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Chao-An Li

Chung-Li Tseng
Missouri University of Science and Technology

E. Hsu

R. B. Johnson

et. al. For a complete list of authors, see https://scholarsmine.mst.edu/engman_syseng_facwork/276

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A ROBUST UNIT COMMITMENT ALGORITHM FOR HYDRO-THERMAL OPTIMIZATION

Chao-an Li, Raymond B. Johnson (Member, IEEE), Alva J. Svoboda (Member, IEEE), Chung-Li Tseng, Eric Hsu

Pacific Gas and Electric Company, San Francisco

Abstract- This paper presents a unit commitment algorithm which combines the Lagrangian Relaxation (LR), Sequential Unit Commitment (SUC), and Optimal Unit Decommitment (UD) methods to solve a general Hydro-Thermal Optimization (HTO) problem. We argue that this approach retains the advantages of the LR method while addressing the method's observed weaknesses to improve overall algorithm performance and quality of solution. The proposed approach has been implemented in a version of PG&E's HTO program, and test results are presented.

Keywords: Large scale hydro-thermal optimization, Thermal unit commitment, Thermal unit decommitment, Dynamic programming

1. INTRODUCTION

A wide variety of Lagrangian relaxation techniques for solving the electric power system unit commitment problem have been proposed and developed. These methods share the notable advantages of decomposing the solution of the large scale UC problem using a dual formulation: new constraints and types of resources can be readily added to the problem formulation, and the algorithm finds better solutions faster than previously developed UC methods. One drawback of LR techniques, which find solutions to a dual of the UC problem, is the difficulty of finding a feasible solution to the original UC problem based on the dual solution. The nonconvexities and discontinuities of the UC problem ensure that in general the dual optimum cannot be directly converted into a feasible primal solution. Several methods have been proposed for finding a feasible primal solution given the LR dual solution. [3] presents a Reserve-Feasible-Solution (RSF) procedure which sequentially determines sufficient increments of Lagrangian multipliers for the most severely reserve-violated hour by forcing units to be in 'must-run' to obtain a feasible solution. [1] proposes a feasibility phase algorithm called Adaptive Partial Relaxation (APR) which, as an extension of the optimization phase, updates Lagrangian multipliers for only a subset of all multipliers corresponding to unsatisfied reserve constraints. The APR feasibility phase has been used in PG&E's HTO program for several years.

In this paper we propose a feasibility phase algorithm that addresses problems sometimes observed in the existing feasibility phase algorithms. These problems include solution instability, excessive computational burden, and a tendency to overcommitment.

- **Solution instability**
  The unit commitment obtained from the LR dual may be sensitive to arbitrarily small changes in the Lagrange multipliers, due to resources with flat incremental cost characteristics. This sensitivity can cause oscillations between under-satisfaction and over-satisfaction of system constraints, so that the LR method may not find a near-optimal dual solution in the limited number of iterations usually allowed for performance reasons.
- **Computational burden**
  Feasibility methods which rely on updates to multipliers without other information about resource cost characteristics may not find a feasible solution, or may take too long to do so, due to poor choice of step size for the multiplier updates. Update rules are designed to avoid too large updates of multipliers in order to avoid the oscillation problems discussed above. But large multiplier updates may be required to address large infeasibilities. On the other hand, small infeasibilities will result in small updates to multipliers. But it may require many iterations in order for the cumulative effect of these small updates to change the unit commitment.
- **Overcommitment**
  A unit commitment obtained from an LR dual solution, even a "near-optimal" dual solution, usually displays over-commitment. Quantitative analysis and evaluation of the "near-optimal" or over-commitment is needed to address these questions: 1) How can the existence of overcommitment in the dual solution be examined? 2) If overcommitment exists, how can we evaluate whether it is economically justifiable? 3) If it is not justifiable, how should uneconomical units be decommitted to reduce system total cost?

The Sequential Unit Commitment (SUC) method developed by Fred N Lee [4], takes full advantage of problem decomposition via hourly prices, while maintaining the solution feasibility associated with the basic load balance and reserve constraints. SUC automatically selects the most advantageous units to be committed on the basis of an average operating economic index during the iteration process. The SUC method is limited to all-thermal systems.

