IEEE TRANSACTIONS ON POWER SYSTEMS, VOL. 5, NO. 3, AUGUST 1990

HYDROELECTRIC GENERATION SCHEDULING WITH AN EFFECTIVE DIFFERENTIAL DYNAMIC PROGRAMMING ALGORITHM[†]

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Abstract - This paper presents an effective multiplier method-based differential dynamic programming (DDP) algorithm for solving the hydroelectric generation scheduling problem (HSP). The algorithm is developed for solving a class of constrained dynamic optimization problems. It relaxes all constraints but the system dynamics by the multiplier method and adopts the DDP solution technique to solve the resultant unconstrained dynamic optimization problem. We formulate the HSP of the Taiwan power system and apply our algorithm to it. Results demonstrate the efficiency and optimality of our algorithm for this application. We also suggest some operational strategies based on these results.

Key Words: *hydroelectric generation scheduling, dynamic optimization, multiplier method, differential dynamic programming.*

I. INTRODUCTION

Taiwan Power Company (TPC) owns and operates the electric power generation, transmission, and distribution system of Taiwan area. The system is characterized by

1) lack of interconnection with other power systems for emergency support and economic exchange;
2) large fluctuation of daily load pattern, ranging from 6800 MW at night to 11000 MW in the afternoon and with sharp fall-and-rise at noon;
3) lack of abundant and long-term dependable source of hydraulic energy.

Therefore, TPC must judiciously operate its different types of generation facilities to ensure reliability and economy. Currently TPC has an installed generation capacity just enough for peak load plus spinning and non-spinning reserves. Hydro plants (including a pumped storage plant) only amount to 16% of the total capacity. The major objective of hydro generation scheduling in such a system is to minimize the thermal fuel cost while maintaining certain spinning reserve level by utilizing the limited water resource.

TPC's hydro plants can be divided into three groups: 1) the four Ta-Chia river plants, 2) the Cho-Shui river plants, including a large pumped storage plant and two cascade hydro plants, and 3) ten small to medium hydraulically independent plants of which only three are completely dispatchable by TPC. Both groups 1 and 2 have the feature of "big-head-small-tail", i.e., upstream reservoirs/plants have higher capacities than the lower ones. Such a hydro system is complex because of the number of plants involved, the hydraulic coupling among plants and the big-head-small-tail characteristics of group 1 and group 2. Thus how to schedule the hydroelectric generation under all these complexities so that the fuel cost of thermal generation can be minimized is a practical and challenging problem. Up to present, TPC is still in lack of an effective and systematic solution method for it.

There have been many methods for solving HSP [2, 6, 9 - 12, 14, 17 - 20]. Among them, the dynamic programming (DP) approach has gained much popularity and certain success due to the fact that a large number of HSP's can be translated into a dynamic optimization formulation. According to the literature [14] and our assessment, DDP is a promising DP-based solution method for large-scale problems. Its advantages are that 1) it explicitly exploits system dynamics; 2) its solution has certain feedback nature; 3) it avoids the curse of dimensionality of DP and requires no discretization of control/state variables; and 4) it is efficient for unconstrained dynamic optimization [5,15]. Two DDP algorithms have been developed for problems with linear constraints [9,16]. They have achieved limited success since the two either encountered difficulty in maintaining solution feasibility or suffered from computational inefficiency [5,7].

In this paper, TPC's HSP is formulated as a constrained dynamic optimization problem. We use an aggregated thermal unit, which is obtained through dispatching available thermal units by the simple λ-iteration method [13], to construct the thermal generation cost function. The objective is then to determine the best substitution of hydro for thermal energy so that the fuel cost is minimized while meeting the load and all the system constraints. A multiplier method-based DDP algorithm is developed to solve such a problem. This algorithm can actually tackle a quite general class of dynamic optimization problems, including the ones with nonlinear constraints. It first relaxes all constraints but the system dynamics by using the multiplier method [1,8]. For a given set of multipliers, there is an unconstrained dynamic optimization problem to which DDP applies effectively. The optimal solution is obtained by iteratively updating multipliers and solving the corresponding dynamic optimization problems. This new algorithm is convergent under mild convexity assumptions and is easy to implement.

