Short-term scheduling of thermal units: emission constraints and trade-off curves

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SUMMARY

This paper provides an approach to short-term scheduling of thermal units, designed to simultaneously address the economic issue of the fuel cost incurred on the commitment of the units and the environmental consideration due to emission allowance trading. The simultaneous address of the fuel cost with the emission is modelled by a multi-objective optimization problem, which is solved by a combination of the weighted sum method with the ε-constraining method. A numerical example for different values of a scaling factor is considered in order to obtain the non-dominated solutions of the trade-off curve between fuel cost and emission. Our approach presents a new parameter, ratio of change, and the corresponding gradient angle, to enable the proper selection of a compromise commitment for the units.

KEY WORDS: unit commitment; emission constraints; multi-objective optimization

1. INTRODUCTION

Fossil fuels represent a reliable and affordable source of energy, necessary to satisfy the demand for electric energy.

The widespread adoption of energy economies based on fossil fuels has brought with it the potential harmful problem of the emission of gaseous and particulate products of combustion. When the concentration of emissions reaches a pre-specified threshold, the phenomenon is termed pollution [1].

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Fossil fuelled power plants are classified as stationary sources of emission pollution. The amount of emission pollution as a result of burning fossil fuels to convert into electric energy depends on the fuel used, the level of power and the efficiency of the technology used in the power plant operation. For instance, electric companies with old coal-fired power plants technology have higher emission levels. As a comparison, the emission level for a pulverized coal-fired power plant is about two times and a half higher than the emission level for a natural gas-fired power plant in combined cycle configuration. Although with the actual technology coal-fired power plants are polluting less, if they are in the vicinity of urban or rural zones then concentration of pollution due to weather conditions or the usual night temperature inversion effect [2] can originate environmental impact, even when compared with old coal-fired power plants not in the vicinity of urban or rural zones.

Environmental concerns are becoming increasingly relevant for companies as regulations on pollutants become more stringent and customer awareness of environmental impacts increases. Firstly, it is now recognized that the greenhouse effect can be slowed down only if emissions of carbon dioxide and other harmful gases are reduced drastically. A major step in this direction is the Kyoto Protocol [3], which establishes a 5% drop in carbon dioxide emissions compared to emissions in 1990 for the industrialized countries. Recently, the European Parliament adopted the world's first multi-national Emissions Trading Scheme covering greenhouse gases in the Union [4]. The six main greenhouse gases are: carbon dioxide, methane, nitrous oxide, hydro fluorocarbons, per fluorocarbons and sulphur hexafluoride. The Emissions Trading Scheme, entered into force on January 2005, caps emissions from plants in the oil refining, smelting, steel, cement, ceramics, glass and paper sectors and allows trading of emission allowances. The environmental issues imposed by the Kyoto Protocol imply new emission constraints regarding production decision in thermal units burning fossil fuels.

The position of a power plant in the merit order list has been based traditionally on minimized total cost. Hence, old coal-fired power plants achieved a superior merit order, producing at the lowest cost electric energy, although with considerable impact on the environment. The lifetime of these plants was extended, causing a delay in development of efficient and clean technologies.

An unprecedented change is bound to occur in the new carbon constrained world and with the new environmental regulations implemented worldwide the role of the old coal-fired power plant is likely to change. In the presence of emission allowances, old coal-fired power plants may move down in the merit order, due to higher carbon emission intensity. They will run less than it was normal in the old carbon unconstrained world. Hence, natural gas-fired power plants in combined cycle configuration, or even the new promising technology for coal power plants with zero emissions, will go up in the merit order. Gas plants will need less emission allowances than coal plants, resulting in a tendency for a shift in the merit order of power plants. Also, the utility manager has to consider that the emission rights can be freely traded, having the option to sell the allowances if not needed.

Market prices to buy more emission allowances will add up a cost to the marginal cost of electric energy production for fossil-fuelled power plants [5]. Instead, hydro plants which can be regarded as renewable energy sources [6] will not have to buy or own allowances for their electric energy produced and therefore will face a competitive advantage.

