A Hybrid LR–EP for Solving New Profit-Based UC Problem Under Competitive Environment

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***Abstract*—With the opening of the power industry to competition, the power system structure is changing. According to these changes, power system operation, planning, and control need modifications. In the past, utilities had to produce power to satisfy their customers with objective to minimize costs and all demand/reserve were met. However, it is not necessary in a restructured system. Under new structure, generation companies (GENCOs) schedule their generators with objective to maximize their own profit without regard for system social benefit. Power and reserve prices become important factors in decision process. This paper proposes a new tool, profit-based unit commitment (UC) considering power and reserve generatings. The proposed method helps GENCO to make a decision, how much power and reserve should be sold in markets, and how to schedule generators in order to receive the maximum profit. A hybrid method between Lagrange Relaxation (LR) and evolutionary programming (EP) is used for solving this problem. Simulations are carried out to show the performance of the proposed methodology.**

***Index Terms*—Competitive environment, deregulation, evolutionary programming, Lagrange relaxation, power system operation planning and control, profit-base unit commitment, restructured system.**

I. Introduction

RESTRUCTURING of a power system has resulted in market-based competition by creating an open market environment. Traditional power system operation, planning, and control need changes [1]–[3]. In the past, utilities had to produce power to satisfy their customers with the minimum production cost. That means utilities run unit commitment (UC) with the condition that all demand and reserve must be met. After the structure changed; however, they are more competitive under deregulation. The objective of UC is not to minimize costs as before, but to make the maximum profit for company. Generation companies (GENCOs) can now consider the amount of power and reserve sold on the market as well as generator scheduling plan that create the maximum profit without regard that demand and reserve have been completely met or not.

In this paper, authors present a new profit-based UC problem under a competitive environment. The proposed method helps GENCOs decide how much power and reserve should be sold into energy and ancillary markets, respectively. Based on the market's forecasted information, the proposed method considers both power and reserve generation at the same time. A new hybrid method between Lagrange Relaxation (LR) and evolutionary programming (EP) is used as a tool for solving this optimization problem. Two strategies for selling power and reserve are simulated using three- and ten-unit systems. Simulation results are compared with the solutions obtained from a traditional UC problem.

II. New Unit Commitment Problem Formulation

A new profit-based UC problem under competitive environment is an optimization problem and can be formulated mathematically by the following equations:

The objective function

$$\max . PF = RV - TC \tag{1}$$

or

$$\min . TC - RV. \tag{2}$$

Constraints

1) Demand Constraint:

$$\sum_{i=1}^{N} P_{it} X_{it} \le D'_t, \qquad t = 1, \ldots, T. \tag{3}$$

2) Reserve Constraint:

$$\sum_{i=1}^{N} R_{it} X_{it} \le SR'_t, \qquad t = 1, \ldots, T. \tag{4}$$

Here, demand and reserve constraints are different from traditional UC problem because GENCO can now select to produce demand and reserve less than the forecasted level if it creates more profit.

3) Power and Reserve Limits:

$$P_{i\min} \le P_i \le P_{i\max}, \qquad i = 1, \ldots, N \tag{5}$$

$$0 \le R_i \le P_{i\max} - P_{i\min}, \qquad i = 1, \ldots, N \tag{6}$$

$$R_i + P_i \le P_{i\max}, \qquad i = 1, \ldots, N. \tag{7}$$

4) Minimum Up and Downtime Constraints: Where variables are defined as follows:

PF profit of GENCO;
RV revenue of GENCO;
TC total cost of GENCO;
P_{it} power generation of generator i at hour t;
R_{it} reserve generation of generator i at time t;
X_{it} on/off status of generator i at hour t;
D'_t forecasted demand at hour t;
SR'_t forecasted reserve at hour t;
$P_{i\min}$ minimum generation limit of generator i;,
$P_{i\max}$ maximum generation limit of generator i;
N number of generator units;
T number of hours.

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In the new problem, predicted demand, reserve, and prices are important parameters. These parameters are forecasted by another technique not described here. We, for now, assume that we have all data in hand. Another important factor is the strategy for selling power and reserve, described in the next section. This parameter is used to determine the expected revenue in (1) which directly affects the expected profit.

III. Strategies for Selling Power and Reserve

In a restructured system, GENCO sells power in energy market and sells reserve in the reserve (ancillary) market. The amount of power and reserve sold depends on the way reserve payments are made. In this paper, we present two examples of reserve payment method [3].

A. Payment for Power Delivered

In this method, reserve is paid when only reserve is actually used. Therefore, the reserve price is higher than the power (spot) price. Revenue and costs in (1) can be calculated from

$$RV = \sum_{i=1}^{N}\sum_{t=1}^{T}(P_{it}\cdot SP_t)\cdot X_{it} + \sum_{i=1}^{N}\sum_{t=1}^{T} r\cdot RP_t\cdot R_{it}\cdot X_{it} \tag{8}$$

$$TC = (1-r)\sum_{i=1}^{N}\sum_{t=1}^{T}F(P_{it})\cdot X_{it} + r\sum_{i=1}^{N}\sum_{t=1}^{T}F(P_{it}+R_{it})\cdot X_{it} + ST\cdot X_{it} \tag{9}$$

where

- SP_t forecasted spot price at hour t;
- RP_t forecasted reserve price at hour t;
- F_i fuel cost function of generator i;
- ST start up cost;
- r probability that the reserve is called and generated.

