SmiSSION CONSTRAINED DISPATCHING
** OF ELECTRIC POWER

by

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ABSTRACT

Dispatching is the process of allocating the total demand for -electric energy among the available generators. Dispatching can provide powerful means for controlling the total emissions of pollutants in a region. Existing pollution regulations in the US have not been combined in regional terms and so dispatching has not been used for pollution control. However, regional constraints are now receiving serious consideration. In order to study these constraints and to implement them, should they be adopted, we need algorithms to solve the emission constrained dispatching problem. This paper reviews prior work in the area and then develops an improved algorithm for finding the best tradeoffs between cost and emissions. Thereby, the algorithm determines the least cost schedule for meeting any demand subject to any selected emission constraint.

INTRODUCTION

The release of sizable quantities of a wide range of pollutants is one of the unfortunate side effects of running the generating plants in an electric power system. SO_2, NO_x, CO, various hydrocarbons, suspended particulates, sludges and radioactive wastes are some of pollutants generating plants can generate. How can the quantities of such pollutants be reduced ? The relevant strategies can be divided into two classes:

1. Hardware intensive strategies: Examples are building new, clean plants to replace old, dirty ones; retrofitting existing plants with pollution control hardware; and increasing the efficiency of the customer's end uses of electricity and thus, reducing demand.

2. Operating Strategies: Two important subgroups of this class are:

- fuel scheduling: By changing to a cleaner fuel - a low sulfur coal instead of a high sulfur coal, for instance - the pollutants produced per pound of fuel can be reduced.
- dispatching: This term currently refers to the process of allocating the total demand for electric energy among the generating plants. In the future, the term may be extended to include the modification of demand by load management techniques. In either case, dispatching provides a means for adjusting regional emissions. For instance, the diversity in generating plant characteristics can be used to reduce emissions by shifting the load from the dirtier plants to the cleaner ones.

By and large, the hardware intensive strategies take years to be implemented. Fuel scheduling strategies are also slow to take effect (the time constants are of the order of a year because of the long term contractual agreements and other large time constants involved in fuel acquisition). Dispatching decisions* however, can be implemented in seconds. Therefore, dispatching can be used as a means to instantaneously change the rate of emissions of pollutants in a region. The amounts of these changes can be considerable especially in regions with some surplus of generation and some diversity in the pollution characteristics of their generating plants. When load management becomes widespread the range of possible adjustments will become larger.

We come now to the question: what constitutes a good mix of strategies for pollution control ? From a utility's viewpoint, the concerns are cost and regulations. In the US, the regulations that deal with pollutants tend to be prescriptive rather than performance oriented and focus on individual plants rather than on collections of them. The result has been a virtual mandate for the use of the more sluggish means of control - the hardware intensive and fuel scheduling strategies- to the exclusion of dispatching. In fact, the only exceptions seem to be the Los Angeles Valley, where dispatching is used to minimize the total NO_x emissions, and certain episodes of very high pollution, where dispatching was invoked as an emergency measure.

There were good reasons for . adopting the prescriptive, micro-directed regulations. But now needs are emerging for more performance oriented regulations that would embrace collections of plants over fairly extended geographical regions. A class of such regulations that will at least be seriously considered, if not adopted, is the imposition of caps on the total regional emissions of SO_2 and NO_x in areas with large number of coal burning plants. One intent of such regulations would be to reduce the amounts of acid rain in some parts of the country.

The appearance of regional constraints on emissions would provide the incentives to utilities to use dispatching as a pollution control strategy. The added degree of freedom will provide cost savings (to achieve the same pollution control levels) and add a much needed measure of flexibility. (There is still much to be learned about pollution disposal and its impacts. Therefore, it is important that regulatory policy not lock us onto a single, unalterable course. Dispatching strategies, since they can be implemented quickly and at a little cost, provide the means for "mid-course corrections". Hardware intensive strategies, however, require large initial capital outlays, and once adopted are difficult to modify. Fuel scheduling suffers from the same disadvantages but to a lesser extent.)

If we are to analyze the effects of regional emission constraints and implement them (when and if they are adopted) we will need methods for solving emission constrained dispatching problems. This paper briefly surveys such methods and then proposes one with some improvements.

