Optimization Strategy of Electric Heating with Load Regulation Ability

Qing Wang1*, Xu Liu2, Song Liu3, Zhongyu Lin2, Yang Chen2, Congcong Li1

1 State Grid Shandong Electric Power Research Institute Jinan, China
2 State Grid Shandong Electric Power Rizhao Supply Company, Jinan, China
3 State North China Electric Power University Beijing, China
*Corresponding author’s e-mail: Wangqing_sgcc@126.com

Abstract. In recent years, more and more users choose electric heating to replace traditional centralized heating mode in the northern area. The flexibility of electric heating, the energy consumption characteristics of buildings, the regulation ability of users and Time-of-Use (TOU) electricity tariff give much possibility to optimize the output power strategy of electric heaters. The existing electric heating control system, where the suitable working temperature is usually used as the only set value for human life and working environment, leads to unnecessary energy consumption in some low heat demand area.

This paper, focused on a commercial used building in Shandong province, takes different heating demand characteristics into consideration, establishes electric heating load model and analyses each load’s regulation ability. Six distributed electric heaters are installed in the building, with one room equipped with one electric heater. The heater is modelled based on the parameters and output power characteristics. For the building itself, the energy consumption characteristics and thermal inertia are also analysed and presented.

1. Introduction

Distributed electric heating is a kind of scattered heating mode which converts electricity into heating energy and releases the heat directly to the load. This kind of electric heating mode is wildly accepted by users with its high regulation ability, better thermal characteristics and easy to control [1]. It can be predicted that, with the rapid development of economy and high demand of free population, the electric heating is bound to be popularized and applied on a larger scale [2].

The thermal characteristics of the building make the heat load of the building change sometimes, and the heat load is also affected by the building parameters, outdoor temperature, indoor setting temperature and other factors [3]. Paper [4], from the perspective of meteorological factors, puts forward an electric heating load prediction method mainly based on temperature and humidity by regression analysis. Paper [5], based on the principle of building heat transfer characteristics, establishes heat load model from three aspects, electric heater power, heat dissipation and heat storage. The heterogeneous load clustering is also analysed based on outdoor temperature, heat capacity and thermal resistance. The heating load demand and its optimization, on the one hand, depends on the electricity price curve, and on the other hand, closely related to the heating energy loss characteristics of the building [6]. Paper [7] studies the building energy consumption characteristics in a campus scenario.

At present, the research of electric heating optimization mainly focused on the optimization of heating storage type electric heating [8] or the optimization strategy with participating in demand side...
response [9]. This paper emphasizes the thermal characteristics of the building and heating load characteristics, based on TOU electricity tariff curve, puts forward an optimized operation strategy for electric heaters with the objective of minimizing electricity cost and also compares the economy of different operation strategies. If you don’t wish to use the Word template provided, please use the following page setup measurements [1].

2. Electric heating modelling

Time-varying characteristic of electric heating load links to the building’s thermal process, including electric heater’s output power, heat dissipation and heat storage [10]. This paper takes an office area in a building located in Jinan, Shandong province as the research object. This office area has six rooms as the electric heating load, which are respectively conference room, tea room, general manager office, welding room warehouse and computer room. The detailed info of each room is listed in Table 1.

| Room               | Area/ m² | Heat resistance (°C/W) | Heat capacity (J/°C) |
|--------------------|----------|------------------------|----------------------|
| Conference room    | 27.3     | 0.078                  | 18263875             |
| Tea room           | 16.9     | 0.077                  | 18563029             |
| General manager office | 19.4 | 0.07                   | 15762098             |
| Welding room       | 19.9     | 0.065                  | 14376036             |
| Warehouse          | 18.2     | 0.08                   | 16354023             |
| Computer room      | 9.8      | 0.08                   | 16839517             |

Each room is equipped with one electric heater and the electric heater could work in four modes, 0W, 900W, 1300W and 2200W.

The electric heater output power is described as \( P_{ij} \), of which \( i \) is the number of the room and \( j \) is electric heater’s working mode.

The heating dissipation is proportional to the temperature difference between indoor temperature and outdoor temperature, represented as:

\[
P_{is}^t = \frac{(T_{in}^t - T_{out}^t)}{R_i}
\]

Equation (1), \( R_i \) is the heat resistance of room \( i \), \( P_{is}^t \) and \( T_{in}^t \) are respectively heat dissipation and indoor temperature of room \( i \) at time \( t \). \( T_{out}^t \) is the outdoor temperature at time \( t \).