The majority of the studies concerning emission constraints are on the economic dispatch problem [7–13], deciding only the power contribution of each thermal unit, but not deciding on which units should be committed for generation at each hour.

The traditional short-term scheduling problem of thermal units, minimizing fuel cost during a time horizon of one day up to one week, does not include concerns due to emission pollution coming from the operation of power plants. This schedule for a thermal unit comprises both deciding the commitment status, a discrete value, and the power contribution, a continuous value. This problem is also known as unit commitment. The account of environmental factors in the unit commitment problem [14–16], did not receive as much attention as in the economic dispatch problem. However, the recent advent of carbon dioxide trading in the European Union has renewed interest in the environmentally constrained unit commitment problem [17–18].

Emission allowances are yearly allocated. Hence, a short-term scheduling of thermal units ruled by an emission allowance market requires a medium-term scheduling [5]. An estimation of the daily allowances of each unit is obtained by means of annual allowances.

The scheduling of the thermal units ruled by an emission allowance market can be organized through a hierarchical structure like the one described in [19]. The schedule of thermal units is divided into three hierarchical levels: the year level, the month level and the day level, with time periods respectively of one month, one day and one hour. At each level, an average load dispatch is computed. Year level average load dispatch is computed, establishing a monthly emission allowance for each unit. Month level average load dispatch is computed, establishing a daily emission allowance for each unit. These daily allowances will comply with the yearly allocated emission allowances. At the year and month levels, all units are supposed to be committed for generation. At the day level, the commitment of the units is decided. It is possible to use a week level instead of a day level for the unit commitment.

Since minimizing fuel cost and minimizing emission tend to be conflicting objectives, an approach based on multi-objective optimization is proposed in this paper to obtain the best compromise solution from the non-dominated or Pareto-optimal solution set. The trade-off curve between fuel cost and emission is presented, graphically illustrating this non-dominated solution set.

This paper is structured as follows. In Section 2, we present a mathematical formulation for scheduling of thermal units with emission constraints, modelled as a dynamic, mixed-integer non-linear constrained optimization problem. In Section 3, an approach designed to simultaneously address the economic issue of the fuel cost incurred on the commitment of the units and the environmental consideration due to emission allowance trading is shown. In Section 4, we present a case study with 11 thermal units and a scheduling time horizon of 168 hours. Finally, Section 5 outlines the main conclusions.

2. PROBLEM FORMULATION

The traditional problem of short-term scheduling of thermal units is defined as the task of establishing the minimum fuel cost for the hourly generation schedule of the thermal units during a time horizon of one day up to one week, satisfying the demand of electrical energy and the considered constraints.

The problem of short-term scheduling of thermal units with emission constraints can be solved by considering that there is a medium-term scheduling which provides daily or weekly allowances for the units. Some of the data involved in the unit commitment problem are stochastic in nature, but for the short-term time horizon considered the corresponding forecasted values are assumed as deterministic data. Therefore, the problem is viewed as a deterministic one [20].

The problem involves integer variables associated with discrete states, continuous variables and also equality, inequality and logical constraints. The problem is a dynamic, mixed-integer non-linear constrained mathematical programming problem. The economic consequences of unit commitment are recognized as very important; savings of a small percent value represent a significant reduction in the fuel consumption [21].

The problem is written as a mathematical programming problem of the type:

$$\text{minimize} \qquad f(\boldsymbol{x}, \boldsymbol{u}, \boldsymbol{p})$$

$$\text{subject to} \qquad (\boldsymbol{x}, \boldsymbol{u}, \boldsymbol{p}) \in F \tag{1}$$

where the objective function is given by:

$$f(\boldsymbol{x}, \boldsymbol{u}, \boldsymbol{p}) = \sum_{k \in K} \sum_{i \in I} C_{ik}(x_{ik}, u_{ik}, p_{ik}) \tag{2}$$

K is the set of hours in the scheduling time horizon, I is the set of thermal units in the power system, C_{ik} is the total fuel cost incurred by a thermal unit i in hour k, and x_{ik}, u_{ik}, p_{ik} are respectively the state, the discrete decision and the power production variables associated with the thermal unit i in hour k.

