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Influence of Environmental Constraints on Profit-Based Short-Term Thermal Scheduling

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***Abstract*—This paper is on the short-term thermal scheduling (STTS) problem, particularly concerning the new competitive and environmentally constrained electricity supply industry. On the one hand, within the electricity market, STTS has evolved from a minimum-cost policy in state-owned monopolistic companies to a profit-based policy under market conditions. On the other hand, as a consequence of growing environmental concern, an unprecedented change points to a scenario where it is necessary to take into account the constraints related to the environment. We propose a multiobjective optimization (MO) approach to solve the profit-based STTS problem with environmental concerns. Two case studies are considered: the IEEE 30-bus system and a 75-bus system. Finally, conclusions are duly drawn.**

***Index Terms*—Emission, multiobjective optimization, power generation dispatch, profit.**

NOTATION

The notation used throughout the paper is stated as follows:

K, k Set and index of hours in the scheduling time horizon.
I, i Set and index of thermal units in the power system.
π_k Forecasted energy price in hour *k*.
C_{ik} Total fuel cost incurred by thermal unit *i* in hour *k*.
x_{ik} State of thermal unit *i* in hour *k*.
u_{ik} Commitment decision of thermal unit *i* in hour *k*.
p_{ik} Power generation of thermal unit *i* in hour *k*.
D_k Demand of electrical energy in hour *k*.
B_n Set of thermal units on the *n*th cumulative constraint.
H_{ni} Function which describes a contribution of thermal unit *i* to *n*th cumulative constraint.
H_n^{req} Upper bound on *n*th cumulative constraint.
N Set of cumulative constraints.
$p_i^{\min}$ Minimum power generation of thermal unit *i*.
$p_i^{\max}$ Maximum power generation of thermal unit *i*.
X_i^0 Set of initial states for thermal unit *i*.
X_i^{f} Set of final states for thermal unit *i*.
E_{ik} Total emission for thermal unit *i* in hour *k*.
$\boldsymbol{x}$ Vector of all state variables.
$\boldsymbol{u}$ Vector of all commitment decision variables.
$\boldsymbol{p}$ Vector of all power generation variables.
w Weighting factor.
ξ Scaling factor.
$\varepsilon_C^{\text{req}}$ Limit deficit allowed on profit.
$\varepsilon_E^{\text{req}}$ Limit emission allowed.

Manuscript received March 24, 2010; revised July 30, 2010, and November 6, 2010.

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I. INTRODUCTION

ENERGY conversion from fossil fuels into electric energy still provides the backbone of the electricity supply industry worldwide [1]-[2]. In 2005, 40% of primary energy supply in the EU-27 was used to produce power, of which 55% is generated by fossil fuel sources [3]. Also, coal has been playing a dominant role in the energy mix in China, which is around 75% of the total installed capacity in 2008 [4]. Fossil fuels provide a reliable and affordable source of energy. However, 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 [5].

All over the world, the electricity supply industry is converging toward a competitive framework and a market environment is replacing the traditional monopolistic scenery for the electricity supply industry. In 1982, Chile was a pioneer country to introduce new market-oriented approaches in the electric power sector, later spreading to Europe, Australia, and various US states [6].

Electric power sector deregulation brought to the electric power business competition through biding to win the best profit in the electricity market. The management decision is in a way to reduce costs and increase income, toning to the best economic perspective. Hence, the economic efficiency is of the utmost importance for generating companies, but new constraints are simultaneously required to ensure admissible emission levels into the environment.

The threat of large-scale climate change and global warming has led to the Kyoto Protocol [7]. Industrialized countries will have to reduce their collective emissions of greenhouse gases by 5% over the 2008–2012 period compared to the year 1990. According to EU agreements, Spain and Portugal are allowed to increase their carbon emissions up to 15% and 27%, respectively, in the 2008–2012 period. Yet, emissions increased more than 50% in both countries in 2005 [8].

Currently, one of the major Kyoto Protocol consequences is the establishment of a carbon emissions trading scheme. Although the global market has barely started, the European Commission has introduced a Directive for an internal Emissions Trading Scheme (ETS) which started in 2005 and is already producing some trade [9].

Environmental policy issues have become more and more important for fossil-fuelled power plants and they have to be considered in their management, giving rise to emission limitations. Fossil-fuelled power plants posing different emission levels should not be considered in the same way in what regards the generation decision.

The research work available in the literature concerning emission limitations is mainly for the economic dispatch problem [10]-[14], deciding only the power contribution of each unit but not its commitment status and availability for generation at each hour.

The short-term thermal scheduling (STTS) problem determines which thermal units should be committed and available for generation at each hour, and the associated nominal generation or dispatch, during a time horizon of one day to one week. The economic consequences of STTS are recognized as very important; savings of a small percent value represent a significant reduction in the fuel consumption [15].

