A Fuzzy-Optimization Approach to Dynamic Economic Dispatch Considering Uncertainties

Pathom Attaviriyanupap, *Member, IEEE*, Hiroyuki Kita, *Member, IEEE*, Eiichi Tanaka, and Jun Hasegawa, *Member, IEEE*

***Abstract*—In this paper, the authors propose a fuzzy-optimization approach to dynamic economic dispatch, considering the uncertainties in deregulated energy and reserve markets. The methodology was developed from the viewpoint of a generation company wishing to maximize its own profit and to hedge its risks as a participant in the energy market and 10-min spinning reserve market. The uncertainties in the current paper were represented with fuzzy numbers, and consist of the demand and reserves required in each market, prices cleared in each market, and the probability that reserves are called upon in actual operation. The energy and reserve markets were coordinated by the generator ramp rate limits. The optimal amounts of power and reserve were determined by solving the optimization problem. Two reserve payment methods, payment for power delivered and payment for reserve allocated, were investigated in this paper.**

***Index Terms*—Competitive environment, deregulation, dynamic economic dispatch, fuzzy approach, restructured power system.**

I. Introduction

The deregulation and restructuring of the electric power industry have created a competitive open market environment. Deregulation, in general, often involves the unbundling of electric utility services resulting in a disaggregation into the basic parts of generation, transmission and distribution. Responsibility of these operations is put on generation companies (GENCOs), transmission companies (TRANSCOs), and distribution companies (DISCOs) with a central coordinator, called an independent system operator (ISO), whose role is to balance supply and demand in real time and to maintain system reliability and security [1]–[3]. Under the new competitive environment, market participants behave so that their own profit is maximized. A number of research studies have examined the concept of profit maximization [4]–[9], and have identified some traditional power generation, operation and control methods that need modification. The dynamic economic dispatch (DED) is one of the methods that require modification.

For the vertically integrated monopolistic environment, DED can be defined as the problem of scheduling online generator output with predicted load demands over a certain period of time so as to operate an electric power system at the minimum production cost. This has been solved by some kind of dynamic optimization, which takes into account the constraints imposed on system operation by generator ramp rate limits [10]–[16].

In contrast, DED under the restructured power system is more complex and more competitive. It is used to create the bidding curves for the generation company. The objective of DED is not to minimize total production costs as before, but to maximize profit. In the past, utilities were obligated to serve all customers, meeting all demands and maintaining reserves. However, under the deregulated system, the GENCO can choose to sell power and reserve less than the predicted values if a higher profit is realized.

Parameters such as demand and prices are not known in advance, but are functions of the time of day, day of week, and holidays. These parameters are usually predicted. However, forecasts are not easily made because many participants exist in the markets. These parameters are associated with a degree of uncertainty that induces risk for GENCO. Therefore, the GENCO must include them in the decision making process. Some research studies have incorporated these uncertainties into the problem [6]–[8], [17]. These papers have considered fuel constraints and/or the hydrothermal subproblem, but have not considered participation in the reserve market and/or ramp rate limits as part of the problem.

In this paper, the authors have proposed a fuzzy-optimization approach to solve DED under the uncertain deregulated power system. We have assumed that the GENCO participates in the energy market and 10-min spinning reserve market. The uncertain parameters were represented with fuzzy numbers. Coordination between energy and reserve markets was managed by the generator ramp rate limits. Two reserve payment methods, payment for power delivered and payment for reserve allocated were investigated. The 10-unit test system was used and the optimization problem was solved, determining the optimal values of power and reserve to be sold into energy and reserve markets.

II. Traditional Dynamic Economic Dispatch

The traditional DED can be formulated as follows.

The objective function is

$$\min \ \mathrm{TC} = \sum_{t=1}^{T}\sum_{i=1}^{N} F_{it}(P_{it}) \tag{1}$$

where

- TC total operating cost over the period dispatched;
- $F_{it}(P_{it})$ fuel cost in terms of real power output P_{it} at time t;
- T number of hours in the time horizon;
- N number of dispatchable units;
- P_{it} real power output of generator i at time t.

Manuscript received January 28, 2004.

The authors are with the Division of Systems and Information Engineering, Graduate School of Engineering, Hokkaido University, Sapporo, Japan (e-mail: pathom@ee4-si.eng.hokudai.ac.jp; kita@ee-si.eng.hokudai.ac.jp; tanaka@ee-si.eng.hokudai.ac.jp; hasegawa@ee-si.eng.hokudai.ac.jp).

Digital Object Identifier 10.1109/TPWRS.2004.831272

The cost function for each unit can be expressed as follows:

$$F_i(P_i) = a_i P_i^2 + b_i P_i + c_i \tag{2}$$

where a_i, b_i, and c_i are coefficients of cost function of unit i. The constraints are

1) *Demand constraint*

$$\sum_{i=1}^{N} P_{it} - D'_t = 0, \quad t = 1, \ldots, T \tag{3}$$

where D'_t is the forecasted total power demand at time t.

2) *Spinning reserve constraint*

$$\sum_{i=1}^{N} P_{it_{\max}} \geq \mathrm{SR}'_t, \quad t = 1, \ldots, T \tag{4}$$

where $P_{it\,\max}$ is the maximum real power output that generator i can supply at time t, and SR'_t is the forecasted spinning reserve demand at time t.

3) *Real power operating limits*

$$P_{it\,\min} \leq P_{it} \leq P_{it\,\max}, \quad i = 1, \ldots, N, \quad t = 1, \ldots, T \tag{5}$$

where $P_{it\,\min}$ and $P_{it\,\max}$ are the minimum and maximum real power outputs that generator i can supply at time t.

4) *Generating unit ramp rate limits*

$$\begin{aligned} P_{it} - P_{i(t-1)} &\leq \mathrm{UR}_i, \quad i = 1, \ldots N \\ P_{i(t-1)} - P_{it} &\leq \mathrm{DR}_i, \quad i = 1, \ldots N \end{aligned} \tag{6}$$

where UR_i and DR_i are the ramp-up and ramp-down rate limits of generator i respectively. Here, the unit of UR_i and DR_i is in MW/h.