The constraints may be divided into global and local constraints. Global constraints may be divided into:

(a) Hourly generation constraints. For instance: the power produced by the thermal units equals the demand D_k in each hour k, ignoring transmission losses

$$\sum_{i \in I} p_{ik} = D_k; \qquad k \in K \tag{3}$$

(b) Cumulative constraints. For instance: the maximum emission of a group of units over the scheduling time horizon cannot exceed a pre-specified value

$$\sum_{k \in K} \sum_{i \in B_n} H_{ni}(x_{ik}, u_{ik}, p_{ik}) \le H_n^{req}; \qquad n \in N \tag{4}$$

where B_n is the set of thermal units on the nth cumulative constraint, H_{ni} is the function which describes a contribution of thermal unit *i* to *n*th cumulative constraint, H_n^{req} is the upper bound on *n*th cumulative constraint and *N* is the set of cumulative constraints.

The local constraints may be divided into:

(a) State equations for the thermal units

$$x_{i,k+1} = A_{ik}(x_{ik}, u_{ik}); \qquad u_{ik} \in U_{ik}, i \in I, k \in K \tag{5}$$

yielding the state variable in hour *k*+1 for the state variable in hour *k* and for the discrete decision variable in hour *k* belonging to the set of feasible discrete decision variables U_{ik}.

(b) Power production admissible set

$$p_{ik} \in P_{ik}(u_{ik}); \qquad i \in I, k \in K \tag{6}$$

for instance, if the unit is on, the power production is between the minimum value and the maximum value of the power for the unit in hour *k*; if the unit is off, the power production is null.

(c) Initial state x_{io} and final state x_{if}

$$x_{i0} \in X_i^0 \quad x_{if} \in X_i^f \qquad i \in I \tag{7}$$

belonging respectively to the initial state set X_i^0 and the final state set X_i^f.

Constraints (3) to (7) define the set of feasible variables:

$$F = \{(\boldsymbol{x}, \boldsymbol{u}, \boldsymbol{p}): \text{constraints } (3),(4)\ldots(7) \text{ are satisfied}\}$$

The total fuel cost incurred by a thermal unit *i* is given by the sum of the start up cost with the operation cost. We consider the start up cost given as a constant, and the operation cost mathematically modelled as a second order Taylor expansion. Hence, the operation cost is given by:

$$C_{ik}^{op}(u_{ik}, p_{ik}) = u_{ik}\ (\alpha_i + \beta_i\ p_{ik} + \gamma_i\ p_{ik}^2) \tag{8}$$

where α_i, β_i and γ_i are the cost coefficients for thermal unit *i*.

The objective function may be considered as the total emission instead of the total fuel cost. We consider the emission due to fossil-fuelled units also mathematically modelled as a second order Taylor expansion, given by:

$$E_{ik}^{em}(u_{ik}, p_{ik}) = u_{ik}(a_i + b_i\ p_{ik} + c_i\ p_{ik}^2) \tag{9}$$

where a_i, b_i and c_i are the emission coefficients for thermal unit *i*.

The objective function for the problem becomes the total emission, given by:

$$g(\boldsymbol{x},\boldsymbol{u},\boldsymbol{p}) = \sum_{k\in K}\sum_{i\in I} E_{ik}(x_{ik}, u_{ik}, p_{ik}) \tag{10}$$

The simultaneous address of the fuel cost with the emission is modelled in this paper by a multi-objective optimization problem, given by:

$$\begin{aligned} &\text{minimize} && [f(\boldsymbol{x},\boldsymbol{u},\boldsymbol{p}),\, g(\boldsymbol{x},\boldsymbol{u},\boldsymbol{p})] \\ &\text{subject to} && (\boldsymbol{x},\boldsymbol{u},\boldsymbol{p}) \in F \end{aligned} \tag{11}$$

3. PROPOSED APPROACH

In the multi-objective problem formulation the two objective functions considered, total fuel cost and total emission, tend to be conflicting. Hence, it is impossible to obtain the minimum at the same point when the objective functions are independently optimized, i.e., for the minimum total fuel cost and for the minimum total emission. A gain in one objective function is due to a sacrifice in the other objective function. Our approach aims to get the best compromise solution from the non-dominated solution set, considering the two objective functions simultaneously.

