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HYDRO UNIT COMMITMENT IN HYDRO-THERMAL OPTIMIZATION

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Abstract- In this paper we develop a model and technique for solving the combined hydro and thermal unit commitment problem, taking into full account the hydro unit dynamic constraints in achieving overall economy of power system operation. The combined hydrothermal unit commitment problem is solved by a decomposition and coordination approach. Thermal unit commitment is solved using a conventional Lagrangian relaxation technique. The hydro system is divided into watersheds, which are further broken down into reservoirs. The watersheds are optimized by Network Flow Programming (NFP). Priority-list-based Dynamic Programming is used to solve the Hydro Unit Commitment (HUC) problem at the reservoir level. A successive approximation method is used for updating the marginal water values (Lagrange multipliers) to improve the hydro unit commitment convergence, due to the large size and multiple couplings of water conservation constraints. The integration of the hydro unit commitment into the existing Hydro-Thermal Optimization (HTO) package greatly improves the quality of its solution in the PG&E power system.

Keywords: Large scale hydro-thermal optimization, Hydro network flow, Hydro unit commitment, Dynamic programming

1. INTRODUCTION

Until now almost all papers have addressed the hydro-thermal optimization problem without consideration of the dynamic constraints of hydro units (e.g. minimum up-time and down-time) and hydro plant ramp rate constraints. As a result, the solution may contain some unsatisfactory behavior, such as frequent switching of hydro units. Frequent cycling of hydro units in daily operations is usually not allowed because of the resulting mechanical stress. Minimizing hydro unit cycling with minimum up-time and minimum down-time and plant ramp rate constraints may also help to decrease wear and tear costs and other start-up costs of hydro units which can depend on the frequency of the cycling constraint violations.

Recently we have developed a model and solution technique for solving the hydro unit commitment problem with dynamic constraints, and integrated it into PG&E’s existing HTO package, which was built using Lagrangian Relaxation for the thermal UC and Network Flow Programming (NFP) for the hydro generation scheduling so as to improve the quality of its applications. The general solution of the new HTO is divided into the following steps:

1. The combined hydro and thermal unit commitment problem is decomposed into thermal and hydro subproblems. The thermal unit generation schedules are optimized by Dynamic Programming.
2. The hydro system is divided into watersheds. Each watershed is optimized by Network Flow Programming, ignoring the minimum up- and minimum down-time constraints, and start-up and shut-down costs. All available units in hydro plants are combined into a single equivalent unit with an aggregated input/output curve. The network flow solution serves as the starting point for the hydro unit commitment.
3. Each watershed is further divided into reservoirs. Each reservoir supplies one or more hydro plants. The hydro unit commitment is performed to determine an optimal combination of units in each hour in each reservoir with constraints of minimum up- and minimum down-time, and start-up and shut-down costs. This commitment is more complicated when the units in the plant are not identical. To decrease the number of combinations, all units at a reservoir are optimized by a priority-list-based Dynamic Programming.

The combined problem is solved by Lagrangian relaxation. The final solution is obtained by solving iteratively the combined thermal UC, watershed NFP and HUC problems. This paper uses a successive approximation method for updating the marginal water values (Lagrange multipliers on hydro conservation constraints) to improve the hydro unit commitment convergence, due to the large size and multiple coupling of the hydro system. To decrease the computational burden of the hydro solution, special modeling for hydro units and hydro plants is presented.

The paper consists of the following sections. The combined hydro and thermal unit commitment problem is formulated in the next section. The hydro modeling is described in Section 3. The dynamic programming model is presented in Section 4. Section 5 describes the general solution algorithms. Section 6 demonstrates some results of the implementation of the proposed approach on a test system.