III. Dynamic Economic Dispatch Under Deregulated Electric Power System

In the deregulated electric power system, bilateral and forward contracts will create the part of the total demand, which can be known a priori. The remaining part of demand will be predicted, as in the past. However, it is difficult to predict a GENCOs share of the remaining demand because it depends on a comparison of its price with those of other suppliers. To achieve maximum profit, GENCOs decide their DED strategy based on the forecasted energy demands, reserve demands, prices in the market and the probability that reserves are called into actual operation. This strategy will be used to build successful bidding curves. The objective of DED under a deregulated electric power system is to maximize a GENCOs own profit. Defining this new DED involves changing the objective function from (1) to the following equation:

$$\max\ \mathrm{PF} = \mathrm{RV} - \mathrm{TC} \tag{7}$$

where

- PF profit of a GENCO over the dispatched period;
- RV revenue of a GENCO over the dispatched period;
- TC total operating costs over the dispatched period.

After deregulation, GENCOs can participate not only in the energy market, but in the reserve market as well. The reserve

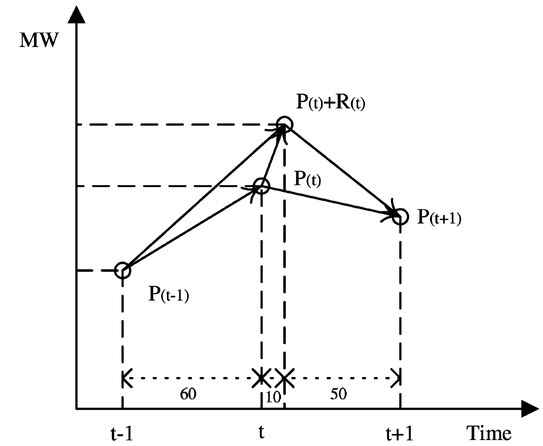

Fig. 1. Ramp rate constraints.

market considered in the present paper is the 10-min reserve, which must provide power within 10 min of being called upon under actual operation. This condition directly relates to the generator ramp rate constraints. In addition, under the deregulated environment, GENCOs are not obligated to serve all MW demand, but may sell their energy and reserve at less than the system's forecasted demand equilibrium. Therefore, constraints (3), (4), and (6) have to be changed as follows, while constraint (5) is not changed:

$$\sum_{i=1}^{N} P_{it} \leq D_t, \quad t = 1, \ldots, T \tag{8}$$

$$\sum_{i=1}^{N} R_{it} \leq \mathrm{SR}_t, \quad t = 1, \ldots, T \tag{9}$$

$$0 \leq R_i \leq \frac{\mathrm{UR}_i}{6}, \quad i = 1, \ldots, N \tag{10}$$

$$P_{it} + R_{it} \leq P_{it\,\max}, \quad i = 1, \ldots, N \quad t = 1, \ldots, T \tag{11}$$

$$P_{it} + R_{it} - P_{i(t-1)} \leq \frac{7}{6}\mathrm{UR}_i, \quad i = 1, \ldots, N \tag{12}$$

$$P_{i(t-1)} + R_{i(t-1)} - P_{it} \leq \frac{5}{6}\mathrm{DR}_i, \quad i = 1, \ldots, N \tag{13}$$

where

- R_{it} reserve of generator i at time t;
- D_t forecasted energy demand required in the market at time t;
- SR_t forecasted reserve required in the market at time t.

Because UR_i and DR_i are measured in MW/h, constraint (10) was derived based on the concept that reserve must be provided within 10 min when called up.

For constraints (12) and (13), considering Fig. 1, $P_{(t-1)}, P_{(t)}$, and $P_{(t+1)}$ are the real power operating points at time $\mathrm{t}-1$, t, and $\mathrm{t}+1$, respectively. When the operating point is increased during hour $\mathrm{t}-1$ to t, the difference between total output (real power and reserve) at hour t, and real power at hour $\mathrm{t}-1$ cannot be greater than the real power ramp-up limit UR plus reserve limit $(\mathrm{UR}/6)$. In contrast, when the operating point is decreased during hour t to $\mathrm{t}+1$, the generator has only 50 min to reduce its output, which means that the difference between total output (real power and reserve) at hour t and real power at hour $\mathrm{t}+1$ must be less than $(5 * \mathrm{DR}/6)$.

In addition to the predictions of energy demand, reserve demand, and market prices, a method for selling energy and reserve is important. It affects the expected profit because the expected revenue is determined directly by them. We will discuss the reserve payment method in the next section.

IV. Reserve Payment Method

In general, there are two types of reserve payments, payment for power delivered and payment for reserve allocated [18].

A. Payment for Power Delivered (Method I)

Reserve power is paid for only when reserve is actually used. The reserve price, therefore, is higher than the energy price. Under this payment method, the revenue and operating costs of GENCO are calculated from the following equations:

$$\mathrm{RV} = \sum_{i=1}^{N}\sum_{t=1}^{T}(\mathrm{SP}_t \cdot P_{it} + r \cdot \mathrm{RP}_t \cdot R_{it}) \tag{14}$$

$$\mathrm{TC} = \sum_{i=1}^{N}\sum_{t=1}^{T}((1-r) \cdot F(P_{it}) + r \cdot F(P_{it} + R_{it})) \tag{15}$$

where

SP_t forecasted energy price at time t;

RP_t forecasted reserve price at time t;

r forecasted probability that the reserve is actually called up.

B. Payment for Reserve Allocated (Method II)

Under this method, GENCO receives the reserve price per unit of reserve power even for the time period when the reserve is allocated and not used. If the reserve is used, GENCO can receive the energy price for the reserve that is generated. In this method, the reserve price is much lower than the energy price. The revenue is calculated from the following equation:

$$\mathrm{RV} = \sum_{i=1}^{N}\sum_{t=1}^{T}(\mathrm{SP}_t \cdot P_{it} + ((1-r) \cdot \mathrm{RP}_t + r \cdot \mathrm{SP}_t) \cdot R_{it}). \tag{16}$$

The operating cost is the same as with Method I.

V. Proposed Algorithm

In Section III, we considered all of the forecasted parameters as having crisp definition. However, in a real power system, some parameters such as energy demands, reserve demands, and market prices are difficult to predict, especially when there are many participants in the market. Thus, the uncertainties of these parameters must be included in the problem.

The uncertain parameters in the current problem consist of the energy demands, reserve demands, market prices, and probability that reserves are actually called upon. We have assumed that these parameters can be predicted based on historical data. The minimum and maximum values and the most possible range of prices can be obtained using the historical database. Here, we have used the standard fuzzy membership numbers, called trapezoidal fuzzy number, to represent the uncertain parameters. We have selected this type instead of triangular type because this type is more similar to the human's thinking which defines possibility as a range rather than a point. And, in fact, a triangular fuzzy number is just a particular case of trapezoidal fuzzy number in which the core is reduced to a point.

