Techno-Economic Analysis of Electric Heating Load Participation in Power System Power Regulation

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Abstract. People are beginning to develop and use new energy sources, but it leads to a lack of power system regulation, so it is crucial to analyse the change of load power. In this paper, the electric heating load is taken as an example, and firstly, the properties of the steady state solution of the differential equation are analysed by changing the parameters of the indoor and outdoor equivalent heat capacity and equivalent thermal resistance, and it is found that the indoor equivalent heat capacity and thermal resistance have a significant effect on the results. Then, after differentiating the differential equations, the indoor temperature changes and the electric heating equipment switching state curves for one day were plotted, and it was found that the daily electricity cost increased as the temperature difference between indoor and outdoor increased. Then, the remaining switchable time values are analysed based on the load's current switch-on state and temperature-limited intervals, and the power upward and downward adjustments of the sustainable time are plotted schematically. In order to enhance the model universality so that it is no longer limited by the current switch on/off state, the switching value of each state is set to change dynamically to obtain a new power regulation diagram, and finally in this paper, we extend the model to multi-family, plot their one-day indoor temperature changes and equipment switching state diagrams and analyse the economic benefits.

Keywords: Power System Power Regulation, Differential Equation Discretisation, Adjustable Load, Dynamic Assessment.

1. Introduction

With the impact of global warming on people's production and life, people are paying more and more attention to the energy conservation of energy-consuming equipment. In this process, people gradually began to use new energy to replace the corresponding non-clean energy, but the new energy is limited by the existing power system scheduling limitations [1]. Based on this background, it is of great significance to study the technical and economic benefits of electric heating load participation in power system power regulation.

Li Shuang [2] et al. proposed a distributed electric heating load peaking method based on big data, which collects electric heating load data through big data technology, analyses the relationship between each variable, forms an LSTM network structure, and at the same time combines with EM algorithms to obtain electric heating load prediction results. Wang Huan [3] et al. proposed a dynamic optimal scheduling strategy for electric heating load in distribution network considering new energy carrying capacity, established a dynamic optimal scheduling model for electric heating load in distribution network with the constraints of distribution network steady state safe operation and electric heating load users' comfort, and put forward a solution strategy based on quantum genetic algorithm.

In this paper, based on the first-order equivalent thermodynamic parameter model (ETP) [4], also with the constraints of customer comfort and economic operation of the grid [5], the influence of each parameter in the differential equations on the analytical solution is analysed with a typical customer as the object of study, and differential equations discretisation is also utilised to analyse the switching time and temperature variations of the loads of each customer. This model greatly improves the computational speed while ensuring the approximate accuracy of the prediction.

2. ETP set total parameter model for analysing electric heating loads in typical households

2.1. Change of state analysis of differential equations for a typical room temperature change process

The process is analysed by equating it to a circuit model, where the heat capacity is equivalent to the capacitance, the thermal resistance of the thermal conductivity is equivalent to the resistance, and the temperature in each space is equivalent to the electric potential in each state. After performing the above equivalence, the model can be simplified into a heat transfer model diagram as shown in Figure 1. Combining the analysis with the basic laws of heat transfer, the simplified differential equations of the set parameter method are obtained.

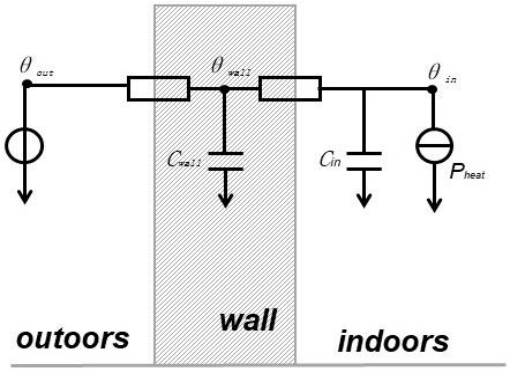


Figure 1. Heat transfer equivalent schematic

In order to facilitate the study of the parameter changes in the equation, This paper sets the initial value, the initial value for the wall temperature, according to the national standards in northern China, the wall temperature in winter can not be lower than 5℃, This paper may wish to set it to 10℃, the indoor temperature and the outdoor temperature of this paper to take the median of the north, approximately located in the north of China in the indoor and outdoor autumn and winter seasons, the initial value of the specific settings in the following Table 1:

