Review of Research on System Thermal Inertia Modelling and Optimal Scheduling from the Perspective of Flexible Resources

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Abstract. The thermal inertia of the existing heating system is often considered an adverse factor, which will affect the operation of the system. However, under the perspective of resource flexibility, the thermal inertia of the system can effectively increase the flexibility of the system operation, significantly reduce the energy consumption and enhance the ability of energy supply and demand balance, and enhance the new energy integration, such as the wind power. Based on the flexible resources, it focuses on the study of the thermal inertia of the "network side" heating pipe network of the system and the optimal scheduling of the heating system. Combined with the thermal inertia of the pipe network, the operation characteristics of the power/heat output of the gas-steam combined cycle unit were analysed theoretically. On this basis, the optimal scheduling model of the system was established. Taking the energy supply system of an industrial park as an example, the model was verified to achieve a more stable power output effect of the unit.

1. Introduction

In recent years, the research on integrated energy system (IES) has been increasing. The emergence of the IES has brought a very important impact on the adjustment of China's energy structure and the reform of energy consumption patterns. Through the overall planning and coordinated operation of various energy distribution, conversion, storage and consumption links, it has broken the existing model of separate planning, design and isolated operation of various energy supply systems such as electricity, gas, cooling/heating, and so on. The complementary advantages of various energy sources and the cascade utilization have been realized, and the efficiency of energy utilization has been improved.

Different from the existing operation mode of traditional energy, the IES includes electric power network, natural gas network, and heating network. Through combined heat and power (CHP), gas turbine, power to gas (Power to Gas, P2G) and other coupling equipment, the mutual conversion of different energy forms can be realized to meet the diverse needs of load-side energy types [1,2,3]. In the context of the development of IES, as the installed capacity of renewable energy continues to increase, the problem of the balance of supply and demand in the energy system has become increasingly prominent, and multiple energy sources need to strengthen flexible coordination and complementarity [4,5]. In order to meet diversified energy demand and promote the consumption of renewable energy, the number of flexible resources required by IES is gradually increasing. Flexible resources are resources that can increase the flexibility of the energy supply and demand system and serve the dynamic supply and demand balance of the energy use system. The system can quickly and accurately regulate its own energy supply and demand balance through flexible resources, and at the same time meet the diversified energy supply and demand requirements of users. The increase of
flexible resources will bring resilience and flexibility to the energy supply and demand system [6, 7]. The conventional flexibility resource is to add auxiliary equipment such as electric boiler [8], electric hydrogen production [9] and energy storage tank [10] outside the system, and use this equipment to realize the conversion of energy forms, store/release energy in a timely manner, and improve the flexibility of system operation, but the initial construction cost of the system will increase accordingly. However, tapping the potential of the system's own structure and operating characteristics can improve the flexibility of the system without adding additional equipment, which has a greater economic advantage.

