Analysis of the behavioural capabilities of electric heating loads to participate in power system power regulation

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Abstract. The high proportion of new energy access leads to the scarcity of power system regulation capacity, and it is important to provide regulation capacity for the power system by reasonably regulating the electricity consumption of electric heating temperature-controlled loads. In this paper, in order to analyse the characteristics of the electric heating behaviour and the electric heating load's ability to participate in grid regulation, the differential equations of a typical room temperature change process are constructed first to establish the equation of state model of a two-input system, and then the state equations are discretised into difference equations according to the bilinear discretisation method for iterative solving. This paper analyses that the equivalent heat capacity and thermal resistance parameters of indoor air and wall will affect the temperature response time and the size of the required heating power, with the lowering of the outdoor temperature of a single household room, the average indoor warming time increases, the average cooling time decreases, the average daily power consumption increases, and the total power consumption of the whole community power also rises.

Keywords: Electric heating load, difference equation, bilinear discrete method.

1. Introduction

The new power system should be dominated by new energy sources [1], which is an important measure to cope with global climate change. However, a high proportion of new energy access may lead to a scarcity of power system regulation capacity. Therefore, by rationally regulating the electricity consumption of electric heating and temperature-controlled loads, the power system can be provided with important regulation capacity. Existing studies have mainly analysed the regulation capacity of electric heating through the establishment of a power system model based on market mechanisms or technical means such as smart meters [2]. In this paper, we calculated and analysed the electricity consumption behaviour of electric heating loads in typical households and the regulation capability of electric heating loads to participate in the power grid by means of the set-total parameter equivalence model of the room temperature change process and the establishment of difference equations by the bilinear discretization method [3].

2. Model building process

2.1. Equivalent modelling of room temperature change process

The temperature change process of the building room [4-5] is determined by the joint action of the heating power of the electric heating equipment and the outdoor temperature, and the temperature change process of the room can be approximated by the equivalent model of the set of total parameters shown in Figure 1.

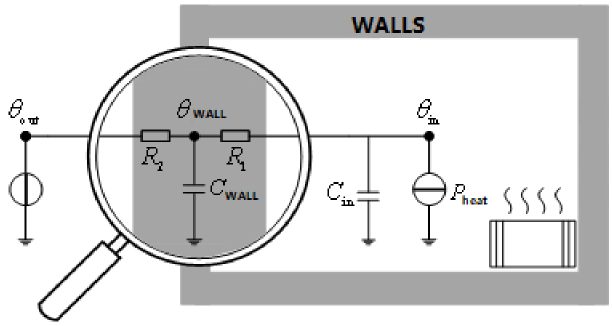

Figure 1. Schematic diagram of the equivalent model of the room temperature change process

The set parameter ordinary differential equation describing the temperature change process in the room is:

$$\begin{cases} C_{\text{in}} \dfrac{\mathrm{d}\theta_{\text{in}}(t)}{\mathrm{d}t} = P_{\text{heat}}(t) - \dfrac{\theta_{\text{in}}(t) - \theta_{\text{wall}}(t)}{R_1} \\ C_{\text{wall}} \dfrac{\mathrm{d}\theta_{\text{wall}}(t)}{\mathrm{d}t} = \dfrac{\theta_{\text{in}}(t) - \theta_{\text{wall}}(t)}{R_1} - \dfrac{\theta_{\text{wall}}(t) - \theta_{\text{out}}(t)}{R_2} \end{cases} \quad \theta_{\text{in}}(0) = \theta_{\text{in}0}, \quad \theta_{\text{wall}}(0) = \theta_{\text{wall}0} \tag{1}$$

In Equation 1, C_{in} and C_{wall} are the equivalent heat capacity of the indoor air and the equivalent heat capacity of the wall, respectively [6]; R_1 and R_2 are the equivalent thermal resistances of the indoor air and the inside of the wall, and the equivalent thermal resistances of the outside of the wall and the outdoor air, respectively; q_{in} , q_{wall} , and q_{out} are the indoor temperature, the wall temperature, and the outdoor temperature, respectively; and P_{heat} *(t)* is the heating power of the electric heating equipment, and $P_{\text{heat}}(t)=S(t)P_N$, in which P_N is the rated power of the electric heating equipment. *S* (*t*) is the switching state of the electric heating equipment, taking 0 when it is closed and 1 when it is opened.