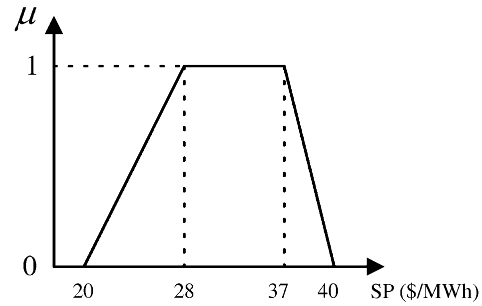

Fig. 2. Example of a trapezoidal fuzzy number.

For example, a linguistic declaration such as "energy price will surely not below 20 or above 40, and the best estimate is between 28 and 37" will be translated into a trapezoidal fuzzy number $(\mathrm{SP}_1, \mathrm{SP}_2, \mathrm{SP}_3, \mathrm{SP}_4) = (20, 28, 37, 40)$ in Fig. 2, [19].

However, to simplify the problem from the beginning, the uncertainties of energy and reserve demands in the market were represented with uniform fuzzy number, which means that all values between minimum and maximum possible values have same probability of occurring. According to the above formulation, the limits of the control variables (P_{it} and R_{it}) are considered to be hard constraints. These variables of the feasible solution must be within their given ranges, which mean that constraints (5), (10)–(12), and (13) are hard constraints. Constraints (8) and (9), however, are considered soft, and violation of constraints can be accepted.

The formulated optimization problem can be solved according to the following steps.

Step 1) Initialize P_{it} and R_{it} ($i = 1$ to $N, t = 1$ to T).

Step 2) Calculate revenue using (14) or (16) for the reserve payment method I and II, respectively. Since $\mathrm{SP}_t, \mathrm{RP}_t$, and r are trapezoidal fuzzy numbers, RV also becomes a trapezoidal fuzzy number. Points $\mathrm{RV}_1, \mathrm{RV}_2, \mathrm{RV}_3$, and RV_4 are calculated by replacing $(\mathrm{SP}, \mathrm{RP}, r)$ in (14) with $(\mathrm{SP}_1, \mathrm{RP}_1, r_1), (\mathrm{SP}_2, \mathrm{RP}_2, r_2), (\mathrm{SP}_3, \mathrm{RP}_3, r_3)$, and $(\mathrm{SP}_4, \mathrm{RP}_4, r_4)$, respectively, for reserve payment method I. For reserve payment method II, since RP is much smaller than SP, the value of $\mathrm{RV}_1, \mathrm{RV}_2, \mathrm{RV}_3$, and RV_4 are calculated by replacing $(\mathrm{SP}, \mathrm{RP}, r)$ in (16) with $(\mathrm{SP}_1, \mathrm{RP}_1, r_1), (\mathrm{SP}_2, \mathrm{RP}_2, r_2), (\mathrm{SP}_3, \mathrm{RP}_3, r_3)$, and $(\mathrm{SP}_4, \mathrm{RP}_4, r_4)$, respectively.

Step 3) Calculate the total operating cost using (15). The total operating cost is also a trapezoidal fuzzy number, for which $\mathrm{TC}_1, \mathrm{TC}_2, \mathrm{TC}_3$, and TC_4 are calculated by replacing r with r_1, r_2, r_3, and r_4, respectively.

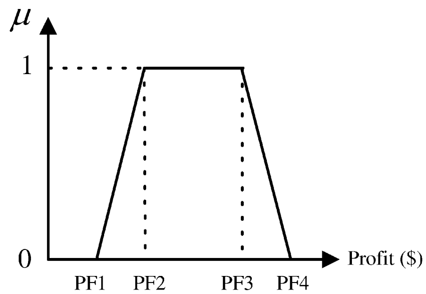

Fig. 3. Membership function of profit.

Step 4) Calculate the profit from (7). Revenue and total operating costs are fuzzy numbers; therefore profit is also a fuzzy number, as seen in the Fig. 3.

Step 5) From Fig. 3, PF_1 and PF_4 represent the minimum and maximum possible profit, respectively. In contrast, PF_2 and PF_3 represent the best estimate range of profit. Here, we will use PF_1 as an index to measure the satisfaction of the decision maker. To do this, we have defined a new objective function as

$$\max\ [\min(\mu_{\mathrm{SUM\_TP}}, \mu_{\mathrm{SUM\_TR}}, \mu_{\mathrm{PF}_1})] \tag{17}$$

subject to new hard constraints (18) and (19), and original constraints (5), (8)–(13)

$$\sum_{i=1}^{N} P_{it} \le D_{\max t}, \quad t = 1, \ldots, T \tag{18}$$

$$\sum_{i=1}^{N} R_{it} \le \mathrm{SR}_{\max t}, \quad t = 1, \ldots, T. \tag{19}$$

Here, $D_{\max t}$ and $\mathrm{SR}_{\max t}$ are the upper bounds of forecasted demand and reserve at hour t. $\mu_{\mathrm{SUM\_TP}}, \mu_{\mathrm{SUM\_TR}}$, and μ_{PF_1} are the membership functions of total power for 24 h, total reserve for 24 h, and minimum possible profit (PF_1), respectively.

$\mu_{\mathrm{SUM\_TP}}$ and $\mu_{\mathrm{SUM\_TR}}$ are calculated from (20) and (21), respectively

$$\min\left(\mu_{\mathrm{tp}}^{i}\right), \quad i = 1, 2, 3, \ldots, 24 \tag{20}$$

$$\min\left(\mu_{\mathrm{tr}}^{i}\right), \quad i = 1, 2, 3, \ldots, 24 \tag{21}$$

where μ_{tp} and μ_{tr} are the membership function of total power and total reserve for each hour. They are defined as shown in Fig. 4(a) and (b).

$D_{\min}$ and $\mathrm{SR}_{\min}$ are the lower bounds of forecasted demand and reserve. Therefore, if the total power $P_1 + P_2 + \cdots + P_N$ and total reserve $R_1 + R_2 + \cdots + R_N$ for each hour are less than $D_{\min}$ and $\mathrm{SR}_{\min}$, respectively, the membership functions of total power and reserve for that hour should be set at one and should decrease as the total power and total reserve increase. When the total power and reserve are greater than $D_{\max}$ and $\mathrm{SR}_{\max}$, the membership function must be set at zero. This definition considers (8) and (9) as soft constraints.