2. Model Study of Thermal Inertia

2.1. Thermal Inertia Model of Pipe Network

The thermal inertia of the pipe network is a passive flexible resource that exists on the "network side" of the system, which can effectively improve the flexibility of system operation [11]. A large number of scholars have conducted research on the thermal inertia model of the "grid-side" heating pipe network. References [12-14] take the water supply temperature and outdoor temperature in the heating pipe network as input parameters, take the return water temperature and the indoor temperature of the building as output parameters, and use the AMRA time series model to establish the relationship between the input and output parameters. Reference [15] separately established models at the heating network branch level and the heating network level, the heating network branch model comprehensively considers the thermal characteristics of the pipeline (heat loss, transmission time lag) and hydraulic characteristics (pressure drop). The heating network model uses graph theory modelling to analyse the thermal balance characteristics and hydraulic balance characteristics of the heating network. Reference [16] used the network topology description method in the power system for reference when modelling the heating network, considering the hydraulic and thermal characteristics, and established the branch characteristic equation and the network balance equation respectively. Furthermore, references [17-18] are based on the node method, taking into account the transmission time lag and heat loss, to characterize the dynamic process of the temperature change of the heat medium in the central heating pipe network. Reference [19] based on the node method to model and analyse the heating network pipeline, and calculate the temperature dynamic distribution of the heating network by solving the matrix equation. Reference [20] used the node method to consider time delay and heat loss, established a unit combination model with transmission constraints, and provides a sufficiently accurate simulation result of the temperature dynamics in the heating pipe network. On the other hand, the pipeline is equivalent to the role of a heat storage tank, and a large part of the heat energy is stored in the pipeline. Reference [21] considers the heat transfer time lag and heat loss to establish a dynamic model of heat energy transmission, and treats the heat network as a virtual heat storage system, which is beneficial to improve the flexibility of the IES system. Reference [22] equates the transmission delay of hot water in the pipe network as virtual energy storage, and constructs a transmission delay model of the ring heating network. Reference [23] based on the optimal unit combination model, considering the thermal inertia of the heating network without considering the heat loss, the dynamic external approximation model of the heating network based on the state of charge formula and the dynamic model of the heating network based on energy storage prediction are established respectively; the former cannot get accurate results, and the latter reduces the modelling effort and is easy to apply in the real heating network. References [24-25] had considered the heat loss and pipeline thermal inertia, a new improved model was established. Combined with experimental data and simulation results, it is verified that when the temperature of the inlet water temperature changes rapidly, the thermal inertia of the pipeline has a significant influence on the temperature response of the outlet water temperature. Reference [26] considers the heat loss, pressure loss and transmission time lag of the heating network. According to the distance from the heat load to the heat source, the heat load is partitioned and a more simplified heating network model is established.
Regarding the model study of the thermal inertia of the “grid-side” pipe network, whether it is a steady-state model or a dynamic model, the time lag and heat loss of thermal energy transmission must be considered, both of which are the main influencing factors leading to thermal inertia. In addition, parameters such as heat medium mass flow rate, pipeline transmission distance, supply/return water temperature and external temperature determine the accuracy of the simulation results of the thermal inertia model. The dynamic model of the heating network can describe the thermal inertia more accurately, but it is also more complicated. How to simplify the establishment of the model without losing the accuracy of the model is a difficult point in current research.

Based on the principle of energy transfer balance, the thermal inertia model of the pipe network is established, as shown in Figure 1:

![Figure 1. Diagram of energy transmission in the pipeline](image)

For a specific pipe of the heating pipe network, the heat energy transmission is affected by the heat loss of the fluid heat energy and the transmission time lag, which can be described by the following partial differential equation:

$$\frac{\partial T}{\partial t}(x, t) + \frac{G}{\pi R^2} \frac{\partial T}{\partial x}(x, t) + \frac{2 \mu_p}{\rho c_p R} (T(x, t) - T_w) = 0$$ (1)

Where, $T(x, t)$ is the fluid temperature at time $t$ from the inside of the pipe to the pipe inlet length $x$, $^\circ C$; $x=0$ means the entrance of the pipeline; $T_w$ is the ambient temperature outside the pipe, $^\circ C$; $G_p$ is the fluid mass flow, kg/s; $c_p, \rho_0$ is the specific heat capacity and density of fluid; $R$ is the radius of the pipe, m; $\mu_p$ is the heat loss coefficient of pipe, MW/(m²·°C).

Solve the differential equation (1-1) to get a mathematical model about the thermal energy transmission delay time and heat loss:

$$T_{out}(t) = T_w + (T_{in}(t_o) - T_w) \exp\left(-\frac{2 \mu_p}{\rho c_p R}(t - t_o(t))\right)$$ (2)

Where, $T_{out}(t), T_{in}(t_o)$ is the fluid temperature at the inlet and outlet of the pipe. The delay schedule of $t - t_o$ is as follows:

$$\int_{t_o(t)}^{t} \frac{G_p}{\pi \rho R^2} dt = L_p$$ (3)

Assuming that the mass flow rate of the fluid in the pipe network remains unchanged, that is, in the quality adjustment mode, the simplified delay time can be expressed as:

$$\Delta t = t - t_o(t) = \frac{\pi \rho R^2 L_p}{G_p}$$ (4)