EMISSION CONSTRAINED DISPATCH - AN OVERVIEW

NOTATION

P	Demand (in MW) to be met in the region
N	Number of generating plants in the region
p_i	Power output of the i-th plant
$k_i(p_i)$	Cost (in \$/hr) of operating the i-th plant
K	Cost (in \$/hr) of operating the N plants, that is, $K = \Sigma k_i(p_i)$
$e_i(p_i)$	Emissions (in lb/hr) of the i-th plant
E	Emissions (in lb/hr) of the N plants, that is, $E = \Sigma e_i(p_i)$ (In the remainder of the paper we will use E as a metric to measure the impact of the emissions in the region. For many purposes this is a reasonably good metric, but it is certainly not the best metric for all situations. Other metrics may be substituted where necessary in the algorithms that will described later in the paper)
$\bar{E}$	Limit on emissions (in lb/hr) for the region

ECONOMIC DISPATCH

The conventional or economic dispatch schedules generator power outputs to meet the total demand while minimizing cost. In other words, it solves the following problem:

(ECO): $\min_{p_i} K = \Sigma k_i(p_i)$

subject to: $\Sigma p_i = P$

$\underline{p}_i \le p_i \le \bar{p}_i \ \forall i$

For further details on this problem see [1].

EMISSION CONSTRAINED DISPATCH

Gent and Lamont [2] have suggested that a minimum dispatch strategy be formulated as an analog to the economic dispatch:

(EMMh $\underset{p_i}{\mathrm{Min}}\ E = Ze_i(p_i)$

subject to: $Zp_i * P$

$g_i \pounds p_i\ S\ \bar{p}_i\ V\ i$

Gent and Lamont have developed a program for online dispatch that results in minimizing NO_x emissions. The problem is formulated as a non-linear programming problem, where the NO_x emissions of units are modeled by exponential functions of the units's outputs.

Cadogan and Eisenberg [3] have developed a dynamic emissions management system for online control of SO_2 emissions. Their system contains six strategies for cost and emissions control (strategies to minimize cost, minimize emissions, minimize cost with controlled emissions, optimum economy with constrained concentration, minimize emissions with constrained cost and minimize an SO_2 tax). The load dispatcher selects the strategy to be used. Ail six strategies are obtained by solving linear programming problems. For instance, the **strategy** for emission controlled dispatch is obtained by solving:

(ECDh $\underset{p_i}{\mathrm{Min}}\ K » 2c_i(p_i)$

subject to: $Ip._i * P$

$E = ZeX_i p_i) \pounds E$

$g_i \pounds p_i \pounds \bar{p}_i\ V\ i$

Lamont and Gent [4], Delson [5] and Shepard [6], have also proposed emission constrained dispatch algorithms, based on an emission tax. The objective in these formulations is a sum of the system operating costs and penalty proportional to the pollutants. •

Sullivan [7] has used quadratic representations for costs and emissions. This formulation uses an objective function which is the sum of the ground line SO_2 concentration. A similar, non-linear programming model to control NO_x has been formulated by Fannigan and Fouad [8]. Lamont et al., [9] have applied related algorithms to a set of dispatch regions.

Other mathematical programming models have been suggested, for selecting fuel mix, cleaning fuel and scheduling the generation to meet environmental constraints [10-13]. Emission controlled dispatch has also been viewed in the control theoretic framework, where a performance index combining the operating costs and emissions penalty, is minimized [14,15].

BI-OBJECTIVE APPROACHES

The techniques surveyed in the previous section all deal with dispatching as a single objective problem. Actually, cost and emissions are conflicting objectives. We would like to minimize both, but decreases in one of them must usually be paid for with increases in the other. The set of the best possible tradeoffs between them is called the Pareto Frontier or Noninferior surface. Some examples are shown in Fig. 3.

To generate the Pareto Frontiers in cost and emissions, one must solve a biobjective optimization problem. If the frontier is convex this problem can be reduced to a sequence of single objective problems [16], namely:

(TOF): $\underset{p}{\mathrm{Min}}$ »(/i.p.)

subject to: $Zp._{i} \bullet P$

$Q._{i}$ £ $p._{i}$ £ $\bar{p}._{i}$ V i

where 4>(/i,p_{i}) = (1-/*)k_{i}(p_{i}) • /^(Pj) and // is a parameter whose value is varied between 0 and 1. For each value of /i, (TOF) is solved and the solution provides one point on the frontier.

