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Frequency Response Strategies Considering Gas-thermal Inertia in the Integrated Energy System

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ABSTRACT

Due to the intermittence of renewable energy and its large-scale access in the power grid, frequency stability control faces severe challenges. To address this issue, this paper considers gas-thermal inertia in the integrated energy system (IES) to provide frequency response. Due to their similar slow dynamic characteristics, this paper gives detailed explanations on power support characteristics of gas-thermal inertia, based on which presents a new method to provide frequency response in IES. The proposed method is tested in an actual scenario and the advantages of considering gas-thermal inertia are verified.

Keywords: frequency response, gas-thermal inertia, integrated energy system

1. INTRODUCTION

In IES, due to the volatility, uncertainty and uncontrollability of renewable energy, it is difficult to maintain the power balance between supply side and demand side of power grid[1]. Also, with large-scale renewable energy access and replacement of traditional thermal power units, the dynamic response of power grid frequency tends to show characteristics of low inertia or even zero inertia, which further increases the uncertainty of power grid operation. Therefore, the frequency stability control of IES faces severe challenges.

To cope with it, and to save resources and avoid additional cost of system configuration, taking use of existing configuration and resource flexibility will greatly reduce the cost of providing frequency response. In IES, gas-thermal systems are slow dynamic systems, which can increase the flexibility of energy utilization potential.

For natural gas system, gas generation is playing an increasingly prominent role in providing flexibility to meet net-load requirements [2]. In [3], natural gas network can serve as a back-up technology to ensure security of supply and provide short-term flexibility. For thermal system, [4] uses thermal inertia to provide frequency response in central heating system, which provides a new way of using thermal inertia.

Many studies have considered gas or thermal inertia in the operation of IES, but there is a lack of detailed explanation on their basic theory. Therefore, this paper will present mathematical models, along with physical models for the validation of gas-thermal inertia. And due to their power support characteristics, a new means to provide frequency is proposed. Besides, proper use of inertia will replace part of energy consumption, thus reducing carbon emission. Therefore, carbon cost is also considered in the optimization.

The rest of paper is organized as following: the definition and support characteristics of gas-thermal inertia are presented in section 2; in section 3, a new method to provide frequency response in IES considering gas-thermal inertia is proposed; in section 4, the new method is carried out in a real scenario and the results are shown; finally, in section 5, we draw the conclusion.

2. DEFINITION AND SUPPORT CHARACTERISTICS OF GAS-THERMAL INRETIA

In an electric system, electric inertia is characterized as “providing frequency response without using external energy”. This "inertia" is quite similar to that of gas-thermal system in dealing with energy fluctuations. Therefore, this paper starts with introducing the concept of "gas-thermal inertia".

2.1 Definition of gas-thermal inertia

In IES, thermal inertia can be defined as thermal delay and thermal fuzziness. Firstly, due to the long transmission pipe, it takes a few minutes to a few hours for thermal fluctuations transmitted from the source to the load side. Secondly, thermal load can always maintain the comfortable temperature despite small

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power fluctuations, unless the temperature exceeds the upper or lower limits of its comfort range.

In IES, gas inertia can be defined as gas delay and gas pipe storage. Firstly, gas pressure at the end of pipe will decrease with a time delay if the load increases with a sudden increase gas flow rate. Secondly, gas pipe storage can always be released quickly within limits to supply the sudden increasing load.

2.2 Support characteristics of gas-thermal inertia

2.2.1 Support characteristics of thermal inertia

Based on the thermal delay, fuzziness and loss, the indoor temperature response model of thermal buildings is established.

$$\begin{cases} T_{b,t+\Delta t} = T_{b,t} + \dfrac{\left(H_{b,t} - H_{loss,b}\right)\Delta t}{CM} \\ H_{loss,b} = \varepsilon_{loss}\left(T_{b,t} - T_{out,t}\right) \end{cases} \quad (1)$$

$T_{b,t+\Delta t}$、$T_{b,t}$ are the indoor temperature of the thermal building at time *t* and *t*+1. $T_{out,t}$ is the outdoor temperature at time *t*. $H_{b,t}$ is the thermal power for the building b at time *t*. $H_{loss,b}$ is the thermal loss power of the building. C is the specific heat capacity of indoor air, M is the mass of indoor air. ε_{loss} is the heat dissipation coefficient of the building.