2.2. Heat Storage/Release Model of Pipe Network

Due to the thermal inertia of the pipe network, it takes a certain time for the heat medium to flow in the pipe. During this time, the heat carried by the heat medium is stored in the pipe, and another part is transferred to the pipe wall and insulation layer, making the heating pipe network have Because of the heat storage characteristics, the heating pipe network can be regarded as a heat storage body. When the system is dispatched for unit output, the heat stored in the pipe network is considered, so as to reasonably store and release the heat in the pipe network.
The balance of heat storage/release of the pipe network is as follows:

\[
\sum_{n=1}^{N} Q_{sto,n,t} = \sum_{n=1}^{N} (Q_{in,n,t} - Q_{out,n,t} + m_{w,n} \varepsilon_{w,n} T_{w,n})
\]

Where, \(Q_{sto,n,t}\) is the heat storage capacity of pipe section \(n\) at the current time \(t\), a positive value means that the supply exceeds demand, and the pipe network stores heat, and a negative value means that the supply is less than demand, and the pipe network releases heat.

\(Q_{in,n,t}\) is the heat at the inlet of pipe section \(n\) at time \(t\); \(Q_{out,n,t}\) is the heat at the outlet of pipe section \(n\) at the current time \(t\); \(m_{w,n}\) is the wall quality of pipe section \(n\), \(\varepsilon_{w,n}\) is the specific heat of tube wall, \(kJ/(kg \cdot k)\); \(T_{w,n}\) is the average temperature of pipe section \(n\), \(k\).

The heat storage capacity of the pipe network is limited, and the heat storage of the pipe network should not exceed the maximum heat storage capacity:

\[
0 < Q_{sto,t} \leq Q_{sto}^{max}
\]

In order to maintain the basic heat supply capacity of the unit, the heat release of the pipe network should not exceed the minimum heat release:

\[
Q_{sto}^{min} < Q_{sto,t} \leq 0
\]

Where, \(Q_{sto}^{max}\) is the maximum heat storage of pipe network; \(Q_{sto}^{min}\) is the minimum heat release of pipe network.

3. Research on Optimal Dispatch of Integrated Energy System Considering Thermal Inertia

Based on the actual heating status of an industrial park and the load characteristics of industrial production users, this section studies how to use the thermal inertia of the pipe network to optimize the output of the unit. First, from the theoretical level, combined with the thermal inertia and heat storage characteristics of the pipe network, the electrical/heat output operating characteristics of the gas-steam combined cycle unit are analysed. On this basis, an optimal scheduling model of the system is established. Taking the energy system as a case, model verification is carried out to analyse the optimization effect that the thermal inertia and heat storage characteristics of the pipe network can achieve on the output dispatch of the system units.

3.1. System Output Optimization Analysis Based on Thermal Inertia of Pipe Network

In the actual operation project of the steam heating pipe network, when the source side unit in the heating system adjusts the output or the heat user demand fluctuates, it will cause the energy consumption at both ends of the supply and demand to be mismatched, resulting in the steam parameters and the heating pipe network. The steam flow rate changes, and when the situation is serious, pipe bursts and water hammers may even cause extremely adverse effects on the safe operation of the system, affecting the normal production work of industrial users at the end of the system or the daily heating of residential users. The actual operating conditions of the steam pipe network are a process in which steam temperature, pressure, and flow are constantly changing and influencing each other. These changes further amplify the thermal inertia of the pipe network, which is its own characteristic; therefore, the research on the matching of system supply and demand is being carried out. At the same time, the influence of thermal inertia of the pipe network needs to be considered. On the other hand, under certain working conditions, the entire heating pipe network can be regarded as a natural heat storage body to achieve short-term heat storage/release. In order to improve the accuracy and feasibility of the production scheduling plan, combined with the thermal inertia of the pipe network, rational use of the steam pipe network as a heat storage body is of great significance to the formulation of the system's optimization scheduling plan.