The frontiers display all the best possible tradeoffs between cost and emissions. Therefore, they present the dispatcher and other decision makers with a more complete picture of the available options than the other forms of information display. Note that we can read from the frontier curves, the minimum possible cost for any feasible emission constraint. For instance, the minimum cost is $900,000/hr when the demand is 30,000 MW and the emissions are constrained to be less than 20 tons/hr (see Fig. 3). Thus, the frontiers contain the solutions to all possible emission constrained dispatch problems.

Zahavi and Eisenberg [17,18] have used the biobjective formulation for dispatching a portion of a realistic system containing coal, oil, and gas turbine generation. Quadratic segments were used to represent the costs and emissions for each generator

$$k_i(p_i) * a_i + b_i(p_i - a) \bullet c_i l p_i - g_i r^{2} \tag{1}$$

$$e_i(p_i) \ll q_i * r_i f o_i - B_i) + s_i t p_i - e_i)^2 \tag{2}$$

where g_i and $\bar{p}_i$ are bounds on p^ and a_i, b_i, c_i, q_i, r_i and s_i are experimentally determined parameters. As a result, (TOF) becomes a quadratic programming problem. Zahavi and Eisenberg used a Fletcher-Powell algorithm to solve it. No computational timing data was given.

AN IMPROVED ALGORITHM

In this section we will describe a fast algorithm for generating Pareto frontiers for the biobjective dispatching problem. The algorithm is an extension of a method developed by Ron Davis [19].

We use quadratic segments for cost and emissions as in equations (1) and (2).

As a result the term •.ı in the objective function df (TOF) take on the form:

$$\Phi_i(\mu,p_i) - a_1 + \beta_i(p_i-\underline{p}_i) + \gamma(p_i-\underline{p}_i)^2 \qquad (3)$$

where

a_1 * (1"/i)^{a}i * /»Q|

$$\beta_i = (1-\mu)b_i + \mu r_i$$

r-ı » (I-^C, • yiS,

the Lagrangian of (TOF) is:

L * Z^/i.p.,) • X[Zp, - P]

where X is the Lagrange multiplier.

The stationarity conditions on the Lagrangian (the necessary conditions for a solution) are:

3u3p, * 0, if p, € (g,,^) and *BUdX* » 0 (4)

Simplification yields:

P, ^s Qj ^ X ^ *fi.*,

p, - (X - *fi)l2y*, * B, if 4 $ X S J, • 2r.,($\bar{p}$j - Q,) (5)

p. = $\bar{p}$. otherwise

These conditions are used to produce an algorithm for calculating the tradeoff curves and thereby, a solution to the emission constrained dispatch problem.

THE ALGORITHM

1. Select a value between 0 and 1 for //. Suppose we begin with /i=0.
2. Set Q, = y£ and Q. = *ft* + 2y.($\bar{p}$. - g.) for all generating units.
3. Arrange the C^s in ascending order to give a vector

C *ty* fj. . . . .f^] = F

4. Using the expressions in equation (5), calculate the value of **$P = Zp_i$ and the total cost and emissions for these demands. This provides a table containing the values of X, P, K and E, for all the possible breakpoints in the system. These breakpoints refer to generation levels when a new generator is added for supplying the increased demand. This table contains a sequence of points on the tradeoff curves as shown in Figure 1.**

5. For desired values of demand, a similar table is generated by interpolating for the value of X and then using equation (5) to calculate K and E for those demand values.

6. Choose another value of *p* and repeat steps 2-5.

7. Repeat step 6 until enough points have been generated for each demand level, to allow interpolation for arbitrary values of E.

USAGE

The algorithm is used as follows:

1. Take the given load duration curve and form a discrete approximation to it, as shown in Figure 2.

2. Make the time segments small enough for only **one emission** limit **to apply to each segment.**

3. Using **the suggested** algorithm, **calculate the tradeoff** curves for **each discretized load value,** by using **several values of** /i **(/i** * 0.0, 0.1, 0.2, . . ., 0.9, 1.0 has been found to be sufficiently accurate). Then, from the tradeoff curves, find the cost per hour to meet the given emission constraint. If necessary, use the calculated tables and find the individual generator outputs.

A FORTRAN program has been written to implement the steps mentioned above. It can dispatch up to 400 generating units to **meet a** daily or yearly emission constraint.

