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MULTIOBJECTIVE THERMAL GENERATION DISPATCH

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Abstract. This paper presents a multiobjective approach to thermal units generation dispatch. The competing objectives are minimization of the cost of delivered power and minimization of environmental and ecological impacts. A mathematical model of 24-hour load allocation problem is developed. The model is dynamic in nature due to the ramp-rate constraints imposed on the thermal units generation. A new multicriteria optimization algorithm, which is based on compromise programming, is proposed. The algorithm is applied to a real dispatching problem with 26 thermal generating units. Sensitivity analysis treating the variations of criteria weighting coefficients is given.

Key words and phrases: Thermal generation dispatch, multicriteria optimization, air pollution control, compromise programming, quasigradient method

1. INTRODUCTION

There is a number of objectives in the operation of an electric power system. Of course, the first operating objective is continuity of service to customers, which means that power generation must be adjusted, in real time, to match prevailing demand. Some other objectives to be achieved as long as they are consistent with continuity of service and dependable operations, are treated in the literature extensively. Over a period of nearly half a century the majority of papers were devoted to the tasks how to allocate the total system generation among alternative system sources for optimum economy, i.e. for minimum of the cost of delivered power [**1**]. The last years, however, have seen an acceleration of interest in treating environmental and ecological criteria [**2–5**]. This interest was aroused by the dramatically growing air pollution that was, to a great extent, caused by thermal units power generation. Instead of economic dispatching, increasing attention is allocated among alternative system sources for optimum ecology. Optimum ecology is understood to mean a minimum of acid gases emissions, i.e. SO_2 emission, NO_x emission and particulates emission. The generating units differ in size, type and age, and have not only differing efficiencies, differing operating costs but also differing ecological effects. It is therefore possible to state a real problem of loading a set of thermal generating units taking simultaneously into account competing objectives, i.e. economic and ecological criteria. This paper considers the problem of 24-hour operations planning for many thermal generating units of an electric power system such that the prevailing customer demand, specified for each hour, is fulfilled, and that the outputs of available alternative thermal sources are maintained over each hour at such levels as will provide satisfactory overall economy and ecological impact. The paper is organized in the following way. Section 2 gives the problem statement in purely verbal terms followed by the corresponding analytical formulation. A new multicriteria allocation algorithm, which is a generalization of the known quasigradient "per-pound" procedure is presented in Section 3. Section 4 applies the method proposed to a medium size case study of loading 26 thermal generating units.

2. PROBLEM STATEMENT

We shall consider 24-hour thermal generation scheduling, where a constant demand over each hour is to be allocated to J thermal generating units in an optimum way with regard to both the total cost of fuel consumption and avoidance of unacceptable environmental and ecological impacts. Generally an hour-by-hour thermal power demand may be viewed as a part of total power demand in a combined hydro-thermal electric power system. A typical daily demand curve has a relatively stable part of high demand over day-hours and a significant decrease over midnight period. We need to take into account the lower and upper bounds of each thermal unit capacity. Also each thermal unit is subject to a constraint on the change in power generated per hour. Transmission losses over power system network lines are implicitly included in the demand forecast.

Associated with each thermal unit are K performance functions which form a K-vector optimization criterion. These functions measure the dependence of the fuel costs and ecology impacts upon the load allocated to a thermal unit. In particular, four performances have been treated simultaneously: fuel costs, SO_2 emission, NO_x emission and particulates emission. All performance functions are generally nonlinear/nondecreasing functions of load allocated. In particular, they are either quadratic or exponential functions, or linear combinations of these functions.

The following notation is used in the analytical formulation.

Notation

$\mathcal{J}$ — set of indexes associated to thermal units, $j = 1, \dots, J$,

D^i — constant active power demand during one hour time interval i, $i = 1, \dots, I$,

P_j^i — active power generated by a thermal unit j over time i,

$P_{j\,\min}$, $P_{j\,\max}$ — lower and upper bounds of active power generation of a thermal unit j, respectively,

$\Delta P_{j\ \max}$ — ramp rate limit, i.e. maximum allowable change per hour of active power generation of a thermal unit j,

$f_{kj}(P_j^i)$ — component k, $k = 1, \dots, K$ of vector criterion function associated with a thermal unit j,

w_k — normalized weighting coefficient, giving the importance of criterion k, $\sum_{k=1}^{K} w_k = 1$,

l — iteration index.

Vector optimization problem is stated as: find the minima of K-vectors

$$F^i = \left\{ \sum_j f_{1j}(P_j^i), \dots, \sum_j f_{kj}(P_j^i), \dots, \sum_j f_{Kj}(P_j^i) \right\} \tag{1}$$

for all $i = 1, \dots, I$, subject to constraints:

$$\sum_{j=1}^{J} P_j^i = D^i, \qquad i = 1, \dots, I \tag{2}$$

$$P_{j\ \min} \le P_j^i \le P_{j\ \max}, \qquad j \in \mathcal{J} \tag{3}$$

$$\Delta P_j = |P_j^{i+1} - P_j^i| \le \Delta P_{j\ \max}, \qquad i = 1, \dots, I-1, \quad j \in \mathcal{J}. \tag{4}$$

All D^i and P_j^i are integers, representing the rounded values of active power in MW.

