UNIT COMMITMENT WITH ENVIRONMENTAL CONSIDERATIONS: A PRACTICAL APPROACH

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Abstract – This paper provides a practical approach to the unit commitment problem designed to simultaneously address the economic issue of the fuel costs incurred on the commitment of the units and the environmental considerations due to emission allowance trading. A simultaneously address of fuel costs with the emission implies the consideration of a multiobjective unit commitment emission problem. A trade-off between fuel cost and the emission in a way to aid decision-makers concerning emission allowance trading is obtained, due to this practical approach.

Keywords: Unit commitment, Environmental considerations, Multiobjective optimisation

1 INTRODUCTION

Energy conversion from fossil fuel into electric energy provides the backbone of the electricity generation system worldwide, but this conversion is for the most part obtained in power plants operating with low efficiency cycles. Coal is by far the most abundant and cheapest fossil fuel with sufficient resources to sustain our long run needs for energy during centuries, but combustion of coal in old coal-fired power plants discharge significant quantities of ash, nitrogen, sulphur oxides, mercury and greenhouse gases such as carbon dioxide into the atmosphere. This discharge is one of the causes for the enhanced greenhouse effect, which is believed to be responsible for climate change on our environment. As a consequence of growing environmental concern governments are acting in the way to regulate greenhouse gas emission.

In the Europe, the Sixth Community Environment Action Programme established by Decision No 1600/2002/EC of the European Parliament and of the Council identifies climate change as a priority for action and provides for the establishment of a community-wide emissions trading scheme by 2005. This programme recognizes that the Community is committed to achieving an 8% reduction in emissions of greenhouse gases by 2008 to 2012 compared to 1990 levels, due to the Protocol of Kyoto, approved by Council Decision 2002/358/EC of 25 April 2002, already into force. Finally, Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 establishes the scheme for greenhouse gas emission allowance trading within the Community. To meet Kyoto requirements, the European Union have an internal market for carbon dioxide allowances, the European Union Emissions Trading Scheme (ETS). Emission allowances are allocated to participating power system installations accordingly with Kyoto requirements. Member States shall ensure that no power system installation undertakes an energy activity with a rated thermal input exceeding 20 MW resulting in pollutant emission unless its operator holds a permit issued by a competent authority or the installation is temporarily excluded from the Community scheme.

An unprecedented change is bound to occur in the new carbon constrained world and with the new environmental regulations going worldwide the role of the old coal-fired plant is likely to change. In the past, the old coal-fired power plants, typically with lower fuel costs, achieved lower marginal costs and therefore a superior merit order. In the presence of emission allowance cost, old coal-fired power plants may move down the merit order and run less relative to the past carbon unconstrained case, due to the lower efficiency and higher carbon emission intensity. 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. Also, the utility manager has to consider that the emission rights can be freely traded, living the option to sell the allowances if electricity production is not in favour.

The environmental protection of our habitat in what regards limiting the pollutant emission due to thermal power plants burning fossil fuels to convert into electric energy gives rise to new constraints regarding pollutant emission on thermal plants. Some research work has already been done, but mainly concerning the economic dispatch problem, deciding only the level of electric power [1-4], but not deciding on which generating units should be committed and available for generation at each hour.

Traditional unit commitment minimising fuel cost is inadequate when pollutant emissions are also to be included in the operation of power plants [5,6]. Since minimising the fuel cost and emissions are conflicting objectives, a practical approach based on multiobjective optimisation is proposed in this paper to obtain compromise solutions, also known by non-inferior or Pareto-optimal solutions, graphically illustrated by the trade-off curves between criterions fuel cost and pollutant emission. The decision-maker may choose a point on the trade-off curve, according to his or her judgement to express preferences.

We present a practical approach for the unit commitment with environmental considerations, modelled as a dynamic, mixed-integer non-linear mathematical programming problem. The approach merges technical and economic knowledge with environmental considerations and is illustrated by a realistic case study with 11 thermal units and a scheduling time horizon of 168 hours.