The way that scheduling has been approached and solved is now reformulated from being cost-minimization to profit-maximization [16]-[17]. In the competitive environment, the obligation to serve is removed. The generating company can now consider a schedule that produce demand less than the forecasted level if it creates more profit.

The account of emission limitations in the STTS problem [18]-[20] did not receive lately as much attention as in the economic dispatch problem. Moreover, the environmental concerns have been included mostly in the minimum-cost optimization problem [2], [21], but not much in the profit-based optimization problem.

Hence, this paper is focused on the new environmentally constrained profit-based STTS problem, considering two case studies: the IEEE 30-bus system, with six thermal units, and a 75-bus system, with fifteen thermal units. Trade-off curves between profit and emission are obtained in a way to aid decision-makers concerning emission allowance trading.

This paper is organized as follows. In Section 2, the mathematical formulation of the STTS problem is provided. Section 3 presents the proposed multiobjective optimization (MO) approach to solve the STTS problem with environmental concerns. Section 4 presents the two case studies. Finally, concluding remarks are given in Section 5.

II. Problem Formulation

In a regulated environment, the STTS problem is defined as the task of establishing the minimum total 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 all physical and operational constraints.

The STTS problem is usually treated as a deterministic one due to the small short-term time horizon. Where stochastic quantities are included, the corresponding forecasts are used.

An electricity market working under locational marginal pricing (LMP) implies that generating units are paid the locational marginal prices corresponding to the nodes they are connected to. The LMP or nodal pricing is used in some electricity markets, such as, PJM and New England ISO in the US. However, other electricity markets do not employ nodal pricing, such as, Powernext and Nord Pool in Europe. In this paper, a single market-clearing price is considered, instead of a LMP associated with each node of the power system. Nevertheless, the application developed in this paper is not constrained by the type of pricing considered, since it can assume as input data any type of price behavior.

In a competitive environment, a generating company has the goal to produce electricity and sell it with maximum profit. The system-wide balance of supply and demand is assumed to be managed by an independent system operator, which maintains the system security and reliability. Hence, the generating company can consider a generation schedule that produce demand less than the forecasted level if it creates more profit.

There is a well known theoretical equivalence between a perfectly regulated integrated monopoly and a perfectly competitive electricity market. Formally this equivalence translates into an equivalence between Lagrange multipliers of the monopoly optimization program and prices in a model of a perfectly competitive electricity market. Redefining the STTS 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.

In the new competitive and environmentally constrained electricity supply industry, a generating company with thermoelectric facilities faces the optimal trade-off problem of how to achieve the maximum profit while minimizing the environmental impact by the management of the energy available in fossil fuels for power generation. For instance, old coal-fired power plants usually imply higher emission levels for the generating companies, in comparison with natural gas-fired power plants in combined cycle configuration, but the production costs are expected to be lower. Hence, profit-based STTS may be qualitatively affected by the environmental policy. For instance, the decision-maker may be willing to accept a small percentage decrease in the total profit in exchange for a large percentage decrease in total emission.

In the profit-based STTS problem, the objective function is a measure of the profit attained by the conversion of the energy available in fossil fuels into electric energy. Thus, the problem is stated as the maximization of the following objective function

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

subject to global and local constraints.

The commitment decision u_{ik} identifies if the unit is on-line or shutdown. The unit's state x_{ik} depends not only on the commitment decision, but also on the start-up and shutdown constraints. If the unit is already on there is no start up cost, but there is a cost if it shift from off to on. Once started or shutdown, a unit must remain committed or uncommitted for minimum durations: min up and min down times.

In addition to constraints on start-up and shutdown, a unit may have ramp-rate constraints: some generation levels cannot be reached from one period to the next [22].

Global constraints may be divided into:

i) hourly generation constraints, for instance, the power generated by the thermal units is less than or equal to the demand of electrical energy in each hour k

$$\sum_{i=1}^{I} p_{ik} \leq D_k \tag{2}$$

ii) cumulative constraints, for instance, it is possible to consider that the maximum emission of a group of units over the scheduling time horizon [18]-[19] cannot exceed a pre-specified value

$$\sum_{i=1}^{B_n}\sum_{k=1}^{K} H_{ni}\,(x_{i,k-1}, u_{ik}, p_{ik}) \leq H_n^{\text{req}} \tag{3}$$

The total emission is not necessarily considered as a constraint in our optimization problem, but it is necessarily considered as one of the objective functions in our approach.

