

Environmental-Economic Power Dispatch with Diffusion Control of Air Pollutants Using a Pareto Optimization

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Abstract—In view of increasingly serious environmental problems, this paper proposes a novel environmental-economic power dispatch considering various targets. In the environmental-economic power dispatch, CO₂ emission is limited to alleviate global warming, while a novel diffusion control is established to deal with air pollution. The diffusion control firstly describes the space-time diffusion of air pollutants with Gaussian puff diffusion model, and then combines the environmental capacity of different districts to dispatch the output of generators, such that the air pollution caused by power generation can be truly reduced. Finally, a generalized normal boundary intersection method is developed to get Pareto solution set of the issue, and a best compromise solution is obtained with a multi-objective decision method. Simulation shows, the proposed power dispatch can reduce the CO₂ emission and the impact on air pollution as much as possible with a slight influence on operating cost.

Keywords—power dispatch; environmental-economic; diffusion control; pareto optimization

I. INTRODUCTION

Global warming and atmospheric pollution are two main environmental problems threatening people. Thermal power plants generate a lot of CO₂ and atmospheric pollutants during power generation, which have serious influence on the environment. In recent years, a considerable amount of researches on low-carbon and low-pollution power system have been made, including after-treatment of generation emissions, clean power generation, as well as power dispatch considering economic and environmental factors. Benefit from advantages of lower cost and quicker efficacy, environmental-economic power dispatch has attracted a wide spread attention.

At present, released pollutants are usually controlled from the perspective of emission amount, such as power dispatch incorporating carbon trading or carbon capture [1], single-objective dispatch taking emission amount as constraints or adding emission amount to objective with a penalty factor [2], and Pareto optimal dispatch simultaneously optimizing emission amount and other objectives [3]. However, regional characteristics including environmental tolerance and self-purification for pollutant emissions are ignored in emission amount control. For air pollutants like SO₂, NO_x and PM_{2.5},

their influence on human lives is closely related to the ground concentration, hence the control considering the ground concentration is more useful to lower the influence of these air pollutants. Due to the influence of environmental conditions like wind and atmospheric stability, as well as emission source conditions like position and emission mass, the influence of power system on the ground concentration varies in different districts. Therefore, it is of great significance to construct the space-time diffusion model of pollutant emissions relevant to environmental conditions and emission source conditions, to model the influence of power generation on air pollutant concentration.

To alleviate increasingly serious environmental problems, this paper proposes a novel environmental-economic power dispatch considering objectives of operation cost, carbon emissions and space-time diffusion of air pollutants. And a generalized normal boundary intersection (GNBI) is developed to get the Pareto solution set of the issue. The traditional NBI is limited to get the Pareto solution set of two-objective problem. While we have promoted NBI [4] and made the developed GNBI as a general method for higher- dimension multi-objective optimization. In addition, a combined-weight technique for order preference by similarity to ideal solution (CW-TOPSIS) is proposed to determine a best comprise solution from the Pareto solution set for the final decision.

II. ENVIRONMENTAL-ECONOMIC POWER DISPATCH

A. Gaussian Puff Diffusion

In a dispatch interval, generators will release a consecutive flow of smoke. In this paper, the smoke flow is approximated with multiple equal smoke clouds and the space-time diffusion of each smoke cloud is described by Gaussian puff diffusion model [5], as shown in Figure 1. Therefore, the dispatch interval Δt is divided into multiple equal emission intervals $\Delta \tau$, namely $\Delta \tau = \Delta t / n_{sc}$, where n_{sc} is the segment amount.

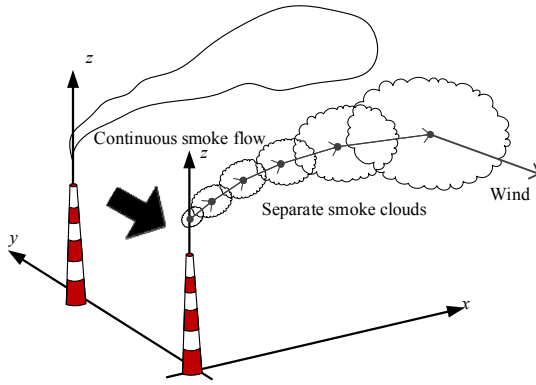


FIGURE 1. GAUSSIAN PUFF DIFFUSION MODEL

The influence of power system on the air pollutant concentration at a monitoring point during emission period τ equals the sum of the influence of smoke clouds released in previous W emission periods and all generators, as:

