Multiobjective Optimization Approach for Profit-based Unit Commitment with Emission Limitations

J. P. S. Catalão*, S. J. P. S. Mariano*, V. M. F. Mendes** & L. A. F. M. Ferreira***

Abstract: This paper is on the problem of profit-based unit commitment with emission limitations. We propose a multiobjective optimization approach to handle the problem with conflicting profit and emission objectives. A trade-off curve between profit and emission in a way to aid decision-makers concerning emission allowance trading is obtained due to this multiobjective optimization approach. Numerical results based on the standard IEEE 30-bus test system illustrate the proficiency of the proposed approach.

Keywords: Emission limitations, multiobjective optimization approach, power generation dispatch

1. INTRODUCTION

One of the main contributions to the emission of greenhouse gases into the atmosphere, which is thought to be responsible for climate change on our environment, is through the use of fossil-fuelled power plants [1].

As a consequence of growing environmental concern, governments are acting in the way to regulate greenhouse gas emission. A major step in this direction is the Kyoto Protocol, which establishes a 5% drop in carbon dioxide emissions by 2008 to 2012 compared to emissions in 1990 for the industrialized countries.


The environmental issues imposed by the Kyoto Protocol imply new emission limitations regarding production decision in thermal units burning fossil fuels [2].

The majority of the studies concerning emission limitations are on the economic dispatch problem [3]-[12], deciding only the power contribution of each thermal unit, but not deciding on which units should be committed for generation at each hour.

The unit commitment (UC) problem comprises both deciding the commitment status, a discrete value, and the power contribution, a continuous value. The economic consequences of UC are recognized as very important; savings of a small percent value represent a significant reduction in the operation cost, as well as in the fuel consumption [13].

In the UC problem a time horizon of one to seven days is considered, usually discretized into hourly periods. Some of the data involved in the UC problem are stochastic in nature, but for the short-term time horizon considered the forecasted values are used. Therefore, the UC problem is viewed as a deterministic one [14].

The account of emission limitations in the UC problem, as in [15]-[18], did not receive as much attention as in the economic dispatch problem. However, the recent advent of emission allowance trading in the European Union has renewed interest in the environmentally constrained UC problem [2], [19]. Emission allowances are yearly allocated. Hence, the environmentally constrained UC problem requires a medium-term scheduling [20]. An estimation of the daily or weekly allowances of each unit is obtained by means of annual allowances.

In a competitive environment, a generating company (GENCO) has the objective to produce and sell energy with maximum profit. This leads to the following profit-based unit commitment (PBUC) problem [21]-[25]: given a forecast of energy prices, establish a generation schedule that maximizes expected profit throughout the time horizon considered, taking into account all constraints.
In the past, utilities had an obligation to serve their customers. This was translated into a demand constraint that ensured all demand would be met. However, in a competitive environment the obligation to serve is removed. The GENCO can now consider a generation schedule that produces demand less than the forecasted level if it creates more profit [26].

In the new emission-constrained competitive environment, a GENCO with thermoelectric facilities faces the optimal trade-off problem of how to make the present profit by the management of the energy available in fossil fuels for power generation without excessive emission.

Since maximizing profit and minimizing emission are conflicting objectives, a multiobjective optimization (MO) approach is proposed in this paper to obtain compromise solutions, also known as non-dominated or Pareto-optimal solutions, graphically illustrated by the trade-off curve between profit and emission. We report our experience with the proposed MO approach on the standard IEEE 30-bus test system, considering a time horizon of one week.

This paper is organized as follows: In Section 3, the mathematical formulation of the PBUC problem is provided. Section 4 presents the proposed MO approach to solve the PBUC problem with emission limitations. In Section 5, the proposed MO approach is applied on the IEEE 30-bus test system to demonstrate its effectiveness. Finally, concluding remarks are given in Section 6.

2. PROBLEM FORMULATION

The traditional UC problem can be stated as to find out the minimum total fuel cost for the generation schedule of each thermal unit $i$ at all scheduling time periods $k$, satisfying the demand of electrical energy and the considered constraints.

Redefining the UC problem for the competitive environment involves changing the demand constraint from an equality, to less than or equal, and changing the objective function from cost minimization, to profit maximization.

2.1. Objective Function

The PBUC problem can be formulated as

Min $f(x, u, p)$

subject to

$(x, u, p) \in F$

where the objective function to be minimized can be expressed as:

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

In (3), the first term is related to the total fuel cost incurred on the commitment of the units and the last term expresses the revenues of each unit in the thermal system during the time horizon considered.

The total fuel cost incurred by thermal unit $i$ in hour $k$ 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 expressed as:

$C_{ik}^F(u_{ik}, p_{ik}) = a_i + b_i p_{ik} + c_i p_{ik}^2 \quad \forall i \in I, \forall k \in K$

where $a_i, b_i$ and $c_i$ are the fuel cost coefficients for thermal unit $i$.

2.2. Thermal Constraints

The optimal value of the objective function is determined subject to constraints of two kinds: global constraints and local constraints.

2.2.1 Global Constraints

\[ \sum_{i=1}^{I} p_{ik} \leq D_k \quad (5) \]

\[ \sum_{i=1}^{I} \sum_{k=1}^{K} H_i(x_{i,k-1}, u_{ik}, p_{ik}) \leq H_{n}^{\text{req}} \quad (6) \]

In (5), the power generated by the thermal units is less than or equal to the demand of electrical energy in each hour $k$. In (6), the maximum emission of a group of units over the time horizon cannot exceed a pre-specified value.

