,2].

In hydro plants with a small storage capacity available, known as run-of-the-river hydro plants, the power generation efficiency depends on the head — head change effect. The efficiency may be defined as the ratio of the total actual gross hydro energy output to the total potential energy contained in the water discharged through the turbines [3]. Significant loss of efficiency can occur in operating hydro plants away from their most efficient operating point. Moreover, a cascaded hydraulic configuration implies spatial-temporal coupling among reservoirs. The head change effect together with the cascaded hydraulic configuration tends to give to the problem complexity and large dimension.

Under a competitive environment, the development of new STHS models, promoting the improvement of hydro resources exploitation efficiency, is needed.

Dynamic programming (DP) is among the earliest methods applied to the STHS problem [4]. Although DP can handle the nonlinear characteristics present in the hydro model, direct application of DP methods for hydro systems with cascaded reservoirs is impractical due to the well-known curse of dimensionality, since the computational burden increases exponentially with problem dimension.

A natural approach is to model the system as a network flow model, because of the underlying network structure subjacent in cascaded reservoirs. The network flow model is often simplified to a linear or piecewise linear one [5]. Linear programming (LP) is a widely used method for STHS. LP algorithms lead to extremely efficient codes, implementations of which can be found commercially [6]. Also, mixed-integer linear programming (MILP) is becoming frequently used for hydro scheduling [7], where binary variables allow modelling of start-up costs which are mainly caused by the increased maintenance of windings and mechanical equipment and by malfunctions of the control equipment [8]. However, LP typically considers that power generation is linearly dependent on water discharge, thus neglecting head dependence to avoid nonlinearities, leading to inaccuracies. Also, the discretization of the nonlinear dependence between power generation, water discharge and head, used in MILP to model head variations, augment the computational burden required to solve this problem.

A nonlinear model has advantages compared with a linear one. This model expresses hydro generation characteristics more accurately and the head change effect can be taken into account [9,10]. For every plant, the nonlinear dependence between the power generation, the water discharge and the head is taken into account through the nonlinear formulation.

The Portuguese fossil fuels energy intensity, in particular, is among the highest in the European Union. Hence, in order to decrease fossil fuel energy intensity, enhancements particularly in the exploitation of the hydro resources are important. In general, promoting power generation efficiency improvement in cascaded and head-dependent reservoirs, thus maximising the profit of the GENCO, also responds to climate change contributing to reduce fossil fuels energy intensity.

This paper proposes a nonlinear programming (NLP) method to solve the STHS problem considering head dependence. The results are obtained on a realistic case study, with three cascaded reservoirs.

2 FORMULATION

The STHS problem is formulated as a NLP problem. The objective function to be maximized can be expressed as:

$$\sum_{k=1}^{K} \sum_{j=1}^{J} \lambda_k \, p_{kj} + \sum_{j=1}^{J} \Psi_j (v_{Kj}) \qquad (1)$$

The objective function in (1) is composed of two terms. The first term represents the profit with the hydro system during the short-term time horizon, where λ_k is the forecasted energy price during period *k* and p_{kj} is the power generation of plant *j* during period *k*. The last term expresses the future value, Ψ_j, of the water stored in the reservoirs at the last period, v_{Kj}. This term is considered if no final water storage requirement is specified as a constraint.

The optimal value of the objective function is determined subject to constraints of two kinds: equality constraints and inequality constraints or simple bounds on the variables. The following equations represent the set of constraints related to every plant over the short-term time horizon.