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unit schedules, UD decommits the most disadvantageous units as determined by unit average spinning reserve cost index. The unit decommitment procedure continues until no further reductions in total cost are possible, or the unit schedules remain unchanged between two consecutive iterations over the time period. The distinguishing feature of this approach is that the total cost decreases monotonically with iterations, and the solution always maintains feasibility with respect to the load balance equality and spinning reserve inequality constraints in every iteration. The current version of UD is also only applicable to all-thermal systems.

The method presented in this paper combines the LR, SUC and UD methods to solve the HTO problem. The combined unit commitment approach makes full use of the advantages of each of these methods while avoiding the disadvantages of each. The LR method is first used to obtain a near-optimal dual solution. SUC is used to obtain a feasible unit commitment from the LR dual solution's possibly infeasible commitment. As a new feasibility algorithm, SUC solves the feasibility problem by dynamic programming with an additional spinning-reserve-decreasing constraint, without any heuristics for updates of system multipliers. Finally, the UD method evaluates overcommitment in this feasible commitment, and decommits overcommitted units to improve the commitment if possible. Implementation of the proposed algorithm in a version of PG&E's HTO program has led to improvements in the solutions of test problems.

The remainder of this paper consists of the following sections. We formulate the unit commitment problem for HTO in the next section. Section 3 gives a general outline and coordination picture of LR, SUC and UD models. Section 4,5 and 6 describe the LR, SUC and UD models and their solution algorithms in detail. In section 7 we describe the overall computational algorithm of the proposed combined unit commitment approach. The computational results of the proposed method are illustrated in section 8.

2. FORMATION OF PROBLEM

Notations

t , i indexes of hour and unit

I, J set of thermal and hydro units

T number of hours of the study period

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

S_{it} start-up cost of unit i at hour t

p_{it} generation of unit i at hour t

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_{it} spinning capacity of unit i at hour t

R_t^{req} required system spinning reserve

dn_i minimum down time of unit i

up_i minimum up time of unit i

T_k^- subset of hours with deficit of spinning reserve

T_k^+ subset of hours with excess spinning reserve

I_k^+ subset of on-line units in subset T^+ in iteration k

Objective

This paper concentrates its discussion on the thermal unit commitment. The hydro optimization which consists of hydro network flow and hydro unit commitment has been described in detail in our previous paper [2] presented at 1996 IEEE Summer Meeting (96 SM 497-8PWRS). The optimal short-term hydro-thermal resource scheduling problem is defined as the following optimization problem:

$$\min \sum_{t\in T}\{\sum_{i\in I} C_{it}(p_{it}) + S_{it}(x_{i,t-1}, u_{it}, u_{i,t-1}) + \sum_{j\in J} C_{jt}(x_{j,t-1}, p_{jt}, u_{jt}, u_{j,t-1})\} \tag{1}$$

where the first and second terms represent the thermal operating cost including fuel and start-up costs; the third term represents the hydro operating costs.

System constraints

Total hydro and thermal generation meets the system demand:

$$gp_t = \sum_{i\in I} p_{it}\cdot u_{it} + \sum_{j\in J} p_{jt}\cdot u_{jt} - D_t = 0 \tag{2}$$

System spinning reserve must be satisfied:

$$gs_t = \sum_{i\in I} R_{it}\cdot u_{it} + \sum_{j\in J} R_{jt}\cdot u_{jt} - R_t^{req} \geq 0 \tag{3}$$

Thermal constraints

Unit maximum and minimum limits:

$$\underline{p}_{it} \leq p_{it} \leq \overline{p}_{it} \tag{4}$$

Unit ramp constraints

$$-rmp_i \leq p_i - p_{i,t-1} \leq rmp_i \tag{5}$$

Unit state dynamic constraints:

$$x_{i,t+1} = x_{it} + u_{it} \qquad \text{if } x_{it}\cdot u_{it} > 0 \tag{6}$$

$$x_{i,t+1} = u_{it} \qquad \text{if } x_{it}\cdot u_{it} < 0 \tag{7}$$

Unit minimum up time constraints:

$$1 \leq x_{it} \leq up_i \quad \text{if } u_{it} = 1 \tag{8}$$

Unit minimum downtime constraints:

$$-dn_i \leq x_{it} \leq -1 \quad \text{if } u_{it} = -1 \tag{9}$$

Hydro constraints

A full set of hydro constraints are represented (see [2]) including:

- Water conservation constraints
- Reservoir maximum and minimum content limits
- Reservoir target condition
- Water spillage constraints
- Hydro unit maximum and minimum limits
- Hydro unit cycling condition

3. DESCRIPTION OF COMBINED APPROACH

The combined unit commitment approach consists of LR , SUC and UD models, which will be described in the next three sections separately. The general outline and coordination of these three models are described in this section.