The local constraints may be divided into:

i) state equations for the thermal units

$$(x_{ik},\, p_{ik}) = A_{ik}\,(x_{i,k-1},\, u_{ik}) \tag{4}$$

providing the state and power generation of thermal unit i in hour k in function of the state in hour $k-1$ and the commitment decision in hour k. The time dependence of the state function A_{ik} is needed to account for the user-specified time-varying state constraints [22].

ii) power generation admissible set

$$p_{ik} \in P_{ik}(u_{ik}) \tag{5}$$

for instance, if the unit is on, the power generation of thermal unit i in hour k is between the minimum power generation and the maximum power generation; otherwise, if the unit is off, the power generation is null.

iii) initial state and final state

$$x_{i0} \in X_i^0 \quad x_{i\text{f}} \in X_i^{\text{f}} \tag{6}$$

belonging respectively to the initial state and final state sets.

Constraints (2) to (6) define the set of feasible variables

$$F = \left\{ (\boldsymbol{x}, \boldsymbol{u}, \boldsymbol{p}):\ \text{constraints (2) to (6) are satisfied} \right\}$$

The profit-based STTS problem may be reformulated into a minimization problem. Thus, the objective function to be minimized can be expressed as

$$g(\boldsymbol{x}, \boldsymbol{u}, \boldsymbol{p}) = \sum_{i=1}^{I}\sum_{k=1}^{K} C_{ik}\,(x_{i,k-1}, u_{ik}, p_{ik}) - \pi_k\, p_{ik} \tag{7}$$

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 mathematically modeled as a convex function. The operation cost is assumed to be computed by a quadratic function of power generation as [12]

$$C_{ik}^{\text{op}}\,(u_{ik}, p_{ik}) = u_{ik}\,(a_i + b_i\, p_{ik} + c_i\, p_{ik}^2) \tag{8}$$

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

In the emission-based STTS problem, the objective function to be minimized is the total emission, expressed as

$$h(\boldsymbol{x}, \boldsymbol{u}, \boldsymbol{p}) = \sum_{i=1}^{I}\sum_{k=1}^{K} E_{ik}\,(x_{i,k-1}, u_{ik}, p_{ik}) \tag{9}$$

The emission is assumed to be computed by the sum of a quadratic and an exponential function [12]

$$E_{ik}^{\text{em}}\,(u_{ik}, p_{ik}) = u_{ik}\,\left[\, 10^{-2}\,(\alpha_i + \beta_i\, p_{ik} + \gamma_i\, p_{ik}^2) + \zeta_i \exp(\lambda_i\, p_{ik}) \,\right] \tag{10}$$

where α_i, β_i, γ_i, ζ_i and λ_i are emission coefficients for thermal unit i. The emission coefficients in (10) are computed by the given data for the type of pollutant.

III. Proposed Approach

The multiobjective decision making models allow the evaluation of options against a wide range of objectives, grouped in a hierarchical structure. Since maximizing profits and minimizing emissions tend to be conflicting objective functions, a MO approach was sought.

The environmentally constrained profit-based STTS problem can be formulated as the following MO problem

$$Min\ \left\{ g(\boldsymbol{x}, \boldsymbol{u}, \boldsymbol{p}),\, h(\boldsymbol{x}, \boldsymbol{u}, \boldsymbol{p}) \right\} \tag{11}$$

subject to

$$(\boldsymbol{x}, \boldsymbol{u}, \boldsymbol{p}) \in F \tag{12}$$

In our generation schedule problem with two individualized objective functions, an efficient solution to the MO problem, also known as non-dominated or Pareto-optimal solution, corresponds to a compromise where attempts to improve the value of one objective function lead to a degradation in the value of the other objective function. The collection of efficient solutions is called the efficient set. The trade-off curve represents the image of the efficient 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 the practical advantage of using the multiobjective criteria instead of a single-objective regarding the profit maximization.

There is usually a tradeoff between using low cost and high emission plants versus high cost and low emission plants, which depends on the emission market prices. Given that the emission market prices change over the scheduling time horizon, the decision maker has to readjust his scheduling continuously. Thus, 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 efficient solutions and trade-off curve is the weighted sum method, especially when the MO problem has only two objectives. Adopting the weighted sum method [23], an efficient solution to the MO problem can be determined by a convex combination of the objective functions

$$o(\boldsymbol{x}, \boldsymbol{u}, \boldsymbol{p}) = w\, g(\boldsymbol{x}, \boldsymbol{u}, \boldsymbol{p}) + (1 - w)\, \xi\, h(\boldsymbol{x}, \boldsymbol{u}, \boldsymbol{p}) \tag{13}$$

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The trade-off curve can be found by parametrically varying the weighting factor w between 0 and 1, thus solving single-objective optimization problems. The weighting factor has an effect due to the conflicting objectives functions, i.e., if there is no conflict the effect is null, but as the conflict increases the effect also increases. Hence, as the environmentally constrained profit-based STTS tends to have conflicting objective functions, this effect also tends to be important. The best emission commitment (BEC) corresponds to $w = 0$, while the best profit commitment (BPC) corresponds to $w = 1$.