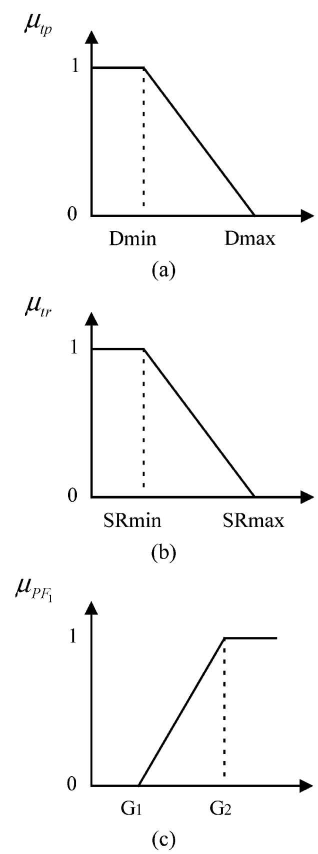

Fig. 4. Membership functions. (a) Membership function of total power for each hour. (b) Membership function of total reserve for each hour. (c) Membership function of possible minimum profit.

TABLE I
CASES OF SIMULATION

Case	Demand and Reserve	Prices and r
A	D_{avg}	Crisp (Average value)
B	D_{min} and R_{min}	Fuzzy
C	D_{max} and R_{max}	Fuzzy
D	Fuzzy	Fuzzy

We have assumed these conditions because the DED solutions will be essential inputs into any successful bidding strategy. A lower amount of total power and reserve would result in a higher probability of satisfying constraints (18) and (19) and a lower risk of an error of expected power and reserve, which might induce a risk of failure from the auction under real operation.

The membership function of minimum possible profit was defined according to the goal satisfaction concept, when the minimum possible profit (PF_1 from Step 4) is less than a goal G_1, the decision maker does not satisfy that profit, and its membership is set at zero. When the minimum possible profit is greater than a goal G_2, the decision maker is satisfied with that value, and the membership function is set at one. When PF_1 falls between G_1 and G_2, its membership aries in accordance with Fig. 4(c).

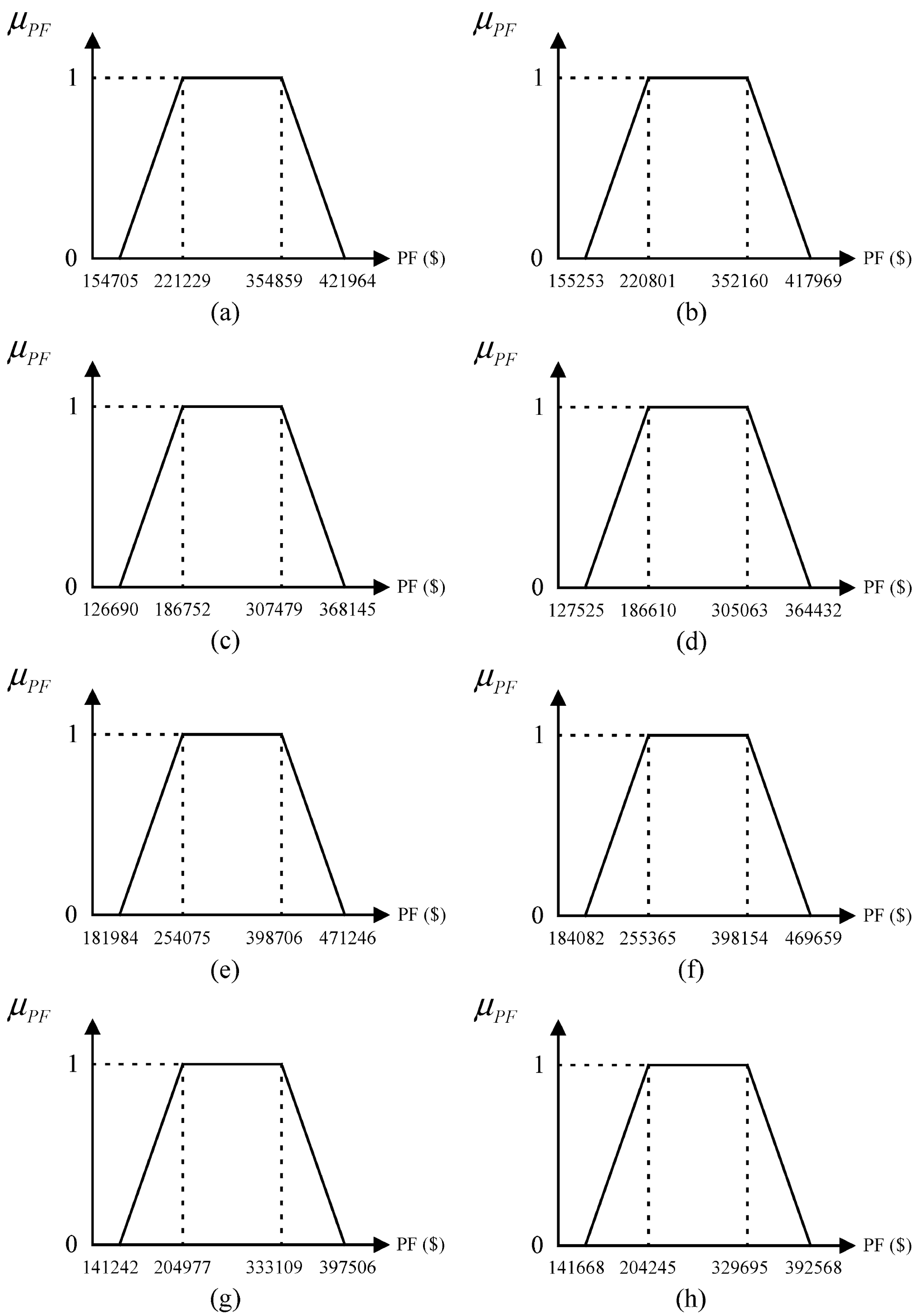

Fig. 5. Simulation Results. (a) Case A—Reserve Payment Method I. (b) Case A—Reserve Payment Method II. (c) Case B—Reserve Payment Method I. (d) Case B—Reserve Payment Method II. (e) Case C—Reserve Payment Method I. (f) Case C—Reserve Payment Method II. (g) Case D—Reserve Payment Method I. (h) Case D—Reserve Payment Method II.

Step 6) Update the values of P_{it} and R_{it} ($i = 1$ to $N, t = 1$ to T) to maximize the objective function in (17) until the terminating criteria is satisfied.

