# A Study of Unit Commitment Considering Environmental Effects by Fuel Substitution

**Buhm Lee, Yong-Ha Kim and Nam-Sup Choi,** *Member, KIMICS*

***Abstract***—This paper proposes a new generation scheduling algorithm which can consider total quantity of contamination and energy limits based on Lagrangian Relaxation. First, we formulate a Lagrangian function which consider quantity of contamination including substitution of fuel, and quantity of fuel. Second, we developed Multi-state S.U.D.P. which can treat multiple fuels. Third, we propose an effective generation scheduling algorithm including Multi-state S.U.D.P.. As a results, unit commitment and generating power can be obtained to meet the environmental and fuel constraints with fuel substitution. By applying it to the test system, effectiveness of the method is verified.

***Index Terms***—**Unit Commitment, Economic Dispatch, Total Quantity of Contamination, Fuel substitution, Multi-state S.U.D.P.**

## I. INTRODUCTION

Because thermal generators draw off a lot of contaminations such as $CO_2$ , $NO_x$ , $SO_2$ etc., people near power plant suffer from air pollution. To improve environmental condition, many nations and local governments regulate the contamination in density and quantity. So, electric power company need effective method which can minimize environmental effect.

The objective of unit commitment and economic dispatch is to minimize total fuel cost, so cheap and low quality fuel, such as coal, is effective. Because these fuels draw off a lot of contaminations, electric power company needs usage of high quality fuel, such as LNG. So generation scheduling algorithm not only which can minimize the total fuel cost of thermal generators, but also which can minimize environmental influence is needed[1].

This paper proposes a new generation scheduling algorithm which can consider total quantity of contamination and energy limits based on Lagrangian Relaxation[2][3].

Newly developed procedure is as follows. First, we formulate a Lagrangian function which can consider quantity of contamination including fuel substitution, and quantity of fuel. Second, we developed Multi-state Single Unit Dynamic Programming (S.U.D.P.) which can treat multiple fuels. Third, we propose an effective generation scheduling algorithm including Multi-state S.U.D.P.. Years ago, we developed powerful unit commitment algorithm which use Fibonacci method and Economic Dispatch[4]. We improved and made an effective algorithm which can consider environmental effects including fuel substi-tution and fuel limitation. As a result, unit commitment and generating power can be obtained to meet environmental constraints including fuel substitution and fuel constraints. By applying it to the test system, effectiveness of the method is verified.

## II. FORMULATION OF LAGRANGIAN

[Notation]
$\alpha_{ij}$ , $\beta_{ij}$ , $\gamma_{ij}$ : fuel coefficients of unit i, fuel j
$f_{ij}$ : contamination coefficient of unit i, fuel j [Kg/$]
$P_i^t$ : generating power of unit i at time t [Mw]
$U_i^t$ : state of unit i at time ('0' or '1')
$S_i^t$ : start up/shut down cost of unit i at time t [$]
$D^t$ : power demand at time t [Mw]
$R^t$ : spinning reserve at time t [Mw]
$P_i^{min}$ : minimum power generated by unit i [Mw]
$P_i^{max}$ : maximum power generated by unit i [Mw]
$\Delta P_{i*}^{max}$ : ramp rates of unit i [Mw/h] (*=up, dn)
$T_{i\,up}$ : time the unit has been in operation [h]
$T_{i\,dn}$ : time the unit has been in shut down [h]
$T_{i\,up}^{min}$ : minimum up time of unit i [h]
$T_{i\,dn}^{min}$ : minimum down time of unit i [h]
$EP_a^{max}$ : upper limit of quantity of contamination [Kg]
J : number of fuel
$N_i$ : number of units
T : number of time steps (t = 1 .. T )
A : number of area (a = 1 .. A), $N_i = A\, a_N$
$a_N$ : number of units at a area (i=$a_1$ .. $a_N$ )

### 2.1. Fuel cost

2.1.1 Objective function

The purpose of unit commitment is to minimize total fuel cost. Assume each unit consume only one fuel at time t, even though many of units can use number of fuels.

$$Min\ F = \sum_{t=1}^{T}\left[\sum_{i=1}^{N_i}\sum_{j=1}^{J}\left\{C_{ij}^t U_i^t + S_{ij}^t\right\}\right] [\$] \qquad (1)$$

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where

$$C_{ij}^t = \alpha_{ij}\left(P_i^t\right)^2 + \beta_{ij}P_i^t + \gamma_{ij} \quad [\$]$$

2.1.2 Constraints

Unit commitment and economic dispatch has coupling constraints, local constraints, and fuel constraints.