B. Payment for Reserve Allocated

In this method, GENCO receives the reserve price per unit of reserve for every time period that the reserve is allocated and not used. When the reserve is used, GENCO receives the spot price for the reserve that is generated. In this method, reserve price is much lower than the spot price. Revenue and costs in (1) can be calculated from

$$RV = \sum_{i=1}^{N}\sum_{t=1}^{T}(P_{it}\cdot SP_t)\cdot X_{it} + \sum_{i=1}^{N}\sum_{t=1}^{T}((1-r)RP_t + r\cdot SP_t)R_{it}\cdot X_{it} \tag{10}$$

$$TC = (1-r)\sum_{i=1}^{N}\sum_{t=1}^{T}F(P_{it})\cdot X_{it} + r\sum_{i=1}^{N}\sum_{t=1}^{T}F(P_{it}+R_{it})\cdot X_{it} + SP\cdot X_{it}. \tag{11}$$

IV. Proposed Methodology

Since UC was introduced, several methods have been applied to solve this problem. Among these methods, the LR method seems to be the most suitable one [4]–[6]. Lagrange Relaxation method can provide a fast solution but sometimes it suffers from numerical convergence problem especially when the problem is nonconvex. Besides, this method strongly depends on the technique used to update Lagrange multipliers. Most researchers dealing with LR use gradient method to achieve this task. However, the solution obtained from gradient-based method suffers from convergence problem and always gets stuck into a local optimum. In order to overcome these problems, many stochastic optimizations such as genetic algorithm (GA) and evolutionary programming [7]–[12] were introduced into power system optimization. These methods begin with a population of starting points, use only the objective functions information, and search a solution in parallel using operators borrowed from natural biology. Therefore, these methods can provide a high-quality solution. However, both GA and EP suffer from a big problem. That is, they take long computation time.

In order to get a high-quality solution within a reasonable time, a hybrid method between LR and EP (LR–EP) was introduced and effectively applied to solve UC in [6]. The hybrid method basically bases on LR method. Lagrange Relaxation method solves the problem by relaxing or ignoring the coupling constraints (power and reserve constraints in this case), then solving the problem through the dual optimization procedure. The dual procedure attempts to reach the constrained optimum by maximizing the Lagrange function L with respect to the Lagrange multipliers λ and μ, while minimizing with respect to the power, reserve generation, and unit status, that is:

$$q^* = \max_{\lambda,\,\mu} q(\lambda,\,\mu) \tag{12}$$

where

$$q(\lambda,\,\mu) = \min_{X,\,P,\,R} L(X,\,P,\,R,\,\lambda,\,\mu) \tag{13}$$

subject to constraints (5)–(7) and minimum up and downtime constraints.

Lagrange function can be formulated directly by adding penalty term of coupling constraints into objective function. In each iteration, Lagrange multipliers are updated using EP in order to improve the solution.

The hybrid LR–EP method is applied to solve a new profit-based UC considering power and reserve generation. Both reserve payment method A and B mentioned before are solved. The detail of the proposed algorithm is described step by step as follows:

A. Payment for Power Delivered

By assigning Lagrange multipliers λ and μ to the constraints (3) and (4), respectively, we can form the Lagrange function as

$$L(P,\,R,\,\lambda,\,\mu) = TC - RV - \sum_{t=1}^{T}\lambda_t\left(D'_t - \sum_{i=1}^{N}P_{it}\cdot X_{it}\right) - \sum_{t=1}^{T}\mu_t\left(SR'_t - \sum_{i=1}^{N}R_{it}\cdot X_{it}\right) \tag{14}$$

replace costs and revenue into (14)

$$L = (1-r)\sum_{i=1}^{N}\sum_{t=1}^{T} F(P_{it}) \cdot X_{it} + r\sum_{i=1}^{N}\sum_{t=1}^{T} F(P_{it}+R_{it}) \cdot X_{it} + ST \cdot X_{it} - \sum_{i=1}^{N}\sum_{t=1}^{T}(P_{it} \cdot SP_t) \cdot X_{it} - \sum_{i=1}^{N}\sum_{t=1}^{T} r \cdot RP_t \cdot R_{it} \cdot X_{it} - \sum_{t=1}^{T}\lambda_t\left(D_t' - \sum_{i=1}^{N} P_{it} \cdot X_{it}\right) - \sum_{t=1}^{T}\mu_t\left(SR_t' - \sum_{i=1}^{N} R_{it} \cdot X_{it}\right) \quad (15)$$

rewritten as

$$L = \sum_{i=1}^{N}\sum_{t=1}^{T}[(1-r)F(P_{it}) + rF(P_{it}+R_{it}) + ST - P_{it} \cdot SP_t - r \cdot RP_t \cdot R_{it}] \cdot X_{it} + \sum_{i=1}^{N}\sum_{t=1}^{T}(\lambda_t P_{it} + \mu_t R_{it}) \cdot X_{it} - \sum_{t=1}^{T}(\lambda_t D_t' + \mu_t SR_t') \quad (16)$$

the last term in (16) is constant and can be dropped. Therefore, we can finally write the Lagrange function as

$$L = \sum_{i=1}^{N}\left[\sum_{t=1}^{T}\{(1-r)F(P_{it}) + rF(P_{it}+R_{it}) + ST - P_{it} \cdot SP_t - r \cdot RP_t \cdot R_{it} + \lambda_t P_{it} + \mu_t R_{it}\} \cdot X_{it}\right]. \quad (17)$$