Our MO approach may merge the weighted sum method [23] with the $\varepsilon -$constraining method into a hybrid method, as presented in [24], adding new constraints majoring the objectives functions by allowable real numbers

$$\sum_{i=1}^{I}\sum_{k=1}^{K} C_{ik} - \pi_k \, p_{ik} \le \varepsilon_C^{\text{req}} \tag{14}$$

or

$$\sum_{i=1}^{I}\sum_{k=1}^{K} E_{ik} \le \varepsilon_E^{\text{req}} \tag{15}$$

in order to overcome the difficulty on finding the non-convex efficient set for the MO problem. A non-dominated solution m in the efficient set delivers the generation schedule during the time horizon and is characterized by a total profit and a total emission in the space of objectives.

The method followed to solve the profit-based STTS problem is a two main steps algorithm, a master problem step and subproblems step, normally well-known as the Lagrangian relaxation methodology. Lagrangian relaxation allows for coordination decomposition method on mixed-integer mathematical programming problem with coupling constraints. Particularly, for the profit-based STTS problem, global constraints, coupling thermal units, are eliminated from the problem feasible set through their addition into the objective function as linear penalized terms by Lagrangian multipliers. Therefore, decomposition on the problem is achieved, i.e., thermal units are somehow secluded but not isolated and the schedule of each unit can be achieved with local convenient optimization method, for instance: dynamic programming, nonlinear convex programming. The Lagrangian multipliers are signal strengths on the penalties terms into the secluded schedule of contributing units, accommodating the satisfaction of a global constraint. The method is implemented by an iterative coordination process until a nearly optimal solution is obtained derived by the mismatch on the global constraint.

In the profit-maximization STTS problem, the uncertainty is mainly due to the price forecast values for the scheduling time horizon. The environmentally constrained profit-based STTS problem can be viewed as an upgrading of the profit-maximization STTS problem. Hence, it inherits the same conclusion regarding sensitivity analysis (SA). Particularly, the SA shows a conditional robustness due to the interaction between objective function coefficients and price forecast values.

For instance, it is expected that for a marginal unit a decrease in the price may eventually change the scheduling by turning off this unit. But, if the units are diversified, normally only one or two units are marginal and may eventually change the scheduling due to another price forecast. As the aggregate objective function (13) is a continuous transformation between the two objective functions, parameterized by the weighting factor, a similar conclusion is expected.

IV. Case Studies

A. Case study based on the IEEE 30-bus system

The proposed MO approach has been applied on a case study based on the IEEE 30-bus system. The single-line diagram of this system is shown in Fig. 1. The fuel cost and emission coefficients are given in Table I.

The IEEE 30-bus system, containing six thermal units, is commonly used as the case study in several papers.

Our MO approach was developed and implemented on a 2.8-GHz-based processor with 512 MB of RAM using FORTRAN language. The scheduling time horizon chosen is one week divided into 168 hourly periods.

The two energy price profiles considered over the time horizon are shown in Fig. 2 (where $ is a symbolic economic quantity). Several methodologies have been tried out for energy prices forecasting, mainly based on time series models [25], or on artificial intelligence techniques [6], [26]-[27]. These energy prices are considered as deterministic input data for our problem. Profile 1, denoted by the solid line, is considered a high-price profile with a peak value of 434.8 $/MWh. Profile 2, denoted by the dash-dot line, is considered a low-price profile with a peak value of 278.3 $/MWh.

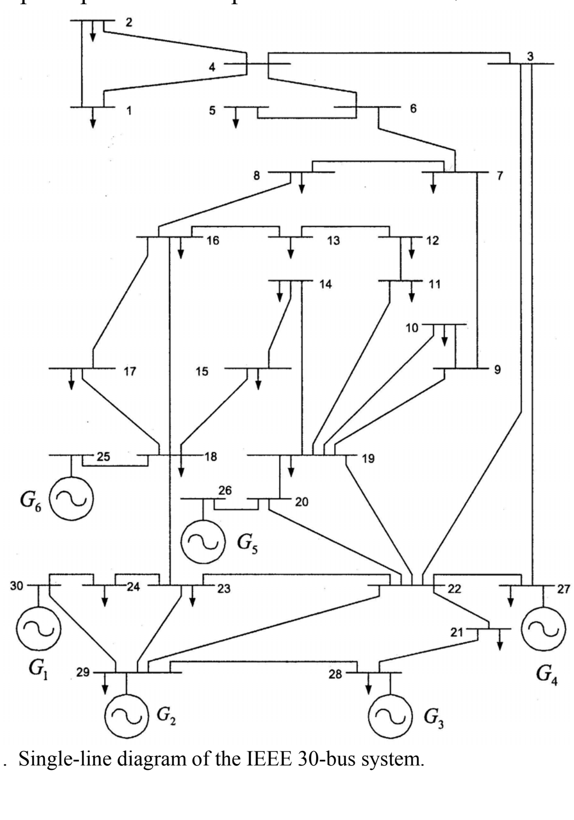

Fig. 1. Single-line diagram of the IEEE 30-bus system.