In addition, there are 600 electric heating households in the residential neighbourhood, and for simplicity, all the households are represented by a typical household, which has only one room with a floor area of 80 m2, and uses an electric heater with a rated power of 8 kW, and a temperature control interval of 18°C-22°C. The total rated power of the electric heating equipment in the residential neighbourhood is 4800 kW. The total rated power of the electric heating equipment in the district is 4800 kW.

Based on the subsequent calculations, the parameters of the equivalent model for the temperature change process in a typical household are set as shown in Table 1:

Table 1. Equivalent model parameters of temperature change process in a typical household (80m^2)

parametric	Thermal resistance R /1 (°C/W)	Thermal resistance R /2 (°C/W)	Heat capacity C /in (J/°C)	Heat capacity C /wall (J/°C)	Electric heating equipment Rated power PN /(kW)
numerical value	1.2 x 10-3	9.2 x 10-3	1.1 x 106	1.86 x 108	8.0

2.2. Establishment of the equation of state

Equation 1 is a formula forθ_{in} andθ_{wall} The system of binary differential equations, the system of binary differential equations can be solved by oed45 [7], but the direct solution process is relatively complicated. For this reason in this paper, the differential equation is converted into a state equation [8] to be solved. Both state equations and differential equations are mathematical tools for describing physical systems, but state equations are simpler to understand, intuitive, and more stable.

The equation of state is of the form:

$$\dot{X} = AX + BU \tag{2}$$

where *X* is the state vector, *U* is the system input, *A* is the system matrix, and *B* is the control matrix.

The specific equation of state of the system can be obtained as follows:

$$\begin{cases} d\begin{bmatrix} \theta_{in}(t) \\ \theta_{wall}(t) \end{bmatrix} = \begin{bmatrix} -\frac{1}{R_1C_{in}} & \frac{1}{R_1C_{in}} \\ \frac{1}{R_1C_{\text{wall}}} & -\frac{1}{R_1C_{\text{wall}}}-\frac{1}{R_2C_{\text{wall}}} \end{bmatrix}\begin{bmatrix} \theta_{in}(t) \\ \theta_{wall}(t) \end{bmatrix} + \begin{bmatrix} \frac{1}{C_{in}} & 0 \\ 0 & \frac{1}{C_{\text{wall}}} \end{bmatrix}\begin{bmatrix} P_{heat}(t) \\ \theta_{out}(t) \end{bmatrix} \\ A = \begin{bmatrix} -\frac{1}{R_1C_{in}} & \frac{1}{R_1C_{in}} \\ \frac{1}{R_1C_{\text{wall}}} & -\frac{1}{R_1C_{\text{wall}}}-\frac{1}{R_2C_{\text{wall}}} \end{bmatrix}, B = \begin{bmatrix} \frac{1}{C_{in}} & 0 \\ 0 & \frac{1}{C_{\text{wall}}} \end{bmatrix} \end{cases} \tag{3}$$

From the above state equation, it can be seen that the system has two inputs, the heating power $P_{heat}(t)$ of the electric heating equipment and the outdoor temperature θ_{out},The two state variables, indoor temperature $\theta_{\text{in}}$and wall temperature θ_{wall} .

