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Capacity Configuration of Integrated Energy System Considering Equipment Inertia

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Abstract: The integrated energy system (IES) plays an important role in the development of clean energy through the complementary advantages of multi energy and the absorption capacity of renewable energy. However, because of the multi energy coupling and the intermittence of renewable energy, the risk of system dynamic instability increases. In order to solve the above issues, this paper considers the influence of the dynamic characteristics of the system from the level of planning and design stage. Based on the solar intensity and load demand curve of typical winter days and considering the daily economic operation of typical days and the dynamic characteristics of the system, an IES capacity configuration optimization model is established, which takes into account the system investment cost and the dynamic characteristics of the system. Then the genetic algorithm with penalty function is used to optimize the solution. Finally, according to the typical winter day data of a certain area in Nanjing, P.R.China, the rationality and validity of the model are verified, and the scientific configuration of an IES capacity considering dynamic performance is realized, which provides ideas and support for the planning and design of an IES later.

Keywords: Integrated energy system, capacity configuration, equipment inertia, genetic algorithm, planning and design.

1. INTRODUCTION

With the trend of increasing consumption of energy, the depletion of fossil energy and rising environmental concerns are becoming increasingly acute, and demand for clean energy is increasing rapidly, which indirectly promotes the development of renewable energy on a large scale. In recent years, some scholars have put forward the concept of Pan energy network, energy hub, etc. Its purpose is to establish a variety of energy integration system, through the complementary advantages of renewable energy, in order to improve the system's ability to absorb wind and solar energy and achieve the optimal utilization of total system energy.

However, the randomness and intermittence of renewable energy make the stable operation of the IES difficult. Meanwhile, the time scales of multiple energies in the IES are different, which have great influence on the energy supply and transmission stage. Therefore, many studies have been carried out on the planning, design, operation scheduling, and coordinated control of the IES, in order to ensure the stable energy supply and rapid response of the IES. Gu, et. al (2017) proposed an IES model which can improve the absorption capacity of wind power by considering the thermal inertial of buildings. The impact of battery lifetime loss on the operation of an IES is concerned by Wang et. al (2018). Zhang et. al (2019) focused on the wind power uncertainty and establish a two-stage distributed robust optimization model to solve the scheduling problem. Yu et. Al (2019) improved and compared the wind utilization by optimizing the operation of combined heat and power system equipped with different power-to-heat devices. As for the research of the planning and design of the IES, Gimelli et. al (2019) integrated the battery energy storage with the CHP system and the optimal capacity was found, which had the most economic benefits. Wang et. al (2019) proposed a novel two-layer economic optimization model to determine the optimal configuration of thermal energy storage and optimize the wind energy consumption. Han and Kim (2019) proposed a comprehensive approach to plan the strategic investment for the design of a national-level IES. In addition to these, simultaneous planning and operation of the IES has also been studied recently. Zhang et. al (2019) combined the planning and operation to design an IES in a Swedish building, which proves that the capacity configuration of the IES can meet the operation requirements of the system. However, for most of the studies, the capacity planning of the IES is only carried out at the steady-state level, without considering the dynamic characteristics of the system. Regarding the integrated system, it includes the coupling and matching between various devices, which leads to the different effects on the operation of an IES due to the differences in the response speed between the devices. Therefore, how to select the equipment is what we should think about. In addition to controlling degrees of freedom, it also includes the equipment inertia and the differences between different energy transmission. Generally speaking, the inertia of electric energy is very small, but in contrast the thermal energy inertia is much larger and the impact of this part cannot be ignored. Based on the above analysis, the consideration of dynamic characteristic in the planning and design stage can improve the controllability of an IES.

To this end, this paper focuses on the impact of the load regulation process of micro gas turbine (MGT), in which the constant change of load leads to the variation of the fuel quantity. The main contribution of this paper are as follows:

(1) The dynamic characteristics of the IES equipment are considered in the planning and design of the IES, and the IES capacity configuration optimization model considering the impact of inertia process on the system investment and operation cost is established, which realizes the innovation of the consideration of dynamic characteristics in IES planning and design process.