EXAMPLES

We have considered emission constrained dispatch for New York state as one region. New York state contains 90 coal, oil, hydro, nuclear, gas, and diesel plants. Quadratic segments were used to represent cost and emissions. Representative load duration curves were considered and discretized into five segments. Two algorithms were applied to determine the total cost per yean a quadratic programming procedure, and the tradeoff curves algorithm. The Pareto tradeoff curves as generated by the latter algorithm, are shown in Figure 3. Figure 4 summarizes the computational results for this case. The tradeoff method, requires no iteration, once the tables have been calculated, and provides more information to the decision maker.

Another example considers a hypothetical generation mix. The resulting Pareto surfaces are shown in Figure 5.

CONCLUSIONS

The proposed algorithm for generating Pareto frontiers for biobjective dispatch problems combines the best features of the prior work in the area and contains innovations that make it convenient and easy to implement. Its immediate uses are for the study of regulatory policies that would place caps on the regional emission of pollutants like SO_2 and $NO_{x>}$ Later, if these policies are adopted, the algorithm could find use for real-time-dispatching.

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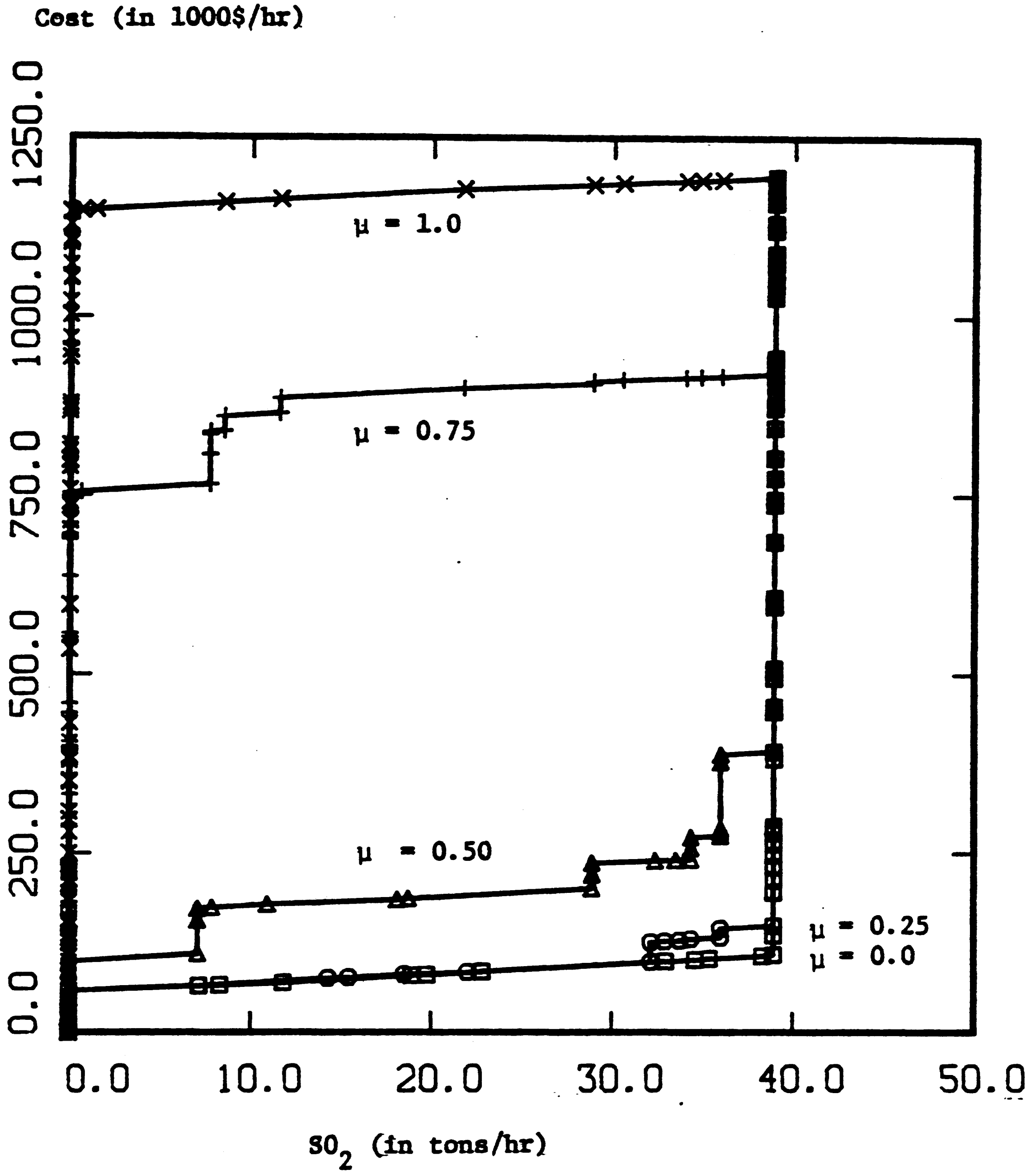

