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

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Abstract: At the present stage, temperature-controlled loads occupy a considerable proportion, and the adoption of the use of temperature-controlled electric loads is the main issue today. This paper transforms the form of temperature change in the house into an ordinary differential equation, establishes a series of models based on this differential equation, and discusses the ability and characteristics of the electric heating loads' electric behaviour in different situations, using the temperature-controlled intervals as the constraints, and evaluates the economic benefits. In this paper, we first analyse the factors affecting the electric behaviour of electric heating equipment, including the temperature difference between the wall and the room, and analyse the process of temperature change in a typical room by referring to the CTTC model. In this paper, the equation of state method is used to process the ordinary differential equations and convert them into difference equations, which are calculated iteratively using MATLAB. Under the constraints of the given temperature control interval, the steady state solution of the differential equation model is solved, and the characteristics of the heating power, room temperature and wall temperature changes in the steady state are analysed. Secondly, in this paper, the differential equation is used to solve the indoor temperature change equation, taking the last day of the steady state condition, and the indoor temperature at each time point is obtained by iterative computation, one step (1 minute) at a time, and according to the continuity of the indoor temperature when it is adjusted upward or downward, we can get the upward or downward duration by adding up the segment and thus obtaining the duration of upward or downward adjustments.

Keywords: Equation of state method, Difference equations, Iterative computation, Steady state solution, MATLAB.

1. Introduction

The construction of a new energy-based power system is an important initiative to face global climate change [1]. At present, a high proportion of new energy access leads to a scarcity of power system regulation capacity, and there is an urgent need to develop new energy regulation methods. Modern power loads in the air conditioning, electric heating and other temperature-controlled loads account for a large proportion of the building thermal inertia under the premise of both maintaining user comfort, reasonable regulation of temperature-controlled loads of electricity, but also through the auxiliary service revenue to reduce the cost of temperature-controlled loads of electricity has become the focus of the research in this paper [2].

This paper firstly carried out the analysis of electricity consumption behaviour of electric heating loads in typical households. Secondly, for buildings with thermal inertia, the downward power regulation capability can be obtained by switching off the electric heating equipment in the heating state, and the upward power regulation capability can be obtained by switching on the electric heating equipment in the off state, and the duration is constrained by the temperature control interval.

2. Modelling and Solving

2.1. Analysis of room temperature change processes based on the CTTC model

The temperature change process of the building room is determined by 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 parameters shown in Figure 1 [3].

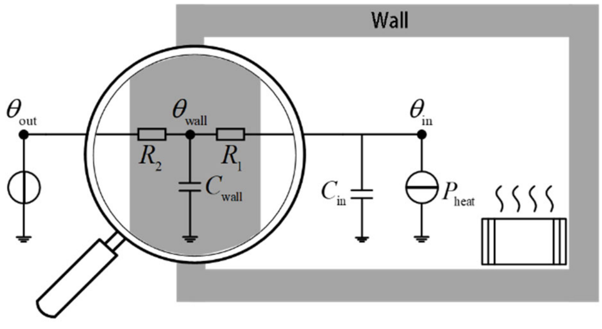

Figure 1. Schematic diagram of the equivalent model of the room temperature change process

The set parameter ordinary differential equation describing the temperature change process in the room is presented as equation (1):

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

where $P_{heat}(t)=S(t)P_n$, $S(t)$ is the switching state of the electric heating device, which is taken as 0 when it is off and 1 when it is on.

The initial indoor temperature T_{in0} =20°C, and under different outdoor temperatures(T_{out} =0°C, -5°C, -10°C, -15°C, -20°C, -25°C), the indoor temperature changes and the corresponding switching state curves of the electric heating equipment are calculated and plotted for 24h a day, so as to count the characteristics of the typical household's heating load and electricity consumption behaviour. Among them, the relevant characteristic quantities should include the average heating up time (min), average cooling down time (min), cycle time (min), average duty cycle (%), daily electricity consumption (kWh), daily average power consumption (kW) and daily electricity cost (yuan).

Where the wall equivalent heat capacity is C_{wall}, R_1、R_2 are equivalent thermal resistances for indoor air and the inside of the wall, and for the outside of the wall and outdoor air respectively, θ_{in}、θ_{wall}、θ_{out} indoor temperature, wall temperature, and outdoor temperature, respectively. And so on, iterating until the end of the iteration. Next, the heating power (i.e., the electric heating equipment switch) is adjusted as follows according to the room's temperature control zone of 18°C-22°C:

i) If the current room temperature is < 18°C, switch on the heating;

ii) If the current indoor temperature > 22°C, switch off the heating;

iii) If the current indoor temperature is 18°C ≤ ≤ 22°C, keep the previous state unchanged.