The two objective functions must be traded off in some way. We treated them by a convex combination, a weighted sum given by:

$$h(\boldsymbol{x},\boldsymbol{u},\boldsymbol{p}) = w\, f(\boldsymbol{x},\boldsymbol{u},\boldsymbol{p}) + (1-w)\,\lambda\, g(\boldsymbol{x},\boldsymbol{u},\boldsymbol{p}) \tag{12}$$

where w is a weighting factor varying between 0 and 1 to generate the non-dominated solutions: $w = 0$ corresponds to the best emission commitment (BEC), and $w = 1$ corresponds to the best cost commitment (BCC); λ is a scaling factor, given for instance by the carbon market price, which is uncertain but assumed constant over the scheduling time horizon. Nevertheless, each scaling factor considered is used to define a scenario. Hence, the uncertainty regarding the scaling factor is divided into a finite number of possibilities.

The weighted sum method obtains the set of non-dominated solutions, *M*, by varying the weighting factor. Our approach combines the weighted sum method, using a convex combination of the objective functions, with the ε-constraining method, constraining the objectives by some allowable levels ε:

$$\sum_{k\in K}\sum_{i\in I} C_{ik} \le \varepsilon_C^{req} \tag{13}$$

$$\sum_{k\in K}\sum_{i\in I} E_{ik} \le \varepsilon_E^{req} \tag{14}$$

in order to overcome the difficulty on finding the non-convex Pareto-optimal solution set for the multi-objective optimization problem.

A non-dominated solution m in the Pareto-optimal solution set, given by a 168 hours schedule, is characterized by a total fuel cost and a total emission in the space of criterions.

The percentage increase in the total fuel cost over the total fuel cost obtained for the BCC, f^{BCC}, is computed for each solution m as follows:

$$f_{\%}(\boldsymbol{x}^m, \boldsymbol{u}^m, \boldsymbol{p}^m) = \frac{f(\boldsymbol{x}^m, \boldsymbol{u}^m, \boldsymbol{p}^m) - f^{BCC}}{f^{BCC}} \times 100\,\% \tag{15}$$

The percentage decrease in the total emission over the total emission obtained for the BCC, g^{BCC}, is computed for each solution m as follows:

$$g_{\%}(\boldsymbol{x}^m, \boldsymbol{u}^m, \boldsymbol{p}^m) = \frac{g^{BCC} - g(\boldsymbol{x}^m, \boldsymbol{u}^m, \boldsymbol{p}^m)}{g^{BCC}} \times 100\,\% \tag{16}$$

The proposed approach upon having the set of non-dominated solutions, graphically illustrated by the trade-off curve between fuel cost and emission, extracts a compromise solution. This solution is defined by the amount of percentage increase in the total fuel cost that the decision maker is willing to accept in exchange for a certain amount of percentage decrease in the total emission.

We obtain the ratio of change 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:

$$\mu^m = \frac{g_{\%}(\boldsymbol{x}^m, \boldsymbol{u}^m, \boldsymbol{p}^m) - g_{\%}(\boldsymbol{x}^{m\text{-}1}, \boldsymbol{u}^{m\text{-}1}, \boldsymbol{p}^{m\text{-}1})}{f_{\%}(\boldsymbol{x}^m, \boldsymbol{u}^m, \boldsymbol{p}^m) - f_{\%}(\boldsymbol{x}^{m\text{-}1}, \boldsymbol{u}^{m\text{-}1}, \boldsymbol{p}^{m\text{-}1})} \times \frac{f_{\%}^{BEC}}{g_{\%}^{BCC}} \tag{17}$$

We also obtain the corresponding gradient angle, given by:

$$\theta^m = \tan^{-1}(\mu^m) \tag{18}$$

The value of the gradient angle increases from 0 to 90º as the weighting factor varies between 0 and 1. On the one hand, if the gradient angle assumes small values, the percentage decrease in the total emission would be small for a significant percentage increase in the total fuel cost. On the other hand, if the gradient angle assumes large values, the decision maker may decide in favour of a further percentage decrease in the total emission at the expense of some percentage increase in the total fuel cost.