Figure 1. Solution of trade-off problem provides optimal envelopes for various values of μ

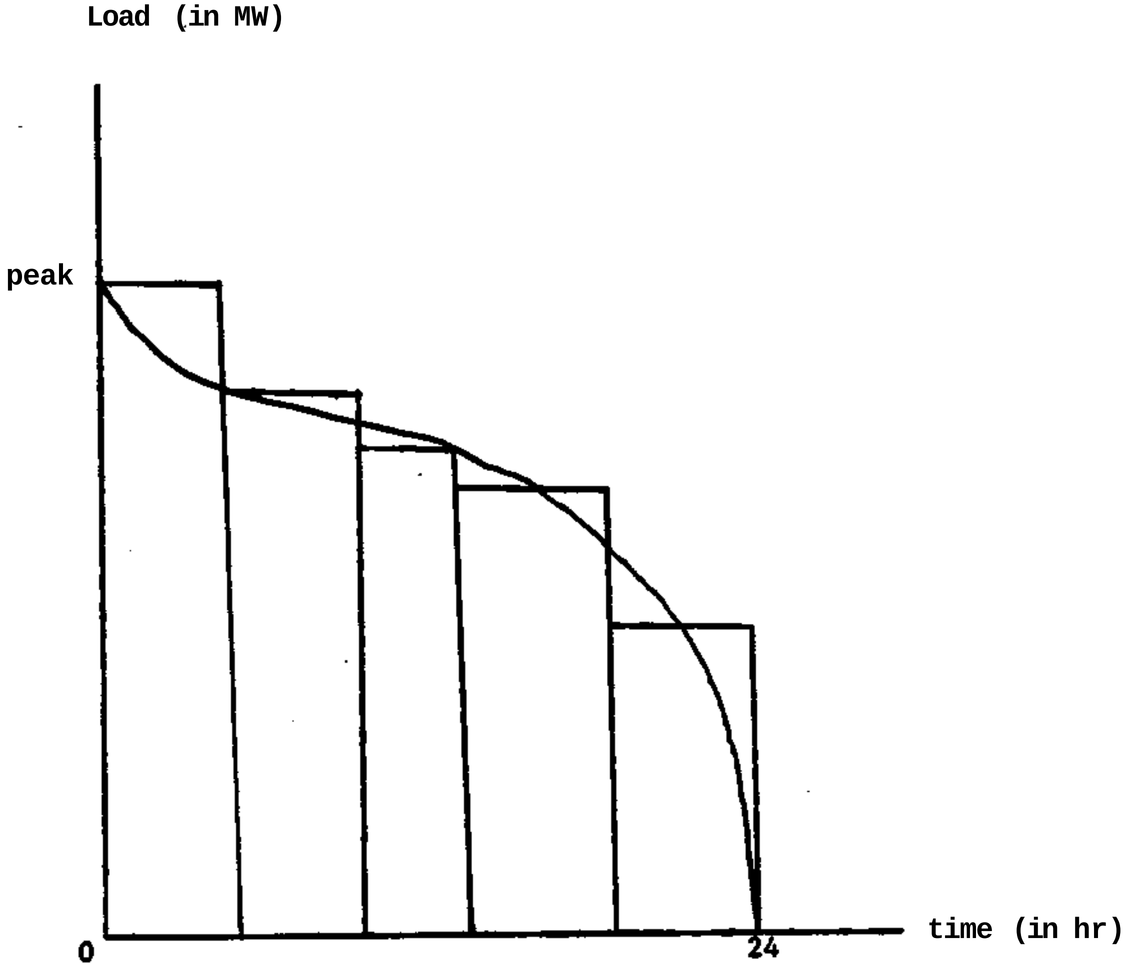

Figure 2. Discrete load segments obtained from the load duration curve.