1) Water Balance:

$$v_{kj} = v_{k-1,j} + a_{kj} + \sum_{m \in M_j} (q_{k-\tau_{mj},m} + s_{k-\tau_{mj},m}) - q_{kj} - s_{kj} \quad \forall k \in K \quad \forall j \in J \qquad (2)$$

2) Power Generation Equation:

$$p_{kj} = q_{kj} \, \eta_{kj} (h_{kj}) \quad \forall k \in K, \quad \forall j \in J \qquad (3)$$

3) Head Equation:

$$h_{kj} = l_{kf(j)} (v_{kf(j)}) - l_{kt(j)} (v_{kt(j)}) \quad \forall k \in K \quad \forall j \in J \qquad (4)$$

4) Water Storage Constraints:

$$v_j^{\min} \le v_{kj} \le v_j^{\max} \quad \forall k \in K, \quad \forall j \in J \qquad (5)$$

5) Water Discharge Constraints:

$$q_j^{\min} \le q_{kj} \le q_j^{\max} (h_{kj}) \quad \forall k \in K, \quad \forall j \in J \qquad (6)$$

6) Water Spillage Constraints:

$$s_{kj} \ge 0 \quad \forall k \in K, \quad \forall j \in J \qquad (7)$$

The water balance equation for each reservoir is given in (2), where v_{kj} is the water storage of reservoir *j* at end of period *k*, a_{kj} is the natural inflow to reservoir *j* during the period *k*, q_{kj} is the water discharge of plant *j* during the period *k*, s_{kj} is the water spillage by reservoir *j* during the period *k*, τ_{mj} is the water travel delay between reservoirs *m* and *j*, *K* is the total number of hours in the scheduling time horizon, *J* is the total number of hydro resources and M_j is the set of reservoirs upstream to reservoir *j*. In (3) power generation, p_{kj}, is considered a function of water discharge, q_{kj}, and of efficiency, η_{kj}, expressed as the output-input ratio, which in turn depends on the head, h_{kj}. In (4) the head, h_{kj}, is considered a function of the water levels in the upstream reservoir $f(j)$, $l_{kf(j)}$, and of the downstream reservoir $t(j)$, $l_{kt(j)}$, depending on the water storages in the respectively reservoirs. In (5) water storage has lower and upper bounds. Here, for each reservoir *j*, $v_j^{\max}$ is the maximum storage and $v_j^{\min}$ is the minimum storage. In (6) a null lower bound is considered for water discharge, having only upper bound. Here, $q_j^{\max}$ is the maximum water discharge, considered as head-dependent. In (7) a null lower bound is considered for water spillage. Water spillage by the reservoirs can occur when without it the water storage exceeds its upper bound, so spilling is necessary to avoid damage. The initial water storages, v_{0j}, and the inflows to reservoirs, a_{kj}, are assumed known.

3 THE PROPOSED NLP METHOD

In order to solve the STHS problem, it is essential to use appropriate models. In run-of-the-river hydro plants, these models should consider power generation as a function of water discharge and also of the head. This relationship is represented by the unit performance curves, a family of nonlinear and nonconcave curves, each for a specified value of the head, as shown in Figure 1.

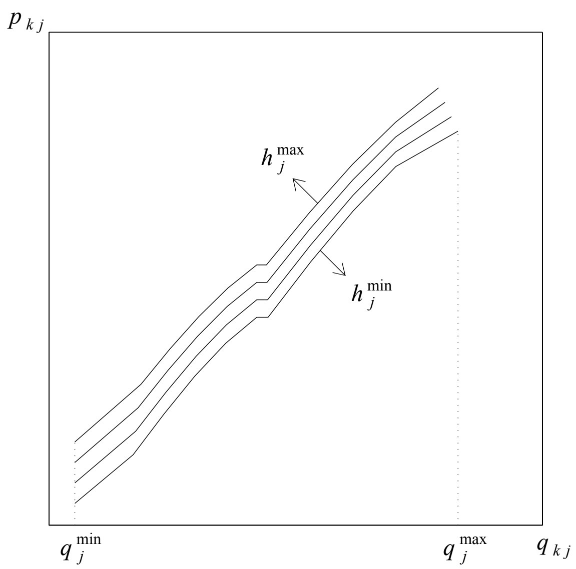

Figure 1: Unit performance curves.