Table 1. Selected initial values for differential equations

parametric	numerical value	unit (of measure)
θ_{in0}	20	℃
θ_{out0}	5	℃
θ_{wall0}	10	℃

After setting the initial values, the parameters are analysed by associating the following equations with the ETP set total parameter model:

$$C_{in}\frac{d\theta_{in}(t)}{dt} = P_{heat}(t) - \frac{\theta_{in}(t)-\theta_{wall}(t)}{R_1} \tag{1}$$

$$C_{wall}\frac{d\theta_{wall}(t)}{dt} = \frac{\theta_{in}(t)-\theta_{wall}(t)}{R_1} - \frac{\theta_{wall}(t)-\theta_{out}(t)}{R_2} \tag{2}$$

In order to analyse the heating power $P_{heat}(t)$ and room temperature $\theta_{in}(t)$ and wall temperature $\theta_{wall}(t)$ characteristics, and the influence of model parameters on the variation pattern of the steady state solution. Profiling from the equation itself, the following relation holds when the equation has a steady state solution:

$$\lim_{t\to\infty}\frac{d\theta_{in}(t)}{dt} = 0 \tag{3}$$

$$\lim_{t\to\infty}\frac{d\theta_{wall}(t)}{dt} = 0 \tag{4}$$

The heat transfer heat conduction equation is also considered [6]:

$$\frac{\partial \theta}{\partial t} = \frac{\lambda}{\rho C_p} \nabla^2 \theta + \frac{q_v}{\rho C_p} \tag{5}$$

In the equation, the latter term on the right-hand side of the equation corresponds to the energy produced by the internal heat-producing heat source, and this equation is based on the conservation law.

Based on the equations and conditions as above, The following equations can be derived in this paper:

$$P_{heat}(t) = \lambda \mathrm{A}(\theta_{in}(t) - \theta_{wall}(t)) \tag{6}$$

In this paper, the parameters of which C_{wall} and C_{in}, R_1, and R_2 parameters are dynamically adjusted to observe the subsequent steady state values in the differential equation $P_{heat}(t)$ and $\theta_{in}(t)$ and $\theta_{wall}(t)$. The dynamic change curves of, found that the adjustment of R_1, and C_{in} produces significant steady state results, and the steady state results of other parameters are less significant than their steady state results, and the specific steady state results are run as Figure 2-5:

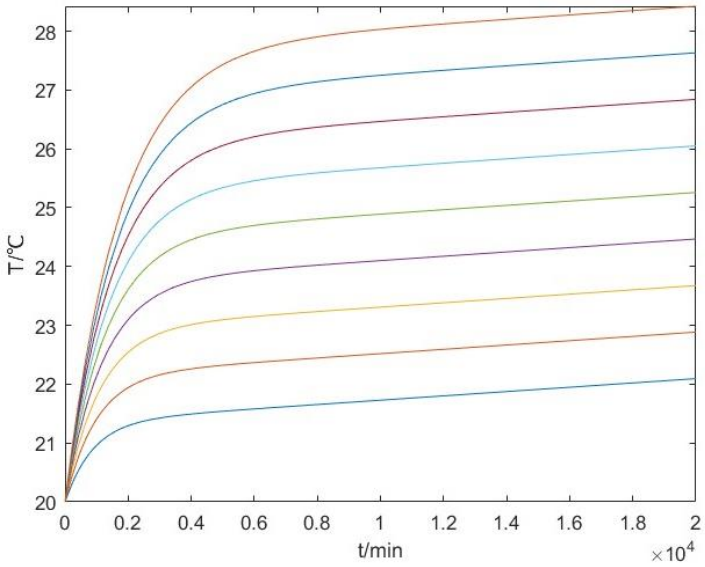


Figure 2. C_{in} effect of dynamic changes on room temperature

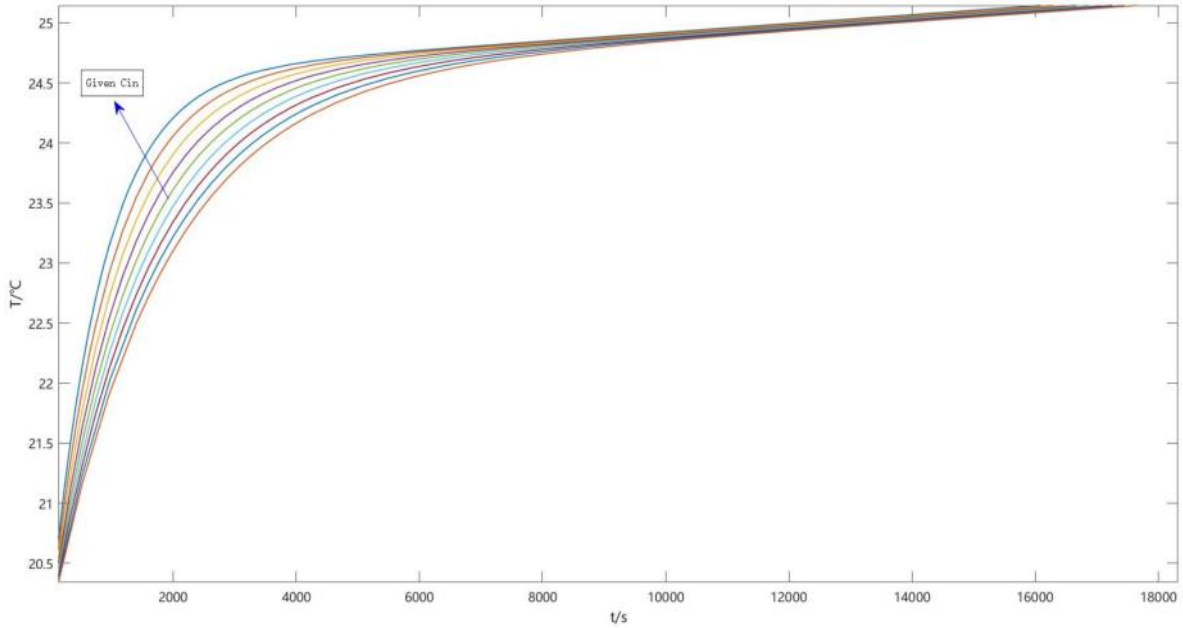


Figure 3. R_1 effect of dynamic changes on room temperature

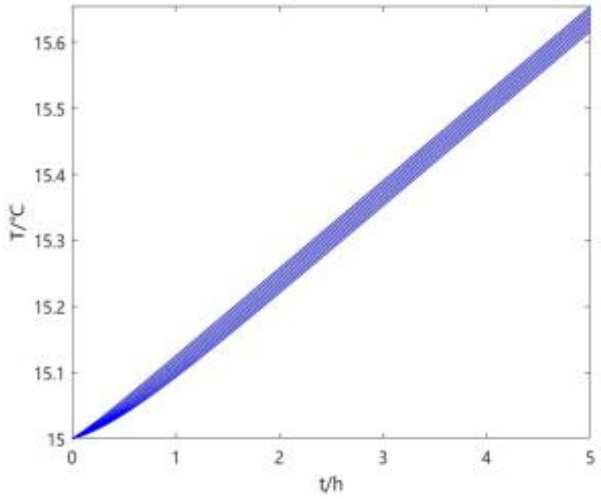


Figure 4. R_1 effect of dynamic changes on wall temperature

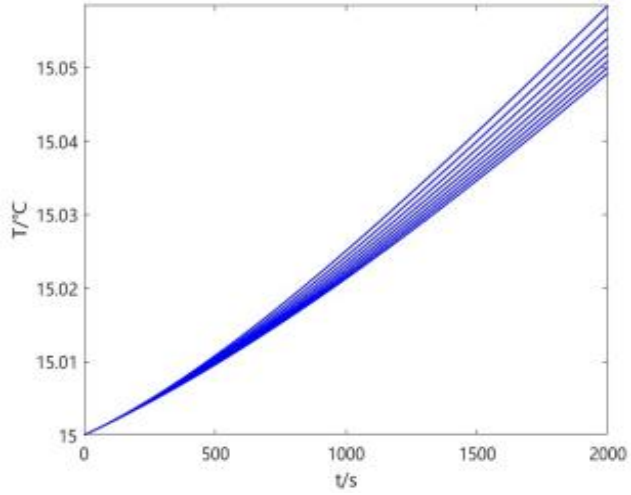


Figure 5. C_{in} effect of dynamic changes on wall temperature

From the above equations and visualisation results, in this paper, it can be found that the room temperature tends to change slowly in steady state as the heat capacity increases. R the increase in the value also leads to a longer time needed to converge to the steady state, similar to the circuit theory, as the resistance increases, the value of the time constant for the steady state of the capacitance also increases. And for the $P_{heat}(t)$, the $\theta_{in}(t)$ and $\theta_{wall}(t)$, in this paper, from the variation of the derived equation (6), it is seen that $P_{heat}(t)$ More power is required as the temperature difference