VI. Simulation Results

In the simulations, GENCO was assumed to use 10 generating units to take part in the energy market and 10-min spinning reserve market. The unit data used here were determined based on [16]. The uncertain parameters are given in the Appendix. Two reserve payment methods were simulated. We divided the simulations into four cases, as shown in Table I.

Case A: Deterministic: Energy demand, reserve demand, prices, and the probability that reserve is actually called upon were considered to be crisp parameters. The average values given in the Appendix were used in the simulation.

The optimal profits obtained by solving crisp optimization problem (7), subject to crisp constraints (8)–(13), are $287 948

TABLE II
AMOUNT OF POWER AND RESERVE SOLD INTO THE MARKET (RESERVE PAYMENT METHOD I

Hour	Total P_i (MW)	Membership of Total P_i	Total R_i (MW)
1	986.2	0.7403	65.1
2	1046.3	0.7872	65.5
3	1205.3	0.7094	60.8
4	1341.4	0.7299	77.1
5	1413.9	0.7233	77.9
6	1550.9	0.7369	62.5
7	1624.5	0.7277	65.9
8	1682.4	0.7635	57.6
9	1842.3	0.7124	46.4
10	1985.3	0.7092	32.8
11	2053.9	0.7145	51.0
12	2124.1	0.7160	26.8
13	1983.8	0.7129	64.6
14	1834.3	0.7332	56.4
15	1700.2	0.7133	51.7
16	1473.9	0.7578	60.6
17	1413.1	0.7259	80.1
18	1558.8	0.7125	50.6
19	1701.0	0.7113	50.3
20	1943.2	0.8109	58.8
21	1842.1	0.7129	52.8
22	1560.6	0.7070	68.5
23	1274.5	0.7160	49.2
24	1123.1	0.7571	58.6

TABLE III
AMOUNT OF POWER AND RESERVE SOLD INTO THE MARKET (RESERVE PAYMENT METHOD II)

Hour	Total P_i (MW)	Membership of Total P_i	Total R_i (MW)
1	978.3	0.7783	63.0
2	1058.4	0.7325	58.7
3	1196.0	0.7463	77.2
4	1316.6	0.8178	87.2
5	1413.3	0.7254	82.2
6	1553.7	0.7283	59.3
7	1628.3	0.7165	39.6
8	1702.0	0.7083	65.6
9	1840.0	0.7183	58.6
10	1982.4	0.7162	31.9
11	2049.7	0.7244	24.0
12	2124.8	0.7145	24.9
13	1984.8	0.7104	56.8
14	1841.4	0.7147	45.7
15	1694.8	0.7285	51.2
16	1480.3	0.7370	73.5
17	1415.4	0.7181	54.3
18	1552.4	0.7322	58.6
19	1696.5	0.7237	50.6
20	1941.7	0.8144	66.4
21	1839.5	0.7195	36.0
22	1556.3	0.7202	43.2
23	1252.1	0.8001	73.0
24	1129.0	0.7322	65.0

and \$286 437 for reserve payment method I and II, respectively. If the results from this simulation are fixed and the uncertainties of parameters are considered, the membership functions of profits are as shown in Fig. 5(a) and (b).

Case B and C: Low Risk–Low Return and High Risk–High Return: In these cases, forecasted demand and reserve are considered to be crisp parameters, while forecasted prices and the probability that reserve is actually called upon are considered to be fuzzy parameters. The optimization problem is to maximize the minimum possible profit subject to constraints (8)–(13). In Case B, D_t, and SR_t in (8) and (9) are replaced with $D_{\min}$ and $\mathrm{SR}_{\min}$, respectively. In Case C, D_t and SR_t in (8) and (9) are replaced with $D_{\max}$ and $\mathrm{SR}_{\max}$, respectively. The membership functions of profits are shown in Fig. 5(c)–(f).

Case D: Proposed Algorithm: In this case, forecasted demand, reserve, prices and the probability that reserve is actually called upon were all considered to be fuzzy parameters. The optimization problem is maximizing the objective function (17), subject to constraints (5), (8)–(13), (18), and (19). The membership functions of profits are shown in Fig. 5(g) and (h).

From Fig. 5, Case C can be seen as providing the highest values of minimum possible profit (\$181 984 and \$184 082 for reserve payment method I and II, respectively). In addition, this case also gave the highest values of maximum possible profit (\$471 246 and \$469 659 for reserve payment method I and II, respectively). However, this case faces highest risk from errors of expectations of power and reserve because the maximum possible forecasted demand and reserve were used in the simulation. The solutions (total power and reserve) have a high possibility of being greater than the exact power and reserve under real operations, which may cause losses for GENCO. In contrast, Case B provided the lowest minimum and maximum possible profits, but has no risk from demand and reserve under real operations. Cases B and C support the high risk - high return concept.

When compared with Case B, Case D (proposed algorithm) provided \$14 552 (=\$141 242 − \$126 690), a higher minimum possible profit for reserve payment method I, and \$14 143 (=\$141 668\$ − 127 525) for reserve payment method II. The membership functions of total power from Case D are 0.7062 and 0.7083 for reserve payment method I and II, respectively, while the membership functions of total power from Case B are almost one. Case D provided \$40 742 (=\$181 984 − \$141 242) and \$42 414 (=\$184 082 − \$141 668), lower minimum possible profit when compared with Case C. However, because the membership functions of total power from Case C are nearly zero, Case D has lower risk.

When compared with the deterministic case (Case A), Case D resulted in lower minimum possible profit (\$13 463 and \$13 585 lower than Case A for reserve payment method I and II, respectively) although it was subject to lower risk from errors of expectations of power and reserve. The memberships of power in Case D are 0.7070 and 0.7083, while in Case A, memberships were 0.5001 and 0.5001, respectively for reserve payment method I and II. The memberships of reserve are one in both cases. This means, considering uncertainties of parameters may cause decreases in expected profits but would reduce risks for GENCO when participating in the uncertain markets.