Our algorithm is applied to schedule one summer and one winter week. Results demonstrate that it is quite efficient for this application. Comparing the results

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[†] This work was supported in part by the National Science Council of the Republic of China under Grants NSC-77-0404-E002-03 and NSC-78-0404-E002-17.

90 WM 014-1 PWRS A paper recommended and approved by the IEEE Power System Engineering Committee of the IEEE Power Engineering Society for presentation at the IEEE/PES 1990 Winter Meeting, Atlanta, Georgia, February 4 - 8, 1990. Manuscript submitted January 31, 1989; made available for printing December 27, 1989.

with those obtained by TPC's experienced engineers, we observe general consistency except that our schedules suggest saving more hydro energy on Sunday for higher hydro generation during weekdays. It is also observed that our schedules are more predictive in operating the big-head-small-tail system than empirical operations.

This paper is organized as follows. Section II contains a detailed HSP formulation. In Section III, the multiplier method-based DDP algorithm is presented. The application of this method to TPC's system and the results are described in Section IV. Section V concludes our study.

II. PROBLEM FORMULATION

Scheduling hydro generation is well known to be coupled with its thermal counter part. Under present TPC system operation conditions, short-term commitment changes are not allowed for most of the base- and medium-load thermal units. The scheduling of hourly thermal generation over a one-week horizon can simply be reduced to an economic dispatch problem, namely, the unit commitment aspect can be ignored. To meet the spinning reserve requirement, TPC keeps a certain percentage of the available thermal capacities (committed units and all the peaking units) as part of the spinning reserve. For a given load level, the remaining spinning reserve capacity that should be contributed from the hydro units can then be determined. According to the previous two operation rules, the coupling between hydro and thermal schedulings is only through the generation cost.

We now decouple the hydro scheduling from the thermal part by first assuming a purely thermal system. For each given load level, the simple λ-iteration method is performed to solve the economic dispatch over the set of available units [13] and to evaluate the thermal generation cost of meeting the load. In other words, we aggregate all the available thermal units into one equivalent unit and construct its generation cost function. The hydro scheduling then finds the best way of substituting hydro for thermal energy based on this function so that the system generation cost is minimized while load and spinning reserve requirements are satisfied.

Let us define a few notations:

L_k: system load at kth hour;
$J_k(\cdot)$: generation cost function at hour k;
x_{ik}: the water volume of reservoir i at the beginning of hour k;
u_{ik}: the volume of water released from reservoir i for generation during hour k;
s_{ik}: the spillage from reservoir i during hour k;
$P_i(\cdot)$: the water-to-energy conversion function of the power plant associated with reservoir i;
R_{ik}: the volume of natural inflow to reservoir i during hour k;
N_i: the set of the immediate upstream reservoirs of reservoir i;
SR_k : the hydro spinning reserve requirement at hour k.

The schematic diagram of hydro plants along both Cho-Shui and Ta-Chia rivers is shown in Figure 2.1. For the one hour time increment under consideration here, there is no significant delay in water reaching a reservoir from its immediate upstream neighbor.

The hydro scheduling problem over a one week horizon is then formulated as follows:

$$\text{(HSP)} \quad \min_{\{u_{ik}\}} \left[\; J = \sum_{k=1}^{168} J_k(L_k - \sum_i P_i(u_{ik})) \; \right]$$

subject to
(1) the water balance equation

$$x_{ik+1} = x_{ik} + \sum_{j\in N_i} u_{jk} - u_{ik} + \sum_{l\in N_i} s_{lk} - s_{ik} + R_{ik},$$

(2) bounds on water releases

$$\underline{u}_{ik} \le u_{ik} \le \bar{u}_{ik} \quad \text{and} \quad \underline{s}_{ik} \le s_{ik} \le \bar{s}_{ik},$$