(2) A new algorithm of embedding constraint conditions into objective function by penalty function is proposed, which solves the programming problem with constraint conditions and realizes the optimal capacity configuration of IES.

2. CAPACITY OPTIMIZATION MODELING CONSIDERING INERTIA

2.1 Basic Model of Integrated Energy System

Generally, the IES mainly uses solar energy, wind energy, natural gas and other energy as the energy input. Through energy production, conversion and transmission, it can meet the load demand of users such as electricity, heat and cooling. In this paper, an IES including cogeneration system, photovoltaic power generation system (PV), energy storage system (ESS) and heat pump (HP) is established, and its structure diagram is shown in Fig. 1. Among them, cogeneration system uses a MGT as power generation and heat generation equipment, and an HP is chosen as auxiliary heating equipment. For the ESS, lead-carbon battery is used for the storage and auxiliary supply of electric energy. The whole system is in off grid state.

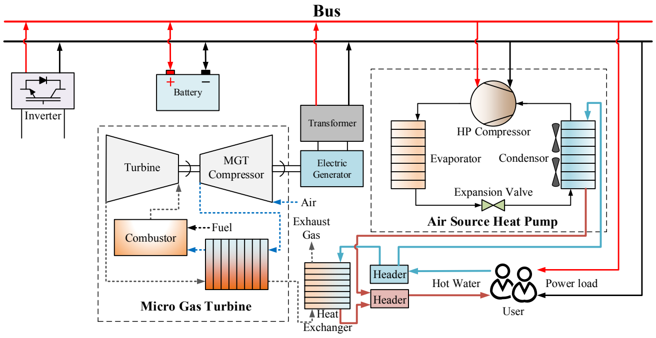

Fig. 1. Structure diagram of the IES

Nomenclature		C_{inf}	initial cost of system investment, $
Decision Variables		C_{om}	cost of operation and maintenance, $
$P_{cap.k}$	the rated power of equipment, kW	C_{fuel}/ C_{fuel_it}	cost of system fuel consumption in stable period and transitional period, $
$P_k^{i,j}$	actual operation power of the kth equipment, kW	C_{infk}	initial investment cost per unit capacity of the equipment, $/kW
$P_{MGT}^{i,j}$ / $P_{PV}^{i,j}$	electric power of MGT and PV, kW	C_{omk}	operation and maintenance cost per unit capacity of the equipment, $/kW
$P_{ESS.out}^{i,j}$ / $P_{ESS.in}^{i,j}$	discharge power and charge power of ESS, kW	Paramaters	
$z_{ESS.out}^{i,j}$ / $z_{ESS.in}^{i,j}$	discharge state and charging state of ESS, kW	k	kth equipment of system
$D_E^{i,j}$	electric load demand of system, kW	K	total number of equipment
$S_{HP}^{i,j}$	electrical power consumed by HP, kW	R	capital recovery rate
$Q_{MGT}^{i,j}$	waste heat utilization power of MGT, kW	Y	service life of equipment, y
$Q_{HP}^{i,j}$	thermal power of HP, kW	R	bank interest rate value
$D_H^{i,j}$	thermal load demand of system, kW	η_{MGT}	generation efficiency of MGT
P_{MGT}^{min} / P_{MGT}^{max}	lowest and highest electric power of MGT, kW	$Q_{net.gas}$	net calorific value of natural gas, kJ/m^3
$E_{ESS}^{i,j}$ / $E_{ESS}^{i,j-1}$	storage capacity of ESS in time j and j-1, kW	c_{fuel}	purchase cost of natural gas, $/m^3
$P_{cap.ESS}$	maximum storage capacity of ESS, kW	$\Delta T_{MGT}^{i,j}$	load regulation time of MGT, s
Q_{HP}^{min} / Q_{HP}^{max}	lowest and highest thermal power of HP, kW	η_{rec}	waste heat recovery rate of MGT
Intermediate Variables		COP_{HP}	coefficients of performance of HP
C_{total}	total cost of system investment and operation, $	i/j	days/hours