In our optimisation model, the effect of the variation of the head is considered.

In (3) the efficiency depends on the head. Assuming a linearization of this efficiency in plants we have:

$$\eta_{kj} = \eta_j^0 + \alpha_j h_{kj} \quad \forall k \in K, \quad \forall j \in J \qquad (8)$$

In (4) the water level depends on the water storage. Assuming linearization of the water level in reservoirs we have:

$$l_{kj} = l_j^0 + \beta_j v_{kj} \quad \forall k \in K, \quad \forall j \in J \qquad (9)$$

This linearization implies reservoirs with vertical walls, which is a good approximation for run-of-the-river reservoirs as our data have shown for the realistic case study.

Substituting (8) into (3) we have:

$$p_{kj} = q_{kj}(\eta_j^0 + \alpha_j h_{kj}) \quad \forall k \in K, \quad \forall j \in J \quad (10)$$

By substituting (4) and (9) into (10) power generation becomes a nonlinear function of water discharge and water storage, given by:

$$p_{kj} = \eta_j^0 q_{kj} + \alpha_j l_{f(j)}^0 q_{kj} - \alpha_j l_{t(j)}^0 q_{kj}$$
$$+ \alpha_j \beta_{f(j)} q_{kj} v_{kf(j)}$$
$$- \alpha_j \beta_{t(j)} q_{kj} v_{kt(j)}$$
$$\forall k \in K, \quad \forall j \in J \qquad (11)$$

The main contribution of this paper is that the maximum water discharge, and thus the maximum power generation, is also considered head-dependent, as shown in (6). In [10], the maximum water discharge in each plant was considered constant and associated with the minimum head of the plant, which may lead to inaccuracies.

Therefore, in this paper, we have:

$$q_j^{\max} = q_j^0 + \delta_j h_{kj} \quad \forall k \in K, \quad \forall j \in J \qquad (12)$$

By substituting (4) and (9) into (12) we have:

$$q_j^{\max} = q_j^0 + \delta_j l_{f(j)}^0 - \delta_j l_{t(j)}^0$$
$$+ \delta_j \beta_{f(j)} v_{kf(j)}$$
$$- \delta_j \beta_{t(j)} v_{kt(j)}$$
$$\forall k \in K, \quad \forall j \in J \qquad (13)$$

The maximum water discharge becomes a function of water storage, given by:

$$q_j^{\max} = \gamma_j^0 + \gamma_j^1 v_{kf(j)} - \gamma_j^2 v_{kt(j)}$$
$$\forall k \in K, \quad \forall j \in J \qquad (14)$$

Therefore, maximum water discharge by plants depends on the water volumes of the reservoirs upstream and downstream to the plant.

4 CASE STUDY

The proposed NLP method, considering the head change effect, has been applied on a cascaded hydro system based on a realistic case study. The spatial coupling among reservoirs is depicted in Figure 2.

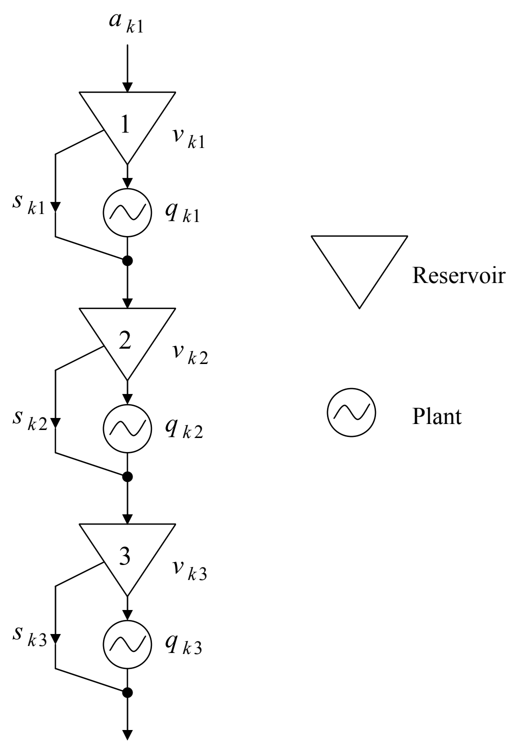

Figure 2: Hydro system with three cascaded reservoirs.

