

Multi-objective Interval Optimization of Virtual Power Plant Considering the Uncertainty of Source and Load

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Abstract. As the proportion of electric vehicles and distributed power sources connected to the power grid continues to increase, virtual power plants provide new ideas for effectively solving electric vehicles and distributed power sources connected to the grid. Considering that there are obvious uncertainties in the number of dispatchable electric vehicles and the output of distributed power sources, this paper focuses on the multi-objective interval optimization problem of virtual power plants considering the uncertainty of source load. Based on the analysis of the virtual power plant architecture, aiming at the uncertainty of the source load, a multi-objective interval optimization model of the virtual power plant was established using the interval number theory; in order to verify the validity of the established model, a virtual power plant in a certain area was selected as an example for analysis. The results show that the uncertainty of distributed power sources and electric vehicles can be better avoided in the interval optimization process, and the proposed scheme has strong robustness.

1 Introduction

In recent years, in response to energy crisis and environmental pollution, China has vigorously developed distributed new energy sources and promoted electric vehicles. The proportion of the two on the power generation side and the power consumption side has been increasing. However, due to the strong advantages of distributed new energy and electric vehicles The randomness and volatility of the power grid will have a certain impact on the operation of the power grid [1-5].

The proposal of virtual power plant (VPP) provides new ideas for solving the above problems. At present, scholars have conducted various researches on the multi-objective optimization of virtual power plants. Literature [6] constructed a virtual power plant economic optimization scheduling model with electric vehicles, used particle swarm optimization to optimize the output of each component, and analyzed the impact of electric vehicle penetration on the economics of the virtual power plant and the output of each unit. Literature [7] constructed a virtual power plant stochastic scheduling optimization model considering the uncertainty of wind and solar, and analyzed the multi-faceted benefits of

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virtual power plants that include electricity-to-gas participation in the power market, carbon trading market, and natural gas market. Since there are obvious uncertainties in the number of dispatchable electric vehicles and the output of distributed power sources, these uncertainties must be considered when optimizing the dispatch of virtual power plants.

First, briefly describe the structure of the virtual power plant and analyze the charging demand for electric vehicles; then, with the goal of maximizing economic benefits, optimal user comfort, and minimal carbon emissions, combined with interval number theory, establish a virtual power plant interval optimization model; finally, pass The calculation example analysis verifies the rationality of the proposed model, and proposes a virtual power plant optimal scheduling scheme.

2 Virtual power plant model

2.1 Basic architecture of virtual power plant

This paper studies virtual power plants including distributed power sources, energy conversion devices, energy storage devices and user loads. It builds bridges with public power grids and natural gas networks to achieve flexible energy interaction. The load mainly includes electric load, residential thermal load and natural gas load. Figure 1 shows the basic structure of a virtual power plant.

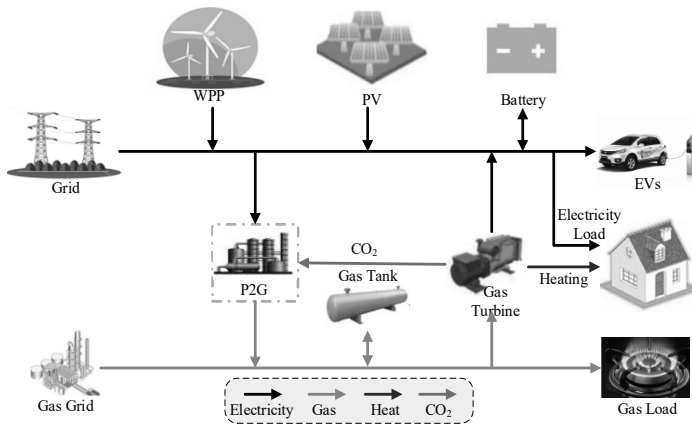


Fig.1. Basic structure of virtual power plant

2.2 Energy conversion equipment model

The core device of power to gas (P2G) technology is the electrolyzer, and the quality of the electrolyzer determines the conversion efficiency of the P2G equipment. The current mainstream electrolyzer technologies include three types: alkaline electrolyzer, solid oxide electrolyzer and proton exchange membrane electrolyzer^[8]. This paper establishes a model of a proton exchange membrane electrolyzer and a model of a methane reactor, and the output hydrogen power:

$$G_{H_2} = \alpha_{P2H_2} \cdot \frac{P_{P2H_2}}{P_{P2H_2, rated}} \cdot V_{ec} \quad (1)$$