The problem stated is complex and perplexing not only due to the existence of multiple criteria [6] but it is dynamic in nature due to the constraints in (3). It cannot be decomposed into I entirely independent allocation subproblems for each i. The multicriteria optimization algorithm described in the next section takes into account the dynamic property of the operations scheduling problem.

3. OPTIMIZATION ALGORITHM

The proposed procedure for the multicriteria optimal thermal generation scheduling consists of three phases:

(1) Determination of the total thermal system demand in each time interval i, which is based on: (a) the requirement for balancing of thermal units loads during the scheduling horizon, (b) available hydro generation, and (c) thermal units operation status. In such a manner a non-dynamic vector optimization problem is defined for each time interval i.

(2) Determination of the optimal load allocation to individual thermal units for all demand levels. It is assumed that the lists of thermal units in operation for each i are known. The committing and withdrawing of thermal units are given in advance for the whole scheduling horizon.

(3) Testing of the thermal units load levels in adjacent time intervals and correction of the loads, in case that ramp rate constraints are violated.

The second and third phase of the proposed method are the main concerns of this paper. In Annexes 1 and 2 the pseudocodes for the determination of multicriteria optimal generation schedule and testing/correction procedure are given.

In order to simplify the description of the optimization algorithm index i for time interval is omitted. The algorithm is essentially simple: starting from the minimal argument values, $P_j^{(0)} = P_{j\ \min}$, $j = 1, \ldots, J$, in order to fulfil condition (1) and minimize vector criterion function, it is necessary to increase iteratively by one the current value P_j of the thermal unit j^* for which the increase of the vector criterion function will be minimal. In other words, the algorithm determines successively in each iteration a new j^* with the following property:

$$\begin{aligned} \min \Delta F = \min\{&\Delta F_1(P_1, \ldots, P_{j^*}, \ldots, P_J), \ldots, \\ &\Delta F_k(P_1, \ldots, P_{j^*}, \ldots, P_J), \ldots, \\ &\Delta F_K(P_1, \ldots, P_{j^*}, \ldots, P_J)\} \end{aligned} \tag{5}$$

$$\Delta F_k(P_1, \ldots, P_{j^*}, \ldots, P_J) = f_{kj^*}(P_{j^*}^{(l+1)}) - f_{kj^*}(P_{j^*}^{(l)}), \quad j^* \in \mathcal{J} \tag{6}$$

with $P_{j^*}^{(l+1)} = P_{j^*}^{(l)} + 1$.

Since the algorithm is based on the computation and use of the direction of the gradient of criterion function, it could be classified in the group of quasigradient methods. As it is known, a common feature of such methods is systematical step-by-step attainment of the nearly optimal criterion function value. Starting from an initial point, the independent variables are successively modified in such a manner that a current solution value is improved mostly.

In developing the algorithm for vector criterion function minimization we applied the principal ideas of compromise programming and moving ideal point methods. Iterative allocation procedure is based on the comparison of the incremental increases of vector criterion function with respect to all variables. In each iteration the ideal and anti-ideal point in K-dimensional criterion space are defined. The distance of the points corresponding to any thermal unit — loading candidate — from ideal point is calculated according to the following formula:

$$L_p(j) = \left\{ \sum_{k=1}^{K} w_k \left[\frac{(\Delta f_k(j) - \Delta f_k^*)}{(\Delta f_k^a - \Delta f_k^*)} \right]^p \right\}^{1/p}, \quad p = 1, 2, \ldots, \infty; \quad j \in \mathcal{J} \tag{7}$$

where

$L_p(j)$ — distance of point corresponding to thermal unit j from ideal point,

$\Delta f_k(j)$ — incremental increase of criterion k for thermal unit j,

Δf_k^* — k-th coordinate of ideal point for set $\mathcal{J}$, (minimum incremental increase of k-th criterion),

Δf_k^a — k-th coordinate of anti-ideal point for set $\mathcal{J}$, (maximum incremental increase of k-th criterion).

The cases of special interest are:

— linear combination ($p = 1$),

$$L_1(j) = \sum_{k=1}^{K} w_k \frac{\Delta f_k(j) - \Delta f_k^*}{\Delta f_k^a - \Delta f_k^*} \tag{8}$$

— Euclidean norm ($p = 2$),

$$L_2(j) = \left\{ \sum_{k=1}^{K} w_k \left[\frac{\Delta f_k(j) - \Delta f_k^*}{\Delta f_k^a - \Delta f_k^*} \right]^2 \right\}^{1/2} \tag{9}$$

— norm L_∞ ($p = \infty$),

$$L_\infty(j) = \max_k \left\{ w_k \frac{\Delta f_k(j) - \Delta f_k^*}{\Delta f_k^a - \Delta f_k^*} \right\}. \tag{10}$$

The procedure is being repeated iteratively, so that in each iteration the load increment is allocated to the thermal unit with the minimum current value of L_p norm. In each iteration the coordinates of the ideal and anti-ideal point are equal to the minimum and maximum value of each criterion incremental increase.