2.3. Discretisation of the equation of state

Since the time interval is required to be one minute and the independent variable t is a discrete quantity, the state equation needs to be discretised. The bilinear discretisation method [9] is used to discretise the system state equations, and the discretised system matrix can be obtained$\overline{A}$ and control matrix$\overline{B}$ for:

$$\begin{cases} \overline{A} = \left(I - \frac{A\Delta t}{2}\right)^{-1}\left(I + \frac{A\Delta t}{2}\right) \\ \overline{B} = \left(I - \frac{A\Delta t}{2}\right)^{-1} B\Delta t \end{cases} \tag{4}$$

The discretisation gives the difference equation of the system as:

$$\begin{gathered} A = \begin{bmatrix} -\frac{1}{R_1C_{in}} & \frac{1}{R_1C_{in}} \\ \frac{1}{R_1C_{\text{wall}}} & -\frac{1}{R_1C_{\text{wall}}}-\frac{1}{R_2C_{\text{wall}}} \end{bmatrix}, \overline{A} = \left(I - \frac{A\Delta t}{2}\right)^{-1}\left(I + \frac{A\Delta t}{2}\right) \\ B = \begin{bmatrix} \frac{1}{C_{in}} & 0 \\ 0 & \frac{1}{C_{\text{wall}}} \end{bmatrix}, \overline{B} = \left(I - \frac{A\Delta t}{2}\right)^{-1} B\Delta t \\ X(t+\Delta t) = \overline{A}X(t) + \overline{B}U(t) \end{gathered} \tag{5}$$

2.4. Discretisation of the equation of statechanges

The temperature control interval of the electric heating equipment is 18℃-22℃, when the indoor temperature is higher than 22℃, the electric heating equipment is turned off, and when the indoor temperature is lower than 18℃, the electric heating equipment is turned on, when the temperature is in the range of 18℃-22℃, the switching state of the electric heating equipment is kept in the same state as that of the previous minute, and the change curve of the switching state of the electric heating equipment, *S(t), is* shown in Figure 2:

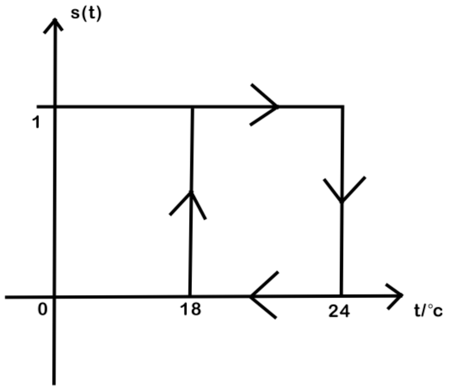

Figure 2. Switch state S(t) change curve

2.5. Iterative solution of difference equation

The rate of change of wall temperature under initial conditions is 0, i.e.$\frac{d\theta_{wall}}{dt}$ = 0, which can be obtained by bringing in the differential equation:

$$\frac{\theta_{in}(0)-\theta_{wall}(0)}{R_1}-\frac{\theta_{wall}(0)-\theta_{out}(0)}{R_2}=0 \tag{6}$$

The initial condition for the wall temperature can be found:

$$\theta_{wall}(0)=\frac{R_1\times\theta_{out}+R_2\theta_{in}}{R_1+R_2} \tag{7}$$

From Equation 6, it can be seen that the initial temperature of the wall is related to the outdoor temperature and indoor temperature, and the outdoor temperature is generally constant, so the initial temperature of the wall can be obtained through the initial temperature of the indoor. The heating power of the electric heating equipment changes as shown in Figure 1, the initial heating power since the formulation is off. The input conditions are known, the initial state of the state variable is known, the difference equation can be solved.

Initialise the values of the system parameters such as R1, represent the system matrix A and the control matrix B as a matrix, and then discretise the process. dt is 1 minute, for ease of power calculation dt is used as 60s, and the length of time is N days, i.e., N*24*60*60s, so the length of time is N*1440, denoted as M. Define the state variable matrix X as 2 rows and M+1 columns, and input matrix U as 2 rows and M+1 columns. the first columns of X and U are put into the initial values of the system. and the first column of U are put into the initial value of the system. The new electric heating power is obtained by iterating through the change rule shown in Fig. 1 and the indoor temperature in the previous minute, the state variables and input conditions in the previous minute are known, and then the values of the state variables in the next minute are calculated iteratively through Eq. 5. The wall temperature and the indoor temperature, obtained by iterating the differential equations [10] are put into matrix X and the electric heating power is put into matrix U. After iterating the calculations for M times, we can solve for the two state variables over the time variation curves.

