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Scheduling of Head-Sensitive Hydro Plants under Profit-Based Environment for Power Engineering Education

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Abstract: - This paper presents an educational approach for teaching on the optimal management of the water available in hydro plants to convert into electric energy. Particularly, in this paper we combine management knowledge of head-sensitive 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, article of trade, under profit-based environment. Under profit-based environment, the optimal scheduling of the hydroelectric facilities available is essential for generating companies to face competitiveness. Moreover, also responds to climate change contributing to reduce fossil fuels energy dependency. Hence, presenting concerns on the 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.

Key-Words: - Hydro scheduling, head dependency, competitive energy market, optimization methods

1 Introduction

As the traditional monopolistic scenery for the electric energy makes way to a competitive energy market, an improved operational planning is crucial for generating companies to face competitiveness toning to the best profit perspective.

In this new profit-based 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. 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 generating company from selling electric energy. This problem is known as hydro scheduling.

Short-term hydro scheduling 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.

Hydro plants with only a small storage capacity available are known as run-of-the-river. Due to the small storage capacity, the operating efficiency becomes sensitive to the head — head change effect. Significant loss of efficiency can occur in operating hydro plants away from their most efficient operating points. Therefore, head dependency has to be considered within the scheduling algorithm in order to obtain accurate and realistic results.

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

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In general, promoting the optimal exploitation of hydro resources, maximizing the profit of the generating company from selling electric energy, also responds to climate change contributing to the reduce fossil fuels energy dependency [9-10].

In this paper we present an educational approach for conceptually teaching the hydro scheduling problem in light of market conditions. The approach is based on computer support simulation and is illustrated by a case study, designed for teaching power engineers in this indubitably important issue to achieve a superiority judgment in head-sensitive hydro plants.

2 Hydroelectric Energy

Electric energy is an article of trade with special characteristics in order to be valuable to mankind. The operation of an energy system has to be conveniently managed in a way such that the conversion into the electric form when required is available for the several needs of the human civilization. The aim of achieving rationality decisions for this conversion and the best efficiency is indubitably necessary to the development and progress of mankind. Computer simulation is important to achieve a superiority judgment in governing this important conversion.

The term hydroelectric energy has been particularly used to express energy of the water falling in rivers. Normally, the water is harnessed in dams, artificial lakes or damming rivers, storing the water and raising the height of the water to increase power output. The water in the dams is drafted through a pipe, the penstock, into the hydraulic turbine, converting the energy of the water under pressure into mechanical energy in the rotating shaft, further converted in the electric generator into electric energy. Finally, the water leaves the turbine through a draft tube if the turbine is submerged in the water or through a tailrace if the turbine operates in the air.

Besides power generation, hydro plants may be used for storing water for domestic, industrial or irrigation use, controlling river floods or saline intrusion in a river estuary, nautical sports, and leisure.

In what regards the water storage capacity, hydro plants may be: run-of-the-river hydro plants, when only a small storage capacity is available; storage hydro plants, when a considerable storage capacity is available, that is, when changing the natural regime of flows in a river by storing the flows for use in a more advantageous conditions is possible; storage and pumping hydro plants, when, besides storage capacity, they are able to launch the water into the upstream reservoir. Pumping is used when it is economic defensible, during periods posing less profitable conditions, to launch the water at a higher level for using during periods posing more profitable conditions.

Furthermore, the hydraulic configuration may be: a cascade one, when the water discharged throw the hydro plant or spilled from the dam goes into the downstream dam, that is, when we have reservoirs with dependent affluences from the upstream reservoir; an independent one, when each reservoir is hydraulically separated of others, but may be interlinked through the electric network.