(3) bounds on a reservoir storage

$$\underline{x}_{ik} \le x_{ik} \le \bar{x}_{ik},$$

(4) the spinning reserve requirement

$$\sum_i [\; P_i(\bar{u}_{ik}) - P_i(u_{ik}) \;] \ge SR_k.$$

Note that the above (HSP) formulation turns out to be a discrete time, deterministic dynamic optimization problem with linear constraints on both decision variables u's and states x's. We shall present in the next section an effective solution algorithm that we developed for (HSP)

III. THE MULTIPLIER METHOD-BASED DIFFERENTIAL DYNAMIC PROGRAMMING

Consider the class of discrete-time, constrained dynamic optimization problem, of which HSP is a special case:

$$\text{(P)} \quad \min_{\underline{u}_k} \sum_{k=0}^{N-1} J_k(\underline{x}_k,\underline{u}_k), \tag{3.1}$$

subject to the system dynamics

$$\underline{x}_{k+1} = \underline{f}_k(\underline{x}_k,\underline{u}_k), \quad k = 0,..,N-1, \tag{3.2}$$

and constraints

$$g_k(\underline{x}_k,\underline{u}_k) \le 0, \; k = 1,..,N-1, \tag{3.3}$$

with $\underline{x}_0$ and $\underline{x}_N$ the given initial and terminal states, k the time index, $\underline{u}$ an m×1 decision vector, $\underline{x}$ an n×1 state vector, J_k the stagewise cost function, and $\underline{g}_k = [g_{k1}, g_{k2}, .., g_{kr_k}]'$ where g_{kj} is a constraint function.

There are two classes of constraints in (P). One is the system dynamics, and the other is the constraints on states and controls of each stage. We first apply a nonprimal approach, the multiplier method [1,8], to relax all constraints of (P) but the system dynamics. Let $p_{kj}(t_{kj},\mu_{kj})$ be a "multiplier-penalty function" associated with the constraint g_{kj}, multiplier μ_{kj} and the penalty parameter c, where $t_{kj} = c \cdot g_{kj}(\underline{x}_k,\underline{u}_k)$. We omit details of constructing such a p_{kj} for the conciseness of presentation. Interested readers may refer to [1,8]. The specific form of p_{kj} that we use in this paper is given in Appendix A.

Define

$$P_k(\underline{t}_k,\underline{\mu}_k) = \sum_{j=1}^{r_k} P_{kj}(t_{kj},\mu_{kj}), \tag{3.4}$$

where $\underline{t}_k$ and $\underline{\mu}_k$ are vectors of t_{kj}'s and μ_{kj}'s respectively. The augmented Lagrangian function (ALF) at each stage k after relaxing constraints of the stage by the multiplier method is defined as

$$L_k(\underline{x}_k,\underline{u}_k,\underline{\mu}_k,c) = J_k(\underline{x}_k,\underline{u}_k) + \frac{1}{c} P_k(\underline{t}_k,\underline{\mu}_k). \tag{3.5}$$

We can then convert problem (P) into a dual problem:

$$\text{(PD)} \quad \max_{\underline{\mu}} \Psi(\underline{\mu},c) \tag{3.6}$$

with

$$\text{(PM)} \quad \Psi(\underline{\mu},c) \equiv \min_{\underline{u}_k} \sum_{k=0}^{N-1} L_k(\underline{x}_k,\underline{u}_k,\underline{\mu}_k,c), \tag{3.7}$$

subject to (3.2) and that $\underline{x}_0$ and $\underline{x}_N$ are given.

We observe that (PM) is an unconstrained dynamic optimization problem which a DDP algorithm solves effectively.

The DDP algorithm for solving (PM) consists of two basic procedures: backward dynamic programming and successive policy construction. For a problem such as (PM), a backward dynamic programming procedure is applied by taking a quadratic approximation of the objective function and a linear approximation of the system dynamics along a nominal trajectory and by formulating at each stage a quadratic programming problem in variational terms of control and state variables. By solving the quadratic programming problem at each stage, coefficients of the linear optimal variational control and coefficients of the quadratic variational cost-to-go function are obtained. The successive policy construction procedure uses these control coefficients and the nominal controls to construct new controls forward in time and to calculate the new cost. If the cost is lower than the nominal one, the nominal trajectory is updated by the new trajectory. Otherwise controls are kept on being modified in a specific way till the constructed controls yield a cost lower than the nominal one. These forward and backward procedures are carried out repetitively to obtain a convergent solution. Details of the DDP algorithm can be found in [5,15].