Considering that the operating efficiency of the methane reactor is actually related to factors such as the ratio of synthesis gas, pressure and temperature, the following methane reactor model is established for the convenience of calculation. The methane reactor's power to produce natural gas is:

$$G_{CH_4} = \frac{\eta_{P2CH_4} \cdot G_{H_2} \cdot H_{CH_4} \cdot \alpha}{m_{CH_4}} \tag{2}$$

2.3 Behavioral characteristics of electric vehicles

Assuming cluster scheduling for 1000 electric vehicles, considering the travel law of electric vehicles, and counting the driving characteristic data of vehicles, its distribution function is as follows.

$$f(x_i) = \begin{cases} \frac{1}{\sigma_i \sqrt{2\pi}} \exp\left[-\frac{(x_i - \mu_i)^2}{2\sigma_i^2}\right] & \mu_i - 12 \leq x_i \leq 24 \\ \frac{1}{\sigma_i \sqrt{2\pi}} \exp\left[-\frac{(x_i + 24 - \mu_i)^2}{2\sigma_i^2}\right] & 0 \leq x_i \leq \mu_i - 12 \end{cases} \tag{3}$$

3 Optimal model of virtual power plant interval

3.1 Interval optimization theory

$a = [\underline{a}, \bar{a}]$ is called an interval number, among them $\underline{a}, \bar{a} \in R$, they are called the lower and upper limits of a , and $\underline{a} \leq \bar{a}$. $w(a) = \bar{a} - \underline{a}$ is called the width, $m(a) = (\underline{a} + \bar{a})/2$ is called the midpoint. In this article, [...] indicate the number of intervals with a certain width.

The interval multi-objective optimization problem can be explicitly defined as follows:

$$\begin{cases} \min_{x \in \Omega} F(x) = (f_1^1(x, c), f_2^1(x, c), \dots, f_M^1(x, c)) \\ s.t. \quad g_j(x, c) \geq a_j = [\underline{a}_j, \bar{a}_j], \quad j = 1, 2, 3, \dots, p \\ \quad \quad h_k(x, c) = b_k = [\underline{b}_k, \bar{b}_k], \quad k = 1, 2, 3, \dots, q \\ \quad \quad x \in \Omega \end{cases} \tag{4}$$

3.2 Variable setting

In the scheduling period, the parameters to be optimized in the model include the decision variables of all scheduling periods. The decision variables are shown in Table 1.

Table 1. Decision variables

Variable name	Variable description
$P_{PMT,t}$	Gas turbine output power
$P_{P2G,t}$	Electric to gas equipment power
$P_{es,t}$	Power of storage equipment
$V_{gs,t}$	Gas storage capacity of gas storage

This paper uses interval numbers $[P_{PV}], [P_{WPP}], [P_{load}], [P_{ev}], [V_{gas}]$ to represent the random fluctuation range of uncertain factors such as photovoltaic power, wind power, conventional electric load, electric vehicle load, and gas load, forming an interval vector $c = ([P_{PV}], [P_{WPP}], [P_{load}], [P_{ev}], [V_{gas}])^T$.

3.3 Objective function

This paper considers operating economic benefits, resident comfort, and carbon dioxide emissions as optimization goals to achieve the optimization of virtual power plants. Considering the uncertainty in the previous section as an interval number, construct an interval objective function As shown in the following formula:

$$F = \begin{cases} \max([f_{sy}]) = [\underline{f_{sy}}, \overline{f_{sy}}] \\ \min([f_{ss}]) = [\underline{f_{ss}}, \overline{f_{ss}}] \\ \min([f_{cpai}]) = [\underline{f_{cpai}}, \overline{f_{cpai}}] \end{cases} \quad (5)$$