Historically, the operation of conversion into electric energy was not always based on large state owned monopolies; small private companies accomplished the beginning of electric energy distribution. Large state-owned monopolies appeared only after the Second World War and were supported by the judgement that electric energy systems were a monopolistic type industry. However, in nowadays, that is pass judgment on this type of industry, leading to the return to the idea of privatisation and liberalisation. Privatisation and liberalisation are frequently coupled for the reason that liberalisation is not as much effective without privatisation. It is not easy for governments as energy enterprise owners to refuse to go along with pressures happening for social and labour reasons to make use of market power. Hence, privatising is important for a proper operation of a market.

Privatisation and liberalisation give raise to private companies competing with each other in the energy markets. European Union started is way to the internal market for electric energy following the Directive 96/92/EC to be put into action by February 1999, but due to unsatisfactory aspects it was not implemented. Hence, the European Council in Lisbon 2000 called for rapid work to be undertaken in order to complete the internal market of energy and to speed up liberalization for achieving a fully operational internal market. Finally, directive 2003/54/EC established new rules for this internal market.

A hydroelectric facility is a complex system. Nowadays, the possibility that the consumer has to choose the electricity supplier brought even more complexity to the management of a hydroelectric facility. Management has to decide what to do with the inflows and the water stored in reservoirs, considering system complexity, in order to put on the market a successful bid, reaching a profit in the present without compromising future potential profit.

3 Problem Formulation

The short-term hydro scheduling problem is guided by the energy prices forecasted for the time horizon. The objective function of our problem is the profit of the generating company from selling electric energy in the day-ahead market. In what follows we use the following notation.

I - Set of indices i for the hydro plants.

K - Set of indices k for the hours in the time horizon.

a_{ik} - Inflow to reservoir i in hour k.

s_{ik} - Water spillage of plant i in hour k.

q_{ik} - Water discharge of plant i in hour k.

v_{ik} - Water storage in reservoir i at end of hour k.

h_{ik} - Head of plant i in hour k.

λ_k - Forecasted energy price in hour k.

p_{ik} - Power generation of plant i in hour k.

Ψ_i - Future value of the water stored in reservoir i.

V_{ik} - Set of admissible v_{ik} for plant i.

Q_{ik} - Set of admissible q_{ik} for plant i.

S_{ik} - Set of admissible s_{ik} for plant i.

The objective function to be maximized can be expressed as

$$\sum_{i=1}^{I}\sum_{k=1}^{K} \lambda_k \, p_{ik}(q_{ik}, h_{ik}) + \sum_{i=1}^{I} \Psi_i(v_{iK}) \qquad (1)$$

The first term is related to the revenues of each hydro plant during the short-term time horizon, where the power generation is considered a function of water discharge and also of the head. The last term expresses the future value of the water stored in the reservoirs.

The optimal value of the objective function is determined subject to constraints. The constraints are of two kinds: equality and inequality constraints.

The equality constraints, corresponding to the water conservation equation for each reservoir, are formulated as

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

assuming that the time required for water to travel from a reservoir to a reservoir direct downstream is less then the scheduling time period.

The inequality constraints, corresponding to the simple bounds on the variables, are formulated as

$$v_{ik} \in V_{ik} = [v\min_i, v\max_i] \quad i \in I \;\; k \in K \qquad (3)$$

$$q_{ik} \in Q_{ik} = [q\min_i, q\max_i] \quad i \in I \;\; k \in K \qquad (4)$$

$$s_{ik} \in S_{ik} = [0, v_{ik} - v\min_i] \quad i \in I \;\; k \in K \qquad (5)$$

Reservoirs water storage and plant water discharge have lower and upper bounds. Spillage can occur when without it the water storage exceeds its upper bound, so spilling is necessary to avoid damage.

4 Case Study

We consider the optimal schedule for one hydro plant in the day-ahead electricity market, that is, during a time horizon of 24 hours.

The forecasted energy price considered is shown in Fig. 1, where $ is a symbolic quantity.