$$c_{\beta}(\tau, j) = \sum_{\tau'=\tau-W}^{\tau-1} \sum_{i \in \Omega_G} Q_{\beta,i}(\tau') \times G_i(\tau', \tau, x, y, z) \quad (1)$$

$$G_i(\tau', \tau, x, y, z) = \frac{\exp(-g/2)}{(2\pi)^{3/2} \sigma_x(\tau', \tau) \sigma_y(\tau', \tau) \sigma_z(\tau', \tau)} \quad (2)$$

$$g = \left(\frac{x - x_i(\tau', \tau)}{\sigma_x(\tau', \tau)} \right)^2 + \left(\frac{y - y_i(\tau', \tau)}{\sigma_y(\tau', \tau)} \right)^2 + \left(\frac{z - z_i(\tau', \tau)}{\sigma_z(\tau', \tau)} \right)^2 \quad (3)$$

where β is the index of air pollutant type; Ω_G is the set of generators; $Q_{\beta,i}(\tau')$ is the smoke cloud mass released at emission period τ' ; G is diffusion function; (x, y, z) is the location of the monitoring point; $\sigma_x, \sigma_y, \sigma_z$ are diffusion parameters; (x_i, y_i, z_i) is the location of the smoke cloud center.

The above diffusion parameters are calculated as:

$$\sigma_{\kappa}(\tau', \tau) = a_{\kappa}(\tau) \times [(\tau' - \tau) \Delta \tau]^{b_{\kappa}(\tau)} \quad (4)$$

where κ is the index of dimensions x, y, z ; $a_{\kappa}(\tau)$ and $b_{\kappa}(\tau)$ are diffusion coefficients determined by atmospheric stability. The diffusion parameters of two adjacent emission periods shall meet the following relation to make diffusion curve continuous.

$$\sigma_{\kappa}(\tau', \tau+1) = \left(a_{\kappa}(\tau+1)^{1/b_{\kappa}(\tau+1)} \Delta \tau + \sigma_{\kappa}(\tau', \tau)^{1/b_{\kappa}(\tau+1)} \right)^{b_{\kappa}(\tau+1)} \quad (5)$$

The position of each smoke cloud can be calculated according to the initial position and wind conditions.

$$\begin{bmatrix} x_i(\tau', \tau) \\ y_i(\tau', \tau) \\ z_i(\tau', \tau) \end{bmatrix} = \begin{bmatrix} x_{i,0} \\ y_{i,0} \\ z_{i,0} \end{bmatrix} + \sum_{n=\tau'}^{\tau} \begin{bmatrix} v_x(n) \\ v_y(n) \\ v_z(n) \end{bmatrix} \Delta \tau \quad (6)$$

where $(x_{i,0}, y_{i,0}, z_{i,0})$ is the position of the generator i ; $[v_x(n), v_y(n), v_z(n)]$ is the wind speed vector.

The above description studies the influence on atmospheric pollution concentration on the time scale of emission periods, while this paper cares more about the concentration at the time scale of dispatch periods. The air pollutant concentration at dispatch period t equals the average of the concentration at all inner emission periods.

$$C_{\beta}(t, j) = (1/n_{sc}) \sum_{\tau \in t} c_{\beta}(\tau, j) \quad (7)$$

B. Constraints Considering Environmental Capacity

As indicated in (1)-(7), the influence of power system on the atmospheric pollution concentration shows a direct dependence on generator output with a given predicted atmospheric condition, hence the air pollutant concentration at a monitoring point can be lowered by limiting power of generators having influence on it. Firstly, minimize the operation cost and get the initial influence of power system on air pollutant concentration $C_{\beta,0}(t, j)$. For monitoring points at densely populated districts, air pollutant concentrations need to be strictly controlled, while for monitoring points at sparsely populated districts, air pollutant concentrations can rise slightly since it is difficult to realize a concentration reduction of all monitoring points.

$$C_{\beta}(t, j) - C_{\beta,0}(t, j) \leq 0, j \in \Omega_{DP} \quad (8)$$

$$C_{\beta}(t, j) - C_{\beta,0}(t, j) \leq \varepsilon_{\max} C_{\beta,0}(t, j), j \in \Omega_{SP} \quad (9)$$

where Ω_{DP} and Ω_{SP} are respectively monitoring points at densely and sparsely populated districts; ε_{\max} is a small tolerance coefficient.

