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Generation Scheduling of Thermal Units with Emission Limitation in Deregulation Environment

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Abstract: During the last few years, emission control has become a problem of global concern due to the constantly increasing pollution of earth's atmosphere. The generator company objectives are to maximize their profit. The traditional generation scheduling problem aims at minimizing the cost of operation subject to fulfillment of demand. Under new structure, generation companies (GENCOs) schedule their generators with objective to maximize their own profit without regard for system social benefit. There is an urgent need to keep a track of international experiences and activities taking place in the field of modern generation scheduling problem under deregulated environment with the social beneficial in consideration with the emission limitations. The proposed method is on the generation scheduling problem, considering not only the economic perspective, but also the environmental perspective. In order to reach the emission reduction targets imposed by the Kyoto Protocol, a limitation of the emissions produced by the generating units is needed. The impact of fossil-fuelled power plants must be considered, giving rise to emission limitations. The simultaneous address of the profit with the emission is taken into account in our practical approach by a Multiobjective Optimization (MO). For the problem of generation scheduling with emission limitations in deregulation environment, propose a multiobjective approach to handle the problem with conflicting profit and emission objectives. The pricing and allocation rules in each market can effectively motivate generator to mitigate its emission. The new mechanism is truly an effective way to coordinate emission market and electricity market. Influence of the emission in the scheduling, power generation scheduling with reduced emission, reduction in the production cost and generation companies (GENCO's) profit maximization is expected. The coordination of wind with emission constraint thermal generation can be done in future.

Keywords: Deregulation, Emission, Generation COmpanies (GENCOs),Multiobjective Optimization (MO), Generation Scheduling (GS).

Notation

I	total number of thermal units
K	total number of hours in the scheduling time horizon
π_k	forecasted energy price during period *k*
C_{ik}	total fuel cost incurred by thermal unit *i* during period *k*
x_{ik}	state of thermal unit *i* during period *k*
u_{ik}	scheduling decision (on-line or shutdown) of thermal unit *i* during period *k*
p_{ik}	power generation of thermal unit i during period *k*
$p_i^{\max}$	maximum power generation of thermal unit *i*
$p_i^{\min}$	minimum power generation of thermal unit *i*
D_k	demand of electrical energy during period *k*
A_{ik}	state function of thermal unit *i* during period *k*
P_{ik}	dispatch function of thermal unit *i* during period *k*

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U_{ik}	set of admissible decisions for thermal unit *i* during period *k*
X^{0}_{i}	set of initial states for thermal unit *i*
X^{f}_{i}	set of final states for thermal unit *i*
E_{ik}	total emission caused by thermal unit *i* during period *k*
ω	weighting factor
n	scaling factor
M	set of Pareto-optimal solutions
ε	allowable level
x	vector of all state variables
u	vector of all commitment decision variables
p	vector of all power generation variables

1. INTRODUCTION

The main economic operation of power system is the cost of generating real power. Therefore attention has to be paid on allocation of real power at generator buses. This problem can be divided into two sub problems namely optimum allocation of units called Unit Commitment (UD) at each generating station at various station load levels and optimum allocation of generation to each hour i.e., Economic Dispatch (ED) problem. Generation scheduling is used to schedule the operation of the generating units with ON/OFF status in order to satisfy the load demand such that the total operation cost over the scheduled horizon is minimized as subject to many system and generator operational constraints.

Nowadays, the electric utility deregulation process has introduced competition through biding to win the best profit in the electricity market, as well as the possibility of the consumer to choose which supplier he or she wants. Under deregulation, UC has evolved from a minimum-cost policy to a profit-based policy,giving rise to the new profit-based unit commitment (PBUC) problem [2].The account of emission limitations in the UC problem, as in [3, 4], did not receive lately as much attention as in the ED problem. The recent advent of the ETS in the EU has renewed interest in the environmentally constrained UC problem [1, 5]. Still, the environmental issues have been included only in the minimum-cost optimization problem, but not in the profit-based optimization problem with different energy price profiles, which represents the new contribution of this paper.

The electric power industry has over the years been dominated by large utilities that had an overall authority over all activities in generation, transmission and distribution of power within its domain of operation. Such utilities have often been referred to as vertically integrated utilities. Such utilities served as the only electricity provider in the region and were obliged to provide electricity to everyone in the region. The utilities being vertically integrated, it was often difficult to segregate the costs incurred in generation, transmission or distribution. Therefore, the utilities often charged their customers an average tariff rate depending on their aggregated cost during a period. The price setting was done by an external regulatory agency and often involved considerations other than economics.