Assuming that $T_{out,t}$ remains the same, through Laplace transformation, indoor temperature response function of the thermal building is obtained, as shown in Eq.2.

$$T_b(t) = \frac{H_{b,2} - H_{b,1}}{\varepsilon_{loss}} + \left[\frac{2H_{b,1} - H_{b,2}}{\varepsilon_{loss}} + \frac{\varepsilon_{loss}T_{out} + CMT_b\left(0^-\right)}{CM}\right] e^{-\frac{\varepsilon_{loss}}{CM}t} \quad (2)$$

The thermal power provided to the building decreases instantaneously from the normal value $H_{b,1}$ to $H_{b,2}$ at time t_1. $T_b(t)$ is the temperature of the building at time *t*. $H_b(t)$ is the thermal power for the building b at time *t*.

From Eq.2, considering thermal loss and thermal inertia, the indoor temperature response of thermal buildings shows a negative exponential trend. Then, a physical model of indoor temperature response of thermal building is set up below in Fig.1. The simulation results are shown in Fig.2.

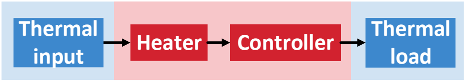

Fig. 1 Physical model of thermal inertia

During t_1 to t_2, the temperature response indeed shows a negative exponential trend. When the thermal input changes rapidly at t_1 and t_2, T_b always changed with a time delay. Meanwhile, as long as T_b does not exceed $T_{b,\max}$ or $T_{b,\min}$, the temperature is allowed to fluctuate within the temperature range.

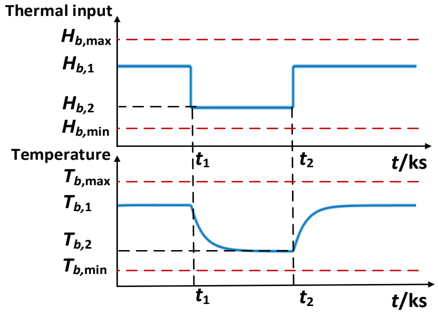

Fig. 2 Support characteristics of thermal inertia

It can be seen that even if power fluctuation occurs at the thermal source, the influence of the imbalance between thermal power supply and demand on the load side can be greatly reduced due to thermal inertia. Therefore, power support from thermal inertia can be provided.

2.2.2 Support characteristics of gas inertia

Pressure response model of gas pipeline end is established based on gas inertia.

The known transient transmission process of natural gas pipeline can be characterized as:

$$\begin{cases} \dfrac{\partial \rho}{\partial t} + \dfrac{\partial \rho v}{\partial x} = 0 \\ \dfrac{\partial \rho v}{\partial t} + \dfrac{\partial \rho v^2}{\partial x} + \dfrac{\partial P}{\partial x} + \dfrac{\lambda \rho v^2}{2D} + \rho g \sin\theta = 0 \end{cases} \quad (3)$$

where ρ、v、P are the density, velocity and pressure of natural gas, λ、D、θ are friction coefficient of pipe, inner diameter and inclination angle of pipe to horizontal plane, g is the acceleration of gravity, x、t are the space variable and time variable.

If f is defined as the flow rate of pipeline:

$$\begin{cases} P = R_M T \rho \\ \mathrm{f} = \rho v A \end{cases} \quad (4)$$

where R_M is the quotient of the gas constant to the molar mass, T is the temperature of natural gas, A is the cross sectional area of pipeline.

Based on the idea of finite element approximation，considering v^2、θ to be 0 and assuming the gas source is in constant pressure control mode, the gas pressure response equation can be solved as Eq.5 through Laplace transformation.

The load demand increases instantaneously at t_1, and the flow rate f_{out} drops from the normal value f_1 to f_2. Meanwhile, $a_1 = \dfrac{AL}{R_M T}$, $a_2 = \dfrac{A\lambda\upsilon L}{2DR_M T}$, $a_3 = \dfrac{A}{L}$,

$b_1 = \frac{\lambda \upsilon}{2D}$, $b_2 = \frac{A}{L} P_{in}$, $P_{out}(0^-) = \dot{P}_{out}(0^-) = 0$. $-x_1$ and $-x_2$ are the two roots of the equation $s^2 + \frac{a_2}{a_1} s + \frac{a_3}{a_1} = 0$.

$$P_{out}(t) = \frac{b_2 - b_1 f_2 + b_1 f_1}{a_1 x_1 x_2} - \frac{1}{a_1(x_2 - x_1)}\left[\frac{(x_1 - b_1)(2f_1 - f_2) - b_2}{x_1} e^{-x_1 t} - \frac{(b_1 - x_2)(2f_1 - f_2) + b_2}{x_2} e^{-x_2 t}\right] \tag{5}$$

Since $x_1, x_2 \geq 0$, it can be concluded that the pressure at the end of the natural gas pipeline also shows a negative exponential trend. Then, a physical model of the pressure response at end of gas pipe is built in Fig.3. Simulation results are in Fig.4.