TABLE I
FUEL COST AND EMISSION COEFFICIENTS FOR THE IEEE 30-BUS SYSTEM

	1	2	3	4	5	6
a	10	10	20	10	20	10
b	200	150	180	100	180	150
c	100	120	40	60	40	100
α	4.091	2.543	4.258	5.426	4.258	6.131
β	-5.554	-6.047	-5.094	-3.550	-5.094	-5.555
γ	6.490	5.638	4.586	3.380	4.586	5.151
ζ	2.0E-4	5.0E-4	1.0E-6	2.0E-3	1.0E-6	1.0E-5
λ	2.857	3.333	8.000	2.000	8.000	6.667
p_i^{max} (MW)	50	60	100	120	100	60
p_i^{min} (MW)	5	5	5	5	5	5
Start-up ($)	20	20	40	20	40	20
Min up (h)	2	2	2	2	2	2
Min down (h)	2	2	2	2	2	2

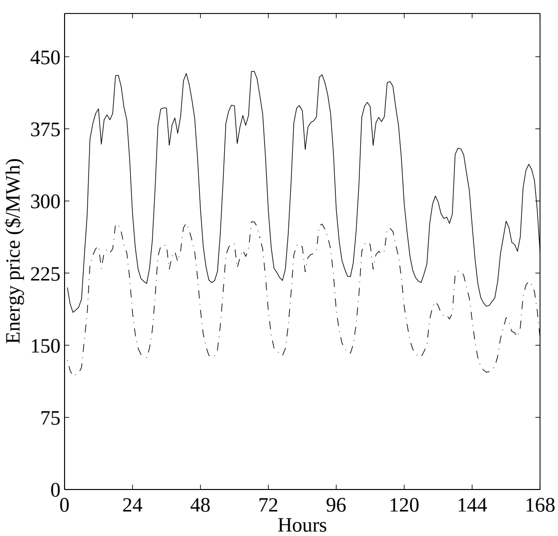

Fig. 2. Energy price profiles considered.

We carried out the following computation strategy: at first, profit and emission are independently optimized to determine the anchor points of the trade-off curves: BPC and BEC; then, profit and emission are merged according to the weighted sum method mentioned in our MO approach.

The computed hourly total generation for profile 1 and 2 are shown in Figs. 3 and 4, respectively. Moreover, the computed hourly units committed for profile 1 and 2 are shown in Figs. 5 and 6, respectively. The previous figures clearly show how the profit-based STTS problem may be affected by the environmental policy. The maximum power generation is reduced as the weighting factor w decreases, in order to attain an adequate emission level, thus implying a lower total profit. Similarly, the number of units committed diminishes as the weighting factor w decreases.

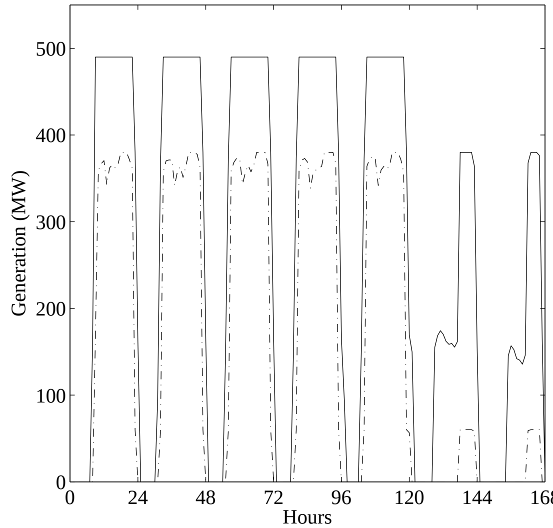

Fig. 3. Hourly total generation for profile 1. The solid and dash-dot lines denote compromise commitment results for $w = 0.6$ and $w = 0.4$, respectively.