2 PROBLEM FORMULATION

The traditional unit commitment problem is defined as the task of establishing the minimum cost for the hourly generation schedule of the thermal units during a time horizon of one day up to one week [7,8]. The schedule for a thermal unit in a particular hour is given by the commitment status, a discrete variable, and the electric power contribution, a continuous variable. Some of the data involved in this problem are stochastic in nature, but for the short-term time horizon considered the forecasted values are assumed. Therefore, the problem is viewed as a deterministic one.

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 mathematical programming problem [9]. The problem is as follows:

$$Min \;\; f(\boldsymbol{x},\boldsymbol{u},\boldsymbol{p})$$

subject to:

$$(\boldsymbol{x},\boldsymbol{u},\boldsymbol{p}) \in F \tag{1}$$

and is stated as the minimisation of the objective function:

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

subject to global and local constraints where K is the total number of hours in the scheduling time horizon, I is the total number of thermal units in the power system, C_{ik} is the total cost incurred by a thermal unit i in hour k, and x_{ik}, p_{ik}, u_{ik} are respectively the state, power production and the discrete decision variable associated with a thermal unit i in hour k.

Global constraints may further be divided into: hourly generation requirements, the power produced by the thermal units is equal to the demand D_k in each hour:

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

hourly area requirement constraints, minimum power production requirements:

$$\sum_{i\in A_{jk}} F_{ji}(x_{ik},p_{ik}) \ge F_{jk}^{req} \qquad j\in J, k\in K \tag{4}$$

and cumulative constraints, maximum emissions by a group of units over the scheduling time horizon:

$$\sum_{k\in K}\sum_{i\in B_n} H_{ni}(x_{ik},u_{ik},p_{ik}) \ge H_n^{req} \qquad n\in N \tag{5}$$

where A_{jk} is the set of all thermal units in area j in hour k, F_{ji} is the function which describes a contribution of thermal unit i for area j requirement, F_{jk}^{req} is the lower bound for area j requirement in hour k, J is the total number of areas hourly requirements, 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 nth cumulative constraint, H_n^{req} is the lower bound on nth cumulative constraint and N is the number of cumulative constraints.

The local constraints are the state equations for the thermal units:

$$(x_{i,k+1},p_{ik}) = G_{ik}(x_{ik},u_{ik}) \qquad u_{ik}\in U_{ik}, i\in I, k\in K \tag{6}$$

yielding the state and power generation for any decision belonging to the set of feasible discrete variables U_{ik} for thermal unit i in hour k; the power produced:

$$p_{ik}\in P_{ik}(u_{ik}) \qquad i\in I, k\in K \tag{7}$$

if the unit is on, between the minimum value and the maximum value of the power of the unit at each hour k, otherwise it is null; and the initial state x_{io} and final state x_{ik}, belonging respectively to the initial state set X_i^0 and the final state set X_i^f:

$$x_{i0}\in X_i^0 \qquad x_{if}\in X_i^f \qquad i\in I \tag{8}$$

The set of decision variables satisfying all requirements define the set of feasible values:

$$F = \left\{(\boldsymbol{x},\boldsymbol{u},\boldsymbol{p})\text{: constraints (3),(4)}\ldots\text{(8) are satisfied}\right\}$$

The total cost incurred by a thermal unit i is given by the sum of the start up cost with the fuel cost:

$$C_{ik}(x_{ik},u_{ik},p_{ik}) = C_{ik}^{sc}(x_{ik},u_{ik}) + C_{ik}^{fc}(u_{ik},p_{ik}) \tag{9}$$

We considered the start up cost given as a constant and for the fuel cost we consider a second order Taylor expansion:

$$C_{ik}^{fc}(u_{ik},p_{ik}) = u_{ik}\;(\alpha_i + \beta_i\; p_{ik} + \gamma_i\; p_{ik}^2) \tag{10}$$

where α_i, β_i and γ_i are cost coefficients of thermal unit i. Alternatively, minimising emission may be considered as other objective in opposition to the usual minimum cost objective. In this case, using second order Taylor expansion, we consider the pollutant emissions caused by fossil-fuelled thermal units expressed as:

$$E_{ik}(u_{ik},p_{ik}) = u_{ik}(a_i + b_i\; p_{ik} + c_i\; p_{ik}^2) \tag{11}$$

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

3 PRACTICAL APPROACH

Two conflicting objectives are considered in our approach, cost and emission objective functions, thus it is impossible to obtain the minimum at the same point for all the objectives. A gain in one objective implies a sacrifice in the other objective. Therefore the approach aims to get compromise solutions, also known by non-inferior or Pareto-optimal solutions, between these two objectives simultaneously.