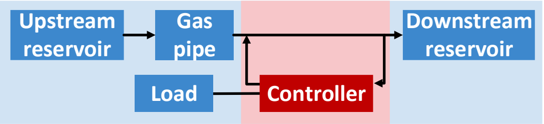

Fig. 3 Physical model of gas inertia

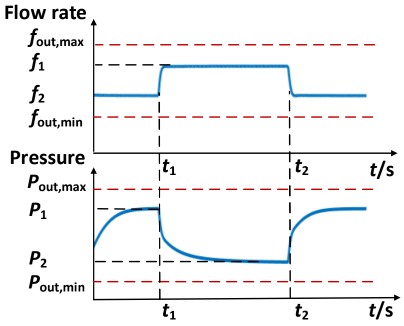

Fig. 4 Support characteristics of gas inertia

During t_1 to t_2, the pressure response indeed shows a negative exponential trend. When the load suddenly changes at t_1 and t_2, the flow rate at the end of the pipe f_{out} changes with a time delay.

It can be seen that even if the load fluctuates in a small range, the gas delay and gas pipe storage can still effectively provide buffer space, so as to reduce the impact of the imbalacnce between power supply and demand at the load side and provide power support for the system.

3. FREQUENCY RESPONSE PROVIDED BY GAS-THERMAL INERTIA

In the operation of power grid, frequency fluctuation often occurs due to the imbalance of power supply. At this time, the generation side needs to supply the power grid in a short time. However, compared with the traditional method, using gas-thermal inertia will be more economical. This chapter first studies the benefits of using gas-thermal inertia as a new means to participate in the frequency response of IES. Then, carbon cost will be considered in the optimization goal, so as to study how economical and environmental gas-thermal inertia is.

3.1 Frequency response methods of gas-thermal inertia

3.1.1 Typical structure of IES

The internal structure of IES studied in this paper is shown in Fig.5.

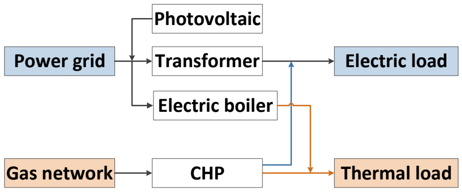

Fig. 5 Internal structure

L_e is the electric load. L_h is the thermal load. P_e is the external power supply. P_g is the external gas network. η_{CHPH} and η_{CHPE} are the gas-heat and gas-electricity conversion efficiency of combined heat and power (CHP) units. η_T and η_{EB} are the transformer and electric boiler conversion efficiency. λ is the electric energy distribution coefficient. Then input and output model of the energy hub is as follows:

$$\begin{bmatrix} L_e \\ L_h \end{bmatrix} = \begin{bmatrix} \lambda \bullet \eta_T & \eta_{CHPE} \\ (1-\lambda)\eta_{EB} & \eta_{CHPH} \end{bmatrix} \bullet \begin{bmatrix} P_e \\ P_g \end{bmatrix} \tag{6}$$

3.1.2 Frequency response methods in IES

If the power grid frequency drops and the power needs to be increased, the electricity supplied to the electric boiler can be transferred to the transformer firstly, so that electric power can be increased. Secondly, the valve of gas pipeline can be opened quickly in a short time, and part of the gas pipe storage can be released to generate more electric power.

However, when the intake gas is increased, thermal power generated by CHP will also be increased. This part can be offset by the reduction of thermal power due to the reduction of electricity supply to the electric boiler, and the other part of the additional thermal power will affect the temperature of the load side. But due to thermal inertia, the load side temperature can still maintain a relatively comfortable temperature only at the expense of user comfort.