To solve problem (PD), a standard step of the multiplier method is applied. Let $\underline{u}^*(\underline{\mu},c)$ be the solution to (PM) obtained by DDP. A sequence of multipliers are generated iteratively according to

$$\underline{\mu}_k^{i+1} = \nabla_{\underline{t}} P_k(\underline{t}_k,\underline{\mu}_k^i),\ k = 0,1,..,N-1, \tag{3.8a}$$

where i is the iteration number index, $\underline{\mu}_k^0$ is an arbitrarily chosen positive vector,

$$\underline{t}_k \equiv c^i \cdot g_k(\underline{x}_k^*(\underline{\mu}_k^i,c^i),\ \underline{u}_k^*(\underline{\mu}_k^i,c^i)), \tag{3.8b}$$

and $\{c^i\}$ is a positive non-decreasing sequence [1]. The high-level updating and the low-level minimization are iteratively alternated until $\underline{u}_k^*(\underline{\mu}_k^i,c^i)$ converges to the optimal solution.

The multiplier method-based DDP algorithm is summarized as follows.

Algorithm

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Step 0. Initialization
    Select initial multipliers $\underline{\mu}_k^0$, initial controls $\underline{u}_k^*$,
    for k=0,..,N-1, initial penalty parameter $c^0$, a
    constant A>0, convergence thresholds $\eta_1>0$ and $\eta_2>0$;
    calculate the initial objective function value $L^0$;
    $i \longleftarrow 0$.
Step 1. Unconstrained DDP
    Set initial nominal control $\bar{\underline{u}}_k \longleftarrow \underline{u}_k^*$, for
    k=0,..,N-1;
    apply DDP to obtain $\underline{u}_k^*$ for the given $(\underline{\mu}^i, c^i)$;
    compute $\underline{x}_k^*$ by substituting $\underline{u}_k^*$ into the system
    dynamics for k = 0,..,N-1;
    calculate $L^{i+1} = \Sigma L_k(\underline{x}_k^*, \underline{u}_k^*, \underline{\mu}^i, c^i)$.
Step 2. Convergence check
    If $| L^{i+1} - L^i | / ( | L^{i+1} | + 0.0001 ) \leq \eta_1$,
      and $g_{kj}(\underline{x}_k^*,\underline{u}_k^*) \leq \eta_2$, for all k and j,
    then stop;
    otherwise, go to step 3.
Step 3. Multiplier update
    Compute $\underline{\mu}_k^{i+1}$ according to (3.8) for k=0,..,N-1;
    $c^{i+1} \longleftarrow c^i \times A$;
    $i \longleftarrow i + 1$;
    go to step 1.
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This algorithm is essentially a hybrid of the multiplier and DDP methods. The convergence rate for multipliers is proven to be linear [1] while it is quadratic for the DDP in solving (PM) [15]. Note that the algorithm is developed based on a very general class of problem (P). It is therefore applicable to hydro scheduling problems with nonlinear constraints.

IV. EXEMPLARY SCHEDULING RESULTS

To evaluate the multiplier method-based DDP algorithm developed in the preceding section, computer code was written in FORTRAN and applied to the hydro scheduling of one summer week and one winter week, which are representative of the wet and dry seasons respectively. Ten major TPC hydro plants were considered for scheduling excluding those run-of-river plants and those with fixed schedules because of contracted water supply requirements. The characteristic data of these 10 plants is given in Table 4.1, where the water-to-energy conversion function is linear. TPC'system load profiles of the two weeks are shown in Figure 4.1. The thermal generation cost function $J_k(.)$ is approximated by a second order polynomial. Cost coefficients for the summer and winter weeks we consider are listed in Appendix B.