3. Results

3.1. Steady state analysis

Analyse the nature of the steady state solution of a differential equation for a typical room temperature change process under the constraint of satisfying the temperature control interval. A steady state solution is one in which the value of the solution tends to be stable and does not change with time as time tends to infinity. Therefore this thesis makes $\frac{d\theta_{in}(t)}{d(t)}$ with the $\frac{d\theta_{wall}(t)}{d(t)}$ value to be 0 and substituting in Eq. 1 to obtain the system of steady state equations in Eq. 8 and Eq. 9:

$$S(t)P_N = \frac{\theta_{in}-\theta_{wall}}{R_1} \tag{8}$$

$$\frac{\theta_{in}-\theta_{wall}}{R_1} = \frac{\theta_{wall}-\theta_{out}}{R_2} \tag{9}$$

To better judge the effect of other variables, transforming Eq. 9 yields the following Eq. 10 for the relationship between θin(t) and θwall(t):

$$\theta_{in} = (1+\frac{R_1}{R_2}) \times \theta_{wall} - \frac{R_1}{R_2} \times \theta_{out} \tag{10}$$

It can be seen from the equation that the heating power Pheat(t) at steady state solution is related to the room temperature θ_{in}(t), wall temperature θ_{wall}(t) are related to the equivalent thermal resistance, and the temperature difference between indoor and outdoor.

Characteristics of heating power variation:

There is a linear relationship between the heating power Pheat(t) and the indoor temperature θ_{in}(t), wall temperature θ_{wall}(t), The larger the temperature difference between the θ_{in}(t) and the θ_{wall}(t), the larger the heating power; conversely, the smaller the heating power.

Indoor temperature $\boldsymbol{\theta_{in}}$(t) and wall temperature $\boldsymbol{\theta_{wall}}$(t) are characterised:

There is a linear relationship between the θ_{in}(t) and the θ_{wall}(t), and the slope between them is determined by the ratio of R1 and R2, and will be affected by the outdoor temperature and the heating power. When the thermal resistance R2 of the outdoor air is large, the wall temperature has less influence on the indoor temperature; Thermal resistance R2 is small and vice versa.

Indoor temperature decreases with increasing indoor-outdoor temperature difference; wall temperature increases with increasing indoor-outdoor temperature difference. When the heating power is higher and the wall temperature is lower, the indoor temperature rises faster; conversely, the indoor temperature rises slower. The reason for this is that the higher the heating power, the more heat is provided, and the faster the heat is transferred when the wall temperature is lower.

The effect of model parameters on the pattern of change in the steady state solution

The variation law of the steady state solution is affected by the equivalent heat capacity parameters Cin and Cwall, and the equivalent thermal resistance parameters R1 and R2.

The equivalent heat capacity parameter indicates the ability of an object to store and release heat over a given period of time. When the equivalent heat capacity of the indoor air and the wall is large, the response time between the θ_{in}(t) and the θ_{wall}(t), will be longer and change slowly.

The thermal resistance parameter indicates the size of the obstacle to heat transfer, the larger thermal resistance parameter, the greater obstacle to heat transfer. The larger the equivalent thermal resistance of the indoor air and the inner side of the wall, the smaller heating power required when the temperature difference is the same; the larger the equivalent thermal resistance of the outer side of the wall and the outdoor air, the smaller the effect of the wall temperature on the indoor temperature.

The value of each parameter will have a certain impact on the characteristics of the steady state solution, so in actual design and production process, you need to choose the appropriate parameters according to the actual situation of the room to achieve the desired temperature control effect.