3.2 Optimization model of gas-thermal inertia

3.2.1 The objective function

This paper considers gas-thermal inertia, generation side, user comfort and thermoelectric ratio cost in the modeling. On the premise of ensuring the system reliability level, the objective function is to minimize the system total cost of providing frequency response during the occurrence period of the studied fault:

$$\begin{aligned}\min \mathrm{Cos}tf\left(t\right) = C_{GRf}\left(t\right)+C_{HRf}\left(t\right)+C_{COM}\left(t\right) \\ +C_{HE}\left(t\right)+C_{sf}\left(t\right)\end{aligned} \tag{7}$$

If carbon cost is included, the objective function is as follows:

$$\begin{aligned}\min \mathrm{Cos}tf\left(t\right) = C_{GRf}\left(t\right)+C_{HRf}\left(t\right)+C_{COM}\left(t\right) \\ +C_{HE}\left(t\right)+C_{sf}\left(t\right)+C_{cb}\left(t\right)\end{aligned} \tag{8}$$

where $Costf\left(t\right)$, $C_{GRF}\left(t\right)$ and $C_{HRF}\left(t\right)$ are the total cost, gas inertia and thermal inertia cost at time *t*. $C_{COM}\left(t\right)$, $C_{HE}\left(t\right)$, $\mathrm{C}_{sf}\left(t\right)$ and $\mathrm{C}_{cb}\left(t\right)$ are the user comfort, thermoelectric ratio, generation side and carbon cost at time *t*. *t* is the fault occurrence period. Each cost calculation method is shown below.

$$\begin{cases} C_{GRf}\left(t\right)=c_{GR}RG\left(t\right) \\ C_{Sf}\left(t\right)=c_{S}RS\left(t\right) \\ C_{HRf}\left(t\right)=c_{HR}RH\left(t\right) \\ C_{COM}\left(t\right)=\sum_{n=1}^{N}c_{COM}\left(n\right)\left|P_h^n\left(t\right)\right| \\ C_{HE}\left(t\right)=\sum_{a=1}^{M}c_{HE}\left(a\right)RG\left(t\right) \\ C_{cb}\left(t\right)=\left[Q_{CHP}\left(t\right)+Q_{E}\left(t\right)\right]p_c \end{cases} \tag{9}$$

Among them, gas inertia cost price and thermal inertia cost price are fixed price. c_{GR} is the output cost price of gas inertia. $RG\left(t\right)$ is the output of gas inertia in *t* period. c_{HR} is the dispatching cost price of thermal inertia, and $RH\left(t\right)$ is the thermal inertia output in *t* period. Generation side adopts time-of use price, so $c_S\left(t\right)$ is the output cost price of generation side, and $RS\left(t\right)$ is the output of generation side in *t* period. Q_{CHP} and Q_E are carbon emission of CHP and conventional generation units respectively. p_c is unit carbon emission cost.

User comfort cost adopts ladder price and are divided into class N response levels, where $c_{COM}\left(n\right)$ is the cost of user comfort at *n* response level. N is the total number of steps of user comfort cost ladder price. $P_h^n\left(t\right)$ is the difference between the present thermal power on the load side and the original power at *n* response level.

Usually CHP units have the optimal thermoelectric ratio, at which the energy supply is the most economical. When the thermoelectric ratio increases gradually, the energy economy of CHP decreases. Therefore, the consumption of gas at different thermoelectric ratios also corresponds to different prices. $c_{HE}\left(a\right)$ is the output cost when the thermoelectric ratio changes to different values. M is the total ladder number of thermoelectric ratio cost ladder price.

3.2.2 Constraint conditions

According to the actual operation of each output in IES, the constraint conditions are as follows.

a. Electric power balance constraint

$$\eta_T\left[RH\left(t\right)+RS\left(t\right)\right]+\eta_{CHPE}RG\left(t\right)=P_e \tag{10}$$

$RH\left(t\right)$ is the electricity transferred from electric boiler to transformer in *t* period. The feasibility of this means is due to the existence of thermal inertia on the load side, so this output is regarded as thermal inertia output. P_e is the power deficiency caused by frequency failure.

b. Thermal power balance constraint

$$-RH\left(t\right)\eta_{EB}+\eta_{CHPH}RG\left(t\right)=P_h \tag{11}$$

P_h is total thermal power difference on the load side.

c. Carbon emission constraints

$$Q_E=R_E\left(t\right)\Delta tQ_e \tag{12}$$

$$Q_{CHP}=\left[H_E\left(t\right)+H_H\left(t\right)\right]Q_{chp} \tag{13}$$

Q_E is the total carbon emission of generation side in $\Delta\mathrm{t}$. Q_{CHP} is the total carbon emission of CHP in $\Delta\mathrm{t}$. Q_e is the unit carbon emission of generation units. Q_{chp} is the unit carbon emissions of CHP. H_E is the heating quantity of thermal power produced by CHP in $\Delta\mathrm{t}$. $H_E\left(t\right)$ is the equivalent heating quantity of electric power produced by CHP in $\Delta\mathrm{t}$.