Finally, since the equations will reach and remain in a steady state for a long period of time, the error between the cycle time per cycle before the room temperature reaches steady state in the starting case and the cycle time at steady state can be ignored. Therefore, we will slice the last day's data, i.e., the last day's data at steady state for the subsequent analysis.

Try to assume that $\frac{d\theta_{\mathrm{in}}(t)}{dt}$、$\frac{d\theta_{\mathrm{wall}}(t)}{dt}$ in equation(1) are zero, which leads to two linear equations present as equation (2) and (3):

$$\mathrm{Pheat}=\frac{\theta_{in}(t)-\theta_{wall}(t)}{R_1} \tag{2}$$

$$\frac{\theta_{in}(t)-\theta_{wall}(t)}{R_1}=\frac{\theta_{wall}(t)-\theta_{out}(t)}{R_2} \tag{3}$$

Sex state of the steady state solution when the temperature controlled interval constraints are satisfied:

The steady state solution can be found from the two linear equations (2) and (3). In equation (2), it can be concluded that the heating power Pheat(t) is proportional to the temperature difference $\theta_{in}(t)-\theta_{wall}(t)$, and from equation (3), it can be concluded that $\theta_{wall}(t)=\frac{R_2}{R_1+R_2}\theta_{in}(t)+C(\text{constant})$, i.e., there exists a linear relationship between the indoor temperature $\theta_{in}(t)$ and the wall temperature$\theta_{wall}(t)$.

Influence of model parameters on the pattern of change in the steady state solution:

At an outdoor temperature of 0°C, the steady state period is 55 min and the steady state duty cycle is 0.23636, which is presented as Figure 2.

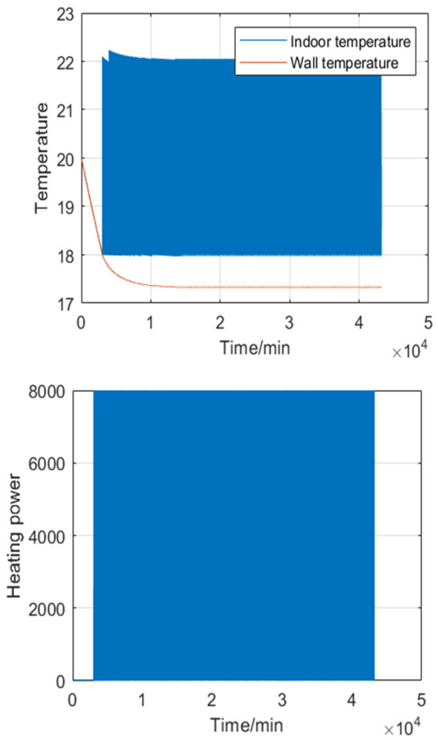

Figure 2. The steady state period at outdoor temperature of 0°C

At an outdoor temperature of -5°C, the steady state period is 47min and the steady state duty cycle is 0.29787, which is presented as Figure 3.

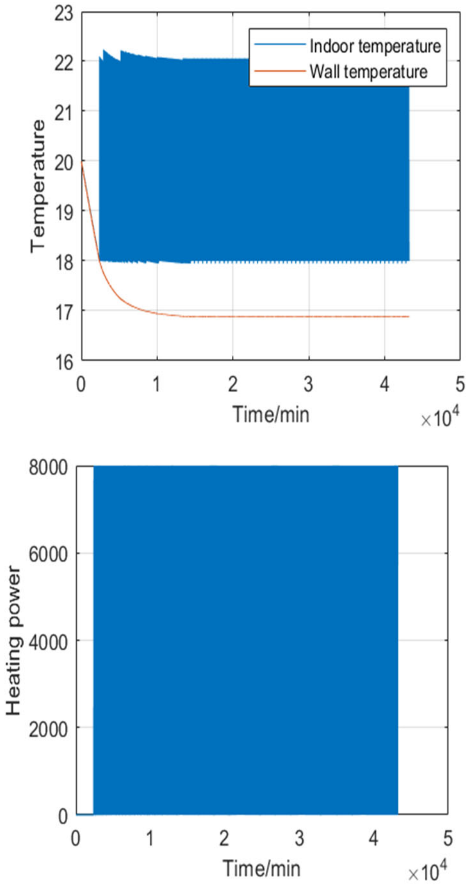

Figure 3. The steady state period at outdoor temperature of -5°C

At an outdoor temperature of -10°C, the steady state period is 42 min and the steady state duty cycle is 0.35714 as Figure 4 showed.