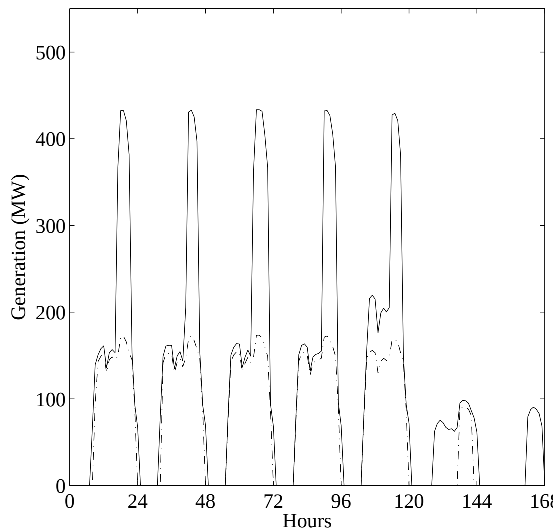

Fig. 4. Hourly total generation for profile 2. The solid and dash-dot lines denote compromise commitment results for $w = 0.7$ and $w = 0.5$, respectively.

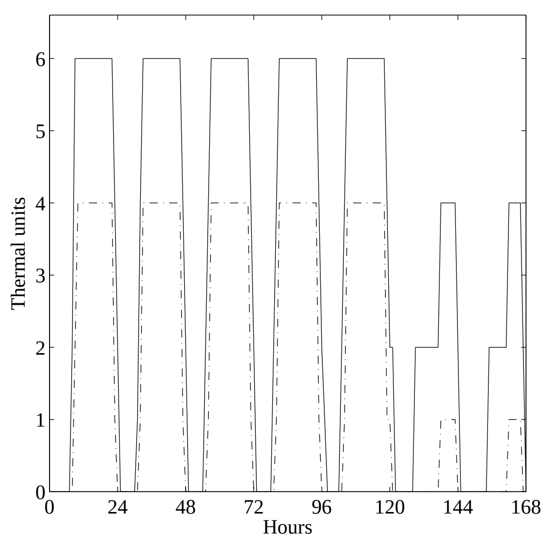

Fig. 5. Hourly units committed for profile 1. The solid and dash-dot lines denote compromise commitment results for $w = 0.6$ and $w = 0.4$, respectively.

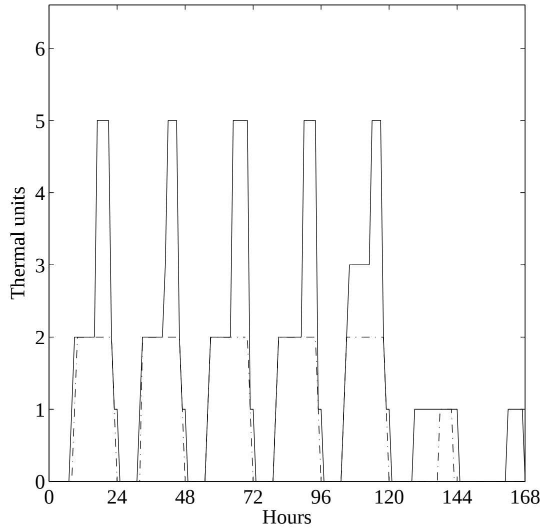

Fig. 6. Hourly units committed for profile 2. The solid and dash-dot lines denote compromise commitment results for $w = 0.7$ and $w = 0.5$, respectively.

Figs. 7 and 8 show the computed trade-off curves for profile 1 and 2, respectively. Trade-off characteristics give the percentage decrease in total emission against percentage decrease in total profit.

The trade-off curves have a sharp slope at the BPC neighborhood. At the beginning of the curves, a significant percentage decrease in total emission is obtained with a small percentage decrease in total profit. For instance, a 16.3% reduction in total emission can be achieved by only a 1.9% decrease in total profit for profile 1. It should be noted that at the end of the curves the opposite occurs.

Table II shows the computational results for the proposed MO approach.

The total CPU-time for a trade-off curve was about 10.98 s, with an average 0.05 s for each non-dominated solution representing a 168 hours generation schedule.

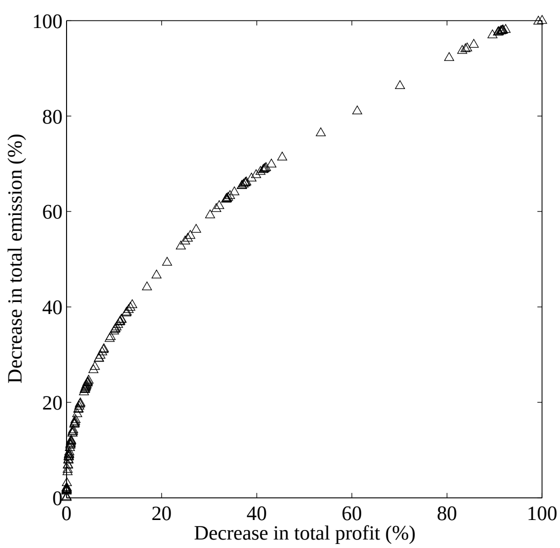

Fig. 7. Trade-off curve with 201 non-dominated solutions for profile 1.