(1) Coupling constraints

① Demand

$$\sum_{i=1}^{N_i} U_i^t P_i^t = D^t \tag{2}$$

② Spinning reserve

$$\sum_{i=1}^{N_i} U_i^t P_i^{Rt} \geq D^t + R^t \tag{3}$$

$$P_i^{Rt} = Min(P_i^{t-1} + \Delta P_{i\,up}^{\max}, P_i^{\max}) \text{ [Mw]}$$

(2) Local constrinats

① Capacity limits of generating units

$$P_i^{\min} \leq P_i^t \leq P_i^{\max} \tag{4}$$

② Minimum up and down time

$$T_{i\,up} \geq T_{i\,up}^{\min}, \quad T_{i\,dn} \geq T_{i\,dn}^{\min} \tag{5}$$

③ Ramp rates

$$P_i^{t-1} - \Delta P_{i\,dn}^{\max} \leq P_i^t \leq P_i^{t-1} + \Delta P_{i\,up}^{\max} \tag{6}$$

(3) Fuel constraints

① Lower limits

$$Q_{ij}^{\min} - \sum_{t=1}^{T}(C_{ij}^t U_i^t + S_{ij}^t) \leq 0 \tag{7}$$

if constraints is not exist

$$Q_{ij}^{\min} = 0$$

② Upper limits

$$\sum_{t=1}^{T}(C_{ij}^t U_i^t + S_{ij}^t) - Q_{ij}^{\max} \leq 0 \tag{8}$$

if constraints is not exist

$$Q_{ij}^{\max} = \infty$$

### 2.2. Total quantity of contamination

Because every thermal generators consume a lot of fossil fuel, these generators draw off contaminations such as $CO_2$, $NO_X$, $SO_2$ etc..

2.2.1 Quantity of contamination

To calculate the quantity of contamination is very complex. So, approximate method[5] was developed by using fuel function. Additionally, we enhanced this function for multiple fuels.

$$EP_a^t = \sum_{i=a_1}^{a_N}\sum_{j=1}^{J}\left\{EC_{ij}^t U_i^t + ES_{ij}^t\right\} \leq EP_a^{\max} \text{ [Ton]} \tag{9}$$

where

$$EC_{ij}^t = f_{ij}\, C_{ij}^t \text{ [Ton]}$$

$$ES_{ij}^t = f_{ij}\, S_{ij}^t \text{ [Ton]}$$

2.2.2 Environmental Cost

Quantity of contamination is in weight, while objective function is in dollar. So, we employ multiplier $e_a^t$ which can convert from weight to dollar. This multiplier means pseudo price.

$$Min\ Env = \sum_{t=1}^{T}\sum_{a=1}^{A} e_a^t \left[\sum_{i=a_1}^{a_N}\sum_{j=1}^{J} f_{ij}\left\{C_{ij}^t U_i^t + S_{ij}^t\right\}\right] [\$] \tag{10}$$

### 2.3. Lagrangian

2.3.1 Formulation of Lagrangian

From eq.(1) and eq.(10), we can get a new objective function.

$$Min\ Cost = F + Env \tag{11}$$

To make single function which has objective function and constraints, Lagrangian function is effective. So, we made Lagrangian which has objective function(eq.(11)), coupling con- straints(eq.(2), eq.(3)), and fuel constraints (eq.(7), eq.(8)). Multiplier $\sigma_{ij}$, $\delta_{ij}$ is added to consider fuel constraints.

$$L(P, U, \lambda, \mu, e_a) = F_{ul} + E_{nv} + C_{ns} + C_{fs} \tag{12}$$

where

$$F_{ul} = \sum_{t=1}^{T}\sum_{a=1}^{A}\sum_{i=a_1}^{a_N}\sum_{j=1}^{J}\{C_{ij}^t U_i^t + S_{ij}^t\}$$

$$E_{nv} = \sum_{t=1}^{T}\sum_{a=1}^{A}\left[e_a^t \sum_{i=a_1}^{a_N}\sum_{j=1}^{J} f_{ij}\left\{C_{ij}^t U_i^t + S_{ij}^t\right\}\right]$$

$$C_{ns} = \sum_{t=1}^{T}\left[\lambda^t\{D^t - \sum_{a=1}^{A}\sum_{i=a_1}^{a_N} U_i^t P_i^t\} \right.$$
$$\left. + \mu^t\{D^t + R^t - \sum_{a=1}^{A}\sum_{i=a_1}^{a_N} U_i^t P_i^{Rt}\}\right]$$

$$C_{fs} = \sum_{a=1}^{A}\sum_{i=a_1}^{a_N}\sum_{j=1}^{J}\left[\sigma_{ij}\{Q_{ij}^{\min} - \sum_{t=1}^{T}(C_{ij}^t U_i^t + S_{ij}^t)\} \right.$$
$$\left. + \delta_{ij}\{\sum_{t=1}^{T}(C_{ij}^t U_i^t + S_{ij}^t) - Q_{ij}^{\max}\}\right]$$

2.3.2 Solution of Lagrangian

To get unit commitment and generating power from Lagrangian, Primal-Dual is widely used.