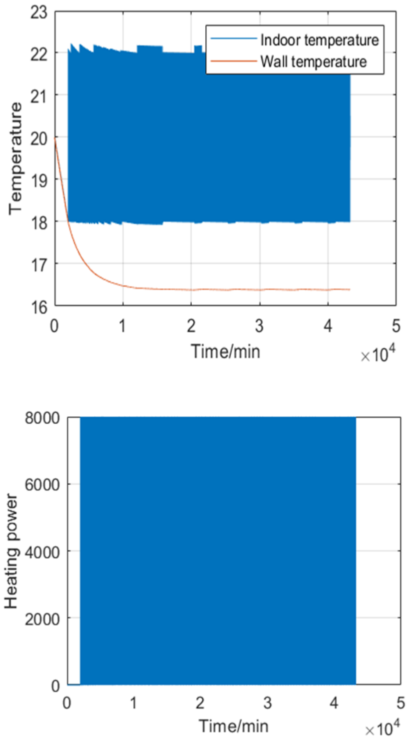

Figure 4. The steady state period at outdoor temperature of -10°C

When the outdoor temperature is -15°C, the steady state period is 40 min and the steady state duty cycle is 0.425 as presented in Figure 5.

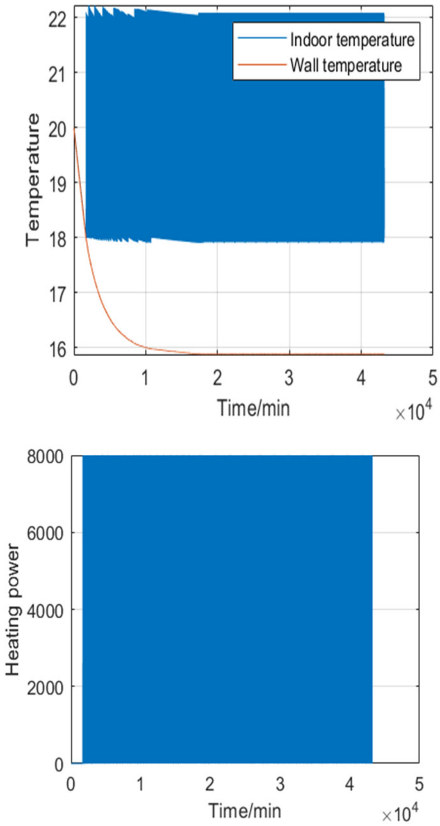

Figure 5. The steady state period at outdoor temperature of -15°C

At an outdoor temperature of -20°C, the steady state period is 40 min and the steady state duty cycle is 0.475 as Figure 6 presented.

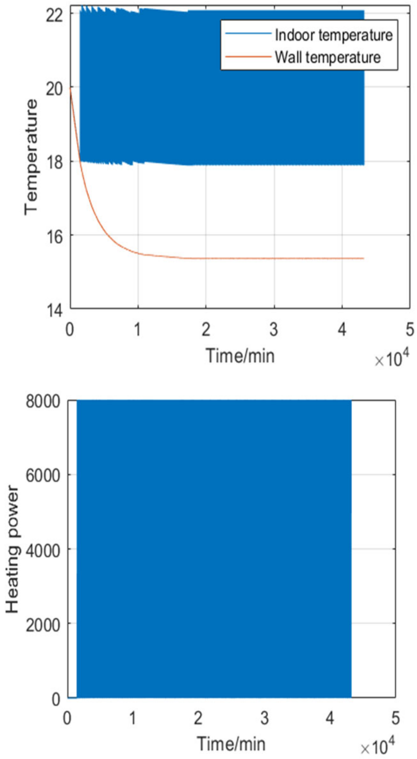

Figure 6. The steady state period at outdoor temperature of -20°C

At an outdoor temperature of -25°C, the steady state period is 40 min and the steady state duty cycle is 0.55 as presented in Figure 7.