2. FORMULATION OF PROBLEM

Notations

\( t, i, r, w \) indexes of hour, unit, reservoir and watershed
\( I \) number of thermal units of the system
\( J \) set of hydro unit indexes
\( T \) number of hours of the study period
\( W \) number of watersheds of the system
\( R \) number of reservoirs of the system
\( R(w) \) number of reservoirs in watershed \( w \)


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$R'(r)$ set of reservoirs immediately upstream with respect to reservoir $r$

$J(r)$ number of hydro units at reservoir $r$

$J'(r)$ set of units immediately upstream with respect to reservoir $r$

$C_{it}$ operating cost of unit $i$ at hour $t$ including startup cost

$p_{it}$ generation of unit $i$ at hour $t$

$stc_{ij}$ hydro unit startup cost

$x_{it}$ state variable indicating hours when unit is on/off-line

$u_{it}$ decision variable of unit $i$ at hour $t$

$1$ -- unit on-line, $0$ -- unit off-line

$D_t$ system load at hour $t$

$R_t$ spinning capacity of thermal unit $i$ at hour $t$

$R_{jt}$ spinning capacity of hydro unit $j$ at hour $t$

$R_{req}$ required system spinning reserve

$T_{jd}^{up}$ minimum down time of hydro unit $j$

$T_{jt}^{up}$ minimum up time of hydro unit $j$

$v_r$ content of reservoir $r$ at hour $t$

$q_{jt}$ water release of hydro unit $j$ at hour $t$

$Q_{rt}$ water release of reservoir $r$ at hour $t$

$spl_{rt}$ spillage of reservoir $r$ at hour $t$

$inf_{rt}$ natural inflow to reservoir $r$ at hour $t$

$\tau_{mr}$ time delay between reservoirs $m$ and $r$

**Objective**

This paper concentrates its discussion on the hydro unit commitment. The thermal unit commitment in PG&E's existing HTO has been described in detail in [1]. To simplify the description only hydro unit startup (costs are considered in the formulation of the problem. The thermal operating cost $g_{pt}$ takes into consideration startup and shut-down costs. Assuming that the reservoir targets are not fixed at the end of the study period, the optimal short-term hydrothermal resource scheduling problem is defined as the following optimization problem:

$$\min \left\{ \sum_{i \in T} \left( \sum_{t \in \tilde{T}} C_{it} (x_{it-1}, p_{it}, u_{it}, u_{it-1}) + \sum_{j \in J} (1 - u_{jt-1}) \cdot stc_{ij} - \sum_{r \in R} \gamma_{rt} \cdot v_{rt} \right) \right\}$$

where the first term represents the thermal operating cost including fuel, start-up and shut-down costs; the second term represents the startup costs of hydro units, the third term represents the future value of water in the reservoirs of the power system.

**Constraints**

Total hydro and thermal generation meets the system demand:

$$g_p = \sum_{i \in T} p_{it} + \sum_{j \in J} p_{jt} - D_t = 0$$

System spinning reserve must be satisfied:

$$gs_t = \sum_{i \in T} R_{it} + \sum_{j \in J} R_{jt} - R_{req}^t \geq 0$$

Water conservation for each reservoir must be observed:

$$gw_{rt} = \nu_{r,t+1} - \nu_{r,t} + Q_{rt} + spl_{rt} - inf_{rt} - \sum_{m \in R'}(Q_{mt-1} + spl_{mt-1}) = 0$$

Release balance in the reservoir is:

$$Q_{rt} = \sum_{j \in J(r)} q_{jt}$$

Maximum and minimum unit release limits are:

$$q_{jt} \leq q_{jt} \leq q_{jt}$$

Reservoir maximum and minimum content limits are:

$$v_{rt} \leq v_{rt} \leq v_{rt}$$

Reservoir target condition is:

$$\nu_{rt} \leq \nu_{rt} \leq \nu_{rt}$$

Water spillage constraints:

$$spl_{rt} \geq 0$$

Hydro unit cycling condition:

$$x_{jt} = \begin{cases} 1 & \text{if } x_{j,t-1} \geq T^{up} \text{ and } u_{jt-1} = 1 \\ 0 & \text{if } x_{j,t-1} \leq T^{up} \text{ and } u_{jt-1} = 1 \end{cases}$$

**Dual problem**

The dual problem is constructed by incorporating constraints (2), (3) and (4) into objective function (1) with multipliers $\lambda_t$, $\mu_t$ and marginal water values $\gamma_t$ respectively.