The term inside the bracket of (17) can be solved separately for each generating unit without regard for what is happening on the other generating units. The minimum of the Lagrange function is found by solving for the minimum for each generating unit over all time periods, that is

$$\min q(\lambda, \mu) = \sum_{i=1}^{N}\min\sum_{t=1}^{T}[(1-r)F(P_{it}) + rF(P_{it}+R_{it}) + ST_t - P_{it} \cdot SP_t - r \cdot RP_t \cdot R_{it} + \lambda_t P_{it} + \mu_t R_{it}] \cdot X_{it} \quad (18)$$

subject to constraints (5)–(7) and minimum up/down time constraints.

This problem is solved as a dynamic programming problem.

On the other hand, in order to maximize the Lagrange function, Lagrange multipliers must be suitably adjusted. In this paper, EP is used.

The proposed method can be divided into two main parts as follows:

1) Dynamic Programming Part: A forward dynamic programming method is used to solve the dual problem. The objective of this problem is to minimize q. This procedure is shown in Fig. 1, which shows the two possible states for unit i (0 or 1).

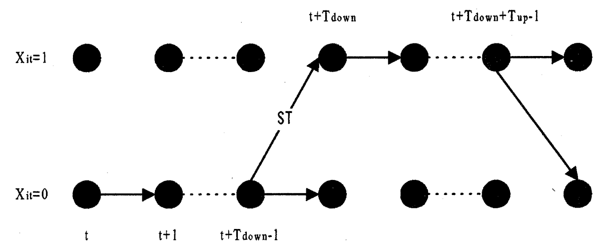

Fig. 1. Two-states dynamic programming.

T_{up} and T_{down} are minimum up and down time constraints of the generator, respectively.

At the state $X_{it} = 0$ the value of the function to minimize is zero. At the state $X_{it} = 1$, the function to be minimize is $\min(K)$ where

$$K = (1-r)F(P_{it}) + rF(P_{it}+R_{it}) - P_{it} \cdot SP_t - r \cdot RP_t \cdot R_{it} + \lambda_t P_{it} + \mu_t R_{it}. \quad (19)$$

The minimum of this function is found by taking the first derivative of K and setting it to zero

$$\frac{\partial K}{\partial P_{it}} = 0$$
$$\frac{\partial K}{\partial R_{it}} = 0. \quad (20)$$

Generator's fuel cost function can be expressed as

$$F_i(P_i) = a_i + b_i P_i + c_i P_i^2 \quad (21)$$

where a_i, b_i and c_i are generator's constants.

The solution of this equation is

$$\begin{bmatrix} P_{it} \\ R_{it} \end{bmatrix} = \frac{1}{1-r}\begin{bmatrix} 1 & -r \\ -1 & 1 \end{bmatrix}\begin{bmatrix} A_{it} \\ B_{it} \end{bmatrix} \quad (22)$$

where

$$A_{it} = \frac{SP_t - \lambda_t - b_i}{2c_i} \quad (23)$$

$$B_{it} = \frac{\left(\frac{r \cdot RP_t - \mu_t}{r} - b_i\right)}{2c_i}. \quad (24)$$

After obtaining the solution, dual value q is calculated from (16).

2) Updating Lagrange Multipliers Part: The adjustment of Lagrange multipliers must be done so as to maximize $q(\lambda, \mu)$. We use EP to achieve this task. Components of EP are described below.

a) *Representation*

For T intervals in the scheduling periods, an array of control variable λ and μ vectors can be shown as

$$\lambda = [\lambda_1 \quad \lambda_2 \quad \cdots \quad \lambda_T]$$
$$\mu = [\mu_1 \quad \mu_2 \quad \cdots \quad \mu_T]. \quad (25)$$

b) *Initialization*

To begin, the population of chromosomes is uniformly random initialized. This population of chromosome is called parent.

c) *Fitness Function*

The value of q is used to indicate the fitness of the candidate solution of each individual.

d) *Creation of the Offspring*

A new population of chromosomes (same amount as parent) is produced from the existing population by adding Gaussian random number $N(0, \sigma^2)$ with zero mean and a predefined standard deviation (σ) to each individual as in (26). This set of chromosomes is called offspring

$$\begin{aligned} \lambda_t' &= \lambda_t + N(0, \sigma_t^2) \\ \mu_t' &= \mu_t + N(0, \sigma_t^2). \end{aligned} \tag{26}$$

e) *Selection and Competition*

The selection techniques used in this paper are the stochastic tournament method. Each individual competes with each other for selection. A weight value w_s is assigned to each individual as follows:

$$w_s = \sum_{j=1}^{P} w_j \tag{27}$$

$$\begin{aligned} w_j &= 1, \quad \text{if } f_s < f_r \\ w_j &= 0, \quad \text{otherwise} \end{aligned} \tag{28}$$

where P is a population size; f_r is the fitness of the rth competitor randomly selected from $2P$ individuals.