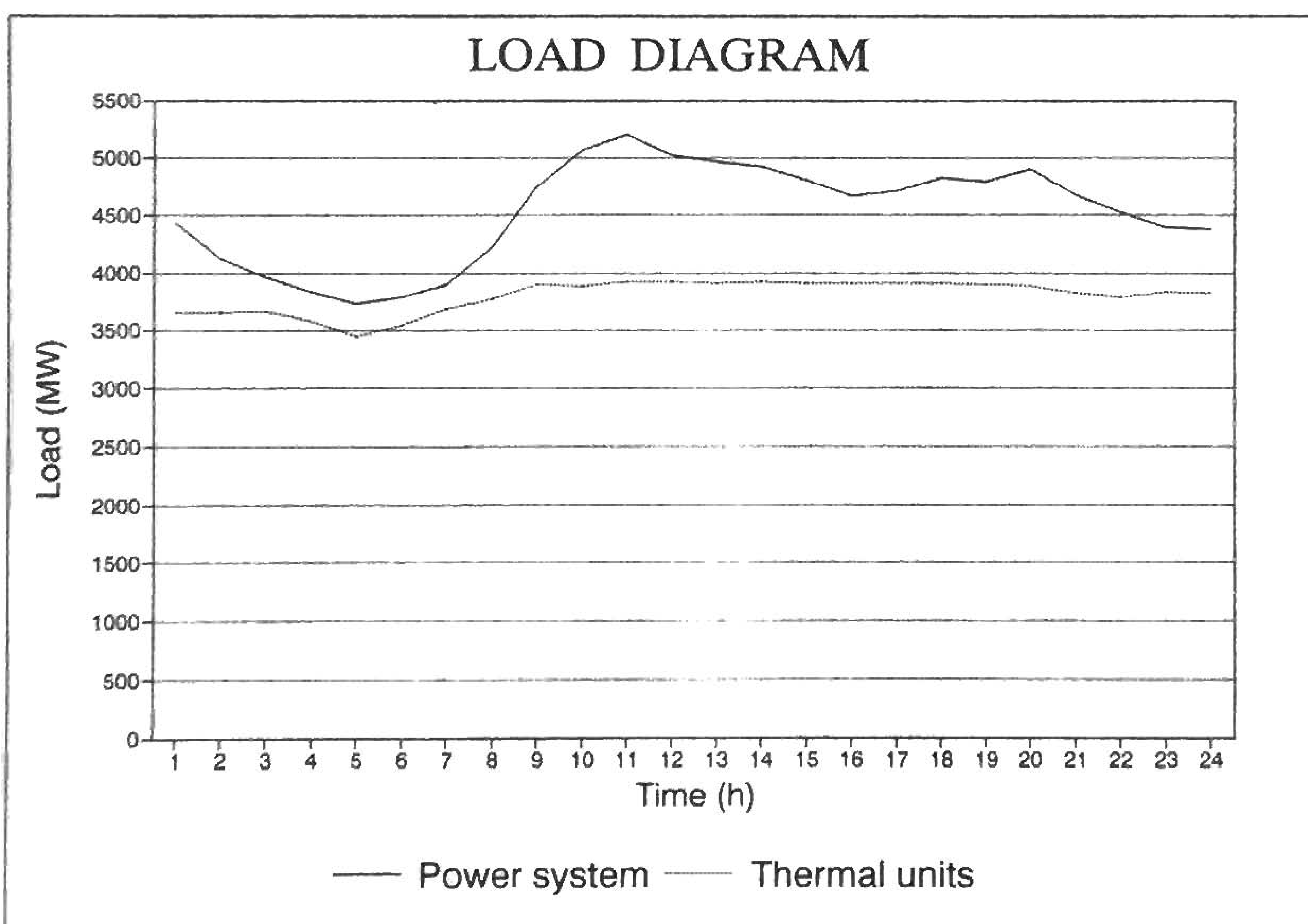

Figure 1. Load diagram for power system and thermal units

4. CASE STUDY

The proposed algorithm has been tested with available characteristics of thermal units of Electric Power Utility of Serbia. Demand has been represented by a typical daily load diagram.

Although in the following example the costs and emission characteristics are given in a linear form, the algorithm is general and the only requirement is that the characteristics should be given in the above stated analytical form.

4.1. Input Data

The illustrative example is based on realistic power system data. A daily load diagram of power system and thermal subsystem is shown in Fig. 1. Thermal units characteristics: fuel prices, heat rate, SO_2 emission, NO_x emission and particulates emission are given in Table 1. Since in this case the amounts of NO_x emissions are tolerable, a correspondent criterion is not included in a vector objective function. Therefore, the set of optimization criteria comprises fuel costs, SO_2 emission and particulates emission.