This case study consists of three cascaded reservoirs with natural inflow only on the first reservoir shown in Figure 3.

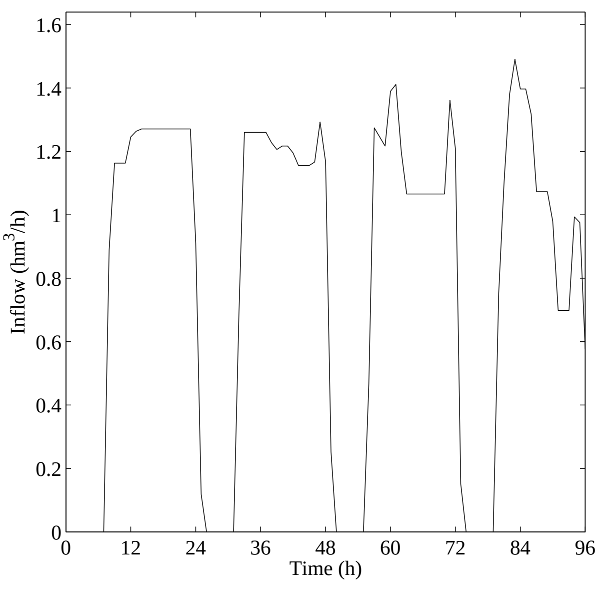

Figure 3: Natural inflow on the first reservoir.

The model developed was implemented on a 1.6-GHz-based processor with 512 MB of RAM using optimisation package MINOS under FORTRAN. The scheduling time horizon chosen is four days divided into 96 hourly periods. The considered energy price profile over the time horizon is shown in Figure 4 (where $ is a symbolic economic quantity).

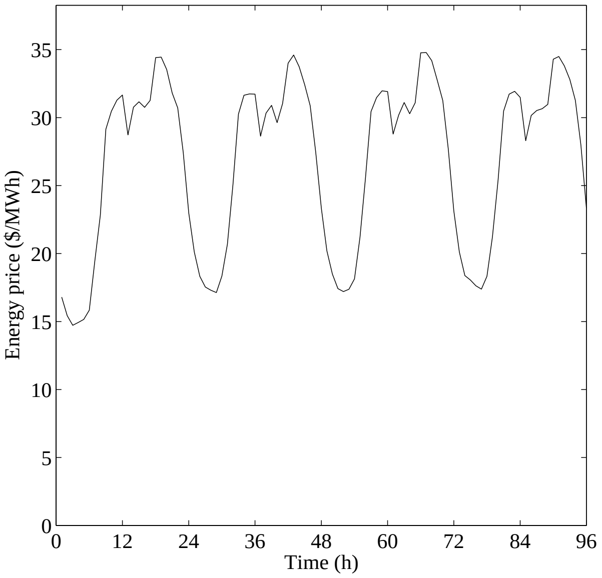

Figure 4: Energy price profile considered.

In this realistic case study the time delay between any connected reservoirs is negligible. The final water storage in reservoirs is constrained to be equal to the value at the beginning of the scheduling horizon. Consequently, the future value of the water stored in reservoirs is not considered. Figure 5 shows the computed 96-hours water volumes of all reservoirs.