$$dl(\lambda, \mu, \gamma) = \min \left\{ \sum_{i \in T} \left( \sum_{t \in \tilde{T}} C_{it} (x_{it-1}, p_{it}, u_{it}, u_{it-1}) + \sum_{j \in J} (1 - u_{jt-1}) \cdot stc_{ij} - \lambda_t \cdot g_{pt} - \mu_t \cdot gs_t + \sum_{r \in R} \gamma_{rt} \cdot gw_{rt} - \sum_{r \in R} \gamma_{rt} \cdot v_{rt} \right) \right\}$$

Substituting $g_p$, $gs$ with (2) and (3), the dual (11) is rearranged as:

$$dl(\lambda, \mu, \gamma) = dl(\lambda, \mu) + dlh(\lambda, \mu, \gamma) + dlS(\lambda, \mu)$$

The dual function (12) is divided into three independent parts. The first part of (12) is related to the thermal unit indices only, and is defined as the thermal unit commitment problem. The corresponding thermal dual function is as follows:

$$dl(\lambda, \mu) = \min \left\{ \sum_{i \in T} \left( C_{it} (x_{it-1}, p_{it}, u_{it}, u_{it-1}) - \lambda_t \cdot g_{pt} - \mu_t \cdot R_t \right) \right\}$$

The second part of (12) is related to the hydro indices $r$ and $j$ only, and is defined as the hydro optimization problem. The corresponding hydro dual function is as follows:

$$dlh(\lambda, \mu, \gamma) = \min \left\{ \sum_{i \in T} \left( (1 - u_{jt-1}) \cdot stc_{ij} - \lambda_t \cdot p_{jt} - \mu_t R_{jt} \right) + \sum_{r \in R} \gamma_{rt} \cdot gw_{rt} - \sum_{r \in R} \gamma_{rt} \cdot v_{rt} \right\}$$

subject to constraints (5)-(10).
The third part of (12) is related to the system load and spinning reserve requirement:

\[ dls(\lambda, \mu) = \min \sum_{t \in T} (\lambda_t \cdot D_t + \mu_t \cdot R^{neg}_t) \quad (15) \]

With known \( \lambda, \mu, \) and \( \gamma, \) the third part is a constant term and will be ignored when optimizing the thermal and hydro unit commitment. The thermal unit commitment and hydro optimization problems are optimized independently. The remainder of the paper will address the hydro optimization, especially the hydro unit commitment problem.

**Hydro Subproblem**

The water conservation equations (4) are highly sensitive to the Lagrangian multipliers \( \gamma. \) Clearly, the choice of the initial value and the proper subsequent updating of \( \gamma \) (see section 5) is crucial to the final solution of the hydro subproblem. The next sections introduce a new model and solution technique for solving the hydro subproblem. First, we formulate the hydro network flow problem by dividing the hydro system into individual watersheds, ignoring the hydro unit cycling constraints (10). The hydro network flow and economic dispatch provide reservoir release schedules and marginal water values as good approximations for input to the HUC. We then formulate the hydro unit commitment problem for each watershed by further dividing the watershed into individual reservoirs, taking into account hydro constraints (5)-(10).

**Watershed Network Flow Problem**

Relaxing the hydro unit cycling constraints (10) for the moment, we reformulate the hydro dual problem (14) as a non-linear convex problem, considering the hydro unit generation a function of the release and water head:

\[ dhl(\lambda, \mu, \gamma) = \min \{ \sum_{t \in T} \sum_{j \in J(w)} (\lambda_t \cdot p_j (q_{jt} \cdot v_{jt}) - \mu_t \cdot R_{jt}) \}
\]

\[ - \sum_{r \in R} r_{rt} \cdot v_{rt} \}
\]

subject to constraints (4)-(9).

Considering the independence of each watershed in the system, the hydro system can be divided into individual watersheds. Regrouping (16) according to the watershed index, we formulate the optimization problem for each watershed as the following convex problem:

\[ dlw(\lambda, \mu, \gamma) = \min \{ \sum_{t \in T} \sum_{j \in J(w)} (\lambda_t \cdot p_j (q_{jt} \cdot v_{jt}) - \mu_t \cdot R_{jt}) \}
\]

\[ - \sum_{r \in R} r_{rt} \cdot v_{rt} \}
\]

subject to constraints (4)-(9).