3.2. Analysis of the electricity consumption behaviour of single-user electric heating loads

The initial indoor temperature is 20°C, and given the outdoor temperatures of 0°C, -5°C, -10°C, -15°C, -20°C, and -25°C, so that the initial switching state of the electric heating equipment S(t)=0, the heating power Pheat (t) of the electric heating equipment is 0. The wall temperatures under the initial conditions can be obtained from Eqs. 4-7 to 17.69°C, 17.11°C, 16.53°C, 15.96°C, 15.96°C, 15.96°C 15.38°C, and 14.8°C.

The input conditions are known and the initial states of the state variables are known, and the state equations can be solved iteratively. Through the iterative solution of the state equation, the indoor temperature change curve in 24h under different outdoor initial temperatures can be obtained. This is shown in Figure 3 to Figure 8:

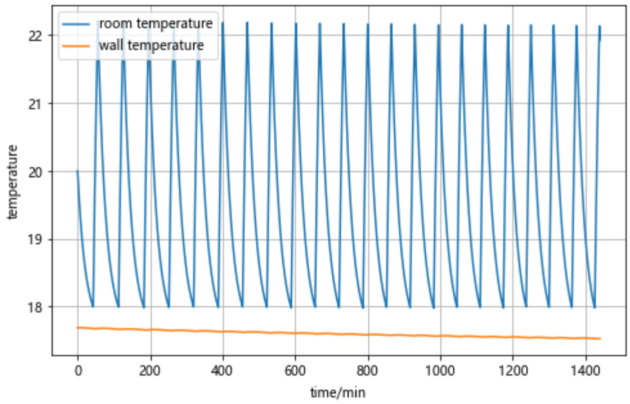

Figure 3. Indoor wall temperature change curve at outdoor temperature 0°C

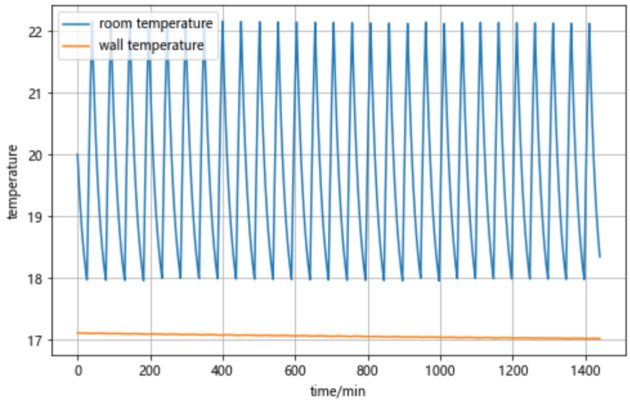

Figure 4. Indoor wall temperature change curve at outdoor temperature -5°C

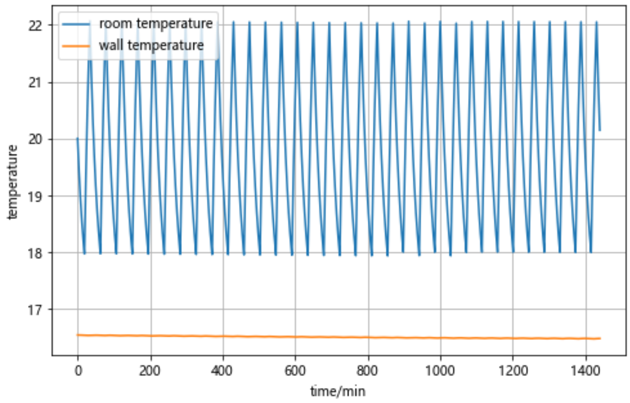

Figure 5. Indoor wall temperature change curve at outdoor temperature -10°C

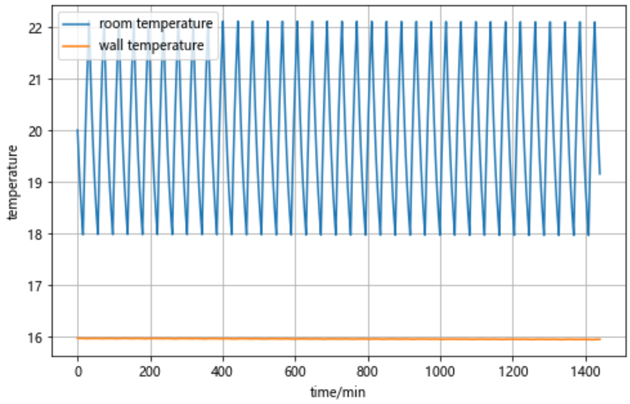

Figure 6. Indoor wall temperature change curve at outdoor temperature -15°C

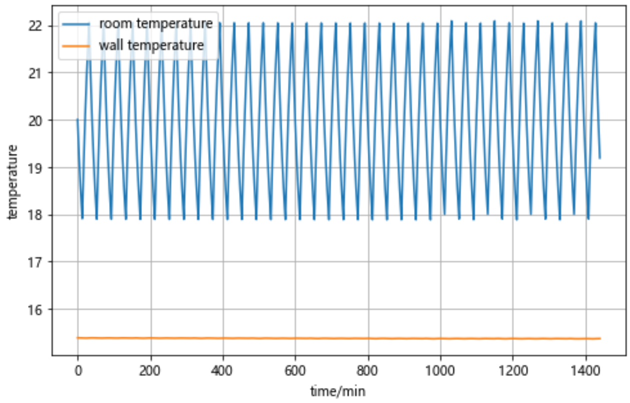

Figure 7. Indoor wall temperature change curve at outdoor temperature -20°C