The P best individuals will be selected into the next iteration.

f) *Terminating Criteria*

In this paper, the difference between primal and dual problem (duality gap, ε) is used as a terminating criteria. Duality gap is defined as

$$\varepsilon = \frac{J - q}{|J|}. \tag{29}$$

J is the primal value and can be calculated from

$$J = TC^* - RV^* \tag{30}$$

where

$$TC^* = \left[(1-r)\sum_{i=1}^{N}\sum_{t=1}^{T} F(P_{it}^*) + r\sum_{i=1}^{N}\sum_{t=1}^{T} F(P_{it}^* + R_{it}^*)\right] \cdot X_{it} \tag{31}$$

$$RV^* = \left[\sum_{i=1}^{N}\sum_{t=1}^{T} (P_{it}^* \cdot SP_t) + \sum_{i=1}^{N}\sum_{t=1}^{T} r \cdot RP_t \cdot R_{it}^*\right] \cdot X_{it}. \tag{32}$$

Here, P_{it}^* and R_{it}^* are the solutions obtained from economic dispatch (ED) when using the answer from dynamic programming part X_{it} as a fixed value. The objective of ED here differs from normal ED. The objective function is to maximize profit while constraints (5)–(7) are satisfied. Sequential quadratic programming (SQP) is used to solve ED problem.

B. Payment for Reserve Allocated

The problem in B can be solved by the same method as A. However, there are some differences between these two cases as follows:

In B, Lagrange function is

$$\begin{aligned} L = &(1-r)\sum_{i=1}^{N}\sum_{t=1}^{T} F(P_{it}) \cdot X_{it} + r\sum_{i=1}^{N}\sum_{t=1}^{T} F(P_{it} + R_{it}) \\ &\cdot X_{it} + ST \cdot X_{it} - \sum_{i=1}^{N}\sum_{t=1}^{T} (P_{it} \cdot SP_t) \cdot X_{it} \\ &- \sum_{i=1}^{N}\sum_{t=1}^{T} ((1-r)RP_t + r \cdot SP_{it}) \cdot R_{it} \cdot X_{it} \\ &- \sum_{t=1}^{T} \lambda_t \left(D_t' - \sum_{i=1}^{N} P_{it} \cdot X_{it}\right) \\ &- \sum_{t=1}^{T} \mu_t \left(SR_t' - \sum_{i=1}^{N} R_{it} \cdot X_{it}\right) \end{aligned} \tag{33}$$

and the dual problem is

$$\begin{aligned} \min q(\lambda, \mu) = &\sum_{i=1}^{N} \min \sum_{t=1}^{T} [(1-r)F(P_{it}) + rF(P_{it} + R_{it}) \\ &+ ST_t - P_{it} \cdot SP_t - (1-r) \cdot RP_t \cdot R_{it} - r \\ &\cdot SP_{it} \cdot R_{it} + \lambda_t P_{it} + \mu_t R_{it}] \cdot X_{it} \end{aligned} \tag{34}$$

therefore, we have to change B_{it} in (24) to

$$B_{it} = \frac{\left(\frac{(1-r) \cdot RP_t + r \cdot SP_t - \mu_t}{r} - b_i\right)}{2c_i}. \tag{35}$$

The overall procedure of the proposed method is described in Fig. 2.

V. Simulation Results

Simulations are carried out using two test systems adapted from [13] and [6]. The first system consists of three generating units, 12 scheduling periods while the second system consists of ten generating units, 24-h scheduling periods. Fuel cost function of each generator is estimated into quadratic form as shows in (21). All data are given in the Appendix. Simulations are classified into two parts. In the first part, the effect of r and price are simulated using a three-unit system. In the second part, a ten-unit system is used to show that the proposed algorithm can also deal with larger system. All simulation results are compared with the results obtained from traditional UC problem.

Three-Unit Test System: First, the effect of probability that reserve is called and generated (r) is investigated using a three-unit system. Here, reserve price is fixed at the triple and 0.01 times of spot price for reserve payment method A and B, respectively, while r is varied from 0.005 to 0.05. Simulation results are shown in Tables I and II.

Second, the effect of reserve price is investigated. In this case, r is fixed at 0.005 while reserve price is varied. Results are given in Tables III and IV for reserve payment methods A and B, respectively.

Tables V and VI show the examples of power and reserve scheduling plans for reserve payment methods A and B, respectively.