Based on the above analysis, take a gas-steam (extraction condensing steam turbine) combined cycle unit as an example to optimize its heat output range. The electric heating operation characteristics of this unit are shown in Fig. 2:
Figure 2. Operating characteristics of combined cycle units with extraction condensing steam turbine

Line AB in Fig. 2 represents the maximum steam inlet operating condition of the steam turbine, and DC represents the minimum steam inlet operating condition; line AD corresponds to the pure condensing operating condition. The line segment BC is similar to the back pressure condition. It can be seen from the electric heating output operation area of the unit that if a certain heat output is given, the corresponding electric output can be adjusted up and down within a certain interval. As the heat output increases, the adjustment interval of the electric output gradually narrows. The specific expression in the figure is that the thermal output of the unit in a certain scheduling period corresponds to the adjustable interval of the electric output \(P\) as \([E, F]\). Point E and Point F correspond to the maximum and minimum electrical output respectively. When the heat output is increased, the adjustable interval \([E, F]\) moves to the right and narrows. When it is adjusted to the maximum thermal output point, the unit will not be able to adjust the electrical output. Due to the thermal inertia of the pipe network and the short-term heat storage/heat release characteristics, the thermal load will no longer strictly limit the heat output of the unit.

Assuming that the operating range of heat output in a certain period of time is \([\overline{H_2}, \overline{H_3}]\), when the heat output is at the minimum \(\overline{H_2}\), it means that the heat load is in the low period of the day. At this time, increasing the heat output to \(\overline{H_3}\) will generate more heat than the heat load needs. This part of the heat is stored in the heat medium of the pipe network due to the thermal inertia of the pipe network, and a small amount of heat energy is lost in the heat medium transmission process. In the next period of high heat load demand, reduce the heat output to \(\overline{H_2}\) to release the heat stored in the pipe network to meet the needs of heat users. This is different from the traditional heat output adjustment method, by optimizing the heat output range of the system unit, it helps to reduce the unit's operating pressure during the peak energy consumption period and enhance the unit's ability to cut peaks and fill valleys.

3.2. Day-ahead Optimization Scheduling Model

In order to tap the potential of the efficient and complementary use of energy forms provided by different units and equipment, and to enhance the advantages of the entire integrated energy system in terms of economy, environmental protection, and energy saving, this section uses the "interconnection and complementarity of each unit equipment and energy flow of the integrated energy system" "Based on the consideration of the heat storage system and the thermal inertia energy storage of the system, an optimal scheduling model for day-ahead operation of the system with the goal of minimizing the cost of single-day system energy consumption has been established.

3.2.1. Objective Function. The objective function is set to minimize the energy consumption cost of the single-day system, as shown in the following formula:

\[
\min C_Z = C_{gas} + C_{steam}(B)
\]
Where, $C_g$ is the overall operating cost of the system. $C_{gas}$ is the system gas purchase cost. $C_{yw}$ is system operation and maintenance cost. $F_{gas}$ is the gas price (2.5 yuan/m$^3$). $F_{yw,i}$ is the operation and maintenance cost of the ith gas turbine (0.173 yuan/kWh); $P_{r,i,t}$ is the gas turbine electrical power at time $t$ (kw); $\eta_{g,i}$ is the power generation efficiency of the gas turbine $i$; $R$ is the natural gas calorific value (9.72 kWh/m3). $\Delta t$ is the dispatch step length (1h).

### 3.2.2. Restrictions

1. **Power balance constraint**: Ignoring grid losses, the sum of the electrical power of all power generation equipment in the system and the electrical load are always in balance.

$$\sum_{i=1}^{4} P_{gen,i,t} = P_{load,t}$$  

Where, $P_{gen,i,t}$ is the electric output of the i-th unit at time $t$, kW; $P_{load,t}$ is the user electrical load, kW.

2. **Unit output constraint**: The upper and lower limits of the output range of each unit and equipment:

$$P_{min,i} \leq P_{t,i} \leq P_{max,i}$$

Where, $P_{t,i}$ is the output of unit equipment $i$ at time $t$ in the energy supply system, kW. $P_{min,i}$ and $P_{max,i}$ is respectively the minimum output and maximum output of unit equipment $i$, kW. $\phi_{t,i}=0,1$ are respectively the minimum output and maximum output of unit equipment $i$ at time $t$, "0" means in shutdown state, and "1" means in operation state.