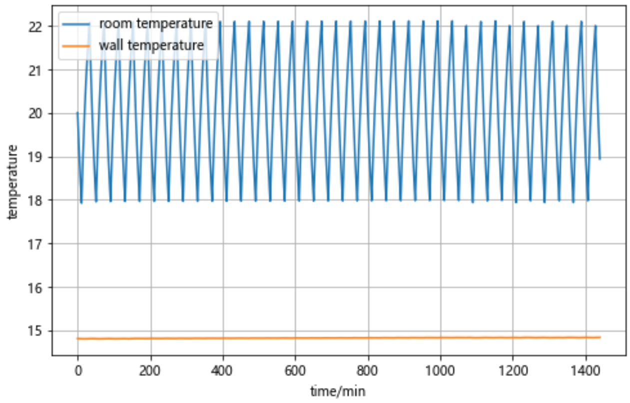

Figure 8. Indoor wall temperature change curve at outdoor temperature -25°C

As can be seen from Fig. 3 to Fig. 8, the indoor temperature oscillates at a certain frequency in the form of a periodic function. The time when the electric heating equipment is turned on is the total time of warming, and the time when the electric heating equipment is turned off is the total time of cooling. The total length of heating divided by the number of oscillations, you can get the average length of heating; similarly, you can get the average length of cooling, you can also get the average duty cycle. The daily electricity consumption can be obtained by the power of the electric heating equipment and the time when the electric heating equipment is turned on. The statistical results under different outdoor initial temperatures are shown in Table 2:

Table 2. Statistical results of characteristic quantities of electricity behaviour of electric heating loads in individual households (initial indoor temperature of 20°C)

Outdoor temperature (°C)	Average temperature rise time/min	Average cooling time/min	Cycle time/min	Average duty cycle/per cent	Daily electricity consumption/kWh	Average daily power consumption/kW
0	13	52	65	0.1985	38.13	1.59
-5	14	36	50	0.2720	52.27	2.18
-10	15	28	43	0.3435	66.00	2.75
-15	17	24	41	0.4129	79.33	3.31
-20	19	21	40	0.4746	91.2	3.80
-25	21	18	39	0.5489	105.47	4.39