The LR model solves hydro and thermal dual subproblems to produce schedules for hydro and thermal units. The schedules obtained from the dual solution usually do not satisfy system load and spinning reserve constraints in some hours of the study period.

We divide the study time period into two subsets of hours: T_k^- is the subset of hours with excess spinning reserve, and T_k^- is the subset of hours with deficit of spinning reserve, calculated in iteration k. The subset of hours with a deficit of spinning reserve is not feasible and will be eliminated by the SUC model. Excess spinning reserve results in uneconomical operation due to extra operational costs and where possible uneconomical units will be decommitted by the UD model. The LR model provides input to the UD model or SUC model depending on whether subset T_k^- is empty or not.

The SUC model works as follows. Given initial Lagrangian multipliers obtained from the dual solution of the LR model, SUC sequentially selects the most advantageous units to be committed according to the unit average spinning reserve cost index. This commitment process terminates when the subset T_k^- becomes empty. The SUC model proposed here starts the commitment process from any initial schedules with deficits of system spinning reserve in contrast with that described in [4] which starts with null schedules of all units. This allows the SUC algorithm to be coordinated with the LR dual solution. In contrast with the RFS model described in [3] the proposed SUC selects a candidate unit with the smallest average spinning reserve cost to be committed to cover the deficit of system spinning reserve in subset T_k^- instead of using the smallest instantaneous spinning reserve cost at the most severely reserve-violated hour. That implies that in SUC, the selected unit in solving its dynamic programming will try to cover the spinning reserve deficits as much as possible in all hours of subset T_k^-, while each RFS iteration only considers the most severely reserve-violated hour of the study period and requires the incremental unit to be must-run only in this particular hour. This modification will in general improve the algorithm's performance in CPU time. SUC therefore replaces the feasibility phase of LR.

The UD model works in the following way. Given a solution (unit schedules and Lagrangian multipliers) obtained from SUC model or LR model (if the dual solution is feasible), UD first evaluates the suboptimality of the solution. If overcommitment exists, UD decommits units according to the unit average spinning reserve cost, until no further reductions in total cost are possible.

The detailed coordination and solution algorithm of the combined approach is discussed in Section 7.

4. LR MODEL

Dual problem

The dual problem is constructed by incorporating constraints (2) and (3) into the objective function (1) with multipliers λ_{it}, μ_{it}.

$$dl(\lambda,\mu) = \min \sum_{t\in T} \{ \sum_{i\in I} C_{it}(p_{it}) + S_{it}(x_{i,t-1}, u_{it}, u_{i,t-1}) + \sum_{j\in J} C(x_{j,t-1}, p_{jt}, u_{jt}, u_{j,t-1})\} - \lambda_t \cdot gp_t - \mu_t \cdot gs_t \} \tag{10}$$

Substituting gp_t, gs_t with (2) and (3) respectively, the dual (10) is rearranged as:

$$dl(\lambda,\mu) = dlt(\lambda,\mu) + dlh(\lambda,\mu) + dls(\lambda,\mu) \tag{11}$$

The dual function (11) is divided into three independent parts. The first part involves the thermal unit index i only, and is defined as the thermal unit commitment problem. The corresponding thermal dual function is as follows:

$$dlt(\lambda,\mu) = \min \sum_{t\in T} \{ \sum_{i\in I} C_{it}(p_{it}) + S_{it}(x_{i,t-1}, u_{it}, u_{i,t-1}) - \lambda_t \cdot p_{it} \cdot u_{it} - \mu_t \cdot R_{it} \cdot u_{it} \} \tag{12}$$

The thermal dual function is further divided into unit subproblem:

$$dlt_i(\lambda,\mu) = \min \sum_{t\in T} C_{it}(p_{it}) + S_{it}(x_{i,t-1}, u_{it}, u_{i,t-1}) - \lambda_t \cdot p_{it} \cdot u_{it} - \mu_t R_{it} \cdot u_{it}) \quad i = 1,2,\ldots\ldots \tag{13}$$