2.2 Objective Function

For the IES, the energy utilization process mainly includes energy production, conversion, transportation and storage. Therefore, the objective function of the capacity optimization model of the IES should be the total investment and operation cost in the whole life cycle of the system, which includes the initial investment cost, operation and maintenance cost and fuel consumption cost. In addition, fuel consumption cost is divided into stable period and transitional period which is related to the inertia time of the equipment. The objective function is as follows:

$$\min f = C_{total} = C_{inf} + C_{om} + C_{fuel} + C_{fuel\_it} \quad (1)$$

The calculation method of each income is shown in Equation (2)-(6):

(1) Initial investment cost of the system. In order to prevent the impact of different equipment life cycle on the investment plan, the life cycle of each equipment in the IES is taken as 15 years, so as to calculate the capital recovery rate. The mathematical expression of the initial investment cost of the system is:

$$C_{inf} = R\cdot\sum_{k=1}^{K}\left(C_{infk}\cdot P_{cap.k}\right) \quad (2)$$

$$R = \frac{r\left(1+r\right)^{y}}{\left(1+r\right)^{y}-1} \quad (3)$$

(2) System operation and maintenance cost. The operation and maintenance cost of the system is mainly composed of equipment operation loss, labor maintenance cost and labor inspection cost. This is related to equipment selection, actual operation power and operation frequency. The calculation formula is as follows:

$$C_{om} = \sum_{i=1}^{365}\sum_{j=1}^{24} C_{omk}\cdot P_{k}^{i,j} \quad (4)$$

(3) Fuel consumption cost of system operation. In the IES of this paper, only the MGT is the equipment that needs to use natural gas energy to produce electric energy and thermal energy. Therefore, the operation energy consumption cost of the whole system in stable period is only related to the MGT. However, it should take a certain time for the MGT to reach the corresponding load setting value when the load demand changes. During the transitional period, the electric power is changing all the time, so the impact of the load regulation process on fuel consumption cost should be considered. It is assumed that the regulation process is a one-order inertia process and the load regulation is shown in Fig. 2. When the MGT receives the scheduling instruction, it cannot reach the set load instantly, so it needs to act in advance to ensure that the set value is reached at the next moment. Therefore, it can be seen from Fig. 2 that the MGT operates at about 55min until the set load is reached at 60min.

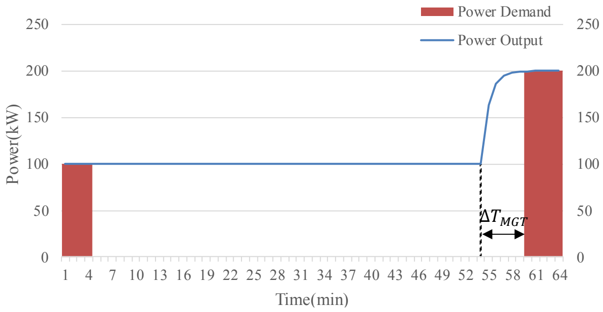

Fig. 2. The load regulation process of MGT

Therefore, its calculation formula in the stable period is as follows:

$$C_{fuel} = \sum_{i=1}^{365}\sum_{j=1}^{24}\frac{P_{MGT}^{i,j}}{\eta_{MGT}\cdot Q_{net.gas}}\cdot c_{fuel}\cdot\left(1-\Delta T_{MGT}^{i,j}\right) \quad (5)$$

And the calculation formula in the transitional period is as follows:

$$C_{fuel\_it} = \sum_{i=1}^{365}\sum_{j=1}^{24}\frac{P_{MGT\_\Delta T}^{i,j}}{\eta_{MGT}\cdot Q_{net.gas}}\cdot c_{fuel}\cdot\Delta T_{MGT}^{i,j} \quad (6)$$

2.3 Constraint Condition

For the IES with multi energy coupling, its operation process should meet the demand of multi-energy load. At the same time, in order to ensure the safe operation of the system, different equipment should also meet the corresponding operating characteristics and power limiting. Therefore, in the system constraints, there are mainly three kinds of constraints: the electric energy balance constraints, the thermal energy balance constraints and the operation characteristics constraints of the equipment.