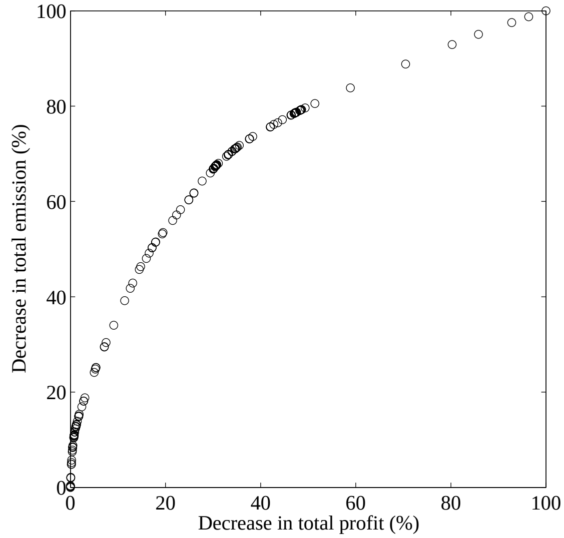

Fig. 8. Trade-off curve with 201 non-dominated solutions for profile 2.

TABLE II
COMPUTATIONAL RESULTS FOR THE PROPOSED MO APPROACH APPLIED ON THE IEEE 30-BUS SYSTEM

		Total Profit ($)	Total Generation (MWh)	Total Emission (Mg)
Profile 1	$w = 1.0$	77926	67668	3199
	$w = 0.6$	69206	46409	2022
	$w = 0.4$	45400	26747	992
	$w = 0.0$	0	0	0
Profile 2	$w = 1.0$	10780	32451	1707
	$w = 0.6$	7544	12619	567
	$w = 0.4$	5772	7038	373
	$w = 0.0$	0	0	0

B. Case study based on a 75-bus system

The proposed MO approach has been also applied on a 75-bus system, with fifteen thermal units, for the purpose of gaining further insight into the environmentally constrained profit-based STTS problem. The single-line diagram of this system is shown in Fig. 9.

The fuel cost and emission coefficients are given in [21]. Again, the scheduling time horizon chosen is one week.

The energy price profile considered over the time horizon is shown in Fig. 10 (where $ is a symbolic economic quantity).

The computed hourly total generation is shown in Fig. 11, while the computed trade-off curve is shown in Fig. 12.

Table III shows the computational results for the proposed MO approach.

The total CPU-time for a trade-off curve was about 24.18 s, with an average 0.12 s for each non-dominated solution representing a 168 hours generation schedule.

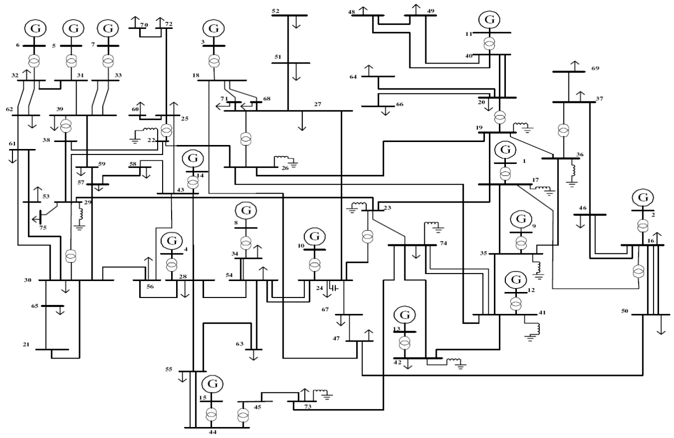

Fig. 9. Single-line diagram of a 75-bus system.

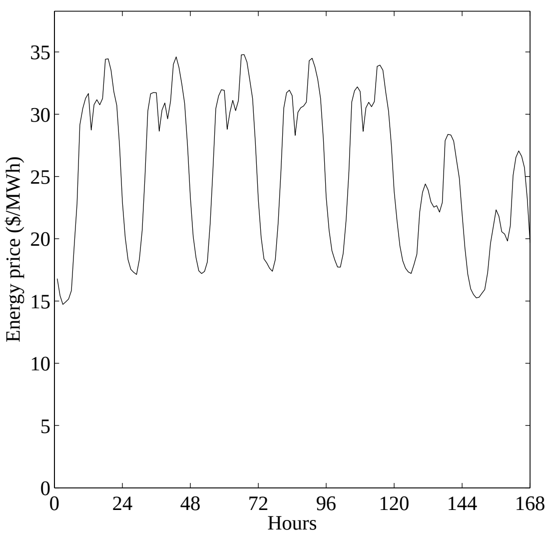

Fig. 10. Energy price profile considered.