All our numerical computations were performed on a VAX/780 minicomputer. The CPU time statistics of our algorithm are listed in Table 4.2, where six runs were conducted for each case by varying the system load profile.

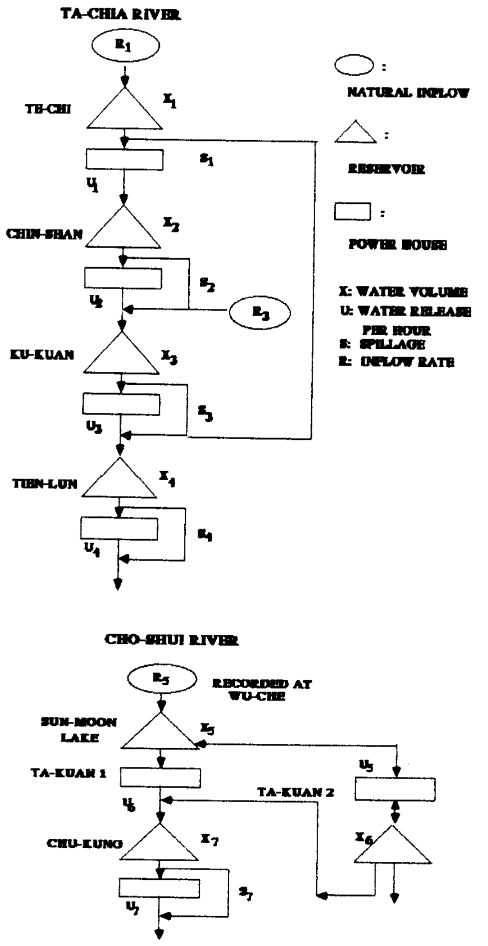


Figure 2.1 Schematic Diagram of Ta-Chia and Cho-Shui Rivers

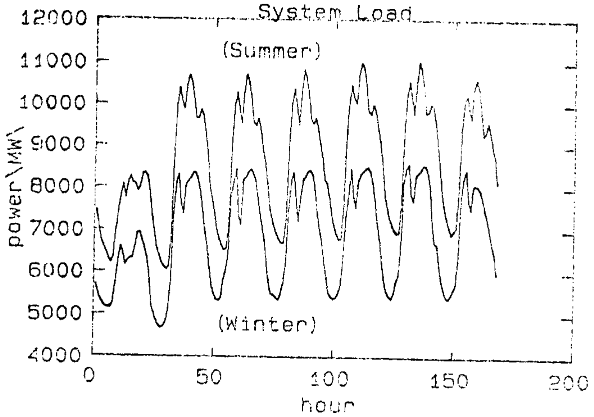


Fig.4.1 Weekly System Load Profiles

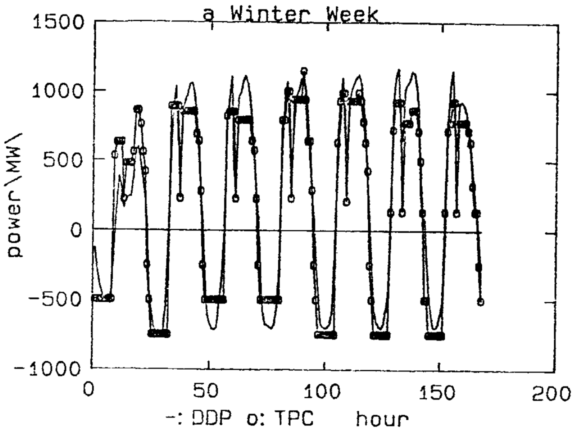
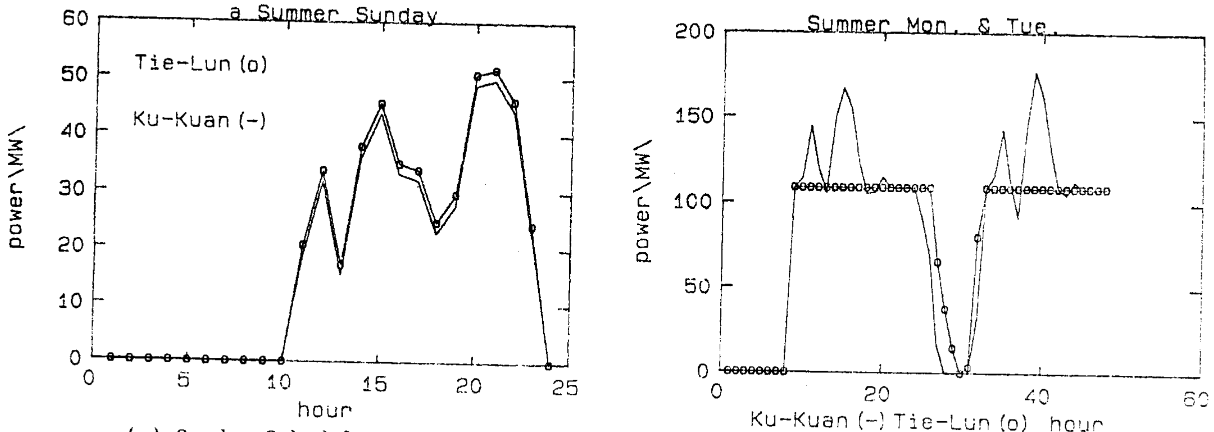