The decision depends on the decision maker who may wish either to venture for high profit or to hedge the risk from uncertainties. The alternative would guarantee a minimum possible profit for GENCO, by solving optimization with the objective to maximize PF_1 (minimum possible profit) subject to constraints

TABLE IV
POWER AND RESERVE GENERATION OF RESERVE PAYMENT METHOD I

HOUR	DYNAMIC ECONOMIC DISPATCH (RESERVE PAYMENT METHOD I)																			
	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	190	217	147	71	114	62	47	56	26	55	16.4	8.8	11.3	5.6	4.2	6.4	6.1	2.5	3.7	0.0
2	260	237	79	77	115	67	68	55	32	55	10.9	13.4	1.7	4.8	12.2	7.7	2.5	9.5	2.8	0.0
3	327	318	126	87	82	95	27	48	40	55	10.4	13.0	18.3	8.9	0.0	1.1	6.0	2.7	0.3	0.0
4	305	376	152	99	126	59	74	57	38	55	3.7	11.1	16.6	11.5	7.7	6.4	6.2	6.3	7.6	0.0
5	325	308	120	79	177	126	126	74	25	55	16.7	18.1	16.1	0.2	1.2	12.4	3.4	0.1	9.7	0.0
6	434	338	199	126	131	95	84	56	33	55	5.0	3.1	11.6	11.2	13.0	4.3	4.2	0.0	10.0	0.0
7	391	322	239	138	163	115	40	115	47	55	7.1	9.2	13.1	10.0	9.1	8.3	7.7	1.0	0.3	0.0
8	388	299	314	179	149	97	88	82	32	55	15.8	1.0	8.9	13.2	4.2	1.1	1.9	2.4	9.0	0.0
9	380	277	324	221	156	158	130	97	44	55	6.3	7.2	14.3	5.4	5.7	0.1	0.0	0.9	6.4	0.0
10	445	367	289	229	232	156	91	82	38	55	1.7	0.8	9.2	3.0	4.9	0.2	6.1	1.7	5.3	0.0
11	439	377	283	289	236	156	100	73	44	55	4.0	12.1	9.6	10.0	6.9	0.2	2.0	5.6	0.7	0.0
12	469	379	312	252	237	160	93	108	60	55	0.1	5.4	0.5	3.0	5.3	0.0	7.1	0.6	4.8	0.0
13	431	389	309	193	234	120	107	113	32	55	12.5	12.5	11.7	13.0	0.0	8.4	4.1	1.7	0.6	0.0
14	375	336	267	171	203	158	121	98	49	55	15.0	9.4	2.5	9.1	5.2	0.0	0.8	7.0	7.3	0.0
15	455	301	220	133	162	151	77	78	69	55	0.3	13.2	17.0	4.9	0.8	0.2	6.6	7.8	0.9	0.0
16	461	228	163	73	192	106	106	47	43	55	0.4	2.0	17.8	11.8	0.0	11.0	4.7	7.4	5.7	0.0
17	405	245	139	104	230	59	74	50	51	55	12.4	17.3	17.8	3.8	0.7	10.5	8.2	0.0	9.4	0.0
18	426	242	197	151	181	108	66	84	50	55	2.0	2.1	10.8	2.9	10.2	9.8	0.4	4.4	8.0	0.0
19	348	337	305	178	175	75	124	58	48	55	0.3	15.3	11.5	4.1	4.8	3.0	3.5	4.5	3.3	0.0
20	398	406	336	248	188	75	126	65	46	55	11.7	8.7	0.3	10.4	5.4	13.1	0.3	2.9	6.0	0.0
21	328	438	294	202	155	124	122	100	24	55	1.6	7.2	14.8	8.7	7.1	3.1	4.2	0.9	5.3	0.0
22	271	363	303	157	106	66	118	67	56	55	17.2	2.6	17.2	12.7	2.8	2.7	0.8	8.4	4.2	0.0
23	211	280	267	120	80	110	74	52	24	55	4.6	10.3	3.7	4.7	8.8	0.2	2.4	6.7	7.8	0.0
24	150	248	200	142	76	92	83	55	22	55	11.8	10.5	8.3	0.8	11.3	3.6	1.0	3.1	8.3	0.0

TABLE V
POWER AND RESERVE GENERATION OF RESERVE PAYMENT METHOD II

HOUR	DYNAMIC ECONOMIC DISPATCH (RESERVE PAYMENT METHOD II)																			
	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	242	232	101	70	93	68	42	48	27	55	2.4	17.6	0.4	12.5	2.4	6.6	8.2	9.6	3.3	0.0
2	155	277	186	63	121	74	36	60	30	55	0.1	17.3	13.0	3.9	6.5	5.4	6.8	0.1	5.6	0.0
3	244	277	253	61	75	65	77	65	24	55	8.6	18.1	8.6	1.7	9.8	11.2	6.7	8.0	4.7	0.0
4	249	321	258	69	141	78	55	69	21	55	9.9	14.8	17.3	9.9	1.8	11.5	7.0	9.3	5.7	0.0
5	169	393	305	87	138	104	41	48	73	55	12.9	11.5	8.9	12.2	11.5	11.5	7.0	9.3	5.7	0.0
6	223	373	326	130	124	126	81	80	37	55	16.0	17.0	0.8	8.4	1.3	3.2	3.9	8.2	0.6	0.0
7	310	341	292	167	152	139	90	55	27	55	5.4	4.6	8.7	4.5	1.0	3.5	3.0	3.3	5.6	0.0
8	282	350	252	213	176	158	103	56	56	55	10.0	18.1	8.0	3.3	4.3	2.0	8.9	5.3	5.7	0.0
9	376	389	261	183	237	93	104	103	39	55	7.2	7.6	16.6	2.8	0.0	5.2	6.5	6.2	6.5	0.0
10	466	435	195	192	219	159	127	112	23	55	0.0	9.3	0.5	13.0	0.3	0.3	1.6	0.1	6.8	0.0
11	410	453	286	250	175	144	126	100	53	55	7.6	2.3	1.8	0.0	5.8	0.2	0.1	4.6	1.5	0.0
12	458	458	269	276	191	157	127	64	69	55	0.2	0.6	0.4	3.6	10.3	0.3	0.2	3.6	5.8	0.0
13	442	454	211	269	159	157	99	85	53	55	18.1	0.0	6.3	4.7	8.2	0.5	3.9	9.0	6.1	0.0
14	369	366	242	252	187	120	122	90	39	55	7.1	4.7	4.3	3.1	6.4	0.8	0.3	9.6	9.4	0.0
15	382	442	207	192	154	87	80	62	33	55	0.5	1.6	7.5	3.5	7.5	10.5	5.9	6.0	8.3	0.0
16	295	364	144	138	129	121	101	106	27	55	4.6	14.9	17.1	13.1	4.3	7.7	9.0	2.6	0.3	0.0
17	273	319	184	99	130	114	102	87	52	55	10.1	2.7	15.4	0.9	5.7	7.9	5.2	3.4	3.0	0.0
18	322	292	173	158	190	138	103	88	31	55	11.9	7.1	15.6	2.0	4.9	8.1	0.4	0.9	7.6	0.0
19	255	375	227	227	153	150	116	86	52	55	8.0	0.0	18.0	0.8	10.3	2.6	4.3	1.2	5.2	0.0
20	350	387	328	277	208	145	90	66	36	55	2.1	8.4	5.5	12.5	6.1	8.9	9.0	5.4	8.6	0.0
21	335	390	242	254	202	128	113	88	32	55	0.7	7.5	5.8	0.1	4.6	0.6	6.3	10.0	0.5	0.0
22	260	359	178	215	166	151	88	48	36	55	11.9	0.0	10.1	2.7	2.0	2.3	7.8	2.2	4.1	0.0
23	223	273	141	170	119	108	57	59	48	55	17.1	11.8	0.4	1.0	12.2	9.4	9.0	9.6	2.5	0.0
24	254	286	103	139	99	63	49	52	29	55	14.9	9.5	18.1	9.0	1.3	1.4	1.8	6.3	2.7	0.0