Table 1 Thermal units characteristics

No.	Pmin (MW)	Pmax (MW)	Fuel cost (m.u./MJ)	Heat rate (MJ/MWh)	SO2 (kg/MWh)	NOx (kg/MWh)	Particulates (kg/MWh)
1	22	29	0.02844	0.1563	19.0	1.7	5.1
2	22	29	0.02844	0.1563	19.0	1.7	5.1
3	22	29	0.02844	0.1563	19.0	1.7	5.1
4	44	58	0.02844	0.1563	19.0	1.7	5.1
5	72	100	0.02844	0.1349	12.5	1.5	4.4
6	70	90	0.02844	0.1349	19.6	0.7	13.4
7	118	191	0.02844	0.1183	22.8	2.6	4.5
8	220	320	0.02844	0.1151	15.0	2.0	1.9
9	85	108	0.03268	0.1119	21.0	4.0	5.6
10	118	191	0.02844	0.1160	9.9	1.5	5.5
11	118	191	0.02844	0.1160	9.9	1.5	5.5
12	200	280	0.02844	0.1160	10.1	1.3	0.8
13	200	280	0.02844	0.1160	10.1	1.3	0.8
14	200	280	0.02844	0.1160	10.1	1.3	0.8
15	370	580	0.02844	0.1055	12.2	2.8	0.2
16	370	580	0.02844	0.1055	12.2	2.8	0.2
17	34	55	0.03054	0.1423	10.4	3.1	23.9
18	115	153	0.03054	0.1263	3.9	3.0	27.8
19	118	157	0.03054	0.1263	5.1	1.7	16.8
20	172	309	0.03054	0.1172	5.7	2.2	2.6
21	70	108	0.07200	0.1004	5.0	1.0	1.0
22	50	100	0.07200	0.1004	5.0	1.0	1.0
23	5	6	0.07600	0.1250	5.0	1.0	1.0
24	8	11	0.07600	0.1250	5.0	1.0	1.0
25	22	29	0.07600	0.1250	5.0	1.0	1.0
26	15	47	0.07200	0.1438	5.0	1.0	1.0

4.2. Overview of Results

The results for given input data are summarized in Tables 2 and 3. In Table 2 are shown the values of total fuel costs, total SO_2 emission and total particulates emission for the following cases:

— single criterion minimization of each criterion,

— single criterion maximization of each criterion,

— vector minimization of all three criteria, simultaneously.

Table 2 Criteria values expressed in physical units

Optimization criterion	Cost (mon.units)	SO2 (t)	Particulates (t)
Cost minimization	32247.45	1056.95	318.81
Cost maximization	34489.09	1021.75	396.87
SO2 emission minimization	34160.80	983.01	370.60
SO2 emission maximization	32458.77	1089.01	333.99
Particulates emission minimization	33680.08	1022.07	301.34
Particulates emission maximization	34344.12	1028.44	398.50
Trade off Cost-SO2-Particulates	32730.66	1013.94	319.44

Table 3 Relative increase of criteria values

Optimization criterion	Cost (%)	SO2 (%)	Particulates (%)
Cost minimization	0.00	7.52	5.80
Cost maximization	6.95	3.94	31.70
SO2 emission minimization	5.93	0.00	22.98
SO2 emission maximization	0.66	10.78	10.83
Particulates emission minimization	4.44	3.97	0.00
Particulates emission maximization	6.50	4.62	32.24
Trade off Cost-SO2-Particulates	1.50	3.15	6.01

The relative increase of each criterion value, shown in Table 3, is defined using criteria minimum as a referent value.

A comparison between the values of observed criteria, obtained in the above seven cases, and their minimum values, resulting from single criterion minimization, has shown the following increases for the case of trade off solution: fuel costs increase of 1.5%, SO_2 emission increase of 3.15% and particulates emission increase of 6.01%.

The relative increase of fuel costs, in cases of minimum SO_2 emission and minimum particulates emission, is equal to 5.93% and 4.44%, respectively.