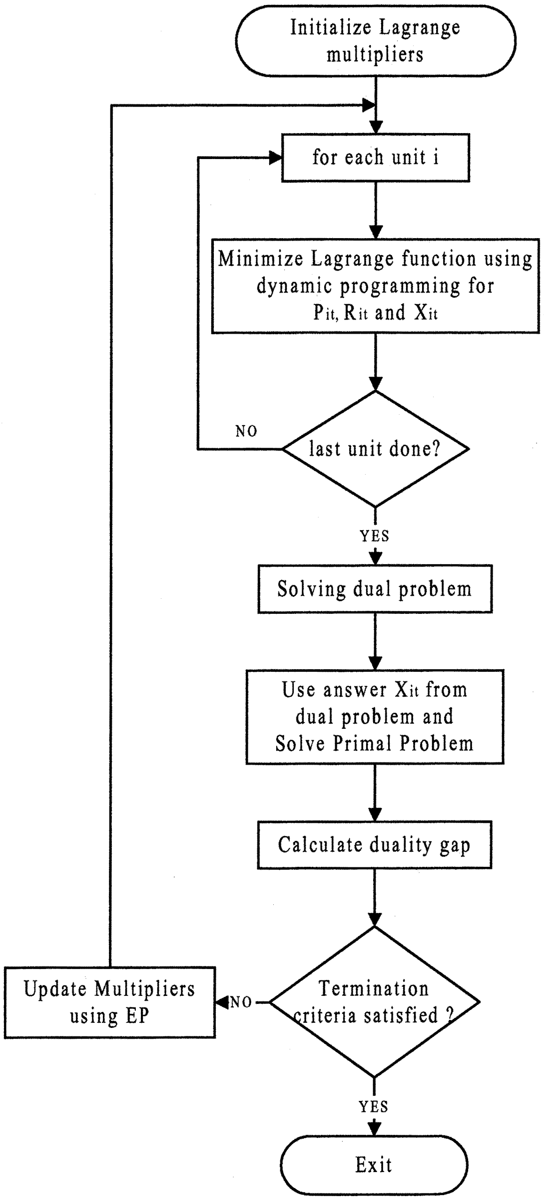

Fig. 2. Flowchart of the proposed method.

TABLE I
EFFECT OF r IN RESERVE PAYMENT METHOD A

r	Profit ($) (Traditional)	Profit ($) (Proposed)
0.005	4048.81	9074.35
0.010	4121.62	9094.23
0.015	4194.43	9116.18
0.020	4267.24	9140.40
0.025	4340.05	9166.98
0.030	4412.86	9195.88
0.035	4485.67	9228.00
0.040	4558.48	9262.87
0.045	4631.29	9300.76
0.050	4704.10	9340.77

For reserve payment method A, reserve is paid only when the reserve power is actually delivered and used. That is why profit in this case is more sensitive than payment method B when r is varied. Large r means reserve has more chance to be called; therefore, GENCO receives more profit when r is increased. On the other hand, in payment method B, reserve is paid all of the time even reserve is not delivered. Therefore, the profit in this case is more sensitive than payment method A when reserve price is varied.

From Tables V and VI, it can be seen that GENCO chooses to off unit 1 in all scheduling periods and to sell power and

TABLE II
EFFECT OF r IN RESERVE PAYMENT METHOD B

r	Profit ($) (Traditional)	Profit ($) (Proposed)
0.005	4048.45	9074.26
0.010	4049.12	9075.40
0.015	4049.79	9076.53
0.020	4050.46	9077.67
0.025	4051.14	9078.80
0.030	4051.81	9079.93
0.035	4052.48	9081.07
0.040	4053.15	9082.20
0.045	4053.82	9083.34
0.050	4054.49	9084.47

TABLE III
EFFECT OF RESERVE PRICE IN RESERVE PAYMENT METHOD A

Reserve price (times of spot price)	Profit ($) (Traditional)	Profit ($) (Proposed)
1	3977.03	9057.72
2	4012.92	9065.78
3	4048.81	9074.35
4	4084.70	9083.42
5	4120.59	9093.00
6	4156.48	9103.07
7	4192.37	9113.65
8	4228.26	9124.75
9	4264.15	9136.48
10	4300.04	9148.75
11	4335.93	9161.56
12	4371.82	9174.90
13	4407.71	9188.79
14	4443.60	9203.41
15	4479.49	9218.87

TABLE IV
EFFECT OF RESERVE PRICE IN RESERVE PAYMENT METHOD B

Reserve price (times of spot price)	Profit ($) (Traditional)	Profit ($) (Proposed)
0.01	4048.45	9074.26
0.02	4119.87	9092.80
0.03	4191.29	9113.33
0.04	4262.71	9136.00
0.05	4334.14	9160.90
0.06	4405.56	9187.94
0.07	4476.98	9217.76
0.08	4548.40	9250.13
0.09	4619.82	9285.20
0.10	4691.24	9322.59

TABLE V
EXAMPLE OF POWER AND RESERVE GENERATION OF THE FINAL SOLUTION FOR RESERVE PAYMENT METHOD A ($r = 0.005$, RESERVE PRICE $= 3$*SPOT PRICE)