The typical structure of a vertically integrated utility where links of information flow existed only between the generators and the transmission system. Similarly, money (cash) flow was unidirectional, from the consumer to the electric utility. The operation and control issues for such systems have been widely examined over the years. The basic objective of the operator in such vertically integrated utilities would be to minimize the total system cost while satisfying all associated system constraints. Apart from operational issues, such vertically integrated utilities also had a centralized system of planning for the long-term.

All activities such as long-term generation and transmission expansion planning, medium term planning activities such as maintenance, production and fuel scheduling were coordinated centrally.

Current installed capacity of Thermal Power as of June 30, 2011 is 115649.48 MW which is 65.34%of total installed capacity. Among that Coal Based Thermal Power is 96,743.38 MW which comes to 54.66%, Gas Based Thermal Power is 17,706.35 MW which is 10.00%, and Oil Based Thermal Power is 1,199.75 MW which is 0.67% of total installed capacity (1,76,990.40 MW). The electricity generation sector is the major source of gaseous emissions such as carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x), sulphur dioxide (SO_2) and particulate matter (PM). Particularly, CO_2 is a greenhouse gas (GHGs) which is a major cause of global warming. In addition, SO_2 and NO_x gases are contributors to acid rain.

By introducing emission market and ecological taxation into the electric power sector, the development of decision making methods concerning of emission trading or emission constraints is becoming increasingly important, and many studies of deciding generators' schedule are conducted [6]-[10].Although there are many studies concerning CO_2constraints, they mainly focus on the economic dispatch problem, deciding the output level of each generator [10, 11].

The Clean Air Act Amendment of 1990 of USA established reductions in the SO_2 emissions. The reduction program was used in two phases. In this program, polluting sources (units) were allowed to trade and transfer allowances to emit pollutants in variable quantities. By definition, an allowance is the permission to emit 1 *t* of SO_2 during 1 year. In order to ensure that utilities did not change generation and emissions from Phase I units to Phase II units Congress added a clause to force Phase I units to burn at least their average annual fuel amount which was consumed in the baseline years 1985–1987 [12,13]. It is important to evaluate the different alternatives for pollution reduction such as scrubbers, fuel switching, and trading in the allowances market [14–18]. The short-term scheduling determines the unit commitment and the load dispatch of the units. In this type of scheduling more detailed information is used [6], [19–21].

An algorithm based on multiobjective function with particle swam optimization is used for solving the generation scheduling in deregulation with emission limitation. After the description of the problem formulation in section II, and the solution methodology is explained in section III, the effectiveness of the method with numerical examples is simulated in section IV.

2. PROBLEM FORMULATION

A. Generation Scheduling

The generation scheduling in deregulation problem is the process of finding the solution that minimizes the total fuel cost, maximizing the profit and at the same time meets various constraints. A generation scheduling problem is usually much complicated compared to the economic dispatch problem because of various constraints such as demand-and supply balance, etc., and the discrete values of each generator. From this background, many optimization algorithms are proposed to solve the PBUC problem [22-27].

B. Cost Minimization and Profit Maximization

The objective function of the original generation scheduling in deregulation problem is formulated as below

$$g(x, u, p) = \sum_{i-1}^{I} \sum_{k-1}^{K} C_{ik}(x_{i,k-1}, u_{ik}, p_{ik}) - \pi_k p_{ik} \tag{1}$$

where, C_{ik} is a quadratic cost function.

$$C_{ik}^{op}(u_{ik}, p_{ik}) = u_{ik}(a_i + b_i p_{ik} + c_i p_{ik}^2) \tag{2}$$

where, a_i, b_i & c_i are the cost coefficients for thermal unit i. The minimization problem is subjected to the following constraints.