For hydro units, the water conservation constraints (4) are complicated by the network interdependencies resulting from the locations of hydro units in a watershed containing reservoirs and connected by river segments. Each watershed as a whole is treated as a resource, and optimized using a Network Flow algorithm as described in [1,5-8]. The network flow model generates water release schedules and unit commitment schedules for each reservoir. It is obvious that if these schedules respect the minimum up- and minimum down-time of all units in the watersheds, the solution is final and optimal. Unfortunately, the network flow solution often contains infeasible schedules in terms of unit minimum up-time and minimum down-time constraints. The objective of the hydro unit commitment is to eliminate the violations of such constraints.

**Hydro Unit Commitment Problem**

The general formulation of the hydro unit commitment problem has been represented in (14). Suppose good approximations of the reservoir releases and marginal water values \( \gamma \) have already been determined from the hydro network flow and economic dispatch model and fed into the hydro unit commitment. Substituting \( gw_r \) with (4), regrouping hydro units according to the reservoir index, the hydro dual function (14) can be rewritten as:

\[ dlr(\lambda, \mu, \gamma, v) = dlr(\lambda, \mu, \gamma, v) + dlc(\gamma, v) \]

where

\[ dlr(\lambda, \mu, \gamma, v) = \min \{ \sum_{t \in T} \sum_{r \in R} (\lambda_t \cdot p_j (q_{jt} \cdot v_{jt}) - \mu_t \cdot R_{jt}) \}
\]

\[ - \sum_{r \in R} r_{rt} \cdot v_{rt} \}
\]

\[ + \gamma_{rt} \cdot y_{d,t+\tau_{rd}} \cdot Q_{rt} \]

\[ (\gamma_{rt} - \gamma_{d,t+\tau_{rd}}) \cdot v_{rt} - (\gamma_{rt} - \gamma_{d,t+\tau_{rd}}) \cdot sp_{rt} \]

subject to constraints (5)-(10).

Suppose that the multipliers \( \lambda, \mu, \gamma \) are given. Also assume that the reservoir contents \( v \) and water spills \( sp \) are determined a priori from the network flow model. From (18-20), we see that the hydro dual function consists of two terms. The first term \( dlr(\lambda, \mu, \gamma, v) \) is dependent on the unit state variable \( x \) in \( stc_j \), the unit on/off decisions \( u \), and the unit water release or generation variables \( q \) or \( p \). The second term \( dlc(\gamma, v) \) is constant. Because \( dlr(\lambda, \mu, \gamma, v) \) is additive and separable in the reservoir index \( r \), we are able to decompose the hydro optimization problem into subproblems in the reservoir index. Then the following dual function is defined as the hydro unit commitment problem (HUC) for the reservoir:

\[ \text{(HUC): } dlr(\lambda, \mu, \gamma, v) = \min \{ \sum_{t \in T} \sum_{r \in R(w)} (\lambda_t \cdot p_j (q_{jt} \cdot v_{jt}) - \mu_t \cdot R_{jt}) \}
\]

\[ - \sum_{r \in R(w)} r_{rt} \cdot v_{rt} \}
\]

subject to hydro constraints (5)-(10). If we ignore the impact of water heads on the hydro unit commitment, it can be shown that the marginal water values are constant over the time horizon. Then the hydro unit commitment problem (HUC) of (21) is simplified as:

\[ \text{(HUC) } dlr(\lambda, \mu, \gamma, v) = \min \{ \sum_{t \in T} \sum_{j \in J(w)} (\lambda_t \cdot p_j (q_{jt} \cdot v_{jt}) - \mu_t \cdot R_{jt}) \}
\]

\[ - \sum_{r \in R(w)} r_{rt} \cdot v_{rt} \}
\]

subject to (10).

