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Optimal Generation Scheduling of Hydropower Plant with Pumped Storage Unit

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Abstract

The generation scheduling problem of hydropower plant in the presence of pumped storage unit is complex. This work has proposed a solution strategy to determine the optimum generation based on the analysis of hourly and annual generation costs. The hourly and annual costs are linear functions of power output and energy generation, respectively. The power output was formulated as a linear function of hydraulic head and discharge rate, without computing the conversion efficiency from a hill diagram. The mathematical relationships between power, hydraulic head, and discharge rate can be determined from loading & efficiency test data and validated by using a field test. The optimum generation was stated as capacity factor and varied with water drawdown of the plant. The optimum time interval and duration of the pumped storage unit can be determined by analyzing the hourly marginal operating costs, simplified by using a composite cost function. The proposed strategy has been simulated with the generation data of the Bhumibol hydropower plant.

Keywords: generation scheduling, hydropower plant, pumped storage

1. Introduction

Hydropower in Thailand is roughly 10% of generation capacity, accounting for 5% of annual generation (Electricity Generating Authority of Thailand, 2012). The hydropower generation in Thailand serves as a peak shaving given that water resource is limited.

The Electricity Generating Authority of Thailand (EGAT) has installed 171-MW pumped storage unit at the Bhumibol hydropower plant, 2x180-MW pumped storage units at Sri Nagarind hydropower plant, and 4x250-MW pumped storage units at the Lam Takong hydropower plant.

A pumped storage unit requires two reservoirs. During periods of high demand (daytime), water is released from the upper reservoir to generate electricity. Conversely, water is pumped from the lower reservoir during periods of low demand (nighttime). In so doing, the marginal operating costs during the low-demand periods must be economically lower than the marginal operating costs during the high-demand periods, given that there are energy losses in the transformation process as shown in Figure 1. Thus, the hourly marginal operating costs are the key determinants of whether pumped storage operation would be economical.

Pumped storage unit can be either reversible hydro turbine or separated generating and pumping equipment. Pumping energy can be supplied by either external grid or another unit of the plant.

The planning and scheduling problems of pumped storage unit are extensive and complex in response to the increasing penetration of intermittent operation of renewable resources. Those problems investigated reservoir size, cycle efficiency, plant characteristics [Galloway & Ringlee, 1966; McDaniel & Gabrielle, 1966; Cohen and Wan, 1985) load characteristics (Hoffer, 1995), inflow rates (Zhao & Davison, 2009), short-term operation (Ferreira, 1992; Borghetti, D'Ambrosio, Lodi, & Martello, 2008), dispatch coordination of hydro and thermal plants (Crampes & Moreaux, 2010).

The existing problems did not take into account the generation costs of hydroelectric units although their costs are significant. By neglecting generation costs, conventional procedure attempted to keep run time of all units equally so that maintenance costs and cycles could be balanced. This is definitely inconsistent with economic operation.

Thus, the objective of this work is to optimize the operation of a hydropower plant with pumped storage unit. Time horizon is both day and week. The generation scheduling problem is to determine the power output of each unit in each time period to minimize the hydro generation costs.