3. **Ramp constraint**: The output adjustment of the power supply unit in two adjacent dispatching periods is limited by the climbing rate. The climbing constraint equation of the unit is:

$$\Delta t R_{down}^i \leq P_{t,i} \leq \Delta t R_{up}^i$$

Where, $R_{down}^i$ is the maximum downward ramp rate of unit $i$; $R_{up}^i$ is the maximum upward ramp rate of unit $i$.

4. **Thermal equilibrium constraint**: Similar to the power network balance, the heating network needs to maintain thermal balance within a dispatch step. The heat balance constraint between the source heat output and heat load is:

$$\sum_{i=1}^{4} H_{gen,i,t} = H_{load,t}$$

Where, $H_{gen,i,t}$ is the heat output of the i-th unit at time $t$, kW; $H_{load,t}$ is the user heat load, kW.

The thermal energy transmission delay time in formula (2) is a time-dependent variable, which is difficult to calculate; it is usually assumed that the flow rate in the pipeline is a constant value and the pipeline distance is a known constant, then the delay time can be easily calculated.

### 4. Case study

#### 4.1. Case Description

Take an industrial park as a case for calculation and analysis. The industrial park is equipped with a comprehensive energy centralized power supply station, which supplies energy for dozens of enterprises in the park. The main energy supply equipment is a gas-steam combined cycle unit, which meets the steam demand of all production users in the park. Among them, the first phase unit includes two 60WM class (i1, i2) units, and the second phase includes two 30WM class (i3, i4) units. The steam turbine of the first-stage unit is of extraction condensing type, and the second-stage steam
turbine of the unit is of back pressure type. There are also heat exchange units and refrigeration units to meet the daily energy needs of the people in the park.

The main parameters of the gas turbine equipment and the parameter information of the heating pipe network are shown in Tables 1 and 2:

### Table 1. Gas turbine performance parameters

| Parameters                          | (#1, #2)value | (#3, #4)value |
|-------------------------------------|----------------|----------------|
| rated power                         | 45409 kW       | 31055 kW       |
| Rated heat rate                     | 9034kJ/kwh     | 9359kJ/kwh     |
| Power generation efficiency         | 30%            | 32%            |
| Single cycle thermal efficiency     | 39.85%         | 39.66%         |
| Fuel consumption (single unit)      | 11.00x10³ Nm3/h | 9.00x10³ Nm3/h |

### Table 2. Main parameters of heating pipe network

| Pipe network             | Medium pressure heating network | High pressure heating network |
|--------------------------|---------------------------------|------------------------------|
| Nominal diameter         | DN500/DN400/DN350               | DN400/DN350/DN250            |
| Total length km          | 11.89                           | 7.8                          |
| Insulation Materials     | Polyurethane rigid foam         |                              |

During the winter heating period, the main energy demand in the park is electricity and heat; this section selects the operating conditions of a normal working day in winter, and launches system optimization scheduling under the conditions of meeting the basic electrical and thermal load requirements. On this working day, Unit #3 was not started, and the steam turbine of Unit #4 was not started. The steam produced by the waste heat boiler was directly supplied to the heating network after temperature reduction and pressure reduction. The heat output of the working unit and the heat load of the high/medium pressure heating network enterprise during the whole day of the day are shown in the figure below. From Fig.3, it can be seen that the unit output tracks the heat load in real time during most of the day, and the curve fluctuates. The trend is similar; on the other hand, the heat output of the unit has obvious peak and valley changes. The first peak of steam consumption appears from 6:00 to 8:00 in the morning, the valley value of steam consumption appears from 9:00 to 13:00, and 15:00 in the afternoon. —The second peak of steam consumption appears at 17:00. This phenomenon is mainly due to the fact that most of the enterprises in the industrial park use steam 24 hours a day, but the amount of steam used shows irregular changes. The steam flow rate reaches the maximum.

This study uses MATLAB R2016a optimization tool to solve the model, the scheduling interval is 1 hour, and the total scheduling time is 24 hours.