Sensitive degrees of districts vary for different population densities. Districts with higher population density have a lower environmental capacity and a higher requirement for environmental quality. This paper takes environmental capacity into account and takes the influence on air pollutant concentration at all districts as a dispatch objective.

$$f_{\beta} = \sum_{t \in T} \sum_{j \in \Omega_{DP}, \Omega_{SP}} \omega(j) C_{\beta}(t, j) \quad (10)$$

where $\omega(j)$ is the reciprocal of environmental capacity to give priority to reduce the atmospheric pollution concentration at important districts, $\omega(j)$ is approximated with population density.

Other constraints. This paper describes power system with DC power flow to make the power dispatch convex. Detailed description of DC power flow can be found in [6].

C. Objectives of Environmental-Economic Dispatch

(1) Operation cost

$$f_1 = \sum_{t \in T} \sum_{j \in \Omega_G} p_j (a_j (P_{G,j}^t)^2 + b_j P_{G,j}^t + c_j) \Delta t \quad (11)$$

where p_j is the fuel price; a_j , b_j and c_j are fuel consumption coefficients, $P_{G,j}^t$ is the output of the generator j .

(2) Carbon emissions

$$f_2 = \sum_{t \in T} \sum_{j \in \Omega_G} \eta_{\text{CO}_2,j} (a_j (P_{G,j}^t)^2 + b_j P_{G,j}^t + c_j) \Delta t \quad (12) \text{ where}$$

$\eta_{\text{CO}_2,j}$ is carbon emission coefficient of the generator j . (3) Influence on atmospheric pollution concentration

This paper studies the influence of power generation on the concentration of three air pollutants, including SO_2 , NO_x , $\text{PM}_{2.5}$. The smoke mass released by the generator j is:

$$Q_{\beta,j}(\tau') = \eta_{\beta,j} (a_j (P_{G,j}^t)^2 + b_j P_{G,j}^t + c_j) \Delta t \quad (13) \text{ where } \eta_{\beta,j}$$

is the emission coefficient of air pollutant β . Then the influence on the concentration of these three air pollutants is:

$$\min f_3 = \sum_{\beta \in \Omega_\beta} f_\beta / \bar{C}_{\beta,0}(t, j) \quad (14) \text{ where } \bar{C}_{\beta,0}(t, j)$$

is the average of $C_\beta(t, j)$.

III. SOLUTION METHODOLOGY

Compared with single-objective problem to obtain single solution, multi-objective problem based on Pareto theory needs to obtain a Pareto solution set. The objective vector set associated with Pareto solution set is called Pareto front [3]. Pareto optimizers aim to obtain a Pareto solution set which corresponds to an extensive and uniform Pareto front to ensure the diversity of solutions.

A. Generalized Normal Boundary Intersection

Based on the above Pareto theory, this paper develops GNBI to get the Pareto solution set of the environmental-economic power dispatch.

(1) Objective normalization

Firstly separately optimize each objective and obtain M extreme objective vectors $F_{B,j}(j=1,2,\dots,M)$. Normalize each objective, as:

$$r_j = (f_j - f_{j\min}) / (f_{j\max} - f_{j\min}), j = 1, 2, \dots, M \quad (15)$$

where M is the amount of objectives; f_j and r_j are the original and normalized value of the objective j ; $f_{j\max}$ and $f_{j\min}$ are the Upper and lower limits of the objective, which can be determined from these extreme objective vectors.

(2) Points selection in Utopia surface

The normalized objective vectors $R_{B,j}$ of the extreme objective vectors $F_{B,j}$ determine a Utopia surface. In order to obtain an extensive and uniform Pareto front, take Utopia surface as a projection surface of Pareto front, then all the intersection points of straight lines through points in Utopia surface and Pareto front constitute the final Pareto front. Points \bar{R}_i in Utopia surface can be determined with a linear combination of the normalized objective vectors.

$$\bar{R}_i = \sum_{j \in M} c_{ij} R_{B,j}, \sum_{j \in M} c_{ij} = 1, 0 \leq c_{ij} \leq 1 \quad (16)$$

where c_{ij} is combination coefficient, c_{ij} is determined from $[0, 1/H, \dots, H/H]$ (H is segment amount) to make points in Utopia surface uniform.