Fig.4.2 Contrast of Two Hydro Generation Schedules



(a) Sunday Schedule

(b) Weekday Schedule

Fig.4.3 Optimal Schedule for a Big-Head-Small-Tail Pair of Reservoirs

Reservoir	$\underline{x}$ (km^3)	x (km^3)	Plant	$\underline{u}$ (m^3/s)	u (m^3/s)	P(MW/m^3)
Sun-Moon	13269	155685	Ta-Kuan 2	-249	380	2.63(G)* 3.01(P)
Storage Pond	1565	9407	Ta-Kuan 2	0	50	2.1
Chu-Kung	1.6	105	Chu-Kung	0	45	1.04
Te-Chi	89886	243120	Te-Chi	0	217.5	1.2
Chin-Shan	26	647	Chin-Shan	0	174.8	2.5
Ku-Kuan	101	6563	Ku-Kuan	0	133.6	1.6
Tien-Lun	90	560	Tien-Lun	0	68	1.6
Li-Wu	0	340	Li-Wu	0	36.7	0.87
Lung-Chien	0	202	Lung-Chien	0	13.2	7.6
I-Hsing	0	1343	I-Hsing	0	31.7	1.26

* G: generation mode P: pumping mode

Table 4.1 Characteristic Data of the 10-Plant Hydro System

Scheduling Horizon	No. of Plants	Average CPU Time (sec.)	Standard Derivation
24 hrs.	3	8.4	0.63
24 hrs.	7	46.3	3.5
24 hrs.	10	182.0	7.1
72 hrs.	10	782.5	82.3
168 hrs.	10	2025.5	307.0

Table 4.2 CPU Time Statistics

According to the study of [3], the computation time of the multiplier method-based DDP algorithm is linearly proportional to the scheduling horizon and to the cube of number of plants. Results in Table 4.2 indicate similar trends. It is also observed that the larger the number of active constraints is for the optimal solution of one run, the more computation time is needed in order to achieve a solution that meets these constraints within a specified accuracy.

Figure 4.2 presents the total hydro generation profile of the winter week resulted from our algorithm and the one from TPC's schedule. It is clear that both profiles basically follow the system load and have the effect of peak-shaving as we compare them with Figure 4.1. The difference between the two is that our schedule suggests saving more hydro energy on Sunday in order to yield higher hydro generation during weekdays than TPC's schedule. Due to certain unstated reasons, TPC restricted itself to using only two units for pumping on Monday and Tuesday nights, which we did not model and caused the discrepancy between two schedules from Monday midnight to Wednesday morning. For the summer week, the two schedules were very close (which were not shown in this paper).