Hour	Traditional Unit Commitment							Profit-based Unit Commitment (A)						
	Power (MW)			Reserve (MW)			Profit ($)	Power (MW)			Reserve (MW)			Profit ($)
	Unit 1	Unit 2	Unit 3	Unit 1	Unit 2	Unit 3		Unit 1	Unit 2	Unit 3	Unit 1	Unit 2	Unit 3	
1	0	100	70	0	0	20	126.5	0	0	170	0	0	20	531.4
2	0	100	150	0	0	25	352.9	0	0	200	0	0	0	570.0
3	0	200	200	0	40	0	103.6	0	0	200	0	0	0	300.0
4	0	320	200	0	55	0	303.1	0	0	200	0	0	0	390.0
5	100	400	200	70	0	0	-363.2	0	379.9	200	0	20.1	0	201.0
6	450	400	200	95	0	0	1017.8	0	400	200	0	0	0	1350.0
7	500	400	200	100	0	0	1040.9	0	400	200	0	0	0	1380.0
8	200	400	200	80	0	0	548.4	0	400	200	0	0	0	990.0
9	100	350	200	15	50	0	308.1	0	400	200	0	0	0	810.0
10	100	100	130	0	0	35	91.1	0	130	200	0	35	0	818.1
11	100	100	200	0	40	0	159.7	0	200	200	0	40	0	804.6
12	100	250	200	0	55	0	359.9	0	350	200	0	50	0	929.2
Total							4048.8							9074.3

TABLE VI
EXAMPLE OF POWER AND RESERVE GENERATION OF THE FINAL SOLUTION FOR RESERVE PAYMENT METHOD B ($r = 0.005$, RESERVE PRICE $= 0.004$*SPOT PRICE)

Hour	Traditional Unit Commitment							Profit-based Unit Commitment (B)						
	Power (MW)			Reserve (MW)			Profit ($)	Power (MW)			Reserve (MW)			Profit ($)
	Unit 1	Unit 2	Unit 3	Unit 1	Unit 2	Unit 3		Unit 1	Unit 2	Unit 3	Unit 1	Unit 2	Unit 3	
1	0	100	70	0	0	20	132.8	0	0	170	0	0	20	537.7
2	0	100	150	0	0	25	360.6	0	0	200	0	0	0	570.0
3	0	200	200	0	40	0	114.3	0	0	200	0	0	0	300.0
4	0	320	200	0	55	0	318.6	0	0	200	0	0	0	390.0
5	100	400	200	70	0	0	-342.3	0	330	200	0	70	0	215.7
6	450	400	200	95	0	0	1049.7	0	400	200	0	0	0	1350.0
7	500	400	200	100	0	0	1074.5	0	400	200	0	0	0	1380.0
8	200	400	200	80	0	0	573.8	0	400	200	0	0	0	990.0
9	100	350	200	15	50	0	328.1	0	387.2	200	0	12.8	0	810.4
10	100	100	130	0	0	35	102.8	0	130	200	0	35	0	829.8
11	100	100	200	0	40	0	172.5	0	200	200	0	40	0	817.4
12	100	250	200	0	55	0	377.3	0	350	200	0	50	0	945.0
Total							4262.7							9136.0

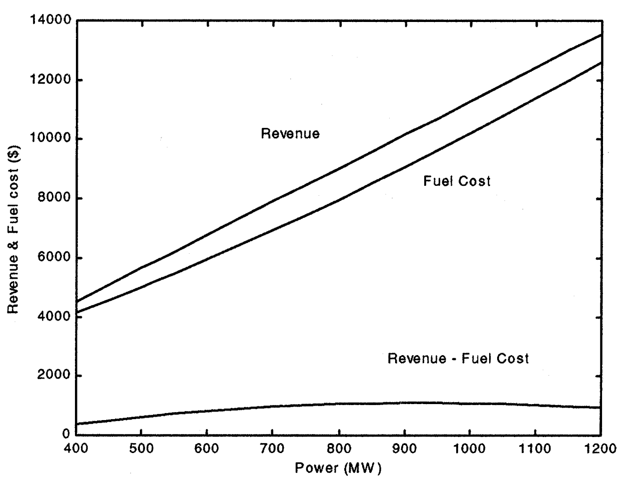

Fig. 3. Revenue and fuel cost at hour-seven when all units are on.

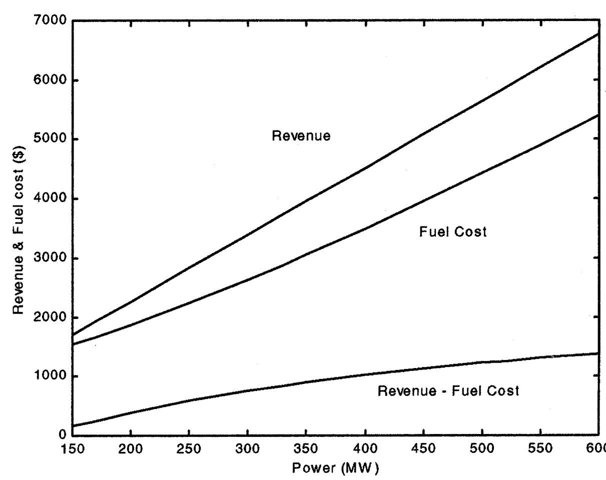

Fig. 4. Revenue and fuel cost at hour-seven when only units two and three are on.

reserve below the forecasted level in some periods. It is because without regard that all demand and reserve have been met or not, running only two units (unit numbers two and three in this case), providing higher profit than running all units as shown in Figs. 3 and 4.