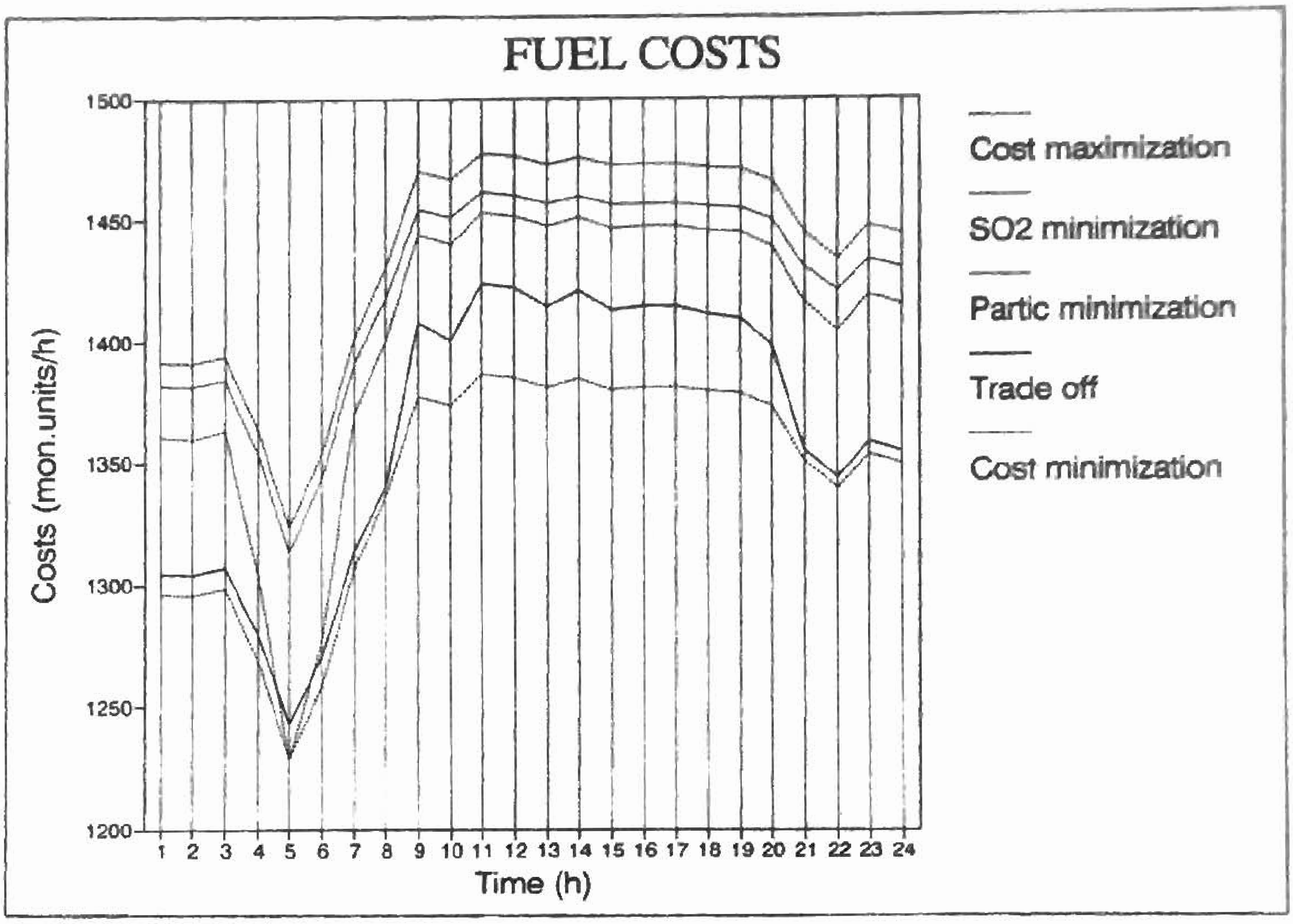

Figure 2. Fuel costs hourly diagram

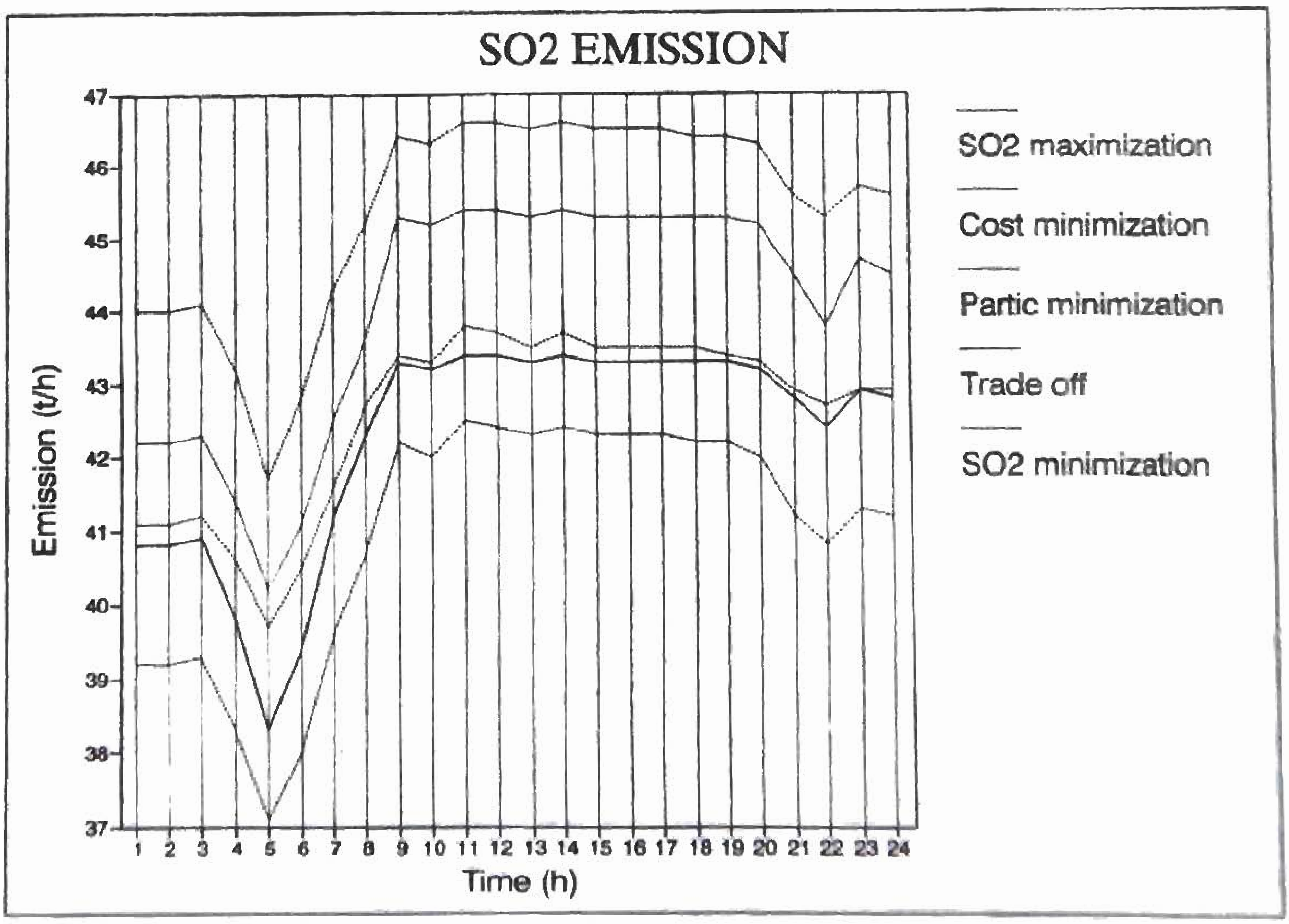

Figure 3. SO_2 emission hourly diagram

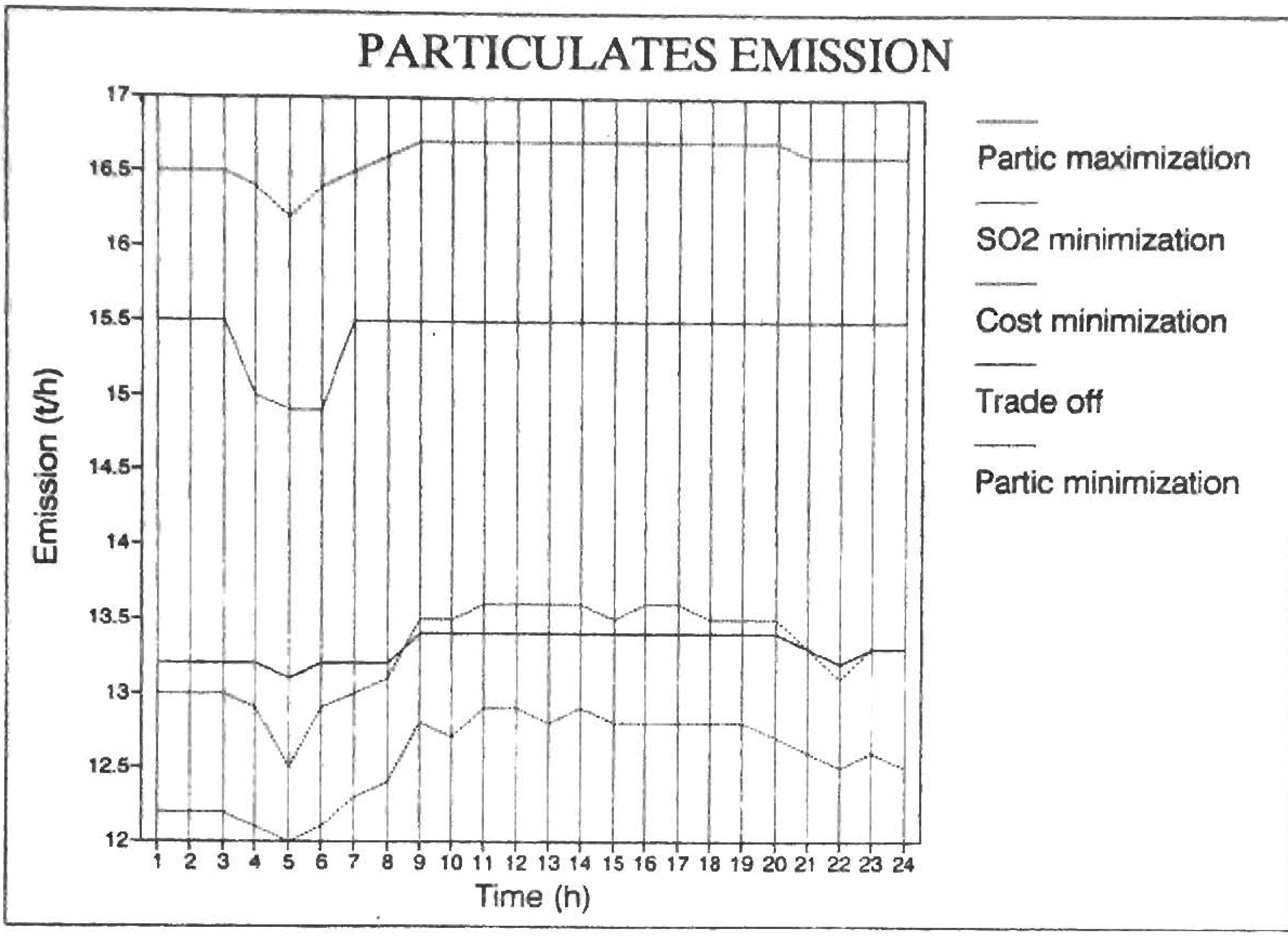

Figure 4. Particulates emission hourly diagram

The relative increase of SO_2 emission and particulates emission, in case of minimum fuel costs, is equal to 7.52% and 5.80%, respectively. A comparison between these values and correspondent values for the trade-off case, demonstrates considerable effects of simultaneous optimization of the observed criteria.

A graphical illustration of the obtained results is given in Figures 2, 3 and 4. The hourly diagrams of fuel costs, SO_2 emission and particulates emission are shown for each of the seven alternative thermal system generation schedules.

The upper and lower center-dashed lines in each diagram correspond to the extreme values of observed criteria. A solid line corresponds to the trade off values. Dotted and dashed lines correspond to the values of selected criteria in cases of minimization of one of the other two criteria. It is obvious that the trade off values are close to the minimum values.