(1)Economic benefits: The operating income of the virtual power plant described in this article refers to the net income of the virtual power plant after deducting the operation and maintenance costs of distributed power sources and the cost of energy purchase. The specific objective function is:

$$\max([f_{sy}]) = [C_{sell}^{energy}] + [C_{buy}^{energy}] - [C_{op}^{DGs}] \quad (6)$$

(2)Users' comfort: The virtual power plant's thermal comfort objective function is to calculate the sum of squares of deviations between the real-time temperature and the set temperature in all dispatch periods. The specific objective function is:

$$\min([f_{ss}]) = \sum_{t=1}^{24} ([T_{in}(t)] - T_s)^2 \quad (7)$$

(3)Carbon dioxide emissions: Assuming that all electricity purchased from the grid is coal-fired power generation, the pollutant emission sources of the virtual power plant described in this article are mainly electricity purchased from the grid and natural gas power generation. However, because the electricity-to-gas device is environmentally friendly. The objective function is:

$$\min([f_{cpai}]) = \sum_{t=1}^{24} ([P_{grid,t}^{ex}] \cdot \lambda_{grid} + [V_{gas,t}^{ex}] \cdot L_{gas} \cdot \lambda_{gas} - Q_{pai,t} \cdot \lambda_{P2G}) \quad (8)$$

3.4 Constraints

(1)Power balance constraints:

$$[P_{grid,t}^{ex}] = [P_{load,t}] + [P_{ev,t}] + P_{P2G,t} + P_{es,t} - [P_{WPP,t}] - [P_{PV,t}] - P_{PMT,t} \quad (9)$$

$$[V_{gas,t}^{ex}] = [V_{gload,t}] + V_{PMT,t} + V_{gs,t} - V_{P2G,t} \quad (10)$$

(2)Transmission power constraint:

$$P_{grid,min}^{ex} \leq [P_{grid,t}^{ex}] \leq P_{grid,max}^{ex} \tag{11}$$

$$V_{gas,min}^{ex} \leq [V_{gas,t}^{ex}] \leq V_{gas,max}^{ex} \tag{12}$$

4 Case analysis

4.1 Planning results

In this paper, a non-dominated sorting genetic algorithm is used, the median value scatter diagram of the objective function is shown in Figure 2.

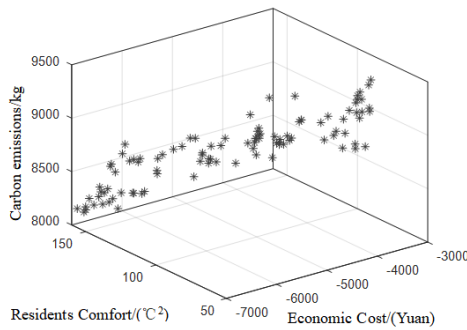


Fig. 2. Typical pareto optimal solution set

The above three graphs respectively represent three objective function values. Draw a specific scheduling scheme diagram and corresponding temperature feedback diagram for the optimal values of the three objective functions, as shown in Figure 3-5.