(1) Primal

Primal is to get unit commitment and generating power for a fixed setting of multipliers. Eq.(12) can be separated into subproblems which deals with only one generating unit. Local constraints(eq.(4), eq.(5), eq.(6)) can meet at this procedure.

$$L(P,U,\lambda,\mu,e_a)=\sum_{a=1}^{A}\sum_{i=a_1}^{a_N}q_i+Const \qquad (13)$$

where

$$q_i=\sum_{t=1}^{T}\Big[\sum_{j=1}^{J}\{(1+e_a^t f_{ij})(1-\delta_{ij}+\sigma_{ij})(C_{ij}^t+S_i^t)\}$$
$$-\lambda^t U_i^t P_i^t-\mu^t U_i^t P_i^{Rt}\Big]$$
$$Const=\sum_{t=1}^{T}\{\lambda^t D^t+\mu^t(D^t+R^t)\}$$
$$+\sum_{a=1}^{A}\sum_{i=a_1}^{a_N}\{\sigma_{ij}Q_{ij}^{\min}-\delta_{ij}Q_{ij}^{\max}\}$$

(2) Dual

Dual is to get optimal values of multiplier $\lambda^t$, $\mu^t$, $e_a^t$ which can minimize objective functions whithout violating coupling constraints.

$$\underset{\lambda,\mu,e_a}{Maximize}\left[\underset{P,U}{Minimize}\ L(P,U,\lambda,\mu,e_a)\right] \qquad (14)$$

## III. NEW METHOD

### 3.1. Multi-state S.U.D.P.

We developed a new single unit dynamic programming to solve primal problem. Traditionally, to get unit commitment and generating power, S.U.D.P. which has two states is used. Even though this two states S.U.D.P. is suitable for simple operation planning, but it is not suitable for eq.(13). So, we developed a new S.U.D.P. which can treat multiple fuels. Concept of this method is basically same as two-state S.U.D.P. except number of states.

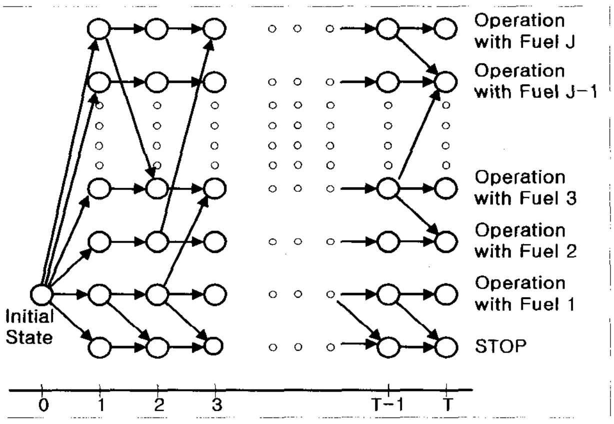

Fig. 1 Multi-state S.U.D.P.

### 3.2 Solution of Primal problem including substitution of fuel

To get unit commitment and generating power which can meet the environmental problem, rescheduling technique[4] by revision $e_a^t$ is used. But, this method is not enough to meet the environmental problem. So, we developed a new method which can substitute fuels based on Multi-state S.U.D.P..

To get the schedule by using Multi-state S.U.D.P., we present new procedure as follows: First, set the state, such as off state, using-first fuel state, using-second fuel state, using-final fuel state. Second, search optimal path from initial stage to final stage. Third, select unit commitment as an optimal path. Finally, by using multipliers, obtaining unit commitment and generating power at multi-fuel system is possible. And, local constraints and fuel constraints can meet in Multi-state S.U.D.P..

### 3.3. Solution of Dual problem

To get conventional Lagrangian multipliers $\lambda^t$, $\mu^t$, We employ the efficient method[4] which use Fibonacci and Economic dispatch.

Environmental constraints are not definite and are in trade-off relations with objective function. So, to get environmental multipliers, fuzzy technique is used.