between indoor and outdoor increases, while $\theta_{in}(t)$ and $\theta_{wall}(t)$ rises as the temperature difference between indoor and outdoor increases, which is also in accordance with the law of thermodynamics law [7].

2.2. Analysis of the ability of typical household electric heating loads to participate in power regulation in the context of building thermal inertia

Due to the thermal inertia of the building body, based on the user's comfort level given the temperature range limit, this paper carries out a dynamic analysis of different outdoor temperatures. In order to facilitate the calculation, this paper discretises the differential equations and converts them into simple difference equations [8], and obtains the indoor temperature change graph of one day of the user as well as the corresponding switching state curve of the electric heating equipment, which is only partially shown in Figure 6-7 due to space reasons:

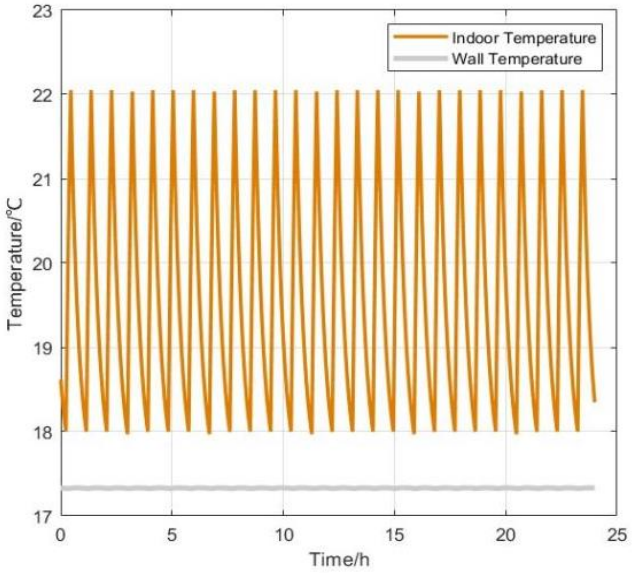


Figure 6. Variation of indoor temperature for 24 hours at 0°C outside temperature