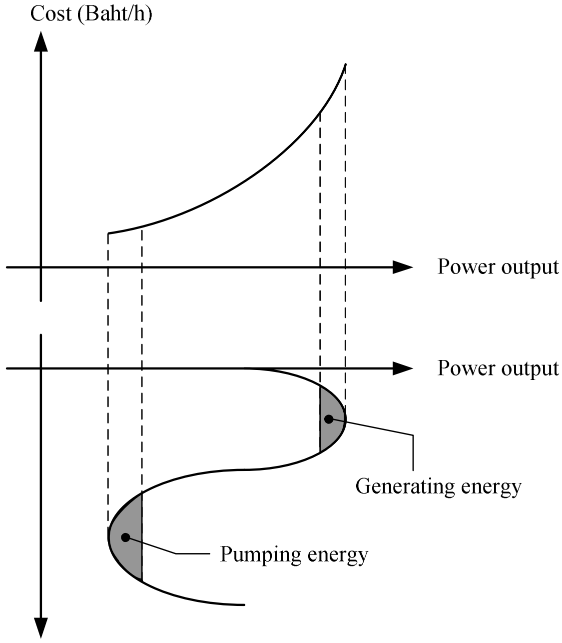

Figure 1. Generation and pumping intervals of pumped storage unit

2. Hydro Scheduling Problem

The power output of hydroelectric unit is a function of discharge rate, net hydraulic head, and conversion efficiencies of turbine and generator, which can be described by using the so-called hill diagram shown in Figure 2. The net head is equal to the gross head less the head losses of penstock. The head loss is proportional to the square of discharge rate. On daily or hourly basis, little changes in both forebay and tailrace elevation are observed so that the net head might be considered constant. As a result, the power output is dependent of the discharge rate in the short run. To avoid using the hill diagram, the power output (P) may be expressed as a linear function of net head (h) and discharge rate (q) as follows:

$$P(h,q) = a + bh + cq \tag{1}$$

where a, b, and c are the linear coefficients obtained from analyzing loading & efficiency test data of hydroelectric unit (Netsawang, 2007). Then, it should be validated by using a field test.

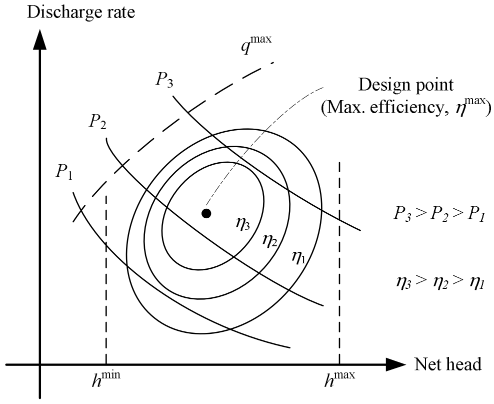

Figure 2. Simpliefied hill diagram

The hydro scheduling problem is an optimization problem involving hydro-thermal coordination. The objective function is to minimize fuel costs. The set of constraints comprises power balance, water balance, generation limits, spinning reserve, storage limits, etc. (Wood & Wollenberg, 1996). The main constraint is water drawdown requirement, specified on daily or weekly basis. The decision variables are unit status (binary) and power output (real) of all units in all time periods. The problem is usually formulated as a Mixed Integer Programming (MIP) problem.

In the presence of pumped storage unit, the problem is complicated because it is divided into generating and pumping intervals. The critical decision is to determine when and how much water should be pumped. Given the amount of water, the pumping energy is higher than the generating energy. Note that the cycle efficiency is defined as the ratio of generating energy to pumping energy. A typical value of the cycle efficiency is 2/3 (Wood & Wollenberg, 1996). Consequently, the marginal operating cost during pumping interval must be less than two-third of the marginal operating cost during generating interval.

3. Costs of Hydro Generation

Although there is no fuel cost for hydroelectricity, but generation costs still exist and should not be ignored especially cost differences among various hydroelectric units. The hydro generation costs can be determined by using the Activity Based Costing (ABC) method (Phoothiwut, 2005). The ABC method identifies activities and their cost drivers. Then, each cost component was classified as fixed or variable cost. Examples of fixed cost are land rent, depreciation, interest, civil O&M cost. Examples of variable cost are fuel oil, chemicals, calcium hydroxide, operating expenses, and electrical O&M cost.

The fixed costs are distributed equally to all hydroelectric units of the plant, while the variable costs are distributed to each unit in proportional to its energy generation and run time.

The hydro generation costs may be stated as hourly cost and annual cost function. The hourly cost is a function of power output, while the annual cost is a function of energy generation or capacity (plant) factor.