The second part of (11) involves the hydro index j only, and is defined as the hydro optimization problem. The corresponding hydro dual function is as follows:

$$dlh(\lambda,\mu) = \min \sum_{t\in T} \sum_{j\in J} C_{jt}(x_{j,t-1}, p_{jt}, u_{jt}, u_{j,t-1})\} - \lambda_t \cdot p_{jt} \cdot u_{jt} - \mu_t \cdot R_{jt} \cdot u_{jt}) \tag{14}$$

The third part of (11) is related to the system load and spinning reserve requirement:

$$dls(\lambda,\mu) = \min \sum_{t\in T} (\lambda_t \cdot D_t + \mu_t \cdot R_t^{req}) \tag{15}$$

With known λ, μ, the third part is a constant term and will be ignored when optimizing the thermal and hydro problems.

Solution to dual problem

The thermal and hydro dual problems are optimized independently by iteratively updating the Lagrangian multipliers λ, μ as shown in Fig. 1. The thermal unit dual problem is solved by dynamic programming [1,3]. The hydro problem is solved by a combined hydro network flow and hydro unit commitment program [2]. The step size for updating Lagrangian multipliers λ, μ has a big impact on the performance of the dual solution and should be tuned for each system.

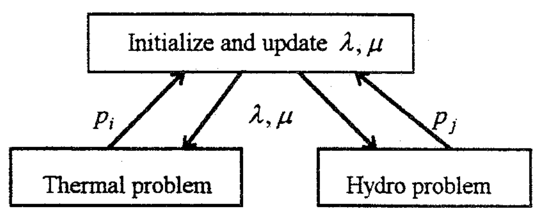

Fig. 1 Flow chart of dual solution

5. SUC MODEL

Formulation of SUC problem

Suppose that an initial solution obtained from the LR model with deficit of spinning reserve in subset T_k^- is given as $(\widetilde{x}_{it}, \widetilde{u}_{it}, \widetilde{p}_{it}, \widetilde{\lambda}_t, \widetilde{\mu}_t)$. Now we relax all units in the subset I_k^- and make them committable. The objective is to select the most economical unit from subset I_k^- to be committed to decrease the deficits of spinning reserve in subset T_k^-. This problem is formulated as a searching process to find the unit to be committed in subset I_k^-

according to the average spinning reserve cost. The unit with the lowest average spinning reserve cost can be found by sequentially solving the dual problems of all units in subset I_k^- :

$$dlt_i(\lambda,\mu) = \min \sum_{t\in T} C_{it}(p_{it}) + S_{it}(x_{i,t-1},u_{it},u_{i,t-1})$$
$$-\widetilde{\lambda}_t \cdot p_{it} \cdot u_{it} - \widetilde{\mu}_t \cdot R_{it} \cdot u_{it})\} \quad i\forall I_k^- \tag{16}$$

s.t. the spinning reserve deficit decreasing condition:

$$dsp_t^k < dsp_t^{k-1} \tag{17}$$

where the spinning reserve deficit at hour t in iteration k, is defined as

$$dsp_t^k = R_t^{req} - \sum_{l\in I} R_{lt} * \widetilde{u}_{lt} \qquad t\forall T_k^- \tag{18}$$

The condition (17) can easily be implemented in the dynamic programming graph (forward paths) by forcing unit i to be must run in the subset T_k^-.

Determine unit average spinning reserve cost

As mentioned above, the unit with the lowest average spinning reserve cost is selected to be committed at the current iteration. The average spinning reserve cost of unit i in iteration k, $asrc_i^k$, is determined as follows:

- Determine the dual value of unit i in iteration k :

$$dlt_i^k = \sum_{t\in T} C_{it}(\widetilde{p}_{it}) + S_{it}(\widetilde{x}_{i,t-1},\widetilde{u}_{it},\widetilde{u}_{i,t-1}) - \widetilde{\lambda}_t \cdot \widetilde{p}_{it} \cdot \widetilde{u}_{it}$$
$$-\widetilde{\mu}_t \cdot R_{it} \cdot \widetilde{u}_{it} \tag{19}$$

where

$\widetilde{p}_{it}, \widetilde{u}_{it}, \widetilde{x}_{i,t-1}$ are the unit generation, on/off status and state variable determined from the tentative commitment of unit i