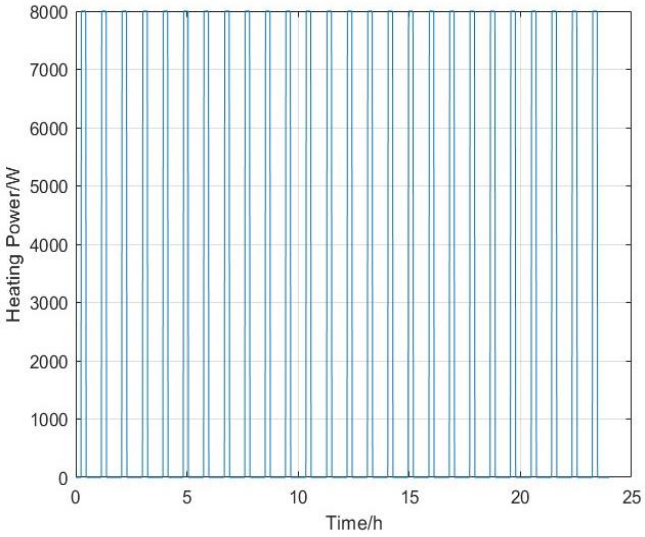


Figure 7. State diagram of electric heating switch with 0°C external temperature

For the above figure this paper gives the following analysis as shown in Table 2 below:

Table 2. Statistical results of characteristic quantities of electricity use behaviour of electric heating loads in typical households

outdoor temperature	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	daily electricity cost/ ¥
0°C	338	1103	55	23.6	45.1	1.9	20.2
-10°C	510	931	42	35.7	68.0	2.8	30.9
-20°C	684	757	39	48.7	91.2	3.8	41.2
-25°C	781	660	39	53.8	104.1	4.3	46.9

Observation shows that as the temperature difference between indoor and outdoor rises, the average temperature rise often shows a positive correlation increase and the average temperature fall often shows a negative correlation decrease, so the power consumption also increases and the daily power cost gradually increases.

This paper calculates and analyses the electricity consumption and cost of electricity for a typical user under the premise of 180 days of heating period, with reference to the peak and valley tariffs of 0.56/0.32 yuan/kWh, and obtains the following results, as shown in Table 3 below:

Table 3. Statistical results of electricity consumption and cost of electricity for a typical household during the heating period

outdoor average temp	number of days	electricity consumption/kWh	eating cost/¥	total electricity consumption during the heating period/kWh	total cost of heating period/¥
0°C	30	1697.5	847.0		
-5°C	40	2602.5	1256.1		
-10°C	40	3050.7	1457.9	13863.5	6667.4
-15°C	40	3496.3	1661.5		
-20°C	30	3016.5	1444.9		

Set the initial state as on, in this paper, based on the temperature control interval on the opening time limit, to carry out the corresponding regulation, for each open time period in the calculation of the subsequent remaining open time value, drawing the following power regulation of the duration of the results of the schematic figure 8:

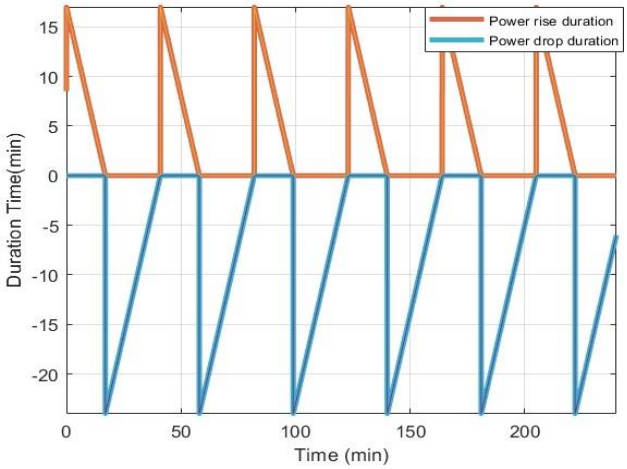


Figure 8. Schematic diagram of power up-regulation and down-regulation at -15°C external temperature