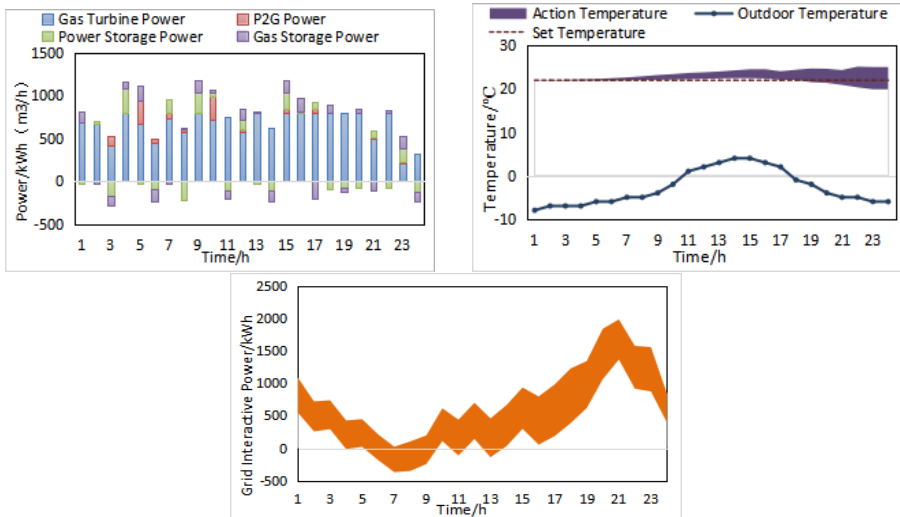


Fig. 3. The most economical solution

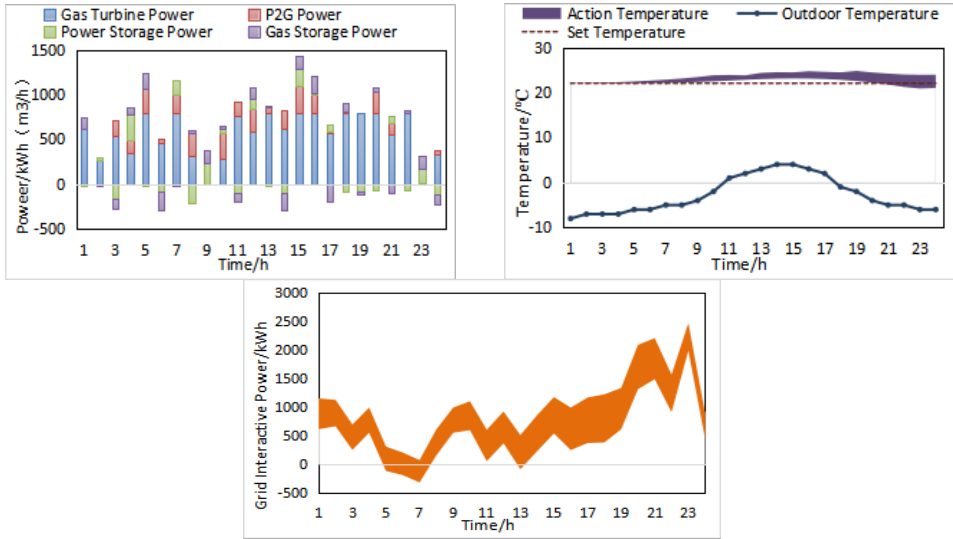


Fig. 4. The optimal solution for comfort

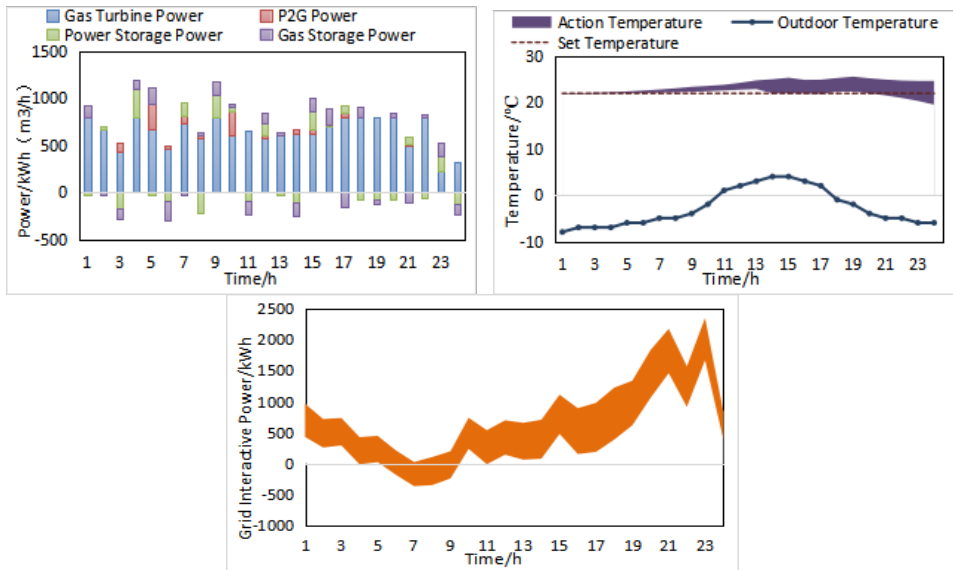


Fig. 5. The best solution for environmental protection

4.2 Result analysis

Referring to the most economical, most comfortable and most environmentally friendly scheduling scheme in the typical Pareto optimal solution set in the previous section, it can be found that there is a pairwise restriction relationship between the three objective functions.