Carbon emission in this paper mainly comes from generation side and CHP units. For electric boiler, LCA carbon emission coefficient of electric boiler is 0[6]. At the same time, although electricity of the electric boiler comes from the coal-fired power plant, its carbon emission can also be counted as 0 if only the additional carbon emission caused by providing frequency response is included.

$$H_H=RG\left(t\right)\eta_{CHPH}\Delta t\mu \tag{14}$$

$$H_E=RG\left(t\right)\eta_{CHPE}\lambda_{eh}\Delta t\mu \tag{15}$$

λ_{eh} is the conversion coefficient of electricity generation converted into heating quantity. μ is the unit conversion coefficient of converting unit kWh of heating quantity into unit conversion coefficient of GJ.

d. Power output constraint

$$\begin{cases} 0\le RH\left(t\right)\le RH_{\max} \\ 0\le RG\left(t\right)\le RG_{\max} \\ 0\le RS\left(t\right)\le RS_{\max} \end{cases} \tag{16}$$

$RG_{\max}$, $RH_{\max}$, $RS_{\max}$ are the upper limit output of gas inertia, thermal inertia and generation side that can be provided at one time.

e. Thermoelectric ratio size constraint

$$\eta_{CHPE} \le \eta_{CHPH} \le k_{HE\max}\eta_{CHPE} \qquad (17)$$

$k_{HE\max}$ is the maximum limit of thermoelectric ratio of CHP units.

4. CASE STUDY

This example is simplified from a northern electricity, gas, thermal coupling IES. The summer typical day of electric load, thermal load data and the photovoltaic (PV) output prediction curve are as shown in Fig.6.

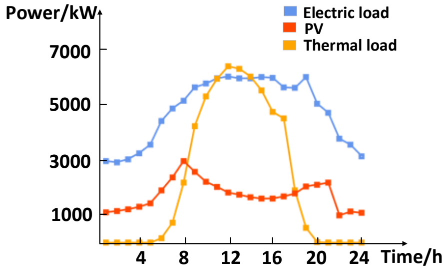

Fig. 6 Load data and PV prediction

C_{GR} is set at 0.0400 ¥/kW, C_{HR} is 0.0100 ¥/kW and p_c is $15 /t. η_{CHPH} and η_{CHPE} are 0.75 and 0.3. Q_e is 1.08t /MWh. Q_{chp} is 0.065t /GJ. λ_{eh} is 6 MJ/kWh. μ is 0.0036. Step price is adopted in user comfort cost and thermoelectric ratio cost price in Table 1-2, while time-of-use price is adopted in generation side cost in Table 3.

Table 1. User comfort cost

Absolute value of thermal power gap (kW)	Cost (¥/kW)
0~50	0.03
50~100	0.04
100~150	0.06
150~200	0.09

Table 2. Thermoelectric ratio cost

Thermoelectric ratio(kW)	Cost (¥/kW)
1~1.333	0.035
1.333~1.833	0.045
1.833~2.5	0.06
2.5~3.1667	0.085

Table 3. Generation side cost

	Low	Ordinary	Peak
Cost (¥/kW)	0.05	0.08	0.12

4.1 Optimization results in IES without carbon cost

4.1.1 Optimization results with gas-thermal inertia

The YALMIP toolbox was invoked in MATLAB2019 to combine the gas-thermal inertia model with actual scenario. At some time, frequency failure of the power grid occurs, resulting in a shortage of electric power. The costs of each power output are as shown in Table 4.

Table 4. Cost condition

Power form	Cost(¥)
Thermal inertia	8.2836
Gas inertia	31.7612
User comfort	6.5000
Thermoelectric ratio	26.0045
Generation side	0
Total cost	72.5493

Among all kinds of output options, gas and thermal inertia outputs are far ahead of generation side output. It shows that when a frequency failure occurs, if there is gas-thermal inertia available for dispatching, they will be top choices in providing frequency response. However, due to the high and uncertain price of the generation side, its power output is 0.

4.1.2 Optimization results without gas-thermal inertia

In this example, using generation side to provide frequency response is compared with using gas-thermal inertia. The result is as shown in Fig.7.