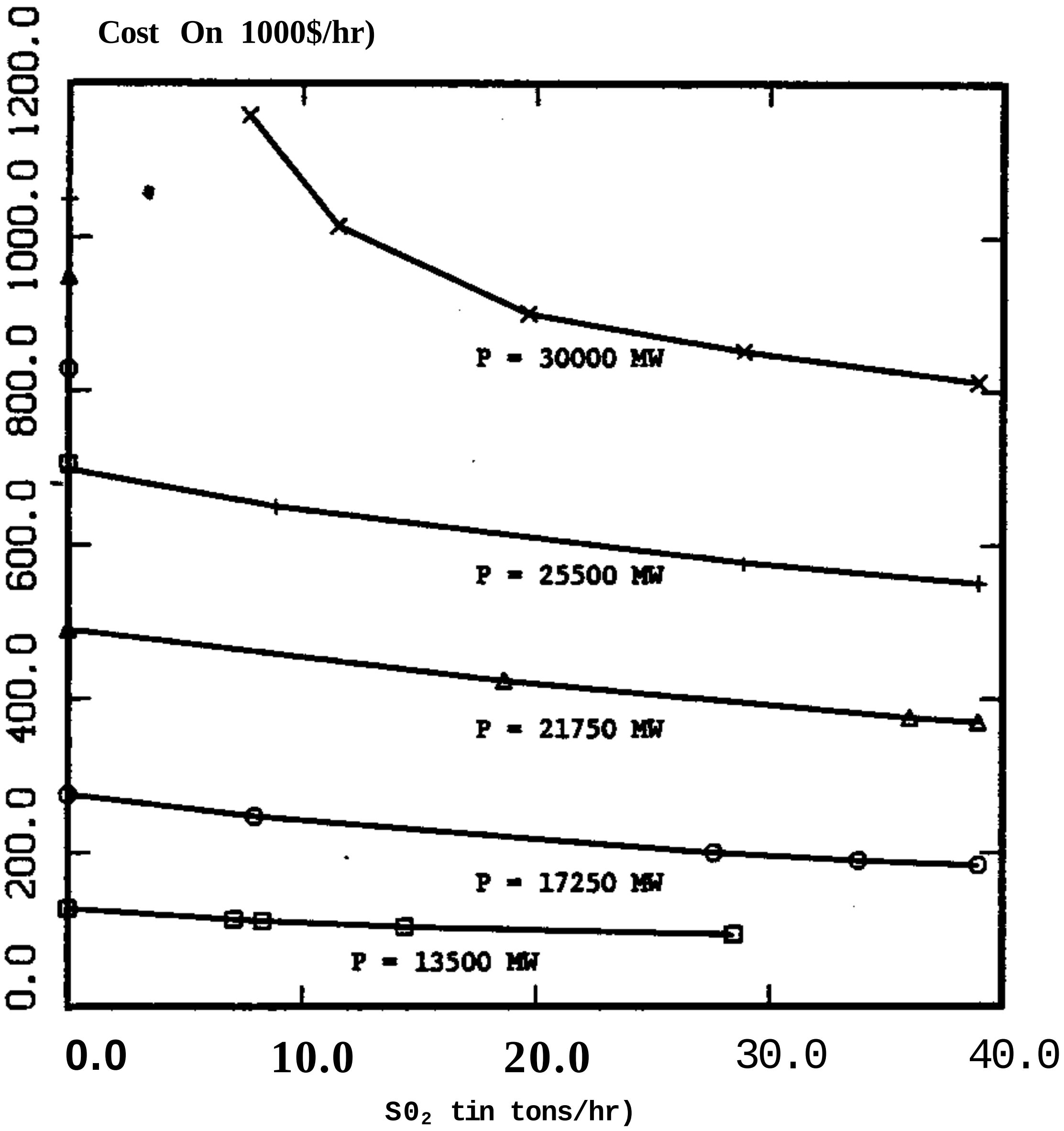

Figure 3. Pareto Frontiers obtained for desired load levels (90 generator example)

1. Load Segments

Load (MW)	Time/day (hr)
30000	4.8
25500	4.8
21750	4.8
17250	4.8
13500	4.8

2. Emission Constraint

I - 2.5 lb/fcWhr - 648 tons/day

3. Results

Optimal solution, K - $10.56 million/day.

Actual emissions * 474 tons/day

4. Timing (DEC-20)

Quadratic Program (Fletcher): 172.6 sec.

Proposed Tradeoff algorithm: 14.2 sec.

Figure 4. Summary of Emission constrained dispatch for a 90 generator example.