Although the total hydro generation scheduled according to our algorithm is similar to that of TPC's, we probe further on the generation patterns of individual units. Since the water storage and generation release capacities of the Tien-Lun reservoir/plant pair are smaller than those of the Ku-Kuan pair (Figure 2.1 and Table 4.1), there exists the feature of big-head-small-tail between Tien-Lun and Ku-Kuan. One existing model aggregates the Tien-Lun plant and Ku-Kuan plant as a big hydro unit, where the Tien-Lun plant release the same volume of water to generate power as Ku-Kuan plant does if Tien-Lun's generation is below its maximum capacity; otherwise the excessive water releases from Ku-Kuan gets spilled at Tien-Lun. This aggregation reduces the problem dimension but our results show that this idea may not be valid when the water resource is abundant. Figures 4.3 (a) and (b) suggest that we can lower the storage level of Tien-Lun reservoir during Sunday and in the evenings of weekdays so that spillage at Tien-Lun can be avoided or much reduced when Ku-Kuan releases water at a high rate the next day during peak hours. This type of operational strategy applies to other big-head-small-tail pairs of plants and is very beneficial in the wet season. This observation indicates that our schedule is more predictive than empirical operations in that the schedule really looks ahead of time to optimize water usage.

V. CONCLUSIONS

A multiplier method-based DDP algorithm has been presented in this paper and has been successfully applied to the short-term hydroelectric generation scheduling problem of the TPC system. The algorithm is a hybrid of the multiplier method and the DDP technique and it exploits advantages of the two. Although the exemplary hydro scheduling problems we considered in the previous section are relatively simple in its constraints, the class of problems (P) that our algorithm is designed for actually covers a wide range of hydro scheduling problems.

Computational results indicated that the growth of the algorithm's run time with respect to the problem size is moderate. CPU times of our testing cases are well within TPC's desirable performance: less than 30 minutes on a VAX/780 mini-computer for a one-week scheduling. Our scheduling results have generally been consistent with schedules obtained by TPC's experienced engineers. In addition, our algorithm generates insights for better operation of the big-head-small-tail reservoir/plant system. We thus believe that our algorithm provides an effective and systematic solution to the short-term hydroelectric generation scheduling of TPC's system.

APPENDIX A

$$p(t,\mu) = \begin{cases} \mu t + \mu t^2, & \text{if } t \geq 0; \\ \frac{\mu t}{1-t}, & \text{otherwise.} \end{cases}$$

APPENDIX B

Scheduling Horizon	No. of Plants	Cost Function of the Aggregated Thermal Unit (NT$)
24 hrs.	3	0.079*p*P - 277.5*P + 1273380
24 hrs.	7	0.074*p*p - 161.3*p + 729088
24 hrs.	10	0.064*p*p - 242.9*p + 2434304
72 hrs.	10	0.064*p*p - 242.9*p + 2434304
168 hrs.	10 (W)	0.064*p*p - 242.9*p + 2434304
168 hrs.	10 (S)	0.073*p*p - 374.5*p + 2918400

(S) : Summer (W) : Winter p : Power Supplied by Thermal Units (MW)

ACKNOWLEDGEMENT

The authors would like to express their appreciations to the System Operations Department of Taiwan Power Co. for providing necessary data and valuable discussions. Thanks are also due to Mr. I-Chung Lee, Mr. Ming-Yang Kuo, and Mr. Wei-Lin Yang for data preparations and many suggestions.

REFERENCES

[1] D. P. Bertsekas, *Constrained Optimization And Lagrange Multiplier Methods*, Academic Press, 1982.

[2] M. F. Carvalho, S. Soares, "An efficient Hydro-thermal Scheduling Algorithm," *IEEE Trans. on Power System*, Vol. PWRS-2, No. 3, pp. 537-542, Aug., 1987.

[3] C. H. Chen, S.-C. Chang, I.-K. Fong, "A Multiplier Method-Based Differential Dynamic Programming Algorithm ," *Proceedings of the 12th National Symposium on Automatic Control*, Hsin-Chu, Taiwan, Dec. 1988, pp. 481-491.