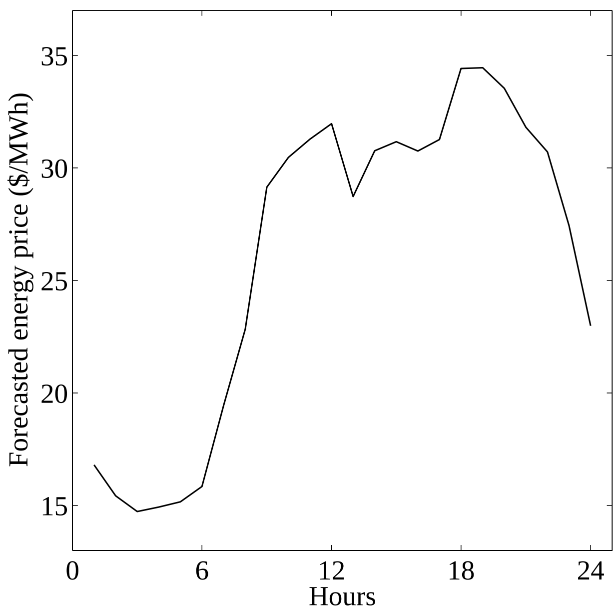

Fig. 1 Forecasted energy price.

The inflow to the reservoir is considered constant during the time horizon. Also, minimum water discharge is zero. Final water storage in the reservoir is constrained, chosen to be equal to the value at the beginning of the scheduling horizon at 70% of the maximum storage. Consequently, the future values of water stored in reservoirs are not considered in this case study.

In Table 1 we show linear network programming results for hydro scheduling, ignoring head dependency, and in Table 2 we show non-linear network programming results for hydro scheduling.

Hours	Discharge [%]	Storage [%]	Energy [MWh]
1	0.00	70.00	0.00
2	0.00	72.61	0.00
3	0.00	75.22	0.00
4	0.00	77.83	0.00
5	0.00	80.43	0.00
6	0.00	83.04	0.00
7	0.00	85.65	0.00
8	0.00	88.26	0.00
9	0.00	90.87	0.00
10	0.00	93.48	0.00
11	0.00	96.09	0.00
12	100.00	83.70	185.76
13	0.00	86.30	0.00
14	0.00	88.91	0.00
15	0.00	91.52	0.00
16	0.00	94.13	0.00
17	0.00	96.74	0.00
18	100.00	84.35	186.37
19	100.00	71.96	174.89
20	100.00	59.57	163.42
21	0.00	62.17	0.00
22	0.00	64.78	0.00
23	0.00	67.39	0.00
24	0.00	70.00	0.00

Table 1 Linear network programming results for hydro scheduling.

Hours	Discharge [%]	Storage [%]	Energy [MWh]
1	0.00	70.00	0.00
2	0.00	72.61	0.00
3	0.00	75.22	0.00
4	0.00	77.83	0.00
5	0.00	80.43	0.00
6	0.00	83.04	0.00
7	0.00	85.65	0.00
8	0.00	88.26	0.00
9	0.00	90.87	0.00
10	0.00	93.48	0.00
11	0.00	96.09	0.00
12	22.80	95.28	44.79
13	0.00	97.88	0.00
14	3.29	100.00	6.61
15	18.25	99.87	36.64
16	16.53	100.00	33.20
17	17.39	100.00	34.93
18	81.47	90.39	156.39
19	100.00	78.00	180.49
20	84.96	67.86	145.38
21	39.79	64.50	66.84
22	15.51	64.78	26.10
23	0.00	67.39	0.00
24	0.00	70.00	0.00

Table 2 Non-linear network programming results for hydro scheduling.

In Fig. 2 we show plant water discharge, bar plot, and reservoir water storage, line plot, during the time horizon, using linear network programming.