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

$$f(\boldsymbol{x}, \boldsymbol{u}, \boldsymbol{p}) = w \sum_{k \in K} \sum_{i \in I} C_{ik} + (1-w)\lambda \sum_{k \in K} \sum_{i \in I} E_{ik} \qquad (12)$$

where λ is a scaling factor given for instance by the carbon market or a different value to access the sensibility of the scaling factor; w is a weighting factor varying between 0 and 1 to generate the non-dominated solutions.

The weighted sum method obtains a set of Pareto-optimal solutions by varying the weighting factor. Our practical approach presented to solve the problem 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:

$$\sum_{k \in K} \sum_{i \in I} C_{ik}^{fc} \le \varepsilon_C^{req} \qquad (13)$$

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

in order to overcome the difficulty of finding a non-convex Pareto-optimal front.

4 CASE STUDY

We consider a case study for a unit commitment with 11 thermal units and an hourly schedule with a time horizon of 168 hours. Table 1 shows the units coefficients for cost and for emission functions.

	Cost			p^{min}	p^{max}	*Emission*		
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 1: Cost and emission coefficients.

Thermal units are available for production during the all period of optimisation. Note that thermal units 1 to 6 have inferior costs but higher emissions, in comparison with thermal units 7 to 11.

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

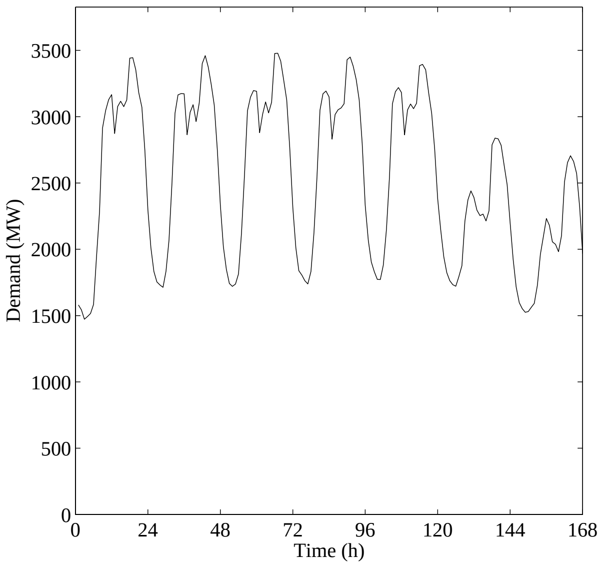

Figure 1: Hourly demand.

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

We followed the following computation strategy: at first, fuel and emission are independently optimised to determine the extreme points of the trade-off curve, the best cost commitment (BCC) and the best emission commitment (BEC); after that, fuel and emission are merged in the optimisation.

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

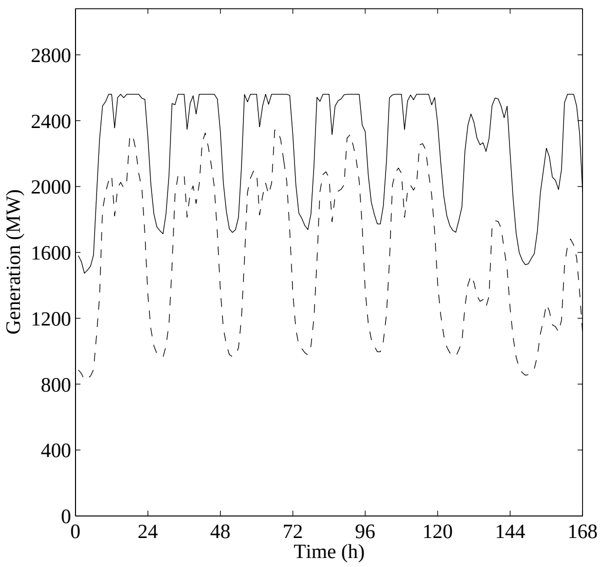

Figure 2: Hourly total generation for thermal units 1 to 6. The solid line represents BCC results while the dashed line represents BEC results.