[4] S. C. Chang, T. S. Chang, P. B. Luh, "A Hierarchical Decomposition For Large Optimal Control Problems With Parallel Processing Structure", To appear in *Automatica*, Jan. 1989.

[5] S. C. Chang, "A Hierarchical Decomposition Approach to Long Horizon Optimal Control Problems", *Ph. D. Dissertation*, Dept. of Electrical and Systems Engineering, The University of Connecticut, Dec. 1986.

[6] Y. Ikura, G, Gross, "Efficient Large-Scale Hydro System Scheduling with Forced Spill Conditions," *IEEE Trans. on PAS*, 84 WM 006-3.

[7] I. C. Lee, S. C. Chang, J. Shi, P. B. Luh, "A Differential Dynamic Programming Algorithm for Discrete Time, Linearly Constrained Problems," *Proceedings of the 12th National Symposium on Automatic Control*, Hsin-Chu, Taiwan, Dec. 1988, pp. 507-516.

[8] D. G. Luenberger, *Linear and Nonlinear Programming*, Addison-Wesley Publishing Co., 1984.

[9] D. M. Murray, S. J. Yakowitz, "Constrained Differential Dynamic Programming and Its Application to Multireservoir Control", *Water Resources Research*, Vol.15, No.5, 1979, pp. 1017-1027.

[10] N. R. Sandell, Jr., D. P. Bertsekas, J. J. Shaw, S. W. Gully, R. Gendron, " Optimal Scheduling of Large-Scale Hydrothermal Power Systems," *Proceedings* of *IEEE International Large-Scale Systems Symposium*, Oct. 1982, pp. 141-147.

[11] A. Turgeon, "Optimal Short-Term Hydro Scheduling From the Principle of Progressive Optimality," *Water Resource Research*, Vol. 17, No. 3, June, 1981, pp.481-426.

[12] F. Wakamori, S. Masui, K. Morita, T. Sugiyama,"Layered Network Model Approach to Optimal Daily Hydro Scheduling," *IEEE Trans. on PAS*, Vol. PAS-101, No. 9, sept. 1982, pp. 3310-3314.

[13] A. J. Wood, B. F. Wollenberg, *Power Generation, Operation, and Control*, Chapter 3, John Wiley & Sons, New York, 1984.

[14] S. Yakowitz, "Dynamic Programming Applications in Water Resources," *Water Resource Research*, Vol. 18, No. 4, Aug. 1982, pp. 673-696.

[15] S. Yakowitz, B. Rutherford, "Computational Aspects of Discrete-Time Optimal Control", *Appl. Math. Comput.*, Vol.15, No.1, 1984, pp. 29-45.

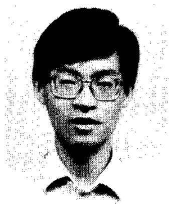
[16] S. Yakowitz, "The Stagewise Kuhn-Tucker Condition and Differential Dynamic Programming", *IEEE Trans. on Automatic Control*, Vol. AC-31, No.1, January 1986, pp. 25-30.

[17] H. Habibollazadeh, J. A. Bubenko, "Application of Decomposition Techniques to Short-Term Operation Planning of Hydro-Thermal Power System," *IEEE Trans. on Power Apparatus and Systems*, Vol. Pas-1, Feb. 1986, pp. 44-47.

[18] V. R. Sherkat, K. Moslehi, E. O. Lo, G. Sanchez, J. Diaz, "Modular and Flexible Software for Medium- and short-term Hydro-Thermal Scheduling," *IEEE trans. on Power Systems*, Vol. 3, No.2, Aug. 1988, pp. 1390-1396.

[19] E. B. Heinsson "Optimal Short-Term Operation of a Purely Hydroelectric System, "*IEEE trans. on Power Systems*, Vol.3, No.3, Aug. 1988, pp. 1072-1077.

[20] S. M. Amado, C. C. Ribeiro, "Short-term Generation Scheduling of Hydraulic Muti-reservoir Muti-area Interconnected Systems," *IEEE trans. on Power Systems*, Vol. 2, No.3, Aug. 1987, pp. 758-763.



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