2.2.2 Local Constraints

\[ (x_{ik}, p_{ik}) = A_{ik}(x_{i,k-1}, u_{ik}) \quad (7) \]

\[ u_{ik} \leq p_{ik} \leq u_{ik} \tilde{P}_i \quad (8) \]

\[ u_{ik} \in \{0, 1\} \quad (9) \]

\[ x_{i0} \in X_i^0 \quad (10) \]

\[ x_{if} \in X_i^f \quad (11) \]

Equation (7) provides the state and power generation of thermal unit $i$ in hour $k$ for the state in hour $k-1$ and for the commitment decision in hour $k$. In (8), the power generation of thermal unit $i$ in hour $k$ is between the minimum and maximum values, if $u_{ik} = 1$; otherwise, if $u_{ik} = 0$, the power generation is null. In (10) and (11), the initial and final states belong respectively to the initial and final state sets.

Constraints (5) to (11) define the set of feasible variables

$F = \{(x, u, p); \text{ constraints (5) to (11) are satisfied}\}$

4. SOLUTION METHODOLOGY

The objective function to be minimized may be the total emission. We consider the emission for thermal unit $i$ in hour $k$ expressed as:
\[ E_d^{em}(u_d, p_d) = u_d \left[ 10^{-2} (\alpha + \beta_i p_n + \gamma_i + \delta p_d^2 + \zeta_i \exp(\lambda_i p_d)) \right] \]
\[ \forall i \in I, \forall k \in K \]

where \( \alpha, \beta, \gamma, \delta, \) and \( \lambda \) are the emission coefficients for thermal unit \( i \).

The objective function to be minimized, the total emission, is expressed as:

\[ g(x, u, p) = \sum_{k=1}^{I} \sum_{k=1}^{K} E_d^{em}(x_k, u_k, p_k) \]

In this solution methodology, the simultaneous address of the profit with the emission is taken into account by the following problem

\[ \text{Min} \{ f(x, u, p), g(x, u, p) \} \]

subject to

\[ (x, u, p) \in F \]

Our MO approach aims to get the non-dominated or Pareto-optimal solution set \( M \), considering the two objective functions simultaneously. The two objective functions must be traded off in some way. We treated them by a convex combination, using the weighted sum method given by

\[ h(x, u, p) = \omega f(x, u, p) + (1 - \omega) \xi g(x, u, p) \]

where \( \omega \) is the weighting factor, which varies between 0 and 1 to generate the non-dominated solutions, and \( \xi \) is the scaling factor.

4. CASE STUDY

The proposed MO approach for the PBUC problem with emission limitations has been applied on the standard IEEE 30-bus test system. The MO approach was developed and implemented on a 2.8-GHz-based processor with 512 MB of RAM using FORTRAN language.

4.1. Input Data

The single-line diagram of the IEEE 30-bus test system is illustrated in Figure 1.

The fuel cost and emission coefficients, along with the unit characteristics, are given in Table 1.

The time horizon chosen is one week divided into 168 hourly periods. The energy prices are illustrated in Figure 2, where \( \$ \) is a symbolic quantity.

The energy prices are considered as deterministic input data in this paper. These energy prices are forecasted using techniques mainly based on time series and ARIMA models [27, 28], or on neural networks [29, 30].

4.2. Result Analysis

We carried out the following computation strategy: at first, profit and emission are independently optimized to determine the extreme points of the trade-off curve: best profit commitment (BPC), \( \omega = 1.0 \), and best emission commitment (BEC), \( \omega = 0.0 \). Afterward, profit and emission are merged in only one function, according to the weighted sum method.

Figure 3 shows the hourly total generation for the thermal units, considering BPC, BEC and two compromise commitments (CC’s) determined by \( \omega = 0.5 \) and \( \omega = 0.4 \).
In the BPC results, the units are committed in order to achieve maximum profit, regardless of emission. The generation profile follows the shape of the energy price profile. In the CC’s results, the maximum power generation is reduced in order to attain an adequate emission level. In the BEC results, all units are uncommitted in order to achieve minimum emission. Hence, a non-null profit or emission should be considered as a minimum value to avoid total shutdown.

Figure 4 shows the hourly units committed, considering BPC, BEC and CC’s determined by $\omega = 0.5$ and $\bar{\omega} = 0.4$.

The trade-off curve has a sharp slope at the BPC neighborhood. At the beginning of the curve, a significant percentage decrease in the total emission, about 29.7%, is obtained with a small percentage decrease in the total profit, about 8.3%. It should be noted that at the end of the curve the opposite occurs, since for the same decrease of 8.3% in the total profit, only a 2.6% decrease in the total emission is obtained.
The main numerical results for the thermal system are summarized in Table 2.

| BPC α = 1.0 | 36203 | 50564 | 2451 |
| BPC α = 0.5 | 26322 | 28116 | 1093 |
| BPC α = 0.4 | 13965 | 12004 | 461 |
| BPC α = 0.0 | 0 | 0 | 0 |

The total CPU-time required for the computation of the trade-off curve was about 10.98 s. This demonstrates that the proposed MO approach is computationally acceptable in handling this problem.

5. CONCLUSIONS
A MO approach is proposed for the PBUC problem with emission limitations. The proposed MO approach merges technical and economic knowledge with environmental issues imposed by the Kyoto Protocol. A trade-off curve between profit and emission in a way to aid decision-makers concerning emission allowance trading is obtained due to this MO approach. Numerical testing results based on the standard IEEE 30-bus test system show that the proposed MO approach is efficient for obtaining the generation schedule and the trade-off curve with an acceptable CPU-time requirement.

REFERENCES