3.3. Analysis of Electricity Behaviour of Electric Heating Loads of Small District Customers

It is proposed that there are 600 users in the district, and the initial indoor temperature of each household is uniformly distributed within the temperature control interval, with the outdoor temperatures of 0°C, -5°C, -10°C, -15°C, -20°C, and -25°C, and the initial state of the electric heating equipment is set to be 200 on and 400 off. The input conditions and the initial states of the state variables are known, and the state equations can be solved iteratively. By iteratively solving the state equation, the total electric power consumption curve of the community in 24h under different outdoor initial temperatures can be obtained. This is shown in Figure 9 to Figure 14:

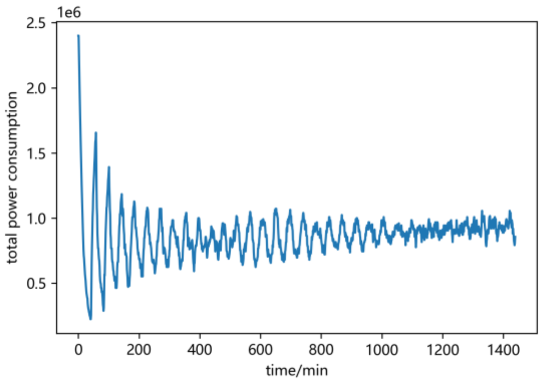

Figure 9. Total power consumption curves for 600 households at steady state with an outdoor temperature of 0°C

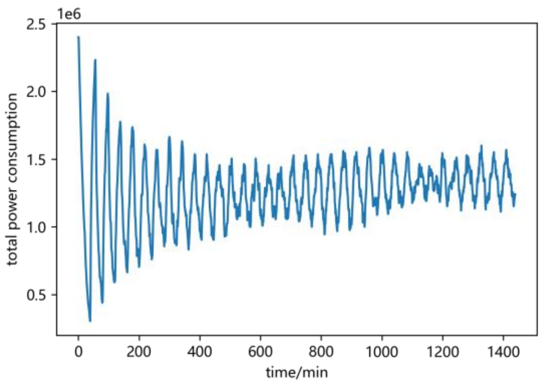

Figure 10. Total power consumption curve for 600 households at steady state with outdoor temperature of -5°C

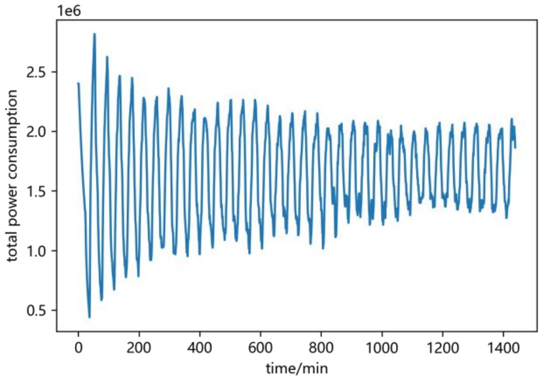

Figure 11. Total power consumption curve for 600 households at steady state with outdoor temperature of -10°C

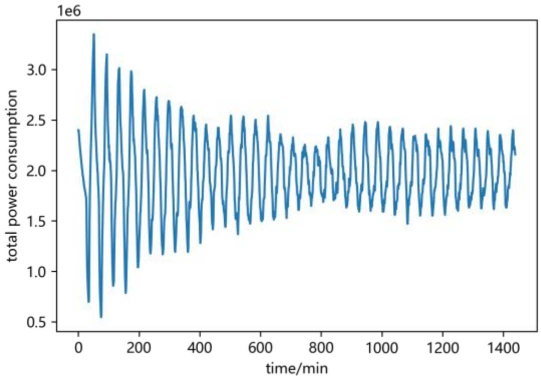

Figure 12. Total power consumption curve for 600 households at steady state with outdoor temperature of -15°C