For hydro units, the water conservation constraints (4) are complicated by the network interdependencies resulting from the locations of hydro units in a watershed containing reservoirs and connected by river segments. Each watershed as a whole is treated as a resource, and optimized using a Network Flow algorithm as described in [1,5-8]. The network flow model generates water release schedules and unit commitment schedules for each reservoir. It is obvious that if these schedules respect the minimum up- and minimum down-time of all units in the watersheds, the solution is final and optimal. Unfortunately, the network flow solution often contains infeasible schedules in terms of unit minimum up-time and minimum down-time constraints. The objective of the hydro unit commitment is to eliminate the violations of such constraints.
The size of multipliers $\gamma$ in (22) is greatly decreased in comparison with (21). The hydro unit commitment problem (HUC) can be solved by Dynamic Programming. Unlike the thermal unit commitment in which only one unit is involved in the DP solution, the hydro unit commitment is to determine the optimal combination of units available in each hour in each reservoir. To decrease the DP computational burden we use a unit priority list instead of a full-blown search of all combinations of units at the reservoir (Section 4).

**Hydro Economic Dispatch problem**

With the fixed unit schedules in the reservoir, the objective function (22) is separable and additive in index of time. Then we formulate the hydro economic dispatch problem for each reservoir for each hour as:

$$he dp(\lambda, \mu, \gamma, v, u) = \min \{ -\lambda, -p_{\mu}(q_{jt}, v_{jt}) +$$

$$\sum_{j=1}^{n} \sum_{r=1}^{T} q_{jt} \gamma_{r} - \gamma_{d} \} \quad t=1,2,...,T$$

s.t. (5). The difference of the marginal water values of reservoir $r$ and its downstream reservoir $d$ represents the plant or unit marginal water value of the reservoir $r$ as:

$$\gamma_{r} = \gamma_{r} - \gamma_{d}$$

(25)

The hydro economic dispatch problem is solved by the equal incremental water rate principle.

### 3. HYDRO I/O CURVE MODELING

This section is confined to describing the creation of water rate curves for different combinations of identical units with consideration of the head effects. The typical curves with 3 units for a specified water head are shown in Fig. 1. The cross points of two consecutive curves represent the switch points from one combination to another.

![Typical curves of unit combinations](image)

The water rate curves are modeled by quadratic functions given for the minimum and maximum water heads. The coefficients of the quadratic forms for intermediate heads are determined by linear interpolation. With the quadratic model the commitment switch points can be determined analytically.

### 4. DYNAMIC PROGRAMMING MODEL

**Unit Combination** is defined as a set of units for on-line operation in a reservoir. A plant with $n$ identical units has $n$ combinations. A plant with $n$ nonidentical units has $2^n - 1$ combinations. All units offline is a special combination called the 0 combination.

**Decision** is defined as the transition of one combination at hour $t$ to another combination at $t+1$. Any change in the unit combination is always accompanied by a change of one or more additional units to on-line or off-line status.

Priority list-based dynamic programming is used for solving the hydro unit commitment problem to reduce the problem’s dimensions (from $2^T - 1$ to $n+1$). All available hydro units at the reservoir are sequenced in increasing order of average full-load water rate.

**State Transition Diagram**

Let $0$ represent the combination state variable of all units off-line, and $1, 2, \ldots, n$ -- unit 1, units 1, 2, ..., and units 1, 2, ..., $n$ committed online respectively. The state transition diagram is depicted in Figure 2. To reduce the number of combinations to consider, we may also account for all manual-schedule and must-run units as one combination and give it a state 1 after the state 0. We will record the number of hours that each unit has been on or off in each state for the optimal path. To avoid frequent cycling of units, we will use the record of hours on and off to determine if a transition between states is feasible given the minimum up- and down-time constraints.

![State transition diagram](image)