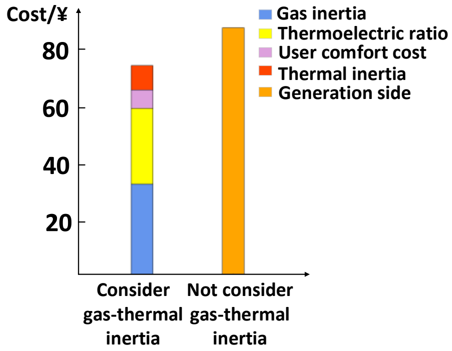

Fig. 7 Comparison result of total cost

It can be concluded that total cost decreases obviously when gas-thermal inertia is considered. It shows that gas-thermal inertia is quite economical. And as a means of providing frequency response, there is no need to configure it separately. Existing facilities can already provide frequency response quickly. Only part of user comfort needs to be sacrificed.

4.2 Optimization results in IES with carbon cost

4.2.1 Optimization results with gas-thermal inertia

When the carbon cost is taken into account, the optimization goal will change into Eq.8. Considering the carbon emission of different energy sources, the cost ratio of each power form is bound to be different from that without the carbon cost, as is shown in Fig. 8.

According to the optimization results, because the output of CHP will increase the carbon emission when carbon cost is taken into account, gas inertia output and thermoelectric ratio cost decrease obviously. Instead, the thermal inertia output is increased due to its zero carbon emission. This method sacrifices more user comfort, so the user comfort cost increases, but ensures the environmental protection and economy.

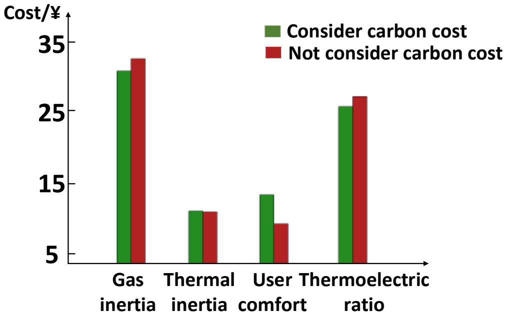

Fig. 8 Comparison result of cost

4.2.2 Optimization results without gas-thermal inertia

a. Carbon emission of frequency response

When carbon cost is taken into account, the carbon emission of two conditions are compared in Fig.9.

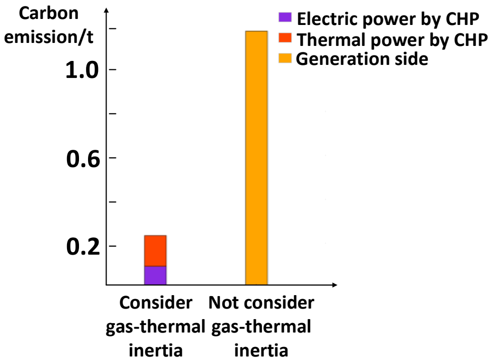

Fig. 9 Comparison result of carbon emissions

It can be seen that the total carbon emission of the IES including gas-thermal inertia are less than those without. Because when gas-thermal inertia is not considered, all electric power provided by the generation side will produce carbon emission. After considering gas-thermal inertia, carbon emission can be greatly reduced by switching to existing electric power or temporarily using the gas pipe storage. So gas-thermal inertia is quite beneficial for environmental protection.

b. Total cost of frequency response

When taking into account the carbon cost, compare the total cost in two conditions in Fig. 10. When the carbon cost is taken into account, the carbon cost and total cost are both lower than those without, which verifies that it's both environmentally-friendly and economical to use gas-thermal inertia to provide frequency response.

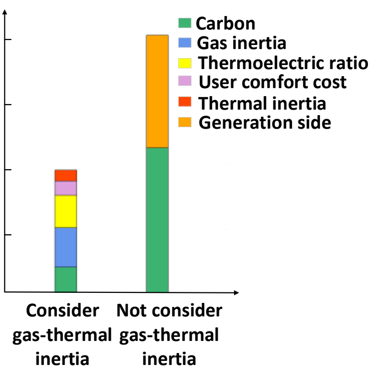

Fig. 10 Comparison result of total cost

5. CONCLUSION

In this paper, gas-thermal inertia of IES is defined and its power support characteristics are explained by mathematical and physical models. The frequency response strategy considering gas-thermal inertia is proposed, and its rationality is verified in actual scenario. The following conclusions are drawn: a. Gas-thermal inertia in IES has power support characteristics, does not need to be configured separately and has little impact on the user side as a form of energy utilization; b. Gas-thermal inertia can be used as a new method to provide frequency response in IES, increasing the flexibility of IES optimization and is quite economical as well as environmentally-friendly.

ACKNOWLEDGEMENT

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