## IV. NUMERICAL RESULTS

### 4.1. Test system

Presented test system is shown at Table I.

TABLE I Characteristics of the generators

| AREA | UNIT | FUEL | $C_i^t$ | | | $f_i$ | $P_i^{min}$ [Mw] | $P_i^{max}$ [Mw] | Startup Cost [$] |
|---|---|---|---|---|---|---|---|---|---|
| | | | $\alpha_i$ | $\beta_i$ | $\gamma_i$ | | | | |
| A | 1 | α | 0.0009 | 4.53 | 1042 | 0.00 | 600 | 1200 | 21072 |
| | 2 | α | 0.0014 | 8.38 | 305 | 1.38 | 100 | 250 | 3512 |
| | 3 | α | 0.0015 | 8.48 | 310 | 1.38 | 100 | 250 | 3512 |
| | | β | 0.0030 | 16.96 | 620 | 0.23 | 100 | 250 | 3512 |
| B | 4 | α | 0.0016 | 8.63 | 314 | 1.38 | 100 | 250 | 3512 |
| | 5 | α | 0.0017 | 8.73 | 320 | 1.38 | 100 | 250 | 3512 |
| | | β | 0.0034 | 17.46 | 640 | 0.23 | 100 | 250 | 3512 |
| A | 6 | α | 0.0023 | 8.60 | 173 | 1.36 | 50 | 200 | 1756 |
| | 7 | α | 0.0024 | 8.87 | 178 | 0.44 | 50 | 200 | 1756 |
| | 8 | α | 0.0025 | 9.13 | 183 | 0.44 | 50 | 200 | 1756 |
| | 9 | α | 0.0044 | 26.00 | 248 | 0.11 | 100 | 400 | 3512 |
| C | 10 | α | 0.0350 | 31.81 | 160 | 0.05 | 50 | 200 | 1756 |
| | 11 | α | 0.0360 | 32.77 | 165 | 0.05 | 50 | 200 | 1756 |

Generators in this system are divided in 3 areas. Limitations of contamination in area A is 3,000[Kg/h], in area B is 8,000[Kg/h], and in area C is 3,000[Kg/h]. And, two of eleven generators can consume multiple fuels. Price of fuel β is 0.5[$/m$^3$] which is as twice as fuel α, while pollution ratio is 1/3. But, fuel β has limitation which cannot exceed 200,000[m$^3$].

Presented system load is shown at Fig. 2, and its spinning reserve is 200[MW].

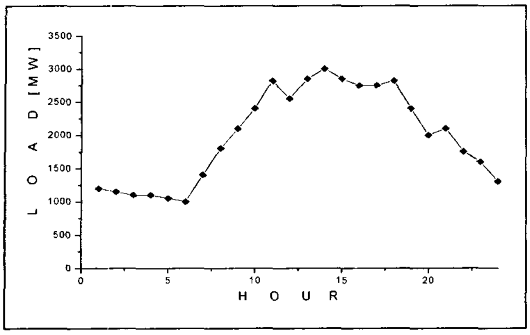

Fig. 2 System load pattern

### 4.2. Solution of environmental problem

From area A, B, and C, only area B exceed the limit of quantity of contamination. So, we studied for area B. To verify this algorithm, we get two types of operation schedule from test system. First, we consider environmental constraints by rescheduling and show the results at table II.

TABLE II Quantity of contamination at area B

| Hour | Rescheduling | Substitution | Hour | Rescheduling | Substitution |
|---|---|---|---|---|---|
| 1 | 4858.2 | 1096.2 | 13 | 7999.0 | 7991.8 |
| 2 | 4858.2 | 1096.2 | 14 | 8979.2 | 7994.8 |
| 3 | 4858.2 | 1096.2 | 15 | 7997.6 | 7989.9 |
| 4 | 4858.2 | 1096.2 | 16 | 8002.8 | 7993.8 |
| 5 | 4858.2 | 1096.2 | 17 | 8002.8 | 7993.8 |
| 6 | 4858.2 | 1096.2 | 18 | 7991.7 | 7984.1 |
| 7 | 7922.2 | 1674.5 | 19 | 7956.1 | 7965.3 |
| 8 | 7901.4 | 1423.7 | 20 | 7800.1 | 7892.0 |
| 9 | 7947.7 | 7218.1 | 21 | 7798.0 | 7874.5 |
| 10 | 8003.9 | 7880.7 | 22 | 7089.1 | 5551.2 |
| 11 | 8979.2 | 7982.3 | 23 | 5484.3 | 4185.1 |
| 12 | 7991.0 | 7976.2 | 24 | 1431.9 | 2470.6 |

In area B, limitation is 8,000[Kg/h], but quantity of contamination is 16,745[Kg/h] at 11,13,14,15,16,17,18th stages. By rescheduling, quantity of contamination can meet at every stage except 11,14th stages. To meet the quantity of contamination, we need reduce the power at these stages. But, it is not possible because of demand constraints. As a results, increase ratio of total fuel cost is 33.3[%]. Second, we consider environmental constraints by fuel substitution and show the results at table III.