Meanwhile, the marginal operating cost varies with load from time to time. To compute the marginal operating cost directly, it requires economic dispatch solution which depends on a number of dispatching (thermal) units. Alternatively, an indirect method may employ the composite cost function (Wood &Wollenberg, 1996), considering the total operating costs as a quadratic function of cumulative generation. In so doing, the marginal operating cost can easily be computed. As shown in Eq. (2); *CC* is the composite cost, *G* is the cumulative generation, while *d*, *e*, and *f* are quadratic coefficients obtained from estimating economic dispatch solution over a pre-specified range of generation.

$$CC(G) = d + eG + fG^2 \tag{2}$$

4. Solution Strategy

It is proposed that the hydro generation costs should be taken into account when solving the hydro-thermal coordination problem. The power output of hydroelectric unit is a linear function of net head and discharge rate as shown in Eq. (1). The hourly and annual costs are linear functions of power output and energy generation, respectively. The cost function coefficients can be determined from fixed and variable costs of each hydroelectric unit. So, the objective function of the problem is to minimize the total costs of hydro generation over all time periods.

When a pumped storage unit is in operation, the marginal operating cost can be determined by using the composite cost function as shown in Eq. (2). Upon solution, it can be foreseen that the high-cost unit, such as pumped storage unit, would have less run time than the low-cost unit. Minimum run time may be enforced as a constraint to satisfy maintenance cycle.

To simplify the scheduling plan, the operating duration and water drawdown are given as parameters on a daily basis. When both parameters have high values, most units would be in operation. On contrary, only low-cost units would be in operation when both parameters have low values. In case of pumped storage operation, the generating and pumping intervals shall be determined from the cumulative generation, without computing the marginal operating cost.

5. Simulation Results

The proposed strategy has been applied to solve the scheduling problem of the Bhumibol hydropower plant, the largest hydropower plant in Thailand. The plant composes of eight units with the total installed capacity of 779.2 MW. Units 1-4 are identical with generation capacity of 4x82.2 MW. Units 5-6 are identical with generation capacity of 2x82.2 MW. Unit 7 has generation capacity of 115 MW. Unit 8 is a pumped storage unit with generation capacity of 171 MW and pumping capacity of 161 MW. The cycle efficiency is 75%. The reservoir has annual inflow of 5,000-6,000 MCM. The plant has annual generation of 1,000-1,500 GWh.

Tables 1 and 2 shows the power output functions and generation cost functions of all eight units, respectively. Figure 3 illustrates the comparisons of annual costs and average costs by varying capacity factor. It was found that units 1-4 have the lowest cost and unit 7 has the highest cost. Units 1-6 have the average cost lower than the average cost of the plant, while units 7-8 have the average cost higher than the average cost of the plant. Figure 4 shows the optimum capacity factor, operating duration, and generation proportion of each unit when capacity factor of the plant was varied between 10-50%. Given the operating cost data in the year 2008, the composite cost function can be computed as follows:

$$\begin{aligned} &CC(G) = 1,051,040.37 + 972.78G + 0.0201G^2 \text{ [Baht/h]} \\ &370 \le G \le 27,300 \text{ [MW]} \end{aligned} \quad (3)$$

Table 1. Power output functions of the Bhumibol hydropower plant

Unit	Power output (MW)
1	$P(h,q) = -58.04 + 0.84h + 0.60q$
2	$P(h,q) = -56.83 + 0.88h + 0.54q$
3	$P(h,q) = -57.43 + 0.83h + 0.61q$
4	$P(h,q) = -57.87 + 0.84h + 0.60q$
5	$P(h,q) = -61.24 + 0.85h + 0.63q$
6	$P(h,q) = -61.16 + 0.85h + 0.62q$
7	$P(h,q) = -87.66 + 1.41h + 0.48q$
8	$P(h,q) = -124.27 + 1.91h + 0.49q$

h net head (m) q discharge rate (CMS)