In this process, the results shown are always subject to the current switch open and closed state, in order to jump out of this constraint, this paper in the setting of the initial opening of the big conditions, so that the opening of the state of the dynamics of the corresponding map, the results are more in line with the actual relative quality of the results, the results are shown in the following Figure 9:

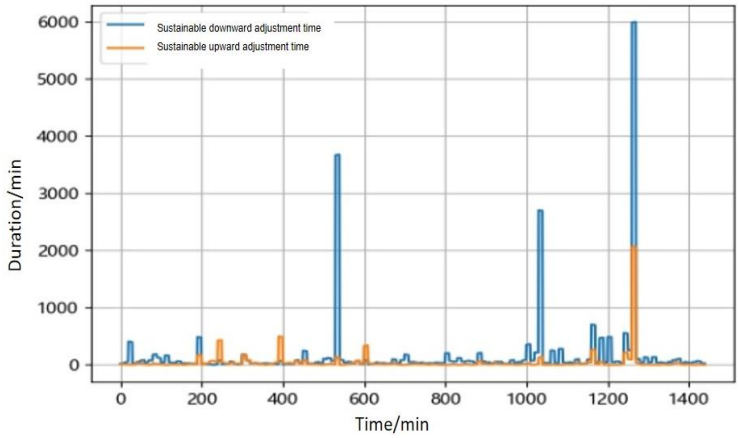


Figure 9. Schematic diagram of power up-regulation and down-regulation for -15°C external temperature based on random states

In this paper, the corresponding calculations for six different external temperatures are carried out, and the variation of the temperature-controlled load's sustainable time with respect to the outdoor temperature is obtained by taking the maximum duration of power adjustment as the target value as a reference, as shown in Figure 10:

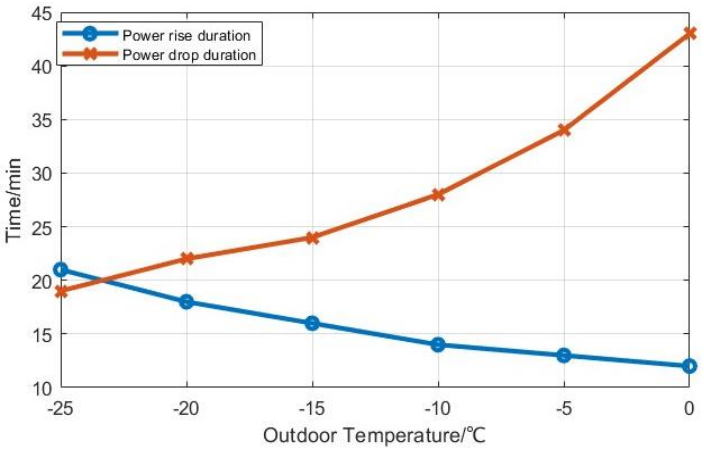


Figure 10. Plot of the change in sustainable time for upward and downward power adjustments of electric heating loads

From the above chart, it can be clearly seen that as the outdoor temperature continues to decrease (under the condition of a constant initial indoor temperature of 20°C), the time of upward adjustment of the electric heating load power gradually increases and the time of downward adjustment gradually decreases. In line with the laws of thermodynamics, as the temperature difference continues to expand, the conservation of energy conditions need to inject more heat into the room to balance the indoor temperature operation in a reasonable and stable interval.