For the most economical dispatching plan, the gas turbine basically maintains full power operation during the period of high electricity price (15:00~22:00), and the power fluctuation range of interaction with the grid is small; the median indoor temperature is always higher than during the period of high electricity price. The optimal set temperature is lower than the set temperature at the end of the scheduling period, indicating that the

program improves operating economy by reducing heating requirements for some time periods.

For the most comfortable scheduling scheme, the interaction power curve between the system and the grid fluctuates significantly. This scheme can effectively control the fluctuation of indoor temperature under the premise of meeting the electric load demand; The working power of the gas turbine is improved compared with the other two scenarios. The figure shows that the median indoor temperature is close to the optimal set temperature in most scheduling cycles.

For the most environmentally friendly dispatching plan, the dispatching result is closer to the most economical dispatching plan. The median indoor operating temperature is always higher than the optimal set temperature during periods of high electricity prices, and is lower than the optimal set temperature at the end of the dispatch period, and the fluctuations in the dispatch cycle are relatively obvious, which indicates that the program mainly reduces energy consumption by reducing heating requirements for certain periods of time, thereby reducing pollutant emissions.

5 Conclusion

This paper studies the interval optimization strategy of the virtual power plant. A calculation example is analyzed for the heating scene in winter, and the conclusions show that:

(1) Considering uncertain factors, the fluctuation range is uncertain, the target function value in the scheduling result fluctuates more obviously and the interval width varies, and it is more realistic to analyze the interval curve to develop a scheduling plan;

(2) Compared with the deterministic optimization scheduling model, the scheduling scheme solved by the interval optimization scheduling model is more conservative and more robust in terms of ensuring thermal comfort.

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Table 2. Appendix

Parameter	Parameter meaning	parameter
G_{H_2}	The amount of hydrogen output	m^3
P_{P2H_2}	Enter the electric power of the electrolyzer	kW
$P_{P2H_2,rated}$	Rated value of input electric power of electrolyzer	kW
α_{P2H_2}	Electrolysis efficiency coefficient of electrolyzer	0.5-0.8
V_{ec}	Rated capacity of electrolyzer	m^3
G_{CH_4}	Output of natural gas	m^3
η_{P2CH_4}	Operational efficiency of methanation reactor	
H_{CH_4}	Low calorific value of natural gas	kW / m^3
α	Conversion coefficient of molar mass of natural gas	
m_{CH_4}	Gas quality per cubic meter of natural gas pipeline	kW / m^3
x	Decision variables	
Ω	Decision space	
c	Interval vector	
$g_j(x,c) \geq a_j$	Interval inequality constraints	
$h_k(x,c) = b_k$	Interval equality constraints	
$f_1^1(x,c)$	Objective function	
f_{sy}	Virtual power plant operating income	Yuan
f_{ss}	Resident user comfort	$(^\circ C)^2$
f_{cpai}	CO ₂ emissions during the virtual power plant cycle	kg
$[C_{sell}^{energy}]$	Virtual power plant energy supply revenue	Yuan
$[C_{buy}^{energy}]$	Virtual power plant energy purchase cost	Yuan
$[C_{op}^{DGs}]$	Operation and maintenance cost of each unit	Yuan
$[T_{in}(t)]$	Operating temperature at time t in the scheduling	$^\circ C$
T_s	Set temperature	$^\circ C$
λ_{grid}	Emission factor for purchasing electricity from the	kg / kWh
λ_{gas}	Natural gas power generation emission factor	kg / kWh
L_{gas}	Low calorific value of natural gas	kWh / m^3
$Q_{pai,t}$	The amount of carbon dioxide emitted by the gas	m^3
λ_{P2G}	P2G equipment absorption coefficient of carbon	kg / m^3