Demand-and-supply balance

$$\sum_{i=1}^{\mathrm{I}} p_{ik} u_{ik} - \mathrm{D}_k = 0 \tag{3}$$

Spinning reserve

$$\sum_{i=1}^{\mathrm{I}} \mathrm{R}_{ik} u_{ik} - \mathrm{S}_t^{\mathrm{req}} \geq 0 \tag{4}$$

Upper and lower bound of generator output

$$p_{ik}^{\min} \leq p_{ik} \leq p_{ik}^{\max} \tag{5}$$

In addition, minimum up and down time constraints of units are also considered using the state variable X_{ik}. When unit i starts up, X_{ik} is set to 1 and incremented as the unit stays on. When the unit is shut down, X_{it} is set to −1 and decremented as the unit stays off. X_{ik} is compared to either minimum up/down time $\mathrm{T}_i^{\mathrm{up}}$, $\mathrm{T}_i^{\mathrm{dn}}$. The unit schedule that minimizes the total production cost can be obtained by solving the above-described problem.

C. Emission Minimization

To obtain the generation schedule that minimizes the total emission, the authors reformulate the problem described above by replacing the objective function (1) with (6). Alternatively, the objective function to be minimized can be the total emission, expressed as

$$h(x, u, p) = \sum_{i=1}^{\mathrm{I}} \mathrm{E}_{ik}(x_{i,k-1}, u_{ik}, p_{ik}) \tag{6}$$

where, E_{ik} is assumed to be a quadratic function

Emission is assumed to be computed by the sum of quadratic and exponential functions of power generation as [28].

$$\mathrm{E}_{ik}^{em}(u_{ik}, p_{ik}) = u_{ik}[10^{-2}(\alpha_i + \beta_i p_{ik} + \gamma_i p_{ik}^2) + \varepsilon_i(\lambda_i p_{ik})] \tag{7}$$

where α_i, β_i, γ_i, ε_i, and λ_i are the emission coefficients for thermal unit i. The emission coefficients in (4) are computed by the given data for the type of pollutant.

D. Multi-objective Function

By replacing the objective function (1) with (6) below, the problem can be reformulated as a cost-emission multi-objective minimization problem [28].

$$\min \left\{ \begin{array}{c} \left[\sum_{i-1}^{\mathrm{I}} \sum_{k-1}^{\mathrm{k}} \mathrm{C}_{ik} C_{ik}(x_{i,k-1}, u_{ik}, p_{ik}) - \pi_k p_{ik} \right], \\ \left[\left[\mathrm{E}_{ik}^{em}(u_{ik}, p_{ik}) = u_{ik}[10^{-2}(\alpha_i + \beta_i p_{ik} + \gamma_i p_{ik}^2) + \varepsilon_i(\lambda_i p_{ik})] \right] \right. \end{array} \right\} \tag{8}$$

In (6), the ω variable shows the weighting coefficient on the emission function. We can obtain the total cost which is needed for reducing the to talemission to a certain target level by calculating this function.

3. SOLUTION METHODLOGY

The PBUC problem with emission limitations is formulated as the following MO problem

$$\mathrm{Min}\{(g(x, u, p)), (h(x, u, p))\} \tag{9}$$

$$\mathrm{F}(x, u, p) \in \mathrm{F} \tag{10}$$

The first application of MO with power systems has been addressed in [31]. MO with conflicting objective functions gives rise to a set of optimal solutions, instead of one optimal solution. The reason for the optimality of many solutions is that no one can be considered to be better than any other with respect to all objective functions. These optimal solutions are known as non-dominated or Pareto-optimal solutions [30]. The trade-off curve represents the image of the Pareto-optimal set into the space of objectives. If the problem had been reduced to a single objective problem by treating the emission as a constraint, it would be difficult to obtain the trade-off relations. This is an advantage of using the MO criteria instead of a single objective regarding the profit maximization. The availability of the trade-off curve between profit and emission will give a quantitative base to decision-makers for readjusting the scheduling according to emission allowance trading. The most widely used method for generating non-dominated solutions and trade-off curve is the weighted sum method, especially when the MO problem has only two objectives. Adopting the weighted sum method, a non-dominated solution to the MO problem can be determined by a convex combination of the objective functions.

$$o(x, u, p) = \omega g(x, u, p) + (1 - \omega)\varepsilon\, h(x, u, p) \tag{11}$$

Where ω is the weighting factor and ε is the scaling factor, given for instance by the emission market price, which is assumed constant over the scheduling time horizon. The trade-off curve can be found by parametrically varying the weighting factor ω between 0 and 1, thus solving single objective optimization problems. The best emission commitment (BEC) corresponds to $\omega = 0$, while the best profitcommitment (BPC) corresponds to $\omega = 1$. Our practical approach may merge the weighted sum method with the *e*-constraining method into a hybrid method, which constraints the objective functions by some allowable levels ε.