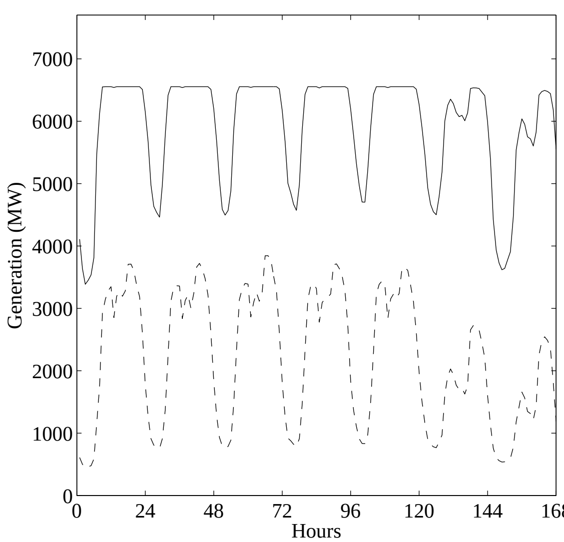

Fig. 11. Hourly total generation. The solid and dashed lines denote compromise commitment results for $w = 0.6$ and $w = 0.4$, respectively.

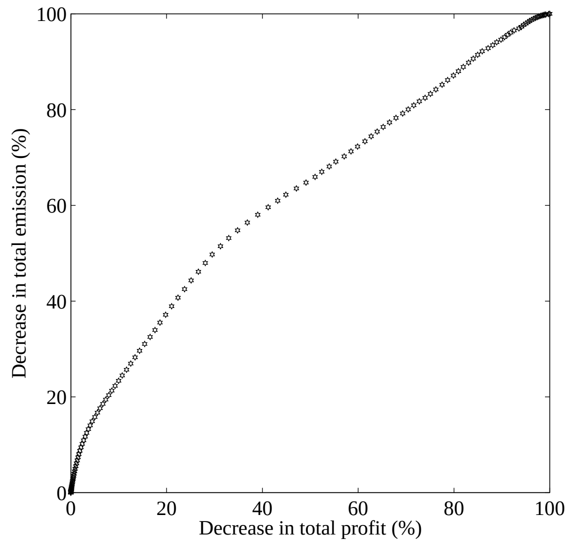

Fig. 12. Trade-off curve with 201 non-dominated solutions.

TABLE III
COMPUTATIONAL RESULTS FOR THE PROPOSED MO APPROACH APPLIED ON THE 75-BUS SYSTEM

	Total Profit ($)	Total Generation (MWh)	Total Emission (Mg)
$w = 1.0$	10780	32451	1707
$w = 0.6$	7544	12619	567
$w = 0.4$	5772	7038	373
$w = 0.0$	0	0	0

Hence, the proposed MO approach is computationally acceptable, enabling the user to obtain an extra value and cope easier with the demands of energy economics.

Real time decisions in a market environment are made taking into account the trade-off curves. The choice of the weighting factor depends on the tolerable emission level for the generating company. For instance, suppose a percentage decrease on emission (relatively to the emission for the BPC) is needed due to a new environmental policy. Then, a percentage decrease on profit is expected, given by the trade-off curve, and accordingly the weighting factor changes. Basically, if no environmental constraints are imposed or required, a weighting factor equal to one is preferable to maximize profit. Otherwise, according to the maximum emission allowed, a lower weighting factor should be selected.

V. CONCLUSION

The new competitive and environmentally constrained electricity supply industry requires new computing tools to ensure both competitiveness to generating companies in the electricity market and environmental protection by limiting the emission of greenhouse gases into the atmosphere.

A multiobjective optimization approach is proposed in this paper to solve the environmentally constrained profit-based short-term thermal scheduling. The proposed multiobjective optimization approach has been successfully tested on two case studies: the IEEE 30-bus system, with six thermal units, and a 75-bus system, with fifteen thermal units. The results show that it is efficient for obtaining the schedule and the trade-off curves with a small CPU-time requirement. Hence, it has been demonstrated that the proposed multiobjective optimization approach can be easily applied on larger test systems, since the computation time scales up linearly with number of hours and units. The study of multiple generating companies competing among themselves in the market, implying the development of bidding strategies and game-theory models, is a topic for a future work.

ACKNOWLEDGMENT

The authors gratefully acknowledge the contributions of Professor L. A. F. M. Ferreira and Dr. S. J. P. S. Mariano. Also, the authors would like to thank the anonymous reviewers for their valuable comments, which greatly helped them to clarify and improve the contents of the paper.

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