(1) Electric energy balance constraints

As the system is in off grid operation state, for power supply, the sum of generation power of the MGT, PV and charge and discharge power of the ESS shall be equal to the sum of system electrical load demand and HP consumption power, namely:

$$P_{MGT}^{i,j} + P_{PV}^{i,j} + P_{ESS.out}^{i,j}\cdot z_{ESS.out}^{i,j} - P_{ESS.in}^{i,j}\cdot z_{ESS.in}^{i,j} = D_{E}^{i,j} + S_{HP}^{i,j} \quad (7)$$

(2) Thermal energy balance constraints

In the heat load supply stage, the heat balance mainly includes the waste heat utilization power of MGT and the heat power of the HP to meet the heat load demand of the whole system, and for the demand of heat energy, people's perception of heat is not as sensitive as electricity. In addition, the transformation of the thermo-balance constraint into the interval constraint can not only satisfy the user's comfort through thermal comfort elasticity, but also reduce the constraint limit of the model optimization, making the model easier to obtain the optimal solution. So the balance of heat energy can be constrained in a certain range to facilitate optimal solution, namely:

$$0.9\cdot D_{H}^{i,j} \le Q_{MGT}^{i,j} + Q_{HP}^{i,j} \le 1.1\cdot D_{H}^{i,j} \quad (8)$$

(3) Operation characteristics constraints of equipment

In order to ensure the safe operation of the system, the equipment shall be required to operate within the specified working conditions. In addition, the operation of the equipment shall also meet its own operation characteristics.

The MGT needs to supply heat and electric power at the same time, so it needs to meet the minimum heat-electricity ratio requirements in the operation process. At the same time, when the MGT is running, its power input should also be within the constraint range, and the constraint conditions are as follows:

$$Q_{MGT}^{i,j} = \frac{\eta_{rec}\cdot P_{MGT}^{i,j}}{\eta_{MGT}}\cdot\left(1-\eta_{MGT}\right) \quad (9)$$

$$P_{MGT}^{min} \le P_{MGT}^{i,j} \le P_{MGT}^{max} \quad (10)$$

When considering the real-time charge and discharge power, the storage capacity of the ESS should also meet the capacity constraints of the ESS itself. It can be seen from the objective function that the ESS equipment also has the decision-making variable of charge and discharge state, so it should be ensured that there is no charge process and discharge process at the same time during the operation of the ESS. In addition, considering the life of the ESS, it also requires the principle of charging and discharging every day, that is, after a day of charging and discharging process, the storage capacity of the ESS maintains the original state. To sum up, the ESS constraints can be obtained:

$$E_{ESS}^{i,j} = E_{ESS}^{i,j-1} + P_{ESS.in}^{i,j}\cdot z_{ESS.in}^{i,j} - P_{ESS.out}^{i,j}\cdot z_{ESS.out}^{i,j} \tag{11}$$

$$0.1\cdot P_{cap.ESS} \le E_{ESS}^{i,j} \le 0.9\cdot P_{cap.ESS} \tag{12}$$

$$0 \le z_{ESS.in}^{i,j} + z_{ESS.out}^{i,j} \le 1 \tag{13}$$

The HP is a conversion device that converts electric energy into heat energy. Therefore, considering the restriction of heat output power of the HP, it should also meet the restriction of energy conversion efficiency. The restriction conditions are as follows:

$$Q_{HP}^{i,j} = COP_{HP}\cdot S_{HP}^{i,j} \tag{14}$$

$$Q_{HP}^{min} \le Q_{HP}^{i,j} \le Q_{HP}^{max} \tag{15}$$

2.4 Algorithm Methodology

The capacity configuration problem of the IES is a typical mixed integer nonlinear programming problem with multiple constraints and variables. Because the genetic algorithm has a great advantage in the combination of discrete variables and continuous variables in the mixed integer programming problem, genetic algorithm is used to solve the planning problem of the IES in this paper. As for the traditional genetic algorithm, it is unable to solve the planning problem with constraints. Therefore, based on the traditional genetic algorithm, this paper makes corresponding improvement that the constraint is written into the objective function in the form of penalty function, and the decision variables are solved in the range of satisfying the constraint condition by the form of objective function. The improved objective function is as follows:

$$min\ F = f + \lambda\cdot H \tag{16}$$

$$H = \sum_{m=1}^{N} p_m(x) \tag{17}$$

$$p_m(x) = \begin{cases} max\{0, g_m(x)\} & m = 1,2,\dots,n \\ |h_m(x)| & m = n+1, n+2,\dots,N \end{cases} \tag{18}$$

where F is the improved objective function; f is the original objective function; λ is the weight coefficient of the penalty function; H is the total penalty term; $p_m(x)$ is the penalty term of each constraint condition; $g_m(x)$ is the inequality constraint; $h_m(x)$ is the equality constraint; n is the number of inequality constraints; N is the number of total constraints.

After the transformation of equation (16)-(18), the multi constrained mixed integer nonlinear programming problem is transformed into the unconstrained mixed integer nonlinear programming problem, which is easy to be solved by the algorithm.

3. SIMULATION ANALYSIS

3.1 Research Objective

This paper takes a hotel in a certain area of Nanjing as the research object. The hotel is open 24 hours a day throughout the year. The power equipment, lighting equipment and population density in the building are set according to the design standards. The hotel is located in the subtropical monsoon climate zone. According to the climate characteristics, the whole year can be divided into three periods: summer, winter and transition season. For the choice of the annual heating load and electric load demand curve of the hotel, the typical daily load demand curve of different periods is selected to represent the load demand of corresponding seasons through historical data. On the other hand, the characteristic curve of solar output is selected from the photovoltaic power station near the hotel on the typical day.

In the IES equipment selected in this paper, the MGT only supplies electrical load and heat load, not cooling load. Therefore, for typical summer days, the cooling load can only be provided by the HP, so for the MGT, it needs to provide much electric energy, and at the same time, the heat load cannot be used. In addition, the load of typical days is representative for the whole year, while the proportion of bad weather for the whole year is small, and the probability of its occurrence is unknown. Therefore, for the convenience of calculation and analysis, only the daily load demand and solar output characteristic curve of typical winter days are selected to represent the annual load and solar intensity in the simulation of this paper. Fig. 3 shows the typical daily load demand curve in winter, and Fig. 4 shows the solar output characteristic curve in typical winter day.

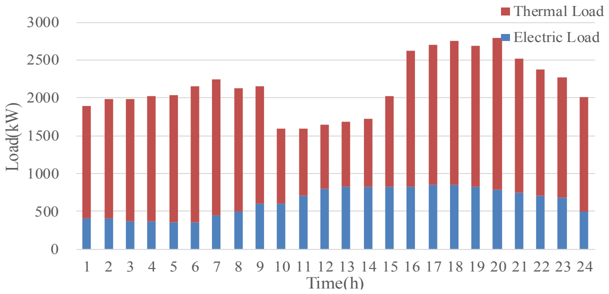

Fig. 3. Typical daily load characteristic curve in winter

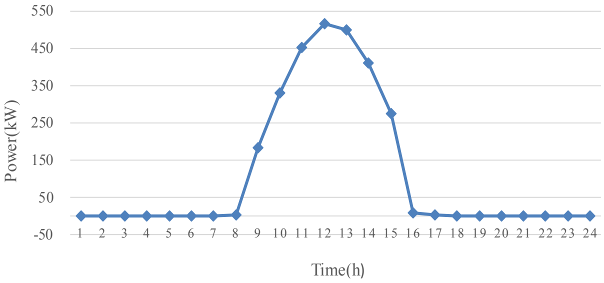

Fig. 4. Solar output characteristic curve in typical winter day

In this paper, the life span of all IES equipment is 15 years. The initial investment cost and operation and maintenance cost per unit capacity are shown in Tab. 1, and the performance parameters of each equipment are shown in Tab. 2. In a year, the purchase cost of natural gas is calculated on the basis of 0.42$ per unit volume.