- Determine the total increase of spinning reserve after committing unit i in iteration k

$$usr_i^k = \sum_{t\in T_k^-} R_{it} \cdot \widetilde{u}_{it} \tag{20}$$

- The average spinning reserve cost for SUC is then defined as

$$asrc_i^k = (dlt_i^k - dlt_i^{k-1}) / usr_i^k \tag{21}$$

Solution to SUC

1. Get dual solution ($\widetilde{x}_{it}, \widetilde{u}_{it}, \widetilde{p}_{it}, \widetilde{\lambda}_t, \widetilde{\mu}_t$) from the LR model as the starting point (0 iteration) for SUC.
2. Calculate system spinning reserve deficits and excesses for all hours.
3. Fill subset T_k^- with hours having spinning reserve deficit
4. Fill subset T_k^+ with hours having excess spinning reserve.
5. If T_k^- is empty, exit from SUC.
6. Fill subset I_k^- with units that are off-line in subset T_k^-.
7. Solve the unit dual problem (16) for each unit i in subset I_k^- by dynamic programming s.t. constraints (17), and obtain a new unit schedule for unit i, ($\widetilde{x}_{it}, \widetilde{u}_{it}, \widetilde{p}_{it}, \widetilde{\lambda}_t, \widetilde{\mu}_t$) in iteration k.
8. Use (21) to calculate the average spinning reserve cost for each unit.
9. Select the unit in subset I_k^- with the lowest average spinning reserve cost to be committed in the corresponding hours in subset T_k^-.
10. Calculate the decreased spinning reserve deficit by subtracting the spinning reserve capacity of unit i just committed from the system spinning reserve deficit of the previous iteration. Remove those hours from T_k^- with no system spinning reserve deficits and add them to T_k^+
11. Delete unit i from subset I_k^- and add to I_k^+
12. If T_k^- is not empty, return to Step 7, and repeat Steps 7-11.
13. Do system economic dispatch. Record the solution of the current iteration as the improved solution ($\widetilde{x}_{it}, \widetilde{u}_{it}, \widetilde{p}_{it}, \widetilde{\lambda}_t, \widetilde{\mu}_t$) .
14. Calculate the system dual value of the current iteration, and compare it with that of the previous iteration. If the difference is less than a small tolerance, stop SUC.
15. Set ($\widetilde{x}_{it}, \widetilde{u}_{it}, \widetilde{p}_{it}, \widetilde{\lambda}_t, \widetilde{\mu}_t$) as new starting point for SUC and repeat Steps 2-14.

6. UD MODEL [5]

Formulation of UD problem

Suppose that a solution from the SUC model with an excess of spinning reserve over the study period in iteration k-1 is given as ($\widetilde{x}_{it}^{k-1}, \widetilde{u}_{it}^{k-1}, \widetilde{p}_{it}^{k-1}, \widetilde{\lambda}_{it}^{k-1}$). The objective is to select the least economical unit from subset I_k^+ to be decommitted to reduce system total cost in current iteration k. Here we ignore Lagrangian multipliers related to the system spinning reserve constraints in the dual formulation, because these constraints are observed at all times during the UD solution without adjusting these multipliers. Relax all units in subset I_k^+, and make them decommittable. Given ($\widetilde{\lambda}_t, \widetilde{p}_{it}$), the following dual subproblem for unit i is formulated:

$$(P){:}\, dlt_i(\widetilde{\lambda}) = \min \sum_{t\in T} C_{it}(\widetilde{p}_{it}) + S_{it}(x_{i,t-1},u_{it},u_{i,t-1})$$
$$-\widetilde{\lambda}_t \cdot \widetilde{p}_{it})\} \qquad i\forall I_k^+ \tag{22}$$

subject to the local constraints of unit i, and the following system excess spinning reserve constraints

$$esp_t^k = \sum_{l\neq i} R_{lt} \cdot \widetilde{u}_{lt} + R_{it} \cdot u_{it} - R_t^{req} \geq 0 \tag{23}$$

The problem (P_i) is solved by dynamic programming for each unit in subset I_k^+ s.t. constraints (23). Constraints (23) can be observed in the DP graph by blocking those paths in which the excess spinning reserve turns negative. Therefore, reserve feasibility is always guaranteed in the decommitment process.