$$\sum_{i=1}^{\mathrm{I}} \sum_{k=1}^{\mathrm{K}} \mathrm{C}_{ik} - \pi_k p_{ik} \le \varepsilon_c^{\mathrm{req}} \tag{12}$$

$$\sum_{i=1}^{\mathrm{I}} \sum_{k=1}^{\mathrm{K}} \mathrm{E}_{ik} \le \varepsilon_c^{\mathrm{req}} \tag{13}$$

In order to overcome the difficulty on finding the non-convex Pareto-optimal set for the MO problem. A non-dominated solution m in the Pareto-optimal set, representing a 168 h generation schedule, is characterized by a total profit and a total emission in the space of objectives. Upon having the Pareto-optimal set and trade-off curve, the proposed practical approach extracts one solution to the decision- maker as the best compromise solution. This compromise solution denotes the amount of percentage decrease in total profit that the decision-maker is willing to accept in exchange for a certain amount of percentage decrease in total emission [32]. The ratio of change is obtained for each non-dominated solution m with respect to the previous non-dominated solution $m - 1$, comparatively to the maximum ratio of change, given by

$$\mu^m = \frac{h_{\%}(x^m, u^m, p^m) - h_{\%}(x^{m-1}, u^{m-1}, p^{m-1})}{g_{\%}(x^m, u^m, p^m) - g_{\%}(x^{m-1}, u^{m-1}, p^{m-1})} \mathrm{X} \frac{g_{\%}^{\max}}{h_{\%}^{\max}} \tag{14}$$

The corresponding gradient angle is also obtained, given by

$$\theta^m = \tan^{-1}(\mu^m) \tag{15}$$

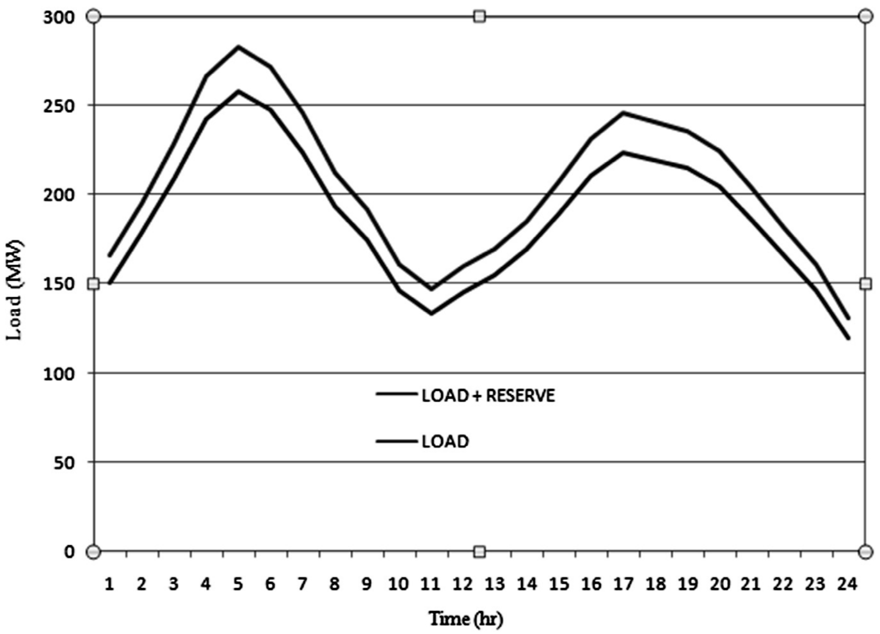

Figure 1: A daily load curve and a spinning reserve

Table 1
Generator Operating Characteristics

Unit	P_{min} (MW)	P_{max} (MW)	Ramp Rate (MW/ Hr)	T^{up} (Hr)	T^{dn} (Hr)	Fuel Cost Coefficient			Emission Coefficient			Shut Down Cost ($)	Init. Unit Status	Startup Cost	
						a	*b*	*c*	*α*	*β*	*γ*			*Hot($)*	*Cold($)*
1	200	50	50	1	1	0.00375	2.0	0	22.983	–0.9000	0.0126	50	-1	70	176
2	80	20	20	2	2	0.01750	1.7	0	25.313	–0.1000	0.0200	60	-3	74	187
3	50	15	13	1	1	0.06250	1.0	0	25.505	–0.0100	0.0270	30	2	50	113
4	35	10	09	1	2	0.00834	3.25	0	24.900	–0.0050	0.0291	85	3	110	267
5	30	10	08	2	1	0.02500	3.0	0	24.700	–0.0040	0.0290	52	-2	72	180
6	40	12	10	1	1	0.02500	3.0	0	25.300	–0.0055	0.0271	30	-3	40	113