The heating storage depends on indoor air and heating storage characteristics of the wall’s material, which could be described as:

\[
P_{ic}^t = C_i \frac{dT_{in}^t}{dt}
\]

Equation (2), \( P_{ic}^t \) and \( \frac{dT_{in}^t}{dt} \) are respectively room \( i \)”s stored heating and change rate of indoor temperature at time \( t \), \( C_i \) is heating capacity of room \( i \) (J/°C).

According to the laws of energy conservation, the energy released by electric heater minus the heat dissipation is equal to the stored heating:

\[
P_{ij} - \frac{T_{in}^t - T_{out}^t}{R_i} = C_i \frac{dT_{in}^t}{dt}
\]

Take the minimum electricity cost as the objective function:

\[
\min \left( \sum_{i=1}^{24} \sum_{t=1}^{24} P_{ij}^t \Delta T \ast Price_t \right)
\]
\( \Delta T \) is data sampling interval, which is 15 minutes and \( Price_t \) is the electricity price at time \( t \). The ToU electricity price in Shandong province is listed in table 2.

| Time          | Electricity price RMB/kWh |
|---------------|---------------------------|
| Peak          | 8:30 – 11:30              |
|               | 16:00 – 21:00             |
|               | 0.9203                    |
| Off-peak      | 7:00 – 8:30               |
|               | 11:30 – 16:00             |
|               | 21:00 – 23:00             |
|               | 0.6226                    |
| Valley        | 23:00 – 7:00              |
|               | 0.3249                    |

The inequality constraints include:

1. The output power of electric heater:
   \[ P_{ij}^t \in (0, 900, 1300, 2200) \]  \( (5) \)

2. The indoor temperature during working hours (8:30 - 17:30):
   \[ 18 < T_{in}^t < 25 \]  \( (6) \)

3. **Economic comparaison among different operation strategies of electric heater**

Each room is equipped with one temperature measurement device and the temperature curve of one day in January is as follows:

![temperature of each room](image.png)

**Figure 1. temperature of each room**

### 3.1 *Electricity cost with no optimal strategy implemented and electric heater’s output power curve*

The working hours of this office floor is from 8h30 to 17h30, generally, the user turn on the electric heater in the morning when they are in the office and set the target temperature at 20°C. After the room indoor temperature reaches the target value, electric heater in the constant temperature mode and the users turn off the electric heater in the afternoon when they leave the office. In this situation, take the conference room as the example, the indoor temperature and the output power curve of electric heater are shown in Fig.2.
The electric heater is started at 8h30 with the output power 2200W and switch to mode 1 with the output power of 900W to maintain the indoor temperature when the indoor temperature reaches the set value. The heater is turned off at 17h30 as people leave the office.

The indoor temperature of the conference room was 11.24℃ at 8h30 in the morning and reaches the set value at 9h10. The room temperature then keeps the set value until 18h15, as the heater is turned off at 17h30. The indoor temperature begins to decline from 18h15.

In this natural condition, where the turn on and turn off state of electric heater depends on the people arriving or leaving time, the total electricity cost of the six rooms in one day is 16.13RMB.

3.2 Electricity cost with intelligent control implemented under constant temperature target

It can be found that in 3.1 that under natural conditions, the starting working time of electric heater is the peak time of electricity price, and it takes about 30 minutes to reach the set temperature value. This kind of operating mode could not guarantee the users’ comfort in the electric heater’s beginning working hours. Therefore, the intelligent control could be implemented by shifting the electric heater’s starting working time to ensure the users’ comfort and avoid the electricity consumption during peak hours.

The set indoor temperature is still 20℃, considering TOU electricity price and thermal inertia, the inequality constraint in (6) is changed to $T_{in}^{t} = 20$℃, $t \in (8h30,17h30)$. The objective function is to minimize the electricity cost and still take the conference room as the example, the output power of electric heater and indoor temperature are shown in Fig.3.
The electric heater starts working at 7h45 with the power of 2200W and the indoor temperature reaches the set value at 8h30. The output power of the heater was 1300W at 11h45 and 15h30. The electricity consumption during peak hours was at 10h in the morning with the output of 900W. The electric heater stops working at 16h in the afternoon, and the room temperature keeps at set value through thermal inertia until 17h30.

In this way, the users’ comfort could be guaranteed during working hours and the electricity consumption during peak hours could be minimized. Besides, The thermal characteristics of the room could be fully utilized. In this operation mode, the total electricity cost of 6 rooms is 12.05RMB.