(8)–(13). However, $D_{\min}$ and $\mathrm{SR}_{\min}$ must replace D_t and SR_t in (8) and (9), respectively.

The best results from 10 runs of Case D are shown in Tables II–V. G_1 and G_2 were set at \$0 and \$200 000, respectively. The amounts of power and reserve sold into the energy and reserve markets and their memberships are shown in Tables II and III. The memberships of the new objective function are 0.7062 and 0.7083 for reserve payment method I and II, respectively. The dispatched schedules are shown in Tables IV and V. The computation time was approximately one hour, using evolutionary programming on a Pentium III 800-MHz processor.

In the above simulation, we have simplified the problem by considering the uncertainties of forecasted energy and reserve demands uniformly. In fact, we can represent these uncertainties using other fuzzy numbers. However, we would need to change

TABLE VI
AVERAGE VALUE OF UNCERTAIN PARAMETERS

Hour	SP_{avg} (\$)	RP_{avg} (I) (\$)	RP_{avg}(II) (\$)	D_{avg} (MW)	SR_{avg} (MW)
1	28.65	57.30	2.01	1036.00	103.60
2	30.00	60.00	2.10	1110.00	111.00
3	32.10	64.20	2.25	1258.00	125.80
4	26.35	52.70	1.84	1406.00	140.60
5	30.25	60.50	2.12	1480.00	148.00
6	32.95	65.90	2.31	1628.00	162.80
7	34.50	69.00	2.42	1702.00	170.20
8	31.15	62.30	2.18	1776.00	177.60
9	36.80	73.60	2.58	1924.00	192.40
10	37.35	74.70	2.61	2072.00	207.20
11	37.15	74.30	2.60	2146.00	214.60
12	38.65	77.30	2.71	2220.00	222.00
13	32.60	65.20	2.28	2072.00	207.20
14	34.50	69.00	2.42	1924.00	192.40
15	30.50	61.00	2.14	1776.00	177.60
16	28.30	56.60	1.98	1554.00	155.40
17	31.25	62.50	2.19	1480.00	148.00
18	34.05	68.10	2.38	1628.00	162.80
19	27.20	54.40	1.90	1776.00	177.60
20	30.65	61.30	2.15	2072.00	207.20
21	31.10	62.20	2.18	1924.00	192.40
22	33.95	67.90	2.38	1628.00	162.80
23	31.75	63.50	2.22	1332.00	133.20
24	28.55	57.10	2.00	1184.00	118.40

the method to determine memberships of total power and reserve, as shown in Fig. 4(a) and (b).

VII. CONCLUSION

In this paper, the authors proposed the fuzzy-optimization approach for solving DED under an uncertain deregulated power system. The proposed algorithm helps GENCO determine the optimal amounts of energy and reserve to be sold into the energy and 10-min spinning reserve markets applying the concept of profit maximization and risk hedging. The uncertainties considered in this paper are energy demands, reserve demands, energy prices, reserve prices, and the probability that reserves are actually used in real time, and were represented with a fuzzy numbers trapezoid. We have used the trapezoidal number rather than the triangular one because the triangular fuzzy number is just a particular case of a trapezoidal fuzzy number in which the range is reduced to a point. Besides, a trapezoidal fuzzy number is more natural and flexible to be applied because there are four parameters. The new objective function has been proposed and the original constraints have been transformed into the new soft and hard sets of constraints. The optimization problem was solved using the goal satisfaction concept. The goal used in this paper was to obtain the minimum possible profit, high enough to satisfy the decision maker. A different kind of goal can also be applied to this problem. For example, one may use the maximum possible profit or the best estimate ranges of profit or even the combination of these two values. Alternatively, one may apply a weight factor to (17), to assign a priority to parameters: minimum possible profit or the possibility of satisfying the power and reserve constraints.

APPENDIX

$$
\begin{aligned}
D_{\min} &= D_{\text{avg}} * 0.9, \quad D_{\max} = D_{\text{avg}} * 1.1,\\
\text{SR}_{\min} &= \text{SR}_{\text{avg}} * 0.9, \quad \text{SR}_{\max} = \text{SR}_{\text{avg}} * 1.1\\
r_1 &= 0.05, \quad r_2 = 0.075\\
r_3 &= 0.125, \quad r_4 = 0.15\\
\text{SP}_1 &= \text{SP}_{\text{avg}} * 0.90, \quad \text{SP}_2 = \text{SP}_{\text{avg}} * 0.95\\
\text{SP}_3 &= \text{SP}_{\text{avg}} * 1.05, \quad \text{SP}_4 = \text{SP}_{\text{avg}} * 1.10.
\end{aligned}
$$

For reserve payment method I

$$
\begin{aligned}
\text{RP}_1 &= \text{RP}_{\text{avg}} * 0.90, \quad \text{RP}_2 = \text{RP}_{\text{avg}} * 0.95\\
\text{RP}_3 &= \text{RP}_{\text{avg}} * 1.05, \quad \text{RP}_4 = \text{RP}_{\text{avg}} * 1.10.
\end{aligned}
$$

For reserve payment method II

$$
\begin{aligned}
\text{RP}_1 &= \text{RP}_{\text{avg}} * 0.90, \quad \text{RP}_2 = \text{RP}_{\text{avg}} * 0.95\\
\text{RP}_3 &= \text{RP}_{\text{avg}} * 1.05, \quad \text{RP}_4 = \text{RP}_{\text{avg}} * 1.10.
\end{aligned}
$$

REFERENCES

[1] L. L. Lai, *Power System Restructuring and Deregulation—Trading, Performance, and Information Technology*. New York: Wiley, 2001.