Table 1. Equipment consumption of IES

Equipment	Initial investment cost($/kW)	Operation and maintenance cost($/kW)
MGT	1129	0.0110
PV	857	0.0043
HP	171	0.0014
ESS	255	0.0714

Table 2. Characteristic parameter of equipment

Characteristic parameter	Value
Generation efficiency of MGT	0.3
Waste heat utilization rate of MGT	0.9
Heating energy efficiency ratio of HP	3

3.2 Simulation Results

In this part, in order to illustrate the impact of dynamic characteristics of equipment on the planning and design of IES, two methods are simulated. Case 1 is the method without considering the inertia time of the equipment. Case 2 is the proposed method considering the inertia time.

Tab. 3 shows the total cost of the whole life cycle and the cost of each single item in two cases. According to Tab. 3, the initial investment cost and the operation and maintenance cost in both cases are close to the same. However, the fuel consumption cost of case 2 is $1.08*10^4 more than the cost of case 1, which means the fuel consumption of MGT has some changes after considering the inertia regulation process of MGT.

Table 3. Cost comparison of two cases (*10^4$)

Cost item		Case 1	Case2
C_{inf}	C_{inf_MGT}	11.600	12.343
	C_{inf_PV}	4.762	4.762
	C_{inf_HP}	0.415	0.542
	C_{inf_ESS}	2.280	1.862
C_{om}	C_{om_MGT}	5.770	5.858
	C_{om_PV}	0.419	0.419
	C_{om_HP}	0.098	0.111
	C_{om_ESS}	5.094	5.235
C_{fuel}		70.621	67.944
C_{fuel_it}		0	3.758

Tab. 4 gives the equipment capacity configuration of two cases. Not only the capacity of the MGT is different in two cases, but also there are some differences between the capacity and the operating power of the HP and ESS due to the discrepancy of the operation curve of MGT in two cases so as to ensure the electric power balance and the thermal energy balance. In the process of load regulation, in order to keep the energy balance, the power output of each equipment is different from that in the stable state, which leads to the difference of the operation cost affected by the operation power. Not only the construction cost of the HP is lower than that of the ESS, but the operation cost is also far lower than that of the ESS. Therefore, in the selection of conversion equipment, the capacity of the HP is higher than that of the case without considering the inertia, and the capacity of the ESS is lower than that of case 1. However, the operating cost of the ESS in case 2 is slightly higher than that of case 1. Because there is no enough ESS to supplement the electric energy and HP to consume the electric energy, MGT needs to increase the capacity to ensure the supply of electric energy. As for PV, the capacity of PV is consistent with the maximum light intensity of the day to guarantee the full utilization of solar energy, resulting in the same capacity in two cases.

Table 4. Equipment capacity comparison of two cases (kW)

Equipment	Case 1	Case 2
MGT	954	1015
PV	516	516
HP	225	294
ESS	831	679

Fig. 6 and Fig. 7 show the electric power balance of two cases in typical winter day respectively. And Fig. 8 and Fig. 9 show the thermal energy balance in both cases. Considering that the calculation of case 2 is divided into two parts, including the steady-state part and the regulation part, the energy balance of the steady-state part and the regulation part per hour is given at the same time. When the inertia process isn't taken into account, the power output of the equipment remains unchanged at every time. However, after considering the inertia process, the power output of the MGT is constantly changing in the load regulation process, so in order to ensure the supply and demand balance of the whole system, the power output of the conversion equipment such as the HP and ESS also changes accordingly. Fig. 10 and Fig. 11 show the power change of the HP and ESS in two cases respectively.