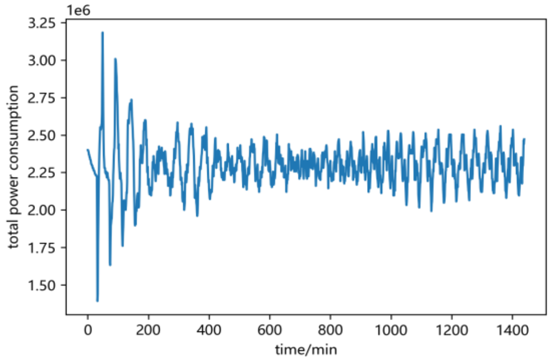

Figure 13. Total power consumption curves for 600 households at steady state with outdoor temperature of -20°C

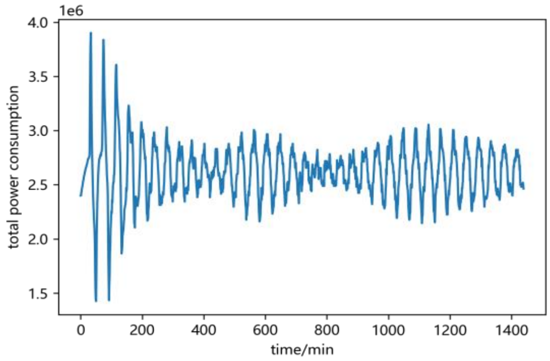

Figure 14. Total power consumption curves for 600 households at steady state with outdoor temperature of -25°C

4. Conclusions

There is a linear relationship between the heating power Pheat(t), the indoor temperature $\theta_{in}(t)$ and the wall temperature $\theta_{wall}(t)$, when the temperature difference increases, the $\theta_{in}(t)$ decreases, the $\theta_{wall}(t)$ rises and the Pheat(t) increases. As the outdoor temperature decreases, the average duration of warming in the occupants' room increases, the average duration of cooling decreases, daily electricity consumption and costs rise, and the total power consumption of the occupants in the neighbourhood increases. These conclusions prove the correctness of the room temperature change process equivalent model, in addition, the equivalent heat capacity and thermal resistance of the indoor air and wall parameters will affect the temperature response time and the size of the required Pheat(t), so in the actual production process, according to the actual situation of the room to choose the appropriate parameters to achieve the desired temperature control effect. Moreover, the paper calculates that the daily electricity consumption of electric heating equipment can reach as high as 30-100 kWh, leading to significant economic costs. To reduce the power consumption cost of electric heating equipment, future measures can involve integrating them into the power grid's demand response, which is expected to yield favorable results.

References

[1] YU Haibin, YAN Wei, WEN Guanglei et al. Characterisation of high penetration new energy power system under dual carbon constraints, upgrading path and design of multiple market mechanisms [J]. Power Big Data, 2023, 26(03): 77-88.

[2] Zhu YJ. Research on electric heating load adjustable capacity assessment and cluster control strategy [D]. Northeast Electric Power University, 2019.

[3] Q. Wang, W. L. You, G. R. Zhang. Periodic solutions of linear difference equations [J]. Journal of Anhui University (Natural Science Edition), 2023, 47(03): 16-21.

[4] Chen X. Simulation study on the influence of operation parameters of radiator heating system on indoor temperature [D]. Hebei University of Architecture and Engineering, 2020.

[5] WANG Xuchao, YAO Delin. Research on temperature change of rooms with time-controlled heat supply [J]. Building Technology, 2023, 54(06): 675-677.

[6] Liang Wanwei. Research on residential air conditioning load forecasting based on statistical modelling [D]. Chongqing University, 2019.

[7] Zhao Linlong. Intrinsic solution of a system of linear differential equations with binary first-order constant coefficients [J]. Henan Science, 2018, 36(01): 6-10.

[8] Liu Bao and Tang Wansheng, Modern Control Theory, Beijing: Machinery Industry Press, 2006, 11.

[9] Han Lihui. Research on several types of exact solutions of nonlinear development equations based on bilinear transformations [D]. Inner Mongolia University of Technology, 2021.

[10] Shangxiong Gao, Computer iterative algorithms for difference equations [J], Mathematics Learning and Research, 2013(17): 91, 2013.