Figs. 3 and 4 show the revenue received from power selling and total fuel cost at hour seven when three units and two units are on, respectively. According to Fig. 3, the maximum profit (= revenue − cost) can be received when power is served between 850–950 MW (below the forecasted level, 1100 MW).

TABLE VII
EXAMPLE OF POWER AND RESERVE GENERATION OF RESERVE PAYMENT METHOD A (TEN-UNIT SYSTEM) ($r = 0.05$, RESERVE PRICE = 5^*SPOT PRICE)

H	Profit-Based Unit Commitment (Reserve Payment Method A)																			
	Power (MW)										Reserve (MW)									
	U1	U2	U3	U4	U5	U6	U7	U8	U9	U10	U1	U2	U3	U4	U5	U6	U7	U8	U9	U10
1	455	245	0	0	0	0	0	0	0	0	0	70	0	0	0	0	0	0	0	0
2	455	295	0	0	0	0	0	0	0	0	0	75	0	0	0	0	0	0	0	0
3	455	395	0	0	0	0	0	0	0	0	0	60	0	0	0	0	0	0	0	0
4	455	455	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	455	390	0	130	25	0	0	0	0	0	0	65	0	0	35	0	0	0	0	0
6	455	455	0	130	53	0	0	0	0	0	0	0	0	0	110	0	0	0	0	0
7	455	455	0	130	47	0	0	0	0	0	0	0	0	0	115	0	0	0	0	0
8	455	455	0	130	42	0	0	0	0	0	0	0	0	0	120	0	0	0	0	0
9	455	455	130	130	32	0	0	0	0	0	0	0	0	0	130	0	0	0	0	0
10	455	455	130	130	162	64	0	0	0	0	0	0	0	0	0	16	0	0	0	0
11	455	455	130	130	162	80	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	455	455	130	130	162	80	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	455	455	130	130	25	0	0	0	0	0	0	0	0	0	137	0	0	0	0	0
14	455	455	130	130	32	0	0	0	0	0	0	0	0	0	130	0	0	0	0	0
15	455	455	130	130	30	0	0	0	0	0	0	0	0	0	120	0	0	0	0	0
16	455	455	0	0	57	0	0	0	0	0	0	0	0	0	105	0	0	0	0	0
17	455	455	0	0	62	0	0	0	0	0	0	0	0	0	100	0	0	0	0	0
18	455	455	0	0	52	0	0	0	0	0	0	0	0	0	110	0	0	0	0	0
19	455	455	0	0	42	0	0	0	0	0	0	0	0	0	120	0	0	0	0	0
20	455	455	0	0	25	0	0	0	0	0	0	0	0	0	137	0	0	0	0	0
21	455	455	0	0	32	0	0	0	0	0	0	0	0	0	130	0	0	0	0	0
22	455	455	0	0	52	0	0	0	0	0	0	0	0	0	110	0	0	0	0	0
23	455	445	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0
24	455	345	0	0	0	0	0	0	0	0	0	80	0	0	0	0	0	0	0	0

* Profit = $112818.93

TABLE VIII
EXAMPLE OF POWER AND RESERVE GENERATION OF RESERVE PAYMENT METHOD B (TEN-UNIT SYSTEM) ($r = 0.005$, RESERVE PRICE = 0.01^*SPOT PRICE)

H	Profit-Based Unit Commitment (Reserve Payment Method B)																			
	Power (MW)										Reserve (MW)									
	U1	U2	U3	U4	U5	U6	U7	U8	U9	U10	U1	U2	U3	U4	U5	U6	U7	U8	U9	U10
1	455	245	0	0	0	0	0	0	0	0	0	70	0	0	0	0	0	0	0	0
2	455	295	0	0	0	0	0	0	0	0	0	75	0	0	0	0	0	0	0	0
3	455	395	0	0	0	0	0	0	0	0	0	60	0	0	0	0	0	0	0	0
4	455	455	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	455	415	0	130	0	0	0	0	0	0	0	40	0	0	0	0	0	0	0	0
6	455	455	0	130	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	455	455	0	130	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	455	455	0	130	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	455	455	130	130	130	0	0	0	0	0	0	0	0	0	32	0	0	0	0	0
10	455	455	130	130	162	68	0	0	0	0	0	0	0	0	0	12	0	0	0	0
11	455	455	130	130	162	80	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	455	455	130	130	162	80	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	455	455	130	130	162	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	455	455	130	130	130	0	0	0	0	0	0	0	0	0	32	0	0	0	0	0
15	455	455	130	130	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	455	455	0	130	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	455	415	0	130	0	0	0	0	0	0	0	40	0	0	0	0	0	0	0	0
18	455	455	0	130	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	455	455	0	130	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	455	455	0	130	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	455	455	0	130	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	455	455	0	130	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23	455	445	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0
24	455	345	0	0	0	0	0	0	0	0	0	80	0	0	0	0	0	0	0	0

* Profit = $107838.57

However, in the traditional problem, demand and reserve must be completely met. Therefore, 1100 MW must be served. In profit-based UC, GENCO can now select to sell power and reserve below the forecasted level if it gives higher profit. Fig. 4 shows that by running two units (units two and three) and selling power at 600 MW, then GENCO can gain maximum profit.