In our approach, the best compromise commitment is chosen for a ratio of change equal to 1, corresponding to a gradient angle of 45º, since a ratio of change less than 1 means that the percentage decrease in the total emission is less than the corresponding percentage increase in the total fuel cost.

4. CASE STUDY

We consider a case study consisting of 11 thermal units and a scheduling time horizon of 168 hours. Table I shows the coefficients for cost and emission.

"See Table I at the end of the manuscript".

Thermal units are available for production during the entire time horizon of optimization. Note that thermal units 1 to 6 have inferior fuel cost but higher emission in comparison with thermal units 7 to 11.

The demand to be satisfied during the time horizon is shown in Figure 1.

Figure 1. Hourly demand.

The computational approach was developed and implemented on a 1.6-GHz-based processor with 512 MB of RAM using FORTRAN language.

We carried out the following computation strategy: at first, fuel cost and emission are independently optimized to determine the extreme points of the trade-off curve: the BCC and the BEC; then, fuel cost and emission are merged in the weighted sum method, as mentioned in our approach.

The BCC and BEC results for units 1 to 6 are shown in Figure 2.

Figure 2. Hourly total generation for thermal units 1 to 6. The solid line represents best cost commitment results while the dashed line represents best emission commitment results.

The BCC and BEC results for units 7 to 11 are shown in Figure 3.

Figure 3. Hourly total generation for thermal units 7 to 11. The solid line represents best cost commitment results while the dashed line represents best emission commitment results.

Units with inferior fuel cost are committed typically at full power regardless of emission, in the BCC. Thus, it was expected that the lesser pollutant units were not needed to be committed in order to satisfy the demand, because these units have higher fuel cost. The commitment status of thermal units achieved for the BCC follows the demand profile, as shown in Figure 4.

Figure 4. Matrix structure representing commitment status of thermal units for best cost commitment results: a filled spot means that the unit is committed, while a blank spot means that the unit is not committed.

In the BEC all units are committed, as shown in Figure 5, and the power of units 1 to 6 is reduced in order to achieve the minimum emission, implying a higher total fuel cost.

Figure 5. Matrix structure representing commitment status of thermal units for best emission commitment results: a filled spot means that the unit is committed, while a blank spot means that the unit is not committed.

Figure 6 to Figure 9 show 100 non-dominated solutions of the trade-off curve considering a scaling factor respectively of 7, 14, 21 and 28, thus posing four different scenarios for the scaling factor.

Figure 6. Non-dominated solutions of the trade-off curve with a scaling factor of 7.

Figure 7. Non-dominated solutions of the trade-off curve with a scaling factor of 14.

Figure 8. Non-dominated solutions of the trade-off curve with a scaling factor of 21.

Figure 9. Non-dominated solutions of the trade-off curve with a scaling factor of 28.

The trade-off curve has a sharp slope at the BCC neighbourhood. The gradient angle is close to 90º, meaning that a significant percentage decrease in the total emission, about 16.5%, is obtained with a small percentage increase in the total fuel cost, about 2.0%. It should be noted that at the end of the curve the opposite occurs, since for the same increase of 2.0% in the total fuel cost only a 0.9% decrease in the total emission is obtained, because at this point the gradient angle is close to 0º. An overall decrease in the total emission of about 42.1% is obtained by a total fuel cost increase of about 12.4%.