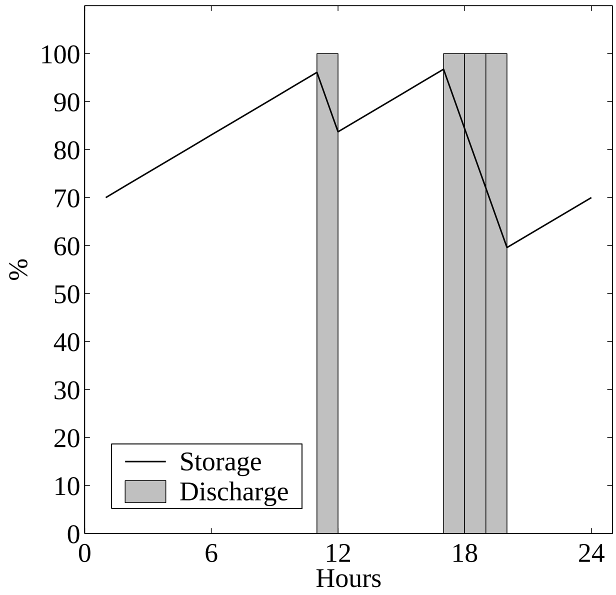

Fig. 2 Discharge and storage with linear network programming.

In Fig. 3 we show plant water discharge, bar plot, and reservoir water storage, line plot, during the time horizon, using non-linear network programming.

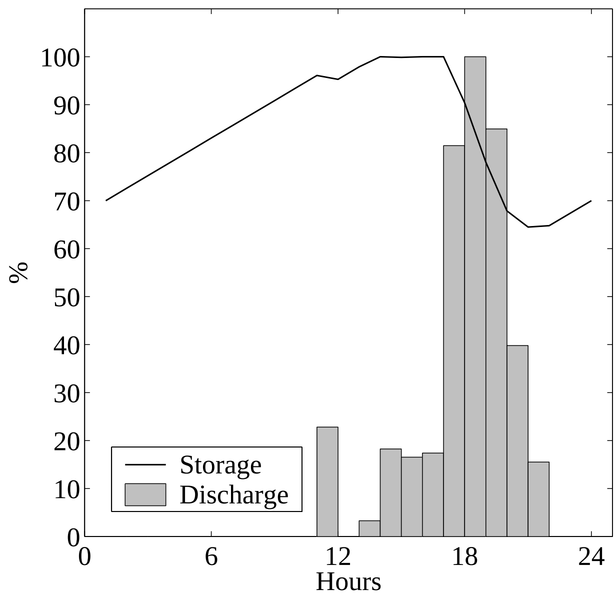

Fig. 3 Discharge and storage with non-linear network programming.

The linear network programming results show that plant water discharge change from the minimum value, zero, quickly to the maximum value while the non-linear network programming results show that the hydroelectric generation is postponed in order to quickly reach high reservoir water storage levels.

The optimization process with non-linear network programming maintains an appropriated water storage level in the reservoir in order to benefit efficiency, as opposed to the optimization process with linear network programming.

To compare linear with non-linear network programming, the main results are given in Table 3.

Method	Average Discharge	Average Storage	Average Energy	Total Profit
	[%]	[%]	[MWh]	[$]
LNP	16.67	80.63	29.60	23859
NLNP	16.67	83.73	30.47	24295

Table 3 Comparison between linear and non-linear network programming results.

As we can see in Table 3, the average discharge is as expected the same with both optimization methods but the average storage is superior with non-linear network programming. Thus, with non-linear network programming we have a larger total profit for the generating company, almost 2%, with negligible additional CPU time required.

5 Conclusion

This paper deals with an educational approach for instruction on management of hydro plants in power engineering, considering head-dependency in the short-term schedule of the plants.

In a competitive energy market, generation companies have to maximize their profits selecting the best strategy. The schedule is formulated as an 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.

Comparison between traditional linear network programming scheduling that ignores head dependency, with the non-linear one, reveals that reservoirs should operate at an appropriated storage level to benefit power generation efficiency, giving a higher global profit for the generation company with negligible extra CPU-time required.

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