TABLE III Quantity of contamination at area B with fuel substitution

| Hour | Not Consider | Consider | Hour | Not Consider | Consider |
|---|---|---|---|---|---|
| 1 | 3213.1 | 4858.2 | 13 | 16745.7 | 7999.0 |
| 2 | 3213.1 | 4858.2 | 14 | 16745.7 | 8979.2 |
| 3 | 3213.1 | 4858.2 | 15 | 16745.7 | 7997.6 |
| 4 | 3213.1 | 4858.2 | 16 | 16745.7 | 8002.8 |
| 5 | 3213.1 | 4858.2 | 17 | 16745.7 | 8002.8 |
| 6 | 3213.1 | 4858.2 | 18 | 16745.7 | 7991.7 |
| 7 | 6348.5 | 7922.2 | 19 | 13148.3 | 7956.1 |
| 8 | 9452.7 | 7901.4 | 20 | 9369.7 | 7800.1 |
| 9 | 14042.9 | 7947.7 | 21 | 9602.2 | 7798.0 |
| 10 | 16254.6 | 8003.9 | 22 | 7710.5 | 7089.1 |
| 11 | 16745.7 | 8979.2 | 23 | 5484.3 | 5484.3 |
| 12 | 15717.3 | 7991.0 | 24 | 1431.9 | 1431.9 |

From table III, quantity of contamination can meet at every stages by fuel substitution. By fuel substitution, increase ratio of total fuel cost is only 28.1[%]. It means cheap generation schedule can be obtained.

### 4.3. Solution of fuel quantity

By considering fuel quantity of fuel $\beta$, new schedule can be obtained. Fuel consumption of $\beta$ is shown at Fig. 3

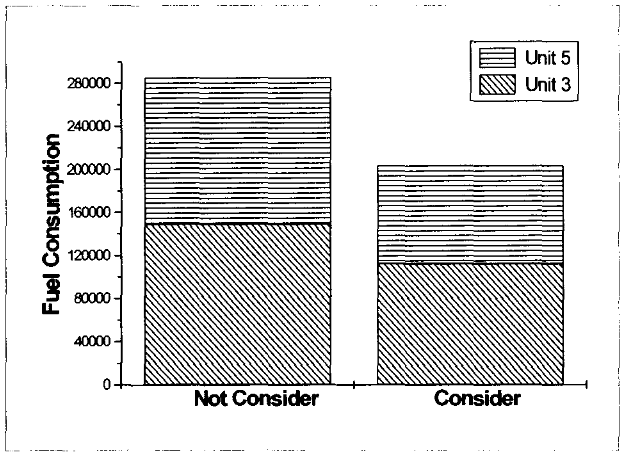

Fig. 3 Fuel consumption of each generator

From fig. 3, usage of fuel $\beta$ of the method is exceed (42[%]). So, we limit the fuel $\beta$ without violating environmental constraints. By using presented method, we can get schedule with satisfying fuel consumption. Pseudo price is obtained as $\sigma_{ij}=0$, $\delta_{ij}=0.15$. And increase ratio of total fuel cost is only 0.14[%].

## V. CONCLUSION

In this paper, we present a new methodology to get unit commitment and generating power which can consider environmental effects and energy limitation. First, we formulated a new Lagrangian function which can consider quantity of contamination including fuel substitution and quantity of fuel. Second, we developed Multi-state SUDP which can treat multiple fuel. Third, we propose an effective generation scheduling algorithm including Multi-state S.U.D.P.. As a result, we can get schedule which can meet quantity of contamination and fuel. By applying it to the test system, effectiveness of the method is verified.

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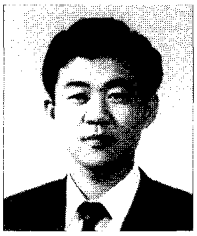

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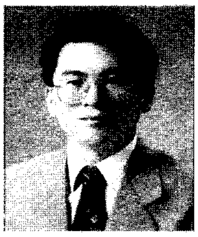

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