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

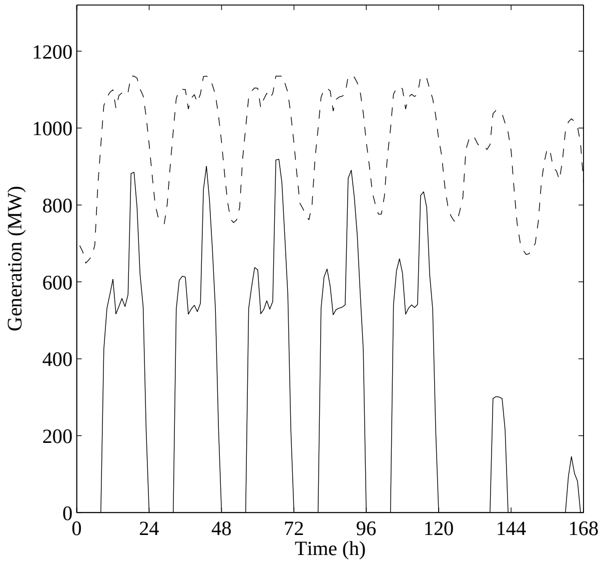

Figure 3: Hourly total generation for thermal units 7 to 11. The solid line represents BCC results while the dashed line represents BEC results.

In the BCC results, units with inferior operational cost are committed and typically at full power regardless of pollutant emissions thus it was expected that the lesser pollutant units were not needed to satisfy the demand, because they have higher costs. The commitment status of thermal units for BCC in Figure 4 follows the demand profile. The BEC results show that all units are committed as shown in Figure 4: the power of units 1 to 6 is reduced to avoid excessive emission, implying a higher total cost as shown in Table 2.

	Total Cost ($)	*Total Generation (GW)*	*Total Emission (Gg)*
BCC	12994446	425.508	601.229
BEC	14611950	425.508	348.237

Table 2: Results for BCC and BEC.

Figures 5 and 6 show the trade-off curves with 100 non-dominated solutions, respectively, considering a scaling factor of one and considering a scaling factor of seven.

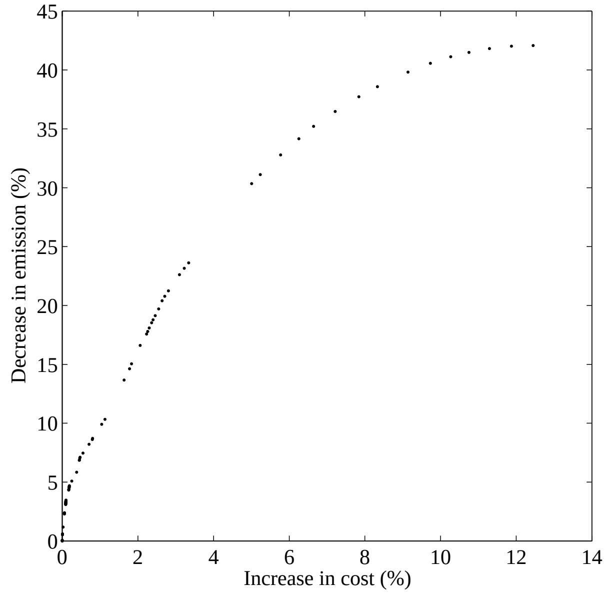

Figure 5: Trade-off curve giving the decrease in emission against increase in cost with a scaling factor of one.