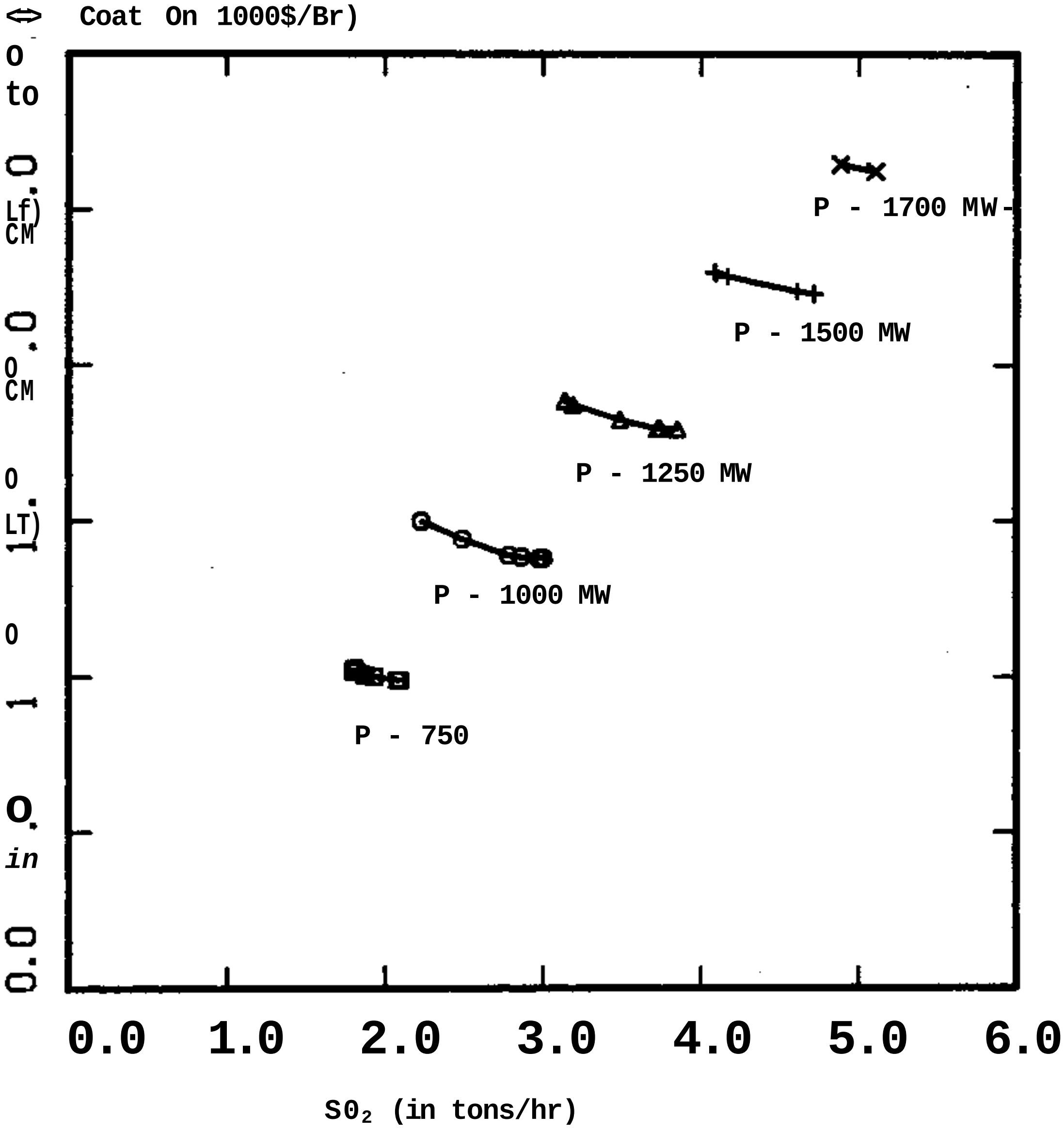

Figure 5. Pareto Frontiers obtained for representative load levels (16 generator example).

BIOGRAPHIES

Kavin Tyle received a B. Tech. degree from the Indian Institute of Technology, Kanpur in 1979 and a M.S. degree in electrical engineering from the University of Tennessee in 1980. Be is presently a graduate student at Carnegie-Mellon University, pursuing a Ph.D. degree in electrical engineering. His areas of Interest are Electric Power systems, Energy conversion, Optimization, and Computer aided design techniques. He is a student member of IEEE, APCA and AIAA.

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