### 3.3 Electricity cost with intelligent control implemented under non-constant temperature target

Different room in reality have different requirements for the comfort range. The indoor temperature setting value directly affects the economy of electric heating. This session firstly analyses the heating demand characteristics of each room and the target temperature is set based on the working period and break time.

| Room                  | Working hours | T for working hours | Temperature | T for break time |
|-----------------------|---------------|---------------------|-------------|------------------|
| Conference room, tea room | 8h30-12h, 13h-17h30 | 12h-13h | 20°C | 18°C |
| General manager office | 8h30-12h, 13h-17h30 | 12h-13h | 20°C | 18°C |
| Welding room          | 8h30-12h, 13h-17h30 | 12h-13h | 10°C | 10°C |
| Warehouse             |               |                     | 18°C        | 10°C |
| Computer room         |               |                     | 18°C        | 10°C |

Conference room, team room and GM office are frequently used and the target temperature during working hours is set at 20°C and 18°C for break time. The target temperature of welding room could be set at 18°C due to the high temperature generated during welding process and considering the dressing code if people enter the welding room. Compared to the frequently used rooms, warehouse and computer room are less used and the target temperature could be adjusted to 18°C.

Based on the above analysis, the target temperature of each room during different time period is set respectively. Mixed integer programming (MIP) is used to solve the electric heater’s output curve of these six rooms. Take the conference room as the example, the output power of electric heater is as follows:

![Figure 4: Indoor temperature of conference room and electric heater’s output power with intelligent control implemented and non-constant target temperature](image-url)
As the temperature demand under non-constant target temperature is lower during break time, the output power of electric heater at 11h45 under constant temperature target will not start up in this scenario. The temperature after 12h begins to decline and the room temperature maintains between 18°C and 20°C.

In this operation mode, the electricity cost of 6 rooms is 10.67RMB.

4. Economic analysis of electric heating optimization

Electricity cost of each room under different operation mode are listed in the table below:

Mode1: non optimal strategy
Mode2: optimal strategy implemented with constant set temperature
Mode3: optimal strategy implemented with non-constant set temperature

| No. | Room                | Mode 1/RMB | Mode 2/ RMB | Mode 3/ RMB |
|-----|---------------------|------------|-------------|-------------|
| 1   | Conference room,    | 2.63       | 1.78        | 1.75        |
| 2   | Tea room            | 2.21       | 2.07        | 1.98        |
| 3   | General manager office | 2.21    | 1.72        | 1.64        |
| 4   | Welding room        | 3.37       | 2.20        | 1.47        |
|     | Total cost of above rooms | 10.42     | 7.7         | 6.84        |
| 5   | Warehouse           | 2.86       | 2.15        | 1.91        |
| 6   | Computer room       | 2.86       | 2.12        | 1.92        |
|     | Total cost of above room 5 and room 6 | 5.72  | 4.27        | 3.83        |
|     | Total electricity cost | 16.13     | 12.05       | 10.67       |

Compared to mode 1, mode 2 could guarantee the people’s comfort and minimize the electricity consumption during peak hours based on the thermal characteristics. The electricity cost saved by mode 2 mainly due to the different energy consumed during different TOU electricity price period. In mode 2, the electricity cost is saved by 25.3% compared to mode 1.

Compared to mode 2, the target temperature in mode 3 is adjusted according to each room’s characteristics. The first four rooms mainly adjust the target temperature during break hours, from 20°C to 18°C. The therefore reduced electricity cost is 11.1%. The overall target temperature of warehouse and computer room are adjusted to 18°C and the electricity cost reduction caused by this part is 10.3%.

Overall, the optimization strategy based on peak valley electricity price can reduce the power cost by 25.3% and the further consideration of setting different target temperature in different time slot could reduce the electricity cost by 11.4%.

5. Conclusion

Electric heater, as a supplementary way of central heating, tends to have a higher demand in residential and commercial users. At the same time, with the rapid development of smart home, it has become possible to embody the optimization strategy in the electric heater.

This paper analyses the heating demand characteristics and the economic result for different operation strategies of electric heaters. Based on the analysis, the best operation strategy of electric heater shall take TOU electric tariff into consideration and set a reasonable target temperature for each room according to the room’s thermal characteristics and the utilization situation. This kind of strategy could not only ensure the users’ comfort, but also greatly reduce the electricity cost.
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