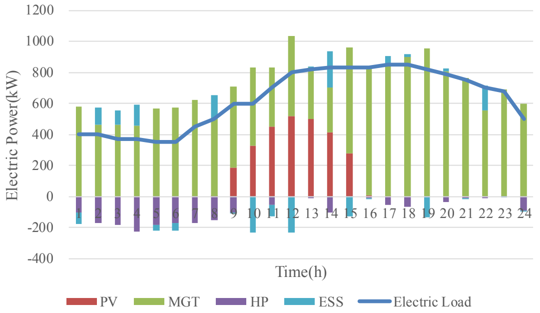

Fig. 6. Electric power balance of case 1

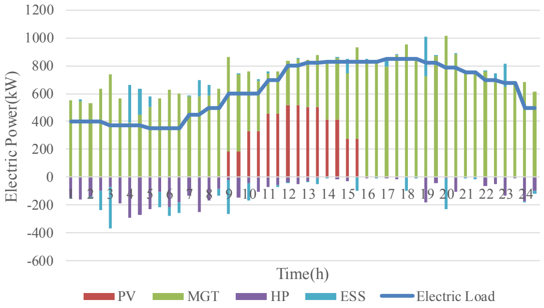

Fig. 7. Electric power balance of case 2

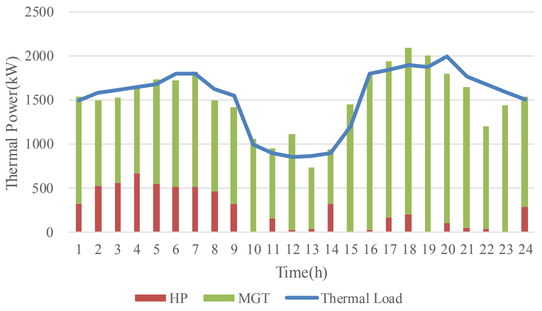

Fig. 8. Thermal energy balance of case 1

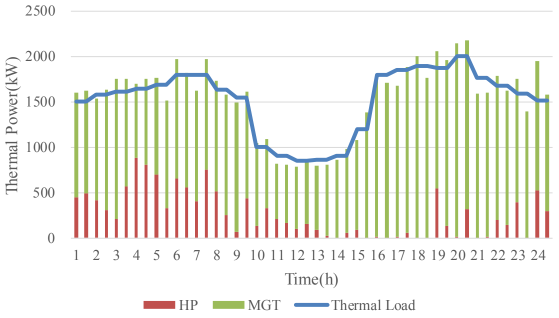

Fig. 9. Thermal energy balance of case 2

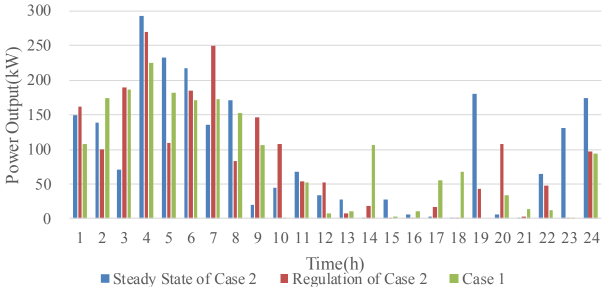

Fig. 10. The power change of the HP in two cases

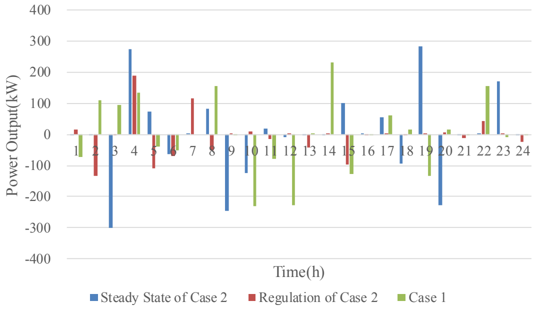

Fig. 11. The power change of ESS in two cases

4. CONCLUSION

This paper has studied the impact of the equipment inertia on the capacity configuration of an IES. The economic benefit model is developed first to calculate the investment and operation cost of the IES in the lifetime. Then based on the economic model, the influence of inertia process on fuel cost is added and the planning model of the IES considering the dynamic characteristic is presented. Moreover, in order to solve the problem that genetic algorithm cannot calculate the constrained programming, the constraint condition is added to the objective function in the form of penalty function compensation to meet the requirements of feasible solution. The results show that the system capacity configuration and typical daily operation have some changes after considering the dynamic characteristics. The conclusions and ideas of this paper also provide theoretical support and guidance for the development of IES.

5. ACKNOWLEDGEMENT

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