4.3. Sensitivity Analysis in Case of Weighting Coefficients Variations

In order to illustrate the influence of the weighting coefficients on solutions obtained with the proposed algorithm, we shall define the following parameters:

— normalized increase of criteria value $\Delta\Phi_k = \dfrac{\Phi_k - \Phi_k^{min}}{\Phi_k^{max} - \Phi_k^{min}}$,

— normalized distance from ideal point $\delta = \sqrt{\dfrac{1}{K}\sum_k \Delta\Phi_k^2}$.

Φ_k is defined as integral value of criterion k, $\Phi_k = \sum_i F_k^i$; Φ_k^{min} and Φ_k^{max} are its correspondent minimum and maximum values; F_k^i is a value of criterion k in time i for thermal system, $F_k^i = \sum_j f_{kj}^i$.

Table 4 Sensitivity analysis

	Weighting coefficients			Normalized increase			Normalized
	Cost	SO2	Particulates	Cost	SO2	Particulates	Distance
1	1.0	0.0	0.0	0.00	0.70	0.18	0.42
2	0.0	1.0	0.0	0.85	0.00	0.71	0.64
3	0.0	0.0	1.0	0.64	0.37	0.00	0.43
4	1.0	1.0	0.0	0.14	0.21	0.70	0.43
5	1.0	0.0	1.0	0.03	0.63	0.09	0.37
6	0.0	1.0	1.0	0.76	0.14	0.18	0.46
7	1.0	1.0	1.0	0.22	0.29	0.19	0.24
8	1.0	0.2	0.5	0.04	0.40	0.14	0.24
9	1.0	0.5	0.2	0.09	0.30	0.34	0.27