![Figure 3. Changes in heat output and heat load power during working days](image)
4.2. Result analysis

When considering the impact of the thermal inertia of the pipe network on the economics of the heating system in the industrial park, this paper designs three comparative cases: Case 1 is a basic reference case, without considering the thermal inertia and heat storage characteristics of the pipe network, the electric heating load needs to meet the time balance constraint shown in 3; Case 2 only considers the scenario of pipe network thermal inertia; Case 3 is a scenario that considers both pipe network thermal inertia and heat storage characteristics.

4.2.1 Economic comparison. The economic cost calculation results of the three cases are shown in Table 3. It can be seen from Table 3 that compared with the initial case 1, the cost of natural gas purchase in the case two and the case three has been reduced, and the case two saves 5600 yuan compared with the case one, and the saving rate is 3.9%. Compared with Case 2, Case 3 saves 8600 yuan, with a saving rate of 6.3%. It shows that the proposed optimization scheme has certain economic efficiency.

| Case | Thermal inertia | Heat storage | cost (ten thousand yuan) |
|------|----------------|--------------|--------------------------|
| 1    | ×              | ×            | 14.24                    |
| 2    | √              | ×            | 13.68                    |
| 3    | √              | √            | 12.82                    |

4.2.2 Thermal output optimization. For the optimization scheme for considering the thermal inertia of the case two, the unit is significantly changed, and the heat transfer force is no longer tracked in the current change in the thermal load, but is displaced on a certain time scale. That is, the red curve in Fig. 4 does not match the fluctuation trend of the red curve in Fig. 3. Considering the thermal inertia of the pipe network, the output of the source-side unit will be distributed to the thermal users after a certain time delay. That is to say, the thermal inertia of the pipe network makes the thermal output of the unit at this moment meet the thermal load after a certain time. This is the characteristic of the pipe network that is different from the power grid. Because the electric energy is transmitted at the speed of light, the electric output at this moment is the electric load at that moment. Therefore, before the peak of steam consumption, the unit adjusts the heat output in advance to meet the load demand of users during the peak period. As shown in Fig. 4, Case 2 started to increase the heat output of the unit from 4:00 to 5:00 in the morning, while maintaining a slightly lower unit's stable output during the steam peak period can meet the steam demand during this period. The steam peak and trough periods have the largest amount of change, indicating that part of the heat output has been transferred.

![Figure 4. Comparison of heat output changes between case 1 and case 2](image-url)
Case 3 further considers the heat storage characteristics of the pipe network on the basis of Case 2, as shown in Fig. 5. The overall output of the unit is maintained at a relatively high level, and the fluctuation of the unit is more stable than the previous two cases. This is because during the high output period of the unit, due to the effect of the pipe wall and the insulation layer, part of the heat energy carried by the steam is stored in the pipeline. During the peak steam consumption period, the heat energy in the pipeline is released to meet the thermal load during this period. During the trough, the unit output continues to maintain a relatively high output level for heat storage. This is equivalent to treating the peak and trough periods of steam consumption as a heat storage/release cycle, and the pipe network acts as a heat storage body for short-term heat storage and release during this cycle. Compared with Case 1, the change in heat output in Case 3 has increased significantly, indicating that the flexibility of heat output has been improved.

5. Conclusion
Thermal inertia is an important part of passive flexibility resources. The operational flexibility of the IES has been significantly improved due to the synergy of thermal inertia on the "grid side" and thermal inertia on the "load side". The effective use of passive flexibility resources makes the system not limited to adding additional energy conversion equipment to improve the flexibility of the system. Tapping the potential based on passive flexible resources provides a new development idea for further research on how to increase the redundant space for system optimization and scheduling in the future.

Considering the time lag of heat energy transmission and heat loss, the thermal inertia model and heat storage model of the pipe network are established. Theoretically combined with the thermal inertia of the pipe network, the electrical/heat output operating characteristics of the gas-steam combined cycle unit are analysed. On this basis, an optimal scheduling model of the system is established. The energy supply system of an industrial park is taken as a case. The model is verified, and the calculation results show that the system unit output takes into account the thermal inertia of the pipe network, and the heating output can stagger the heat load demand on the time scale, and at the same time improve the unit output stability. Then the heat storage characteristics of the pipe network are further considered, and the adjustable amount of heat output is transferred to other time periods to achieve a more stable output effect of the unit.

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7. References
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