Table 2
Generation Schedule

Hr	*Unit Status*						*Fuel Cost ($)*	*Emission Output (lb/hr)*	*Total Operating Cost($)*	*Profit ($)*
	1	*2*	*3*	*4*	*5*	*6*				
1	1	0	1	1	0	0	371.5868	73.3098	670.1	738.825
2	1	0	1	0	0	0	441.3113	86.3209	767.9	849.059
3	1	1	1	0	0	0	506.3165	113.0660	1028.4	1123.362
4	1	1	1	0	0	1	612.3155	169.3727	1286.8	1425.349
5	1	1	1	0	0	1	657.3696	198.0643	1346.6	1479.778
6	1	1	0	0	0	1	625.6587	175.6228	1216.7	1361.365
7	1	1	0	0	0	0	578.5556	141.7408	1048.6	1155.913
8	1	1	0	0	0	0	485.1874	89.1517	772.3	846.340
9	1	1	0	0	0	0	430.9812	67.7910	619.8	683.248
10	1	1	0	0	0	0	353.4512	43.6481	471.0	514.238
11	1	0	0	0	0	0	334.5169	26.8197	463.4	510.713

Hr	*Unit Status*						*Fuel Cost ($)*	*Emission Output (lb/hr)*	*Total Operating Cost($)*	*Profit ($)*
	1	*2*	*3*	*4*	*5*	*6*				
12	1	0	0	0	0	0	368.0000	40.2630	476.3	525.454
13	1	0	1	0	0	0	373.9505	58.7087	646.6	714.040
14	1	0	1	0	0	0	412.5806	73.7066	616.3	681.443
15	1	0	1	0	0	0	473.2075	101.641	763.8	844.916
16	1	1	1	0	0	0	514.0841	116.1373	1047.1	1164.689
17	1	1	1	0	0	1	578.5556	141.7408	1161.6	1287.401
18	1	1	1	0	0	0	537.5458	125.8026	1068.4	1183.951
19	1	1	1	0	0	1	531.2294	135.3012	1050.7	1167.432
20	1	1	1	0	0	0	496.0009	109.0894	847.1	929.353
21	1	1	1	0	0	0	442.6166	90.4108	699.3	777.481
22	1	1	1	0	0	0	388.0821	74.8089	594.2	660.096
23	1	1	0	0	0	0	353.4515	43.6481	501.0	550.549
24	1	1	1	0	0	0	267.1394	54.2494	511.4	564.790
			Total				11133.6947	2350.4156	19675.4	21739.785

The new parameter, ratio of change, and the corresponding gradient angle, enable the selection of the best compromise commitment (BCC) for the units. On the one hand, if the gradient angle assumes small values, the percentage decrease in total emission would be small for a significant percentage decrease in total profit. On the other hand, if the gradient angle assumes large values, the decision-maker may decide in favor of a further percentage decrease in total emission at the expense of some percentage decrease in total profit. In our approach, the BCC is selected for a ratio of change equal to 1, corresponding to a gradient angle of 45°, since a ratio of change less than 1 means that the percentage decrease in total emission is less than the corresponding percentage decrease in total profit.

4. CASE STUDY

A model with 6 generating units over 24 hours for demonstrating our approach. The operating characteristics are listed in Table 1. Because both cost and emission are proportional to the fuel consumption, quadratic models are assumed for the cost and the emission function. Figure 1 shows the system load and spinning reserve assumed in this model. Table 2 show the schedule and output of power generation of 6 units for 24 hours by minimizing the total operating cost and the emission.

5. CONCLUSION

The paper describes a particle swam optimization based approach for the short-term generation scheduling of thermal units considering the environmental constraints of electric power systems in deregulation. The environmental issue is considered as an operating constraint which has a restriction on hourly emission allowances and other related constraints are also considered in the multiobjective procedures. Application results of the proposed algorithm to a test power system are presented which numerically illustrate the effectiveness of the approach.

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