10	1.0	0.5	0.8	0.06	0.38	0.19	0.25
11	1.0	0.8	0.5	0.07	0.33	0.27	0.25
12	0.2	1.0	0.5	0.54	0.13	0.33	0.37
13	0.5	1.0	0.2	0.46	0.15	0.34	0.34
14	0.5	1.0	0.8	0.43	0.21	0.19	0.30
15	0.8	1.0	0.5	0.15	0.29	0.27	0.24
16	0.2	0.5	1.0	0.44	0.21	0.19	0.30
17	0.5	0.2	1.0	0.04	0.40	0.14	0.24
18	0.5	0.8	1.0	0.25	0.28	0.18	0.24
19	0.8	0.5	1.0	0.06	0.38	0.19	0.25
20	1.0	1.0	0.2	0.10	0.25	0.46	0.31
21	1.0	1.0	0.8	0.15	0.29	0.26	0.24
22	1.0	0.2	1.0	0.04	0.40	0.14	0.24
23	1.0	0.8	1.0	0.06	0.38	0.19	0.25
24	0.2	1.0	1.0	0.53	0.19	0.18	0.34
25	0.8	1.0	1.0	0.22	0.29	0.19	0.24

In Table 4 are shown the values of the above parameters for 25 combinations of weighting coefficients values, in case of vector minimization of three optimization criteria: fuel costs, SO_2 emission and particulates emission. Each combination of weighting coefficients is a quantitative expression of a decision maker's attitude towards the significance of each of the observed criteria. For example, the first combination corresponds to the absolute priority of cost criterion, whereas the seventh combination corresponds to formally equal significance of all criteria.