Criteria for decommitting a unit

In contrast with SUC, in UD the unit with the highest average spinning reserve cost is selected to be decommitted at the current iteration. The average spinning reserve cost of unit i in iteration k, $asrdc_i^k$ is determined as follows:

- Use (19) with $\tilde{\mu}_t = 0$ to determine the dual value of unit i in iteration k
- Use the following formula to determine the total decrease of spinning reserve of unit i in iteration k after decommitting the unit

$$dusr_i^k = \sum_{t \in T_{k-1}^+} R_{it} \cdot \tilde{u}_{it}^{k-1} - \sum_{t \in T_k^+} R_{it} \cdot \tilde{u}_{it}^k \quad (24)$$

- The average spinning reserve cost for UD is then defined as

$$asrdc_i^k = (dlt_i^{k-1} - dlt_i^k) / dusr_i^k \quad (25)$$

Solution to UD

The unit decommitment procedure is broken into these steps:

1. Calculate the excess spinning reserve from the SUC solution or the LR dual solution (if original feasible)
$$esp_t^k = \sum_{l \in I_k^+} R_{lt} \cdot \tilde{u}_{lt} - R_t^{req} \quad (26)$$
2. Check for the existence of overcommitment. If the excess of spinning reserve in all hours is less than the spinning capacity of the smallest unit in subset I_k^+, any decommitment will result in a spinning reserve deficit, exit from UD.
3. For each candidate unit in the subset I_k^+, solve (22) by dynamic programming to produce a new commitment schedule.
4. Use (25) to calculate the average spinning reserve cost. Select the unit in I_k^+ with maximum average spinning reserve cost to be decommitted in the corresponding hours in subset T_k^+ and record the schedule of the decommitted unit.
5. Do an economic dispatch for the system and save the current solution. This solution then serves as a new starting point. return to 2.
6. If two consecutive iterations give the same solution, exit from UD; otherwise, return to 2.

7. OVERALL SOLUTION ALGORITHM

The flow chart of the combined approach is depicted in Fig. 2.

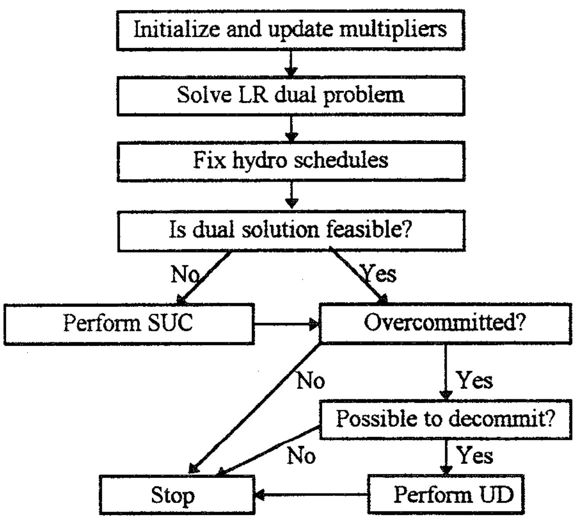

Fig. 2. Flow chart of overall solution

The overall computational procedure is broken into these steps:

1. Initialize multipliers λ, μ.
2. Solve the dual problem using the algorithms described in [1,2].
3. To reduce the computation burden, after the dual solution the hydro schedules are assumed to be fixed. Experience has shown that this assumption does not have significant impact on the final HTO results.
4. Check if the dual solution is feasible. If yes, go to step 6.
5. Perform SUC using the algorithm described in Section 5.
6. Check if the dual solution is overcommitted. if no, stop.
7. Check if the overcommitment is justifiable. If yes, stop.
8. Perform UD using the algorithm described in Section 6.

8. COMPUTATIONAL RESULTS

PG&E's existing HTO was based on a Lagrangian relaxation and has been refined over years. The UD module has already been implemented in the HTO production version as a post-processor after the feasibility phase. The SUC module proposed in this paper is intended to replace the feasibility phase. The combined unit commitment approach has been implemented and tested on the PG&E power system, which covers northern and central California. The proposed approach has been tested in a study case with 115 hydro units and 50 thermal units. The hydro and thermal unit incremental cost curves are modeled by piecewise linear functions. The study case system has peak load of 16785 MW with a load factor of 82.6%. Hourly spinning reserve requirement is taken as 7% of system load. Other system parameters used to drive the test results can be found in [1].

The program is coded in FORTRAN 77 and runs on an HP9000/735 computer.