[2] M. Shahidehpour and M. Marwali, *Maintenance Scheduling in Restructured Power Systems*. Norwell, MA: Kluwer, 2000.

[3] K. Bhattacharya, M. H. J. Bollen, and J. E. Daalder, *Operation of Restructured Power Systems*. Norwell, MA: Kluwer, 2001.

[4] G. B. Sheble, *Computational Auction Mechanisms for Restructured Power Industry Operation*. Norwell, MA: Kluwer, 1999.

[5] C. W. Richter Jr. and G. B. Sheble, "A profit-based unit commitment GA for the competitive environment," *IEEE Trans. Power Syst.*, vol. 15, pp. 715–721, May 2000.

[6] C. Tseng, "A stochastic model for a price-based unit commitment problem and its application to short-term generation asset valuation," in *The Next Generation of Electric Power Unit Commitment Models*, B. F. Hobbs, M. H. Rothkopf, R. P. O'Neill, and H. Chao, Eds. Norwell, MA: Kluwer, 2001, pp. 117–138.

[7] J. Valenzuela and M. Mazumdar, "Probabilistic unit commitment under a deregulated market," in *in The Next Generation of Electric Power Unit Commitment Models*, B. F. Hobbs, M. H. Rothkopf, R. P. O'Neill, and H. Chao, Eds. Norwell, MA: Kluwer, 2001, pp. 139–165.

[8] A. Baillo, M. Ventosa, A. Ramos, M. Rivier, and A. Canseco, "Strategic unit commitment for generation in deregulated electricity markets," in *The Next Generation of Electric Power Unit Commitment Models*, B. F. Hobbs, M. H. Rothkopf, R. P. O'Neill, and H. Chao, Eds. Norwell, MA: Kluwer, 2001, pp. 227–248.

[9] P. Attaviriyanupap, H. Kita, E. Tanaka, and J. Hasegawa, "A hybrid LR-EP for solving new profit-based UC problem under competitive environment," *IEEE Trans. Power Syst.*, vol. 18, pp. 229–237, Feb. 2003.

[10] Y. H. Song and I. K. Yu, "Dynamic load dispatch with voltage security and environment constraints," *Electric Power Syst. Res.*, vol. 43, no. 1, pp. 53–60, Oct. 1997.

[11] F. Li, R. Morgan, and D. Williams, "Hybrid genetic approaches to ramping rate constrained dynamic economic dispatch," *Electric Power Syst. Res.*, vol. 43, no. 2, pp. 97–103, Nov. 1997.

[12] Q. Xia, Y. H. Song, B. M. Zhang, C. Q. Kang, and N. Xiang, "Dynamic queuing approach to power system short term economic and security dispatch," *IEEE Trans. Power Syst.*, vol. 13, pp. 280–285, May 1998.

[13] R. A. Jabr, A. H. Coonick, and B. J. Cory, "A Study of the homogeneous algorithm for dynamic economic dispatch with network constraints and transmission losses," *IEEE Trans. Power Syst.*, vol. 15, pp. 605–611, May 2000.

[14] F. Li and R. K. Aggarwal, "Fast and accurate power dispatch using a relaxed genetic algorithm and a local gradient technique," *Expert Syst. Applicat.*, vol. 19, no. 3, pp. 159–165, Oct. 2000.

[15] X. S. Han, H. B. Gooi, and D. S. Kirschen, "Dynamic economic dispatch: Feasible and optimal solutions," *IEEE Trans. Power Syst.*, vol. 16, pp. 22–28, Feb. 2001.

[16] P. Attaviriyanupap, H. Kita, E. Tanaka, and J. Hasegawa, "A hybrid EP and SQP for dynamic economic dispatch with nonsmooth fuel cost function," *IEEE Trans. Power Syst.*, vol. 17, pp. 411–416, May 2002.

[17] S. Takriti, B. Krasenbrink, and L. Wu, "Incorporating fuel constraints and electricity spot prices into the stochastic unit commitment problem," *Oper. Res.*, vol. 48, no. 2, pp. 268–280, Mar.–Apr. 2000.

[18] E. H. Allen and M. D. Ilic, "Reserve markets for power systems reliability," *IEEE Trans. Power Syst.*, vol. 15, pp. 228–233, Feb. 2000.

[19] M. E. El-Hawary, *Electric Power Applications of Fuzzy Systems*. New York: IEEE Press, 1998.

Pathom Attaviriyanupap (M'04) was born in Bangkok, Thailand, in 1976. He received the B.E. and M.E. degrees from Chulalongkorn University, Bangkok, in 1998, and the Ph.D. degree from Hokkaido University, Sapporo, Japan, in 2003.

He was granted the Japanese MONBUSHO-Scholarship. Under this program, he completed research at Kyushu University, Fukuoka, Japan, in March 2000. Currently, he is working as JSPS Foreign Researcher at The University of Tokyo, Tokyo, Japan. His research interests are intelligent system application in power system planning and operation.

Hiroyuki Kita (M'04) was born in 1963. He received the M.E. and Ph.D. degrees from Hokkaido University, Sapporo, Japan, in 1988 and 1994, respectively.

In April 1989, he was appointed Research Associate with the Department of Electrical Engineering, Hokkaido University. In April 1995, he was appointed to his present position as Associate Professor. His research interests include the analysis and control of electric power systems.

Dr. Kita is a member of the IEE of Japan.

Eiichi Tanaka was born in 1952. He received the M.E. degree from Hokkaido University, Sapporo, Japan, in 1977.

In April 1997, he was appointed Research Associate with the Department of Electrical Engineering, Hokkaido University. His research interests include the analysis and control of electric power systems.

Mr. Tanaka is a member of the IEE of Japan and the Society of Instrument and Control Engineers of Japan.

Jun Hasegawa (M'82) was born in Hokkaido, Japan, in 1943. He received the Ph.D. degree from Hokkaido University, Sapporo, Japan, in 1971.

In April 1971, he was appointed Lecturer with the Department of Electrical Engineering, Hokkaido University, and later became Associate Professor before reaching his present position of Professor in April 1985. His research interests include the planning, operation, analysis and control of electric power systems and energy storage.

Dr. Hasegawa is a member of the Japan Society of Energy and Resources.