As one could expect, solutions with equal values of the above defined parameters are obtained for some combinations. For example, in case of combinations 17 (0.5, 0.2, 1.0) and 22 (1.0, 0.2, 1.0) the relative increase of three criteria is equal to 0.04, 0.40 and 0.14, respectively, with distance from the ideal point equal to 0.24. Obviously, for these values of the weighting coefficients of SO_2 (0.2) and particulates emission (1.0), there is an indifference range of cost weighting coefficient (from 0.5 to 1.0), where its variation doesn't affect optimum solution.

The given example implies that a decision maker has to determine, on the basis of his experience in application of the proposed algorithm, the combination of weighting coefficients which adequately reflects system values.

In analysing the above results, one should take into account the fact that the same values of normalized distance could correspond to inherently different solutions (solutions 7, 15, 17, 18, 21). For example, in cases 7 and 15 the relative cost increase is equal to 0.22 and 0.15; the relative increase of particulates emission is equal to 0.19 and 0.27, respectively. This phenomenon is a natural consequence of the existence of multiple criteria.

5. CONCLUSION

Dispatching electric power from various thermal sources, quite different in generation efficiency, is becoming more complex and more difficult when not only economy but also an avoidance of unacceptable ecological impacts have to be taken into consideration. The pure economic dispatching has been the most thoroughly studied and formalized, whereas compromised economy/ecology dispatch is of most recent vintage. It has become clear that solving the combined economic-ecology dispatch problems offers extensive possibilities for achieving interesting theoretical contributions to the field of multicriteria optimization.

Shifting of generation from one thermal unit to another in daily operation may involve a trade off between cost and avoidance of unacceptable ecological impacts. The multicriteria dispatch methodology looks successful because it is easy to understand and easy to manage. It is of interest to the people in operations research to compare classical nondynamic allocation processes with the dispatching of electrical power, where rapidly changing load demands have to be satisfied instantly and there is no power inventory.

A provocative question arises: what are the expectations in savings and air pollution protection effects in real power system in which economic/ecological dispatching is applied. It appears that overall savings and ecological protection effects are not large: a couple of percents in production costs and/or reduction of acid gases emission. However, these effects could be sufficient to justify the application of the proposed multiobjective approach. Let us add that economic power allocation and ecological requirements are partially conflicting demands.

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ANNEX 1.

MULTIOBJECTIVE THERMAL GENERATION DISPATCH PROCEDURE

1. Define the increasing order of thermal system loads.
2. Define initial load level for each j.
3. Calculate the incremental increase of each k for each j.
4. Identify minimum and maximum incremental increase for each k.
   Define ideal and anti-ideal point.
5. Calculate the distance from current ideal point for each j.
6. Define the list of loading candidates.
   Define loading order.
7. Initialize load level index.
8. Increase load level index.
9. Check the list of loading candidates.
   If the list is exhausted, print message and go to 16.
   Otherwise, go to 10.
10. Select j^* with minimum distance as the best candidate.
11. If load increase at j^* is feasible, go to 12.
    Otherwise, go to 9.
12. Increase load at j^*.
    Calculate new values of incremental increase of each k for j^*.
13. Update the ideal and anti-ideal point.
    Update the list of loading candidates.
    Update loading order.
14. If the current load level is covered, go to 15.
    Otherwise, go to 9.
15. If all load levels are not covered, go to 8. Otherwise, go to 16.
16. Determine total cost and emission values for each j and the whole thermal system.

ANNEX 2.

TESTING AND CORRECTION PROCEDURE

1. For each i define optimal load level P_j^i for each j, using optimal load dispatch at correspondent system demand level.
2. Determine boundary intervals for each period π of monotonical thermal demand changes.
3. Define initial load level P_j for each j. Initialize period and time indexes.
4. Increase period index, $\pi = \pi + 1$
   Define the number of iterations N in correction procedure.
5. Increase time index, $i = i + 1$.
6. Increase iteration index.
   Initialize thermal unit index.
7. Determine, for each j, the load difference between previous and current time interval, $\Delta_j = P_j^i - \mathsf{P}_j$.
8. Increase thermal unit index, $j = j + 1$
9. If the ramp rate constraint for j is violated, go to 10.
   Otherwise, go to 12.
10. Determine the value of required load correction for j.
    Determine the available load margin for each j and for the whole thermal system.
11. Correction of thermal unit j load in time i.
    Proportional correction of other units loads in time i.
12. If all thermal units are not considered, go to 8.
    Otherwise, go to 13.
13. If the ramp rate constraint violations still exist and the number of iterations is smaller than N, go to 6.
    Otherwise, go to 14.
14. Update current load level P_j for each j in time i.
15. If all time intervals in period π are not considered, go to 5. Otherwise, go to 16.
16. If all periods are not considered, go to 4. Otherwise, go to 17.
17. Update values of fuel costs and emissions for each j in each i.