3. Analysis of economic benefits based on the "peak shaving and valley filling" policy Extending the above model for a typical user to multiple users with uniformly

Distributed indoor temperatures in the given 18-22°C interval, this paper here assumes based on empirical values that $\theta_{wall} = 10$ [9] and in order to compare the different conditions, this paper here uses the practice of time-sustained dynamic variable steady state, first assuming that at the beginning, three of them are in the on state, and the other three households are in the off state, and after a period of time, the desired steady state is reached. The one-day indoor temperature change, the switching state of the electric heating equipment and the total electric power change are plotted as shown in Figure 11-13:

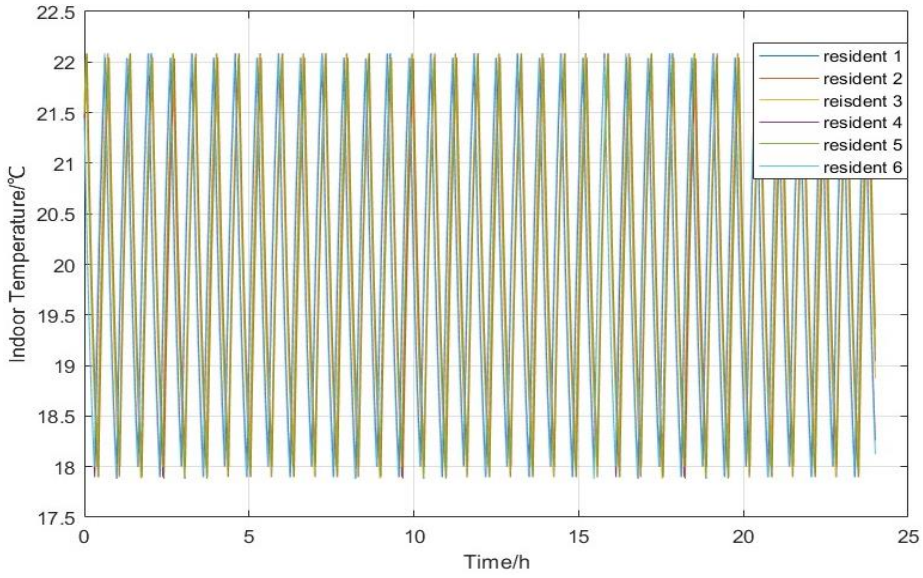


Figure 11. 24-hour indoor temperature variation for six households

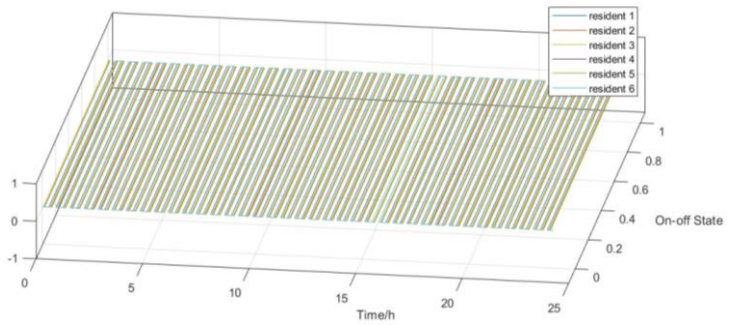


Figure 12. Switching status of electric heating equipment in six households in 24-hour rooms

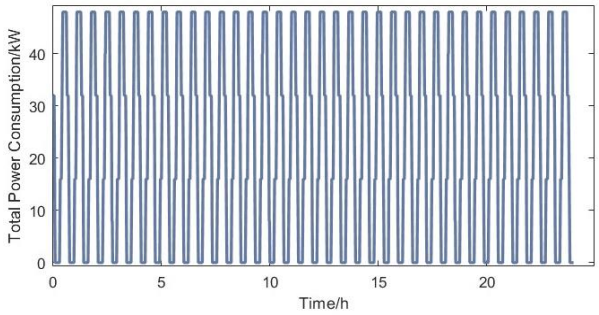


Figure 13. Variation in total electrical power over 24 hours for six households

Based on the total power consumption curves of the six households mentioned above, this paper analyses the serial number diagrams of electric heating equipment that can be involved in upward and downward adjustments during a 24-hour period, as well as the total adjustable upward and adjustable downward power for each time period, as shown in Figure 14-15:

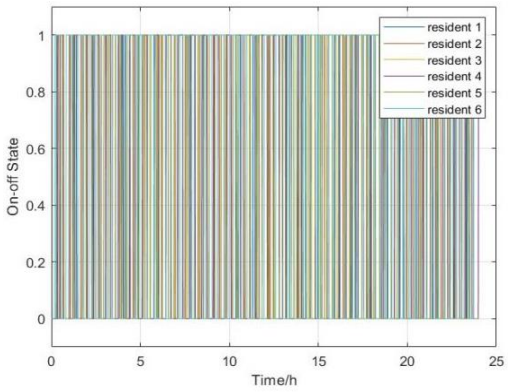


Figure 14. Map of the 24-hour availability of upwardly mobile devices for more than one household

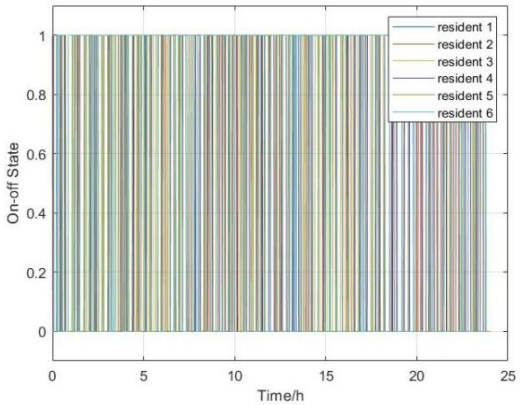


Figure 15. Multi-occupancy 24-hour access to participate in downgrading equipment serial numbers

The compensatory benefits of "peak shaving and valley filling" were analysed for the available data of 600 households, assuming that the average daily power consumption per household is 67.9 KWA (here This paper uses the weighted values of different outdoor temperatures based on the number of days under Table 3 to give the power of Table 2), and that the daily peak shaving period (h_{max}) and the daily valley filling period (h_{min}) are taken to be 4h and the ratio of peak to valley is 13:11 don't cite references in this place, change it.

Electricity consumption per household per outdoor temperature time period:

$$Q_i^{mean} = Q_d^{mean} T_i \tag{7}$$

The average tariff is calculated as follows:

$$P_e^{mean} = \frac{13}{24} P_e^{max} + \frac{11}{24} P_e^{min} \tag{8}$$

Therefore, the total cost is calculated by the formula:

$$C_T = Q_i^{max} P_e^{mean} \tag{9}$$

The formula for the total gain is then derived using the total up-regulated power and the total down-regulated power:

$$R_T = \sum_{i=1}^{5} 600 T_i h_{max} \left(P_{e,c}^{max} - P_e^{max}\right) P_{e,c}^{max} + \sum_{i=1}^{5} 600 T_i h_{min} \left(P_{e,c}^{min} - P_e^{min}\right) P_{e,c}^{inx} \tag{10}$$

The formula for calculating the percentage of heating costs saved is as follows [10]:

$$S_C = \frac{C_T}{R_T} \times 100\% \tag{11}$$

Using the above formula, this paper calculates, based on the available data, that the total benefit is ¥322,920, the average benefit per household is ¥538.2, and the percentage savings in heating costs is 9.7856%.

4. Conclusion

In this paper, to address the problem of power regulation of electric heating loads, the first-order equivalent thermodynamic parameter model is used to predict the duration of load switching on for households under a certain range of temperatures, and at the same time, the economic benefits are analysed by combining with the policy of "peak shaving and valley filling". The results show that the use of differential equations to solve the calculations significantly reduces the calculation volume and increases the calculation speed under the premise of guaranteeing the accuracy of the approximation.

In view of the fact that the temperature-controlled load power in reality presents a dynamic continuous change with a large difference from the step change in the assumptions of the model, in the next step of the study, the differential equations of differential differentiation can be used to solve for the loads in the continuous change state, which is conducive to making the model more relevant to the actual situation and to make the grid scheduling more accurate.

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