Table 2. Generation cost functions of the Bhumibol hydropower plant

	Hourly cost (Baht/h)
Bhumibol plant	$C_h(P) = 286,760 + 192P$
Units 1-4	$C_h(P) = 25,880 + 168P$
Units 5-6	$C_h(P) = 28,330 + 194P$
Unit 7	$C_h(P) = 60,440 + 250P$
Unit 8	$C_h(P) = 89,310 + 222P$
	Annual cost (million Baht/y)
Bhumibol plant	$C_a(E) = 628 + 0.19E$
Units 1-4	$C_a(E) = 68 + 0.17E$
Units 5-6	$C_a(E) = 67 + 0.19E$
Unit 7	$C_a(E) = 90 + 0.25E$
Unit 8	$C_a(E) = 133 + 0.22E$

P power output (MW) E generation (GWh/y)

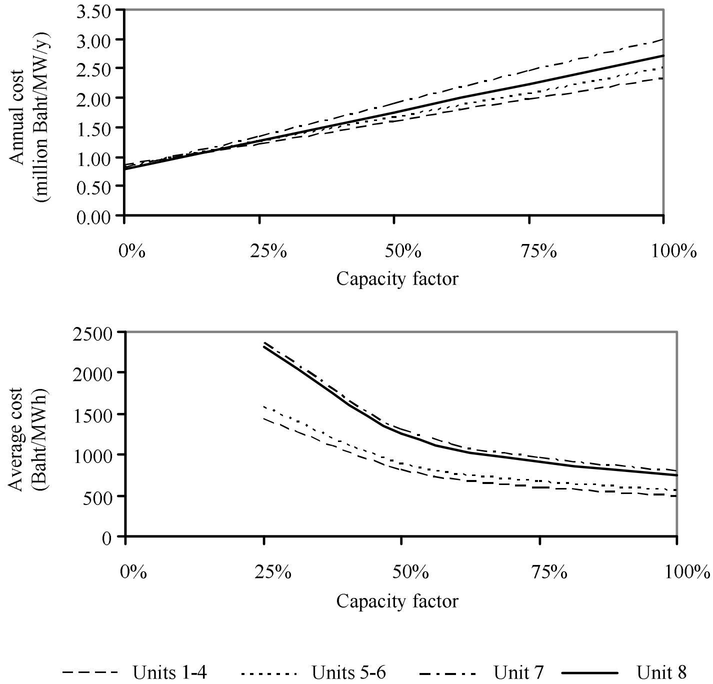

Figure 3. Comparisons of annual costs and average costs of the Bhumibol hydropower plant