Ten-Unit Test System: In addition to the three-unit system, a ten-unit 24-period system is used to show that the proposed algorithm can also work well with a larger system. Tables VII and VIII show the examples of simulation results of reserve payment methods A and B, respectively. Tradition UC results can be found in [6].

TABLE A1
FORECASTED DEMAND, RESERVE AND SPOT PRICES FOR THREE-UNIT 12-PERIOD SYSTEM

HOUR	FORECASTED DEMAND (MW)	FORECASTED RESERVE (MW)	FORECASTED SPOT PRICE ($/MW-H)
1	170	20	10.55
2	250	25	10.35
3	400	40	9.00
4	520	55	9.45
5	700	70	10.00
6	1050	95	11.25
7	1100	100	11.30
8	800	80	10.65
9	650	65	10.35
10	330	35	11.20
11	400	40	10.75
12	550	55	10.60

TABLE A2
UNIT DATA (THREE-UNIT 12-PERIOD SYSTEM)

	Unit 1	Unit 2	Unit 3
Pmax (MW)	600	400	200
Pmin (MW)	100	100	50
a ($/h)	500	300	100
b ($/MWh)	10	8	6
c ($/MW^{2}h)	0.002	0.0025	0.005
Min up time (h)	3	3	3
Min down time (h)	3	3	3
Startup cost ($)	450	400	300
Initial status (h)	-3	3	3

VI. CONCLUSION

In this paper, the authors have proposed an algorithm for helping GENCO decide how much power and reserve should be sold in energy and ancillary markets in order to receive the maximum profit. Based on forecasted data, profit-based UC is solved by considering power and reserve generation simultaneously. The optimization problems were solved using a hybrid method between LR and EP. This method was developed in such a way that a stochastic optimization technique EP is used to update Lagrange multipliers in the traditional LR method. Two reserve payment methods were simulated using three-unit and ten-unit test systems. All simulation results were compared with the results obtained from traditional UC.

VII. FURTHER RESEARCHES

The profit-based UC strongly depends on the forecasted demand, reserve, price, and the probability that reserve is called and generated. Therefore, the accuracy in forecasting all parameters is necessary. In this research, we assumed that GENCO had all data in hand and chose it as a discrete parameter, then by solving the optimization problem GENCO got an expected profit. However, in the practical cases, sometime we know just only the possibile ranges of these parameters. In this case, we have to assume the distributions of these parameters over their ranges, then a method such as Monte Carlo Simulation or fuzzy optimization approach can be applied for solving the same problem and obtaining the expected profit or distribution of profit. Including this uncertainly in the problem is what we are doing presently.

TABLE A3
FORECASTED DEMAND, RESERVE AND SPOT PRICES FOR TEN-UNIT 24-PERIOD SYSTEM

HOUR	FORECASTED DEMAND (MW)	FORECASTED RESERVE (MW)	FORECASTED SPOT PRICE ($/MW-H)
1	700	70	22.15
2	750	75	22.00
3	850	85	23.10
4	950	95	22.65
5	1000	100	23.25
6	1100	110	22.95
7	1150	115	22.50
8	1200	120	22.15
9	1300	130	22.80
10	1400	140	29.35
11	1450	145	30.15
12	1500	150	31.65
13	1400	140	24.60
14	1300	130	24.50
15	1200	120	22.50
16	1050	105	22.30
17	1000	100	22.25
18	1100	110	22.05
19	1200	120	22.20
20	1400	140	22.65
21	1300	130	23.10
22	1100	110	22.95
23	900	90	22.75
24	800	80	22.55

TABLE A4
UNIT DATA (TEN-UNIT 24-PERIOD SYSTEM)

	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5
Pmax	455	455	130	130	162
Pmin	150	150	20	20	25
a	0.00048	0.00031	0.00200	0.00211	0.00398
b	16.19	17.26	16.60	16.50	19.70
c	1000	970	700	680	450
min up	8	8	5	5	6
min down	8	8	5	5	6
ST	4500	5000	550	560	900
Ini.	8	8	-5	-5	-6

	Unit 6	Unit 7	Unit 8	Unit 9	Unit 10
Pmax	80	85	55	55	55
Pmin	20	25	10	10	10
a	0.00712	0.00079	0.00413	0.00222	0.00173
b	22.26	27.74	25.92	27.27	27.79
c	370	480	660	665	670
min up	3	3	1	1	1
min down	3	3	1	1	1
ST	170	260	30	30	30
Ini.	-3	-3	-1	-1	-1

Besides, although at the beginning, this research has been developed based on the viewpoint of GENCOs wishing to maximize their own profit but it can be also applied by independent system operators (ISOs) wishing to maximize social welfare benefit and control system security. By considering both power and reserve at the same time, running security constrained unit commitment (SCUC) [1] provides a wider view and helps ISOs to find the most economical and secure plan for both energy and ancillary part. In the future, the authors would like to apply this algorithm based on the ISO's point of view.

APPENDIX

See Tabels A1–A4.

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