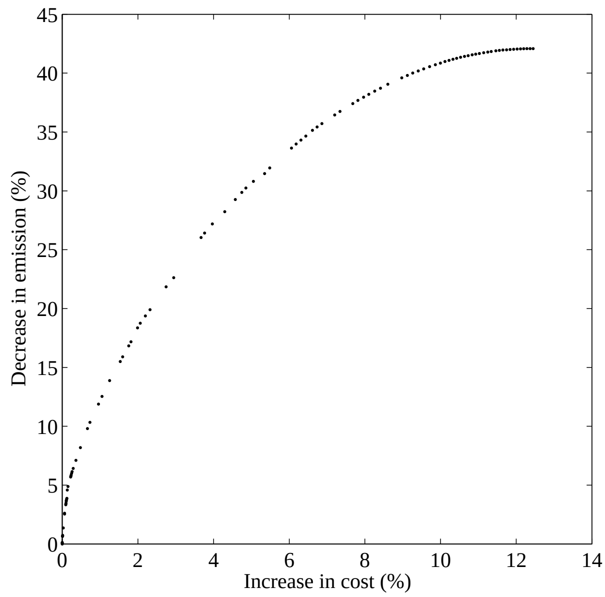

Figure 6: Trade-off curve giving the decrease in emission against increase in cost with a scaling factor of seven.

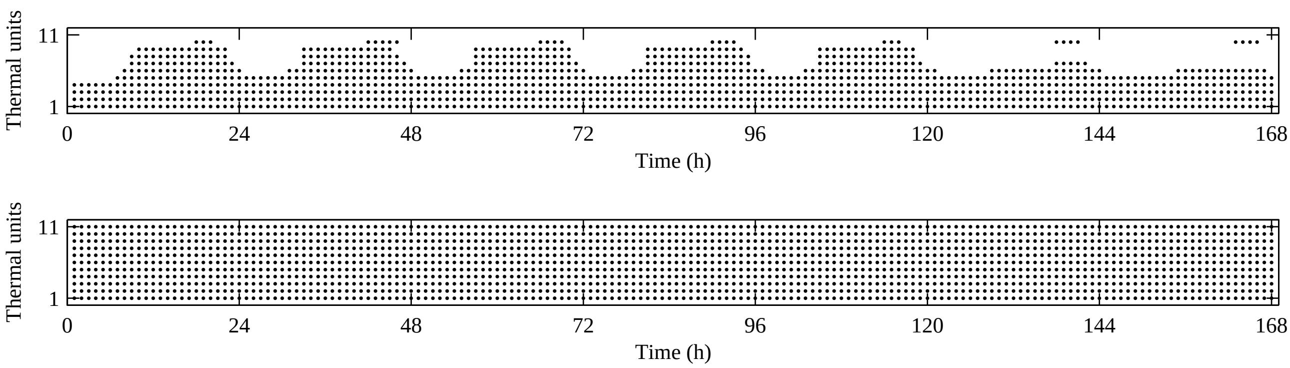

Figure 4: Matrix structure representing commitment status of thermal units for BCC and BEC results: a filled spot means that the unit is committed, while a blank spot means that the unit is not committed.

Figures 5 and 6 show that both trade-off curves have a sharp slope at BCC neighbourhood. Also, we conclude that a decrease in emission of about 42.1% is obtained by a cost increase of about 12.4%. The selection of a scaling factor influences the overall solution diversity and distribution over the trade-off curve. Comparing Figures 5 and 6, it can be concluded that the non-dominated solutions with a scaling factor of seven are better-distributed having enhanced diversity characteristics. However, the non-smooth characteristic shape of the trade-off curve, due to the non-linearity and non-convexity of the problem, cannot be seen in this case.

The total CPU-time for the computation of a trade-off curve was about 270s, with an average 2.7s for each solution corresponding to a 168-hours schedule. This demonstrates that the practical approach presented is fast and efficient in handling this problem. The decision-maker with the help of those trade-off curves may support a sound decision to choose an appropriated commitment for the units, between the BCC and BEC solutions, considering the emission allowance trading.

5 CONCLUSION

This paper provides a practical approach for the unit commitment problem with environmental considerations. A compromise between the fuel costs incurred on the commitment of the units with the level of emission implies the consideration of a multiobjective problem for supporting the decision maker. The decision maker can choose an appropriated commitment for the units with the help of the trade-off curves and taking into consideration the emission allowance trading. In the best emission commitment, thermal units with higher levels of emission are committed at a lower level of output, in comparison with the best cost commitment. Hence, more units have to be committed to satisfy the same demand, incurring in higher fuel costs and operating thermal units at lower efficiency points, implying an increase on the total cost for the best emission commitment. The results show that the proposed approach is efficient for obtaining the schedule and the trade-off curves with a small CPU-time requirement

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