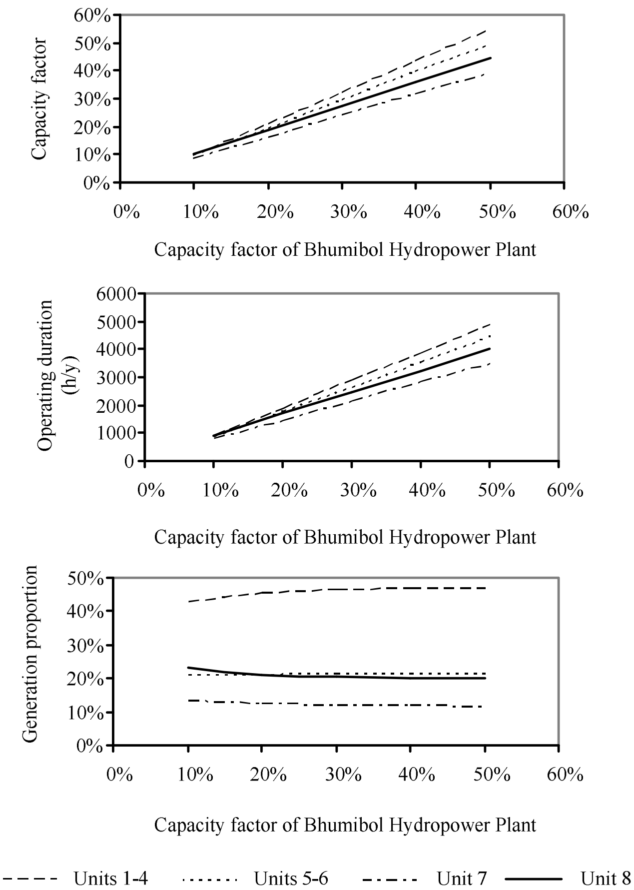

Figure 4. Determinations of capacity factor, operating duration, and generation proportion of the Bhumobol hydropower plant

It was found that the optimum operating duration of units 1-4 is 890-4,870 h/y, units 5-6 is 862-4,423 h/y, unit 7 is 791-3,494 h/y, and unit 8 is 921-3,993 h/y. The optimum generation proportion of units 1-4 is 43-47%, units 5-6 is 21%, unit 7 is 12%, and unit 8 is 20-23%.

Then, the plant was divided into 4 groups of scheduling, sorted by generation costs. It was mentioned that the larger the installed capacity, the higher the generation costs. Given the operating duration, daily discharge, and water rate; the scheduling plan can be set according to those four groups. As shown in Figure 5, group A would be in operation when both operating duration and daily discharge are low. That means low-cost units would be operated when water is limited. On the other hand, high-cost units would be operated when operating duration is low, but daily discharge is high. In such a case, water must be released in a limited time so that there is an opportunity for the high-cost unit to operate.

In particular case, there would be infeasible to operate the plant. For instance, when the water rate is 4 CM/kWh, it is impossible to release more than 20 MCM within 8 hours so that the operation is infeasible.

The pumped storage unit should be in generating mode when the cumulative generation is more than 20,500 MW and in pumping mode when the cumulative generation is less than 11,000 MW. As a result, the pumping duration is 57 h/y, which is approximated to one hour a week. It is observed that the pumping interval of the pumped storage unit is very sensitive to the marginal operating cost. Given that there is a narrow range of cost differences over the year, there is a limited time for the pumped storage unit to operate economically. But, there would be more chance to operate in pumping mode if the cycle efficiency is better.

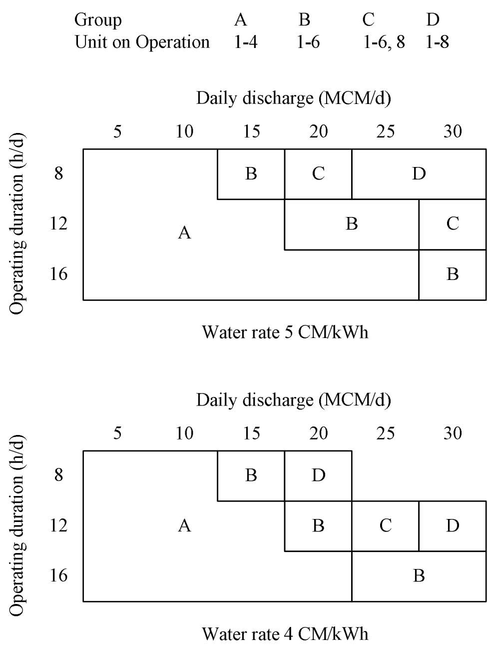

Figure 5. Generation scheduling of the Bhumibol hydropower plant

6. Conclusion

This work presents the solution strategy for generation scheduling of a hydropower plant with pumped storage unit. By considering the generation costs of hydroelectric units, the generation scheduling plan is more economical than the conventional scheduling. Nonetheless, minimum run time may still be observed to avoid large variation of maintenance cycles.

The pumped storage unit could operate in both generating and pumping modes. The generating interval depends on its generation costs, which are relatively higher than those of conventional unit. The pumping interval depends on the marginal operating cost and its cycle efficiency.

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