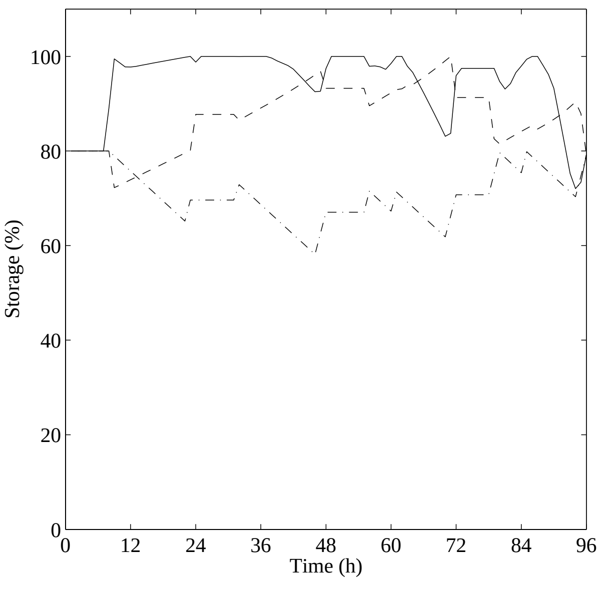

Figure 5: Water volume of all reservoirs. The solid line denotes reservoir 1 results, the dashed line denotes reservoir 2 results and the dash-dot line denotes reservoir 3 results.

Considering the head change effect, the reservoirs operate at an appropriated high storage level in order to achieve the most benefiting point of the overall efficiency for the conversion of potential energy of the water into electric energy. The storage trajectories of the first and second reservoirs are pulled up, opposing to the change in the third reservoir. This behaviour is in favour of the overall power generation efficiency thereby yielding an increase on total profit for the GENCO. Figure 6 shows the computed 96-hours water discharge of all plants.

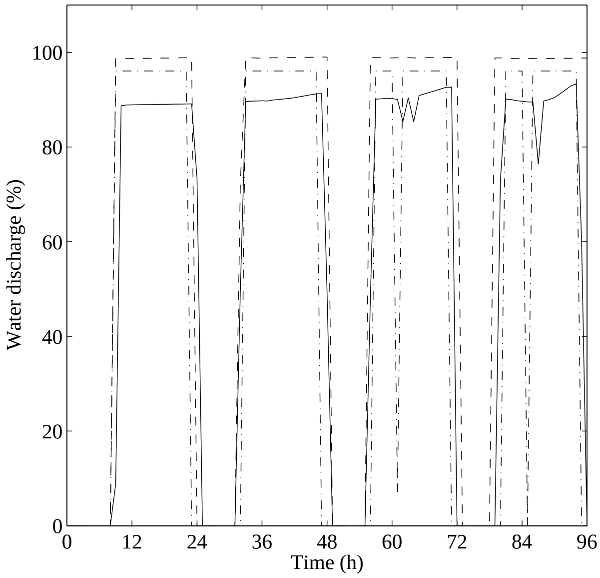

Figure 6: Water discharge of all plants. The solid line denotes plant 1 results, the dashed line denotes plant 2 results and the dash-dot line denotes plant 3 results.

In Figure 6 the power generation in the first reservoir, using NLP and considering the head change effect, is postponed in order to quickly reach an appropriated higher storage level.

It should be noted that the water discharge and consequently the hydro production follows the shape of the price profile in Figure 4.

With NLP and considering the head change effect, the optimal value of the objective function is $1198580, corresponding to a 4.79% increase on the total profit in comparison with a LP method. The CPU computing time for this case study was about 0.5 s.

5 CONCLUSION

The new environment of competitive electricity markets for energy requires new computing tools to allow generating companies to achieve improvement on power generation efficiency, which is crucial to face competitiveness. A generating company should not ignore the head change effect for cascaded and head-dependent reservoirs in order to improve power generation efficiency. This effect implies not only a nonlinear dependence between the power generation, the water discharge and the head, but also implies that the maximum water discharge, giving the maximum power generation, is a function of the head. This paper proposes a nonlinear model for cascaded and head-dependent reservoirs in order to consider the head change effect. This model has been successfully tested on a realistic case study by comparing the nonlinear programming results with linear programming results. The results are in favour that a higher profit is achieved with nonlinear programming at a negligible computation CPU time.

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