(3) Pareto solution calculation

Points R_i in Pareto front and points in Utopia surface satisfy:

$$R_i = \bar{R}_i - \lambda_i n, n = \frac{1}{M} \sum_{j \in M} R_{B,j} \quad (17)$$

where n is the direction vector of straight lines.

Each objective of the obtained solution will decrease as λ_i increases, when λ_i reaches the maximum, the intersection point of straight line and Pareto front is obtained. Therefore, the Pareto solution corresponding to each point in Utopia surface is:

$$\begin{aligned} \max \lambda_i \\ \text{s.t. } R_i = \bar{R}_i - \lambda_i n, G(R_i) \leq 0 \end{aligned} \quad (18)$$

where G is the set of model constraints.

B. Combined-weight TOPSIS

A Pareto solution set is obtained with GNBI for a multi-objective optimization, while only one comprise solution is required in practical decision. This paper employs CW-TOPSIS to determine the comprise solution. The combined weight is determined by both the objective weight and subjective weight.

$$\omega_j^* = \omega_j^{\text{obj}} \omega_j^{\text{sub}} / \sum_{j \in M} \omega_j^{\text{obj}} \omega_j^{\text{sub}} \quad (19)$$

$$\omega_j^{\text{obj}} = C_j / \sum_{j \in M} C_j, C_j = \sigma_j \sum_{k \in M} (1 - \rho_{jk}) \quad (20)$$

where ω_j^{obj} is the objective weight of the objective j , which is associated with the standard deviation of the objective σ_j and the

correlation coefficient with other objectives r_{jk} . The subjective weight is determined by the importance of objectives, which is set as [0.5,0.3,0.2] in this paper.

Finally, calculate the evaluation matrix according to the normalized objective matrix and the combined weight, and then determine the comprise solution according to TOPSIS. Detailed steps of TOPSIS can be found in [7].

IV. CASE STUDIES

This section constructs a region with three cities to study the performance of the proposed environmental-economic power dispatch and the solution methodology. We use IEEE 118-bus test system to represent the power system covering the region. The power system owns 22 coal-fired generators and 12 coal-fired generators. The region owns two types of districts, including city periphery and city center. Distribution of districts, monitoring points and generators is shown in Figure 2.

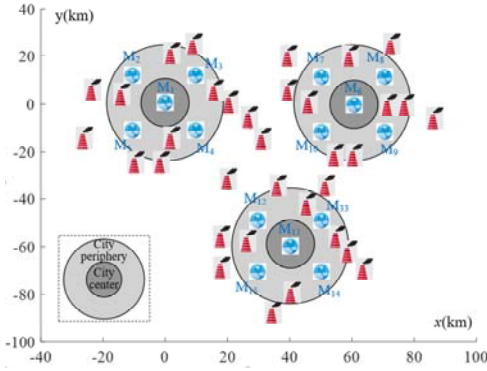


FIGURE II. DISTRIBUTION OF DISTRICTS, MONITORING POINTS AND GENERATORS

A. Superiority of Diffusion Control

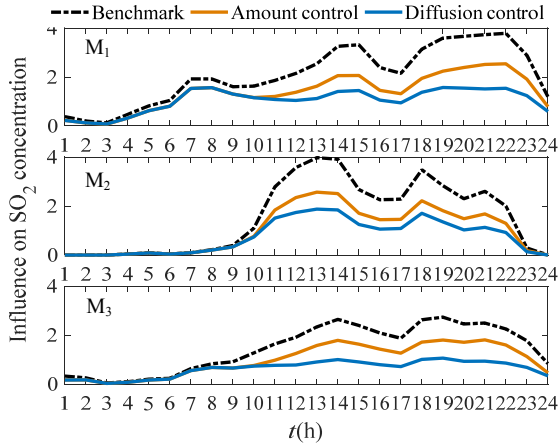


FIGURE III. INFLUENCE ON AIR POLLUTANT CONCENTRATION OF AMOUNT AND DIFFUSION CONTROL

Respectively employ traditional amount control to limit the atmospheric pollution emissions and diffusion control to lower the influence on the atmospheric pollution concentration, and obtain the influence on city center as shown in Figure 3. The

amount control cannot guarantee an enough reduction of atmospheric pollution concentration at important districts. While diffusion control takes precedence to lower the harm of atmospheric pollution since space-time diffusion of atmospheric pollution emissions and regional environmental requirements are considered. Besides, since the fuel cost of clean gas power generation is usually higher, operation cost and atmospheric pollution emissions are strongly contradictory. While influence on atmospheric pollution concentration (IOAPC) is not only relative to the emission parameters of generators, but also to the space-time diffusion of air pollutant emissions, hence operation cost and influence on atmospheric pollution concentration are less contradictory, as shown in Table 1.