### 5. SOLUTION ALGORITHM

**Lagrangian multiplier updates**

The update of $\lambda$ and $\mu$ is described in detail in PG&E’s existing HTO program [1]. The difficulty here is in updating the marginal water value. Our experiences have shown that the conventional method of choosing the initial marginal water value (e.g. using average water value) and its subsequent updating (e.g. using Polyak [9] or another updating formula) often results in non-convergence or oscillation of the hydro schedules. The large number of $\gamma$ multipliers (e.g. there are more than 12000 in the one week PG&E problem) and the multiple couplings of the river system both in space (reservoirs in cascade) and in time (limited usage of water over the time horizon) almost exclude the use of the conventional method. In this paper a successive approximation method is used for updating the $\gamma$ multipliers. With the initial $\gamma$ values determined from NFP and hydro economic dispatch we run the hydro unit commitment. If the reservoir release balance equations (5) are violated due to rescheduling hydro units in HUC to meet the cycling constraints, we will reallocate the reservoir water flow using the following rules: increase water releases in hours when marginal water values are large and decrease water releases in hours when marginal water values are small. We then update the marginal water value and repeat the hydro unit commitment again. The water reallocation in different hours and in different units at each reservoir continues until the marginal water values in different hours are close to each other. This successive approximation method of updating marginal water values has several advantages over the conventional iterative method: 1) The conventional iterative updates are very sensitive to the water conservation equations (23) due to the near-flat hydro incremental characteristics and the coupling feature of the hydro system, i.e., a small change of marginal water value often results in a big change in...
the imbalance of equation (23). This is why the use of the conventional iterative update often leads to the non-convergence in the hydro optimization. 2) The network flow provides a good starting point for the hydro unit commitment, i.e. initial marginal water values in different hours calculated in NFP by hydro economic dispatch are usually close to each other. The marginal water values need to be updated only when the unit minimum up and minimum down-times are violated. These updates are usually small and can be done much more easily by the successive approximation method than by using the conventional updating formula.

Flow chart of solution
The flow chart of the algorithm for solving the combined hydro and thermal unit commitment is shown in Figure 3.

Computation procedure
The computational procedure is broken into the steps:
1. Initialize the system lambdas \( \lambda \) and \( \mu \) at the master coordinator.
2. Run Thermal Network Flow to give the unit commitment and generation schedules of all thermal units.
3. Run the hydro network flow programming for watersheds to give the water release schedules for all reservoirs.
4. Initialize the marginal water values by running the hydro economic dispatch program with the reservoir water release schedules determined from the hydro network flow.
5. Run HUC to give the unit commitment and generation schedules of all hydro units in the reservoir.
6. Check if the reservoir inflow and outflow are balanced. Also check if the absolute value of the difference of marginal water values between two different hours is less than a prespecified tolerance. If yes, go to step 7. Otherwise, reallocate water releases, and update \( \gamma \).
7. Check the optimality of the hydrothermal unit commitment. The optimization phase stops, if the number of iterations of this phase exceeds a specified minimum number, and the difference of norms of the system lambdas \( \lambda \) and \( \mu \) in consecutive iterations are small enough. Otherwise, update \( \lambda \) and \( \mu \), and repeat step 2 to step 7.
8. If the system reserve requirements are observed, go to step 9. Otherwise, repeat step 2 to step 8.
9. Run the system economic dispatch program to schedule the power generation of the committed units and stop computation.

6. COMPUTATION RESULTS
The hydro unit commitment model proposed in this paper has recently been built and integrated into PG&E's existing Lagrangian-Relaxation-based HTO program. The enhanced hydro and thermal unit commitment has been implemented and tested on the PG&E power system with a total of 243 units. 115 hydro units and 50 thermal units participate in the combined hydro and thermal unit commitment program. The hydro system consists of 65 reservoirs in cascade located on 14 watersheds in Northern and Central California, including a pumped storage facility with 3 pumping units. The smallest watershed contains 2 reservoirs with 2 plants and 5 units, the largest watershed 11 reservoirs with 9 plants and 19 units. The system parameters used to drive the test results can be found in our previous paper [1]. The hydro and thermal unit incremental cost curves are modeled by piecewise linear functions. Hydro unit start-up costs are set to zero in the study case.

The computer program is coded in the FORTRAN 77 and runs on the HP9000/735 computer. Some test results are illustrated here:
Table 1 shows the improvement in a unit's schedule by the hydro unit commitment in comparison with the schedule produced by NFP. The minimum up and minimum down-time of this unit are 3 hours.

Table 1 Improvement of daily unit schedules

| After NFP | 0 0 1 0 1 1 1 0 1 1 1 0 1 0 1 0 1 1 1 1 1 1 1 |
| After HUC | 0 0 0 0 1 1 1 0 0 0 1 1 1 0 0 0 0 1 1 1 1 1 1 |

As indicated in the problem formulation, the marginal water values are constant over the hours units are on-line, when ignoring the water head variation. The use of the successive approximation method to update these Lagrange multipliers takes advantages over the use of the conventional iterative updates. Fig. 4 shows the marginal water values over time. The higher values in the graph correspond to the hours when units at the reservoir are all shut down. The lower values correspond to the hours in which at least one unit is
on-line. As shown in Fig. 4, the hydro network flow provides good initial marginal water values for input to the hydro unit commitment. The marginal water values over the on-line hours are close to each other. The rescheduling of units in the hydro unit commitment to meet the unit cycling constraints will cause big changes of marginal water values only in the hours when a unit switches on or off. The reservoir water imbalance due to rescheduling in the unit commitment will be reallocated to all on-line hours in proportion to the hourly releases of the reservoir. Such reallocation has only a minor effect on the marginal water values in the on-line hours.

Table 2 lists some summary results of Hydro-thermal Optimization with and without hydro unit commitment function for a one week study case.

Table 2 Comparison of HTO with and without HUC

<table>
<thead>
<tr>
<th>Comparison items</th>
<th>HTO without HUC</th>
<th>HTO with HUC</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of iterations</td>
<td>20</td>
<td>21</td>
</tr>
<tr>
<td>CPU time (sec)</td>
<td>253.92</td>
<td>269.05</td>
</tr>
<tr>
<td>Total thermal cost ($1000)</td>
<td>10247.078</td>
<td>10247.282</td>
</tr>
<tr>
<td>No. of Cycling constraint violations</td>
<td>&gt;60</td>
<td>0</td>
</tr>
</tbody>
</table>

This table shows that the preferred start-up behavior of hydro units (see Table 1) from HUC can be obtained with only a small increase in CPU time and total system cost.

7. CONCLUSION

A combined hydro and thermal unit commitment taking into full account hydro unit dynamic constraints, is developed by the authors of the paper. The hydro system is divided into reservoir subsystems that cannot be broken down further due to the hydro network structure. All units at reservoirs are committed or decommitted by using priority list-based Dynamic Programming. In order to improve the convergence of the algorithm, a successive approximation approach is used for updating the marginal water values instead of using the conventional iterative updates. The enhancement of the existing HTO with hydro unit commitment improves its value in the PG&E power system.

8. ACKNOWLEDGMENT

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9. REFERENCES


10. BIOGRAPHIES

Chao-an Li graduated from Electric Power System Department of Moscow Energetic Institute, Moscow, USSR. He has broad interests in power system optimization including hydrothermal coordination, economic dispatch, unit commitment, load forecasting, automatic generation control, power flow, power system state estimation, etc. He is currently working as a contractor on PG&E's Hydro-Thermal Optimization project.

Eric Hsu received a B.S. and an M.S. in Operations Research from the University of California, Berkeley, in 1982 and 1983, respectively. He has worked as a systems engineer for Pacific Gas and Electric Company since 1983, developing computer applications for fuel and resource planning, hydro scheduling and forecast management, and hydro-thermal optimization.

Alva J. Svoboda received a B.A. in mathematics from U.C. Santa Barbara in 1980, and an M.S and Ph.D. in Operations Research from U.C. Berkeley in 1984 and 1992. He has worked on contract as an operations research analyst at Pacific Gas and Electric Co. since 1986. His current interest is the extension of utility operations planning models to incorporate new operating constraints.

Chung-Li Tseng received a B.S. in Electrical Engineering from National Taiwan University in 1988 and a M.S. in Electrical and Computer Engineering from U.C. Davis in 1992. He is currently a Ph.D. candidate in Industrial Engineering and Operations Research at U.C. Berkeley.

Raymond B. Johnson received his B.A. in 1976 in Electrical Sciences from Trinity College, Cambridge University, and a Ph.D. in Electrical Engineering from Imperial College, London University in 1985. His professional experience includes positions as a power system design engineer with Hawker Siddley Power Engineering from 1976 to 1980 and an EMS applications developer with Ferranti International Controls from 1987 to 1988. Since 1989, he has been with PG&E where he is currently a Systems Engineering Team Leader responsible for resource scheduling and energy trading applications.