Some test results for the combined approach are illustrated below.

- Fig. 3 shows the maximum spinning reserve deficit vs. iteration.
- In Fig. 4 each bullet represents the hour with maximum spinning reserve deficit occurred in each iteration.
- Fig. 3 and 4 show no indication of convergence with respect to the spinning reserve constraints.

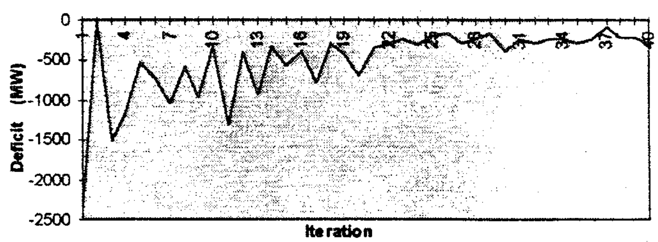

Fig. 3 Spinning reserve deficit vs. iteration

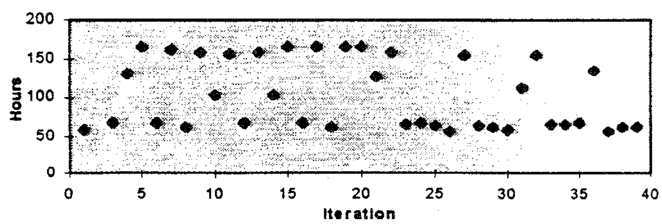

Fig. 4 Hours of maximum spinning reserve deficit vs. iterations

- SUC commits two units to cover deficits of spinning reserve obtained from the LR dual solution.
- Table 1 shows the improvement in the duality gap achieved by performing SUC and UD after the dual solution. The dual value is calculated from the dual solution after 40 iterations.

Table 1. Improvement of duality gaps

	Iteration	Dual value ($1000)	Primal cost ($1000)	Duality gap (%)
LR	40	12043.7		
SUC	41		12154.0	0.916
UD	42		12137.1	0.776
	43		12135.7	0.764
	44		12135.2	0.760
	45		12133.3	0.744

- Comparison of the proposed method with PG&E's existing HTO with the APR feasibility algorithm is presented in Table 1~2. As shown in these tables, the proposed algorithm yelds a better duality gap than the LR-APR-DU algorithm. The LR-SUC-DU algorithm also reduces CPU time. It takes only one iteration to reach the feasible solution in SUC. LR-APR-DU algorithm requires more iterations (4 in this study case). We have tested other study cases which required many more iterations for the cumulative effect of small updates of multipliers to change the unit commitment. This is because small infeasibilities usually result in small updates to multipliers in the LR-APR-DU algorithm, requiring many iterations to drive a solution with small infeasibilities to feasibility.

Table 2. Comparison with PG&E existing HTO

	Iteration	Dual value ($1000)	Primal cost ($1000)	Duality gap (%)
LR	40	12043.7		
APR	44		12177.4	1.110
UD	45		12147.0	0.858
	46		12141.4	0.811
	47		12138.7	0.789

9. CONCLUSION

The combination of Lagrangian relaxation, sequential unit commitment and optimal unit decommitment methods in dealing with the HTO problem has been shown to give excellent performance in preliminary testing. LR obtains a suboptimal dual solution. SUC converts the infeasible dual solution to a primal feasible solution; UD performs a quantitative analysis of the overcommitment of the SUC solution and decommits overcommitted units to reduce system total cost as much as possible. We believe that the algorithms and techniques in our HTO model have now attained a high level of maturity. Inclusion of the various algorithms described in this paper has resulted in a robust program that can handle a wide range of system conditions and still produce highly accurate results without using excessive computational resources.

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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.

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 Siddeley Power Engineering from 1976 to 1980 and an EMS applications developer with Ferranti International Controls from 1987 to 1989. 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.

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 PG&E 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, a M.S. in Electrical and Computer Engineering from U.C. Davis in 1992 and a Ph.D. in Industrial Engineering and Operations Research from U.C. Berkeley in 1996. He has worked as an operations research consultant for PG&E from 1995 to 1996. He is now with Edison Source in City of Industry, California, as a risk management manager. His research interests include optimization applied to industrial applications and neural network

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 PG&E since 1983, developing computer applications for fuel and resource planning, hydro scheduling and forecast management, and hydro-thermal optimization.