TABLE I. OBJECTIVES IN COST OPTIMIZATION, AMOUNT AND DIFFUSION CONTROL

Case	Cost($\times 10^4$ \$)	Emissions(p.u.)	IOAPC(p.u.)
Min cost	825.2615	3.00	128.4699
Amount control	909.5959	2.18	90.6743
Diffusion control	836.4830	2.98	66.4638

B. Performance of Environmental-Economic Dispatch

Optimization solutions of the proposed environmental-economic power dispatch and single-objective optimization of these three objectives are presented in Table 2. As shown in the table, the comparison to the traditional economic dispatch shows that the proposed multi-objective dispatch reduces 3.15% carbon emissions and 24.34% influence on the air pollutant concentration, while the operation cost is only deteriorated by 1.20%. Besides, as shown in Figure 4, through the diffusion control of atmospheric pollution emissions, the influence of power generation on atmospheric pollution concentration is effectively reduced by the environmental-economic dispatch, especially at the city center.

TABLE II. RESULTS OF SINGLE AND MULTIPLE OBJECTIVES OPTIMIZATIONS

Objective	$f_1(\times 10^4$ \$)	$f_2(\times 10^4$ t)	f_3 (p.u.)
Operation cost	825.2615	19.1132	128.4699
Carbon emissions	878.9792	16.9899	101.8202
Air pollutant	836.4830	19.1282	66.4638
Environmental-economic	835.1797	18.5118	97.2009

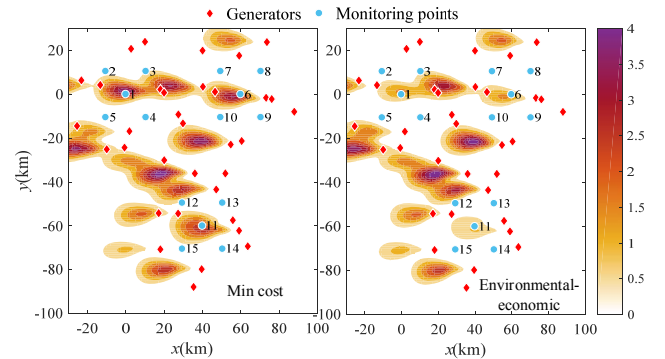


FIGURE IV. DISTRIBUTION OF INFLUENCE ON AIR POLLUTANT CONCENTRATION

C. Analysis of Pareto Optimization

The Pareto front of the environmental-economic power dispatch with three objectives is shown in Figure 5. As shown in the figure, GNBI can obtain an evenly and widely distributed Pareto front, which can provide decision makers with diversified solutions. Decision makers can select an appropriate solution according to practical requirements. When only one objective is considered, the endpoints of Pareto front are the final solutions, when multiple objectives are considered, the final solution can be determined by CW-TOPSIS by properly setting the weights of objectives.

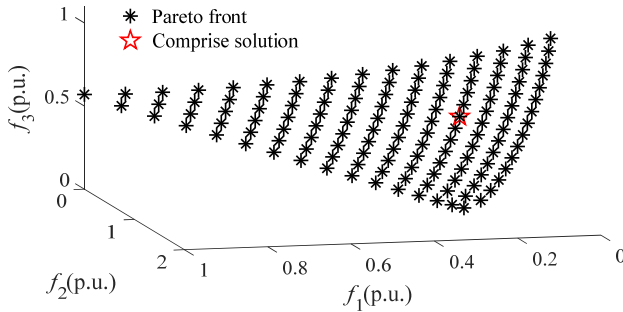


FIGURE V. PARETO FRONT OF THE DISPATCH

V. SUMMARY

To alleviate the two main environmental problems of global warming and atmospheric pollution, this paper propose an environmental-economic power dispatch incorporating diffusion control of air pollutants, and solves the issue with a Pareto optimization. The comparison to the traditional economic dispatch shows that the proposed power dispatch can reduce the CO₂ emission and the impact on air pollution as much as possible with a slight influence on operating cost.

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