The new parameter, ratio of change, and the corresponding gradient angle, enable the proper selection of a compromise commitment for the units between the BEC and the BCC. The increase of the scaling factor favours the predominance of the total emission objective function over the total fuel cost objective function, thus shifting the best compromise commitment into the neighbourhood of the BEC, as shown in Table II.

"See Table II at the end of the manuscript".

The total CPU-time for the computation of the trade-off curve was about 270 s, with an average 2.7 s for each solution corresponding to a 168 hours schedule. This demonstrates that the proposed approach has an acceptable CPU-time in handling this problem.

5. CONCLUSION

This paper provides an approach for the short-term scheduling of thermal units with emission constraints. A compromise between the fuel cost incurred on the commitment of the units and the emission implies the consideration of a multi-objective optimization problem for developing an information management system aiding the decision maker. The non-dominated solutions of the trade-off curve between fuel cost and emission are presented for different values of a scaling factor, assumed constant over the scheduling time horizon. Our approach presents a new parameter, ratio of change, and the corresponding gradient angle, which can be used by the decision maker to choose a compromise commitment for the units. A limitation may result when the carbon market prices are highly volatile over the scheduling time horizon. In this case, the decision maker has to readjust his scheduling continuously. Numerical results show that the proposed approach is efficient for obtaining the trade-off curve and the best compromise commitment for the units with an acceptable CPU-time requirement.

6. LIST OF SYMBOLS

$\boldsymbol{x}$	Array of all state variables
$\boldsymbol{u}$	Array of all discrete decision variables
$\boldsymbol{p}$	Array of all power production variables
K	Set of hours in the scheduling time horizon
I	Set of thermal units in the power system
C_{ik}	Total fuel cost incurred by a thermal unit i in hour k
x_{ik}	State variable associated with a thermal unit i in hour k
u_{ik}	Discrete decision variable associated with a thermal unit i in hour k
p_{ik}	Power production variable associated with a thermal unit i in hour k
D_k	Demand of electrical energy in each hour k
B_n	Set of thermal units on the nth cumulative constraint
H_{ni}	Function which describes a contribution of thermal unit i to nth cumulative constraint
H_n^{req}	Upper bound on nth cumulative constraint
N	Set of cumulative constraints
U_{ik}	Set of feasible discrete decision variables for thermal unit i in hour k
P_{ik}	Set of admissible power production variables for unit i at stage k
X_i^0	Set of initial states for unit i
X_i^f	Set of final states for unit i
E_{ik}	Total emission caused by a thermal unit i in hour k
w	Weighting factor
λ	Scaling factor
M	Set of non-dominated solutions
ε	Allowable levels

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Table I. Cost and emission coefficients.

	Cost ($)			p^{min}	p^{max}	Emission (Gg)		
unit	α	β	γ	(MW)	(MW)	a	b	c
1	1675	18.78	0.013	60	300	25.8	-0.52	0.007
2	1207	18.96	0.018	60	300	26.9	-0.54	0.007
3	2277	19.71	0.010	50	500	30.1	-0.49	0.004
4	2292	20.84	0.010	50	500	25.3	-0.56	0.004
5	2239	21.02	0.009	50	460	30.1	-0.39	0.004
6	2516	19.78	0.012	50	500	25.3	-0.53	0.004
7	1895	20.86	0.019	20	215	23.9	-0.40	0.008
8	1860	22.00	0.015	20	210	23.9	-0.40	0.008
9	1410	20.39	0.049	20	250	31.6	-0.63	0.004
10	1270	17.92	0.077	20	250	34.3	-0.68	0.004
11	1469	19.71	0.077	20	210	22.9	-0.64	0.005
			total	420	3695			

Table II. Computational results for the proposed approach.

	Scaling factor	Total fuel cost ($)	Total generation (GW)	Total emission (Gg)
Best cost commitment	-	12,994,446	425.508	601.229
Best emission commitment	-	14,611,950	425.508	348.237
Best compromise commitment	7	13,510,222	425.508	437.812
	14	13,555,299	425.508	429.086
	21	13,568,139	425.508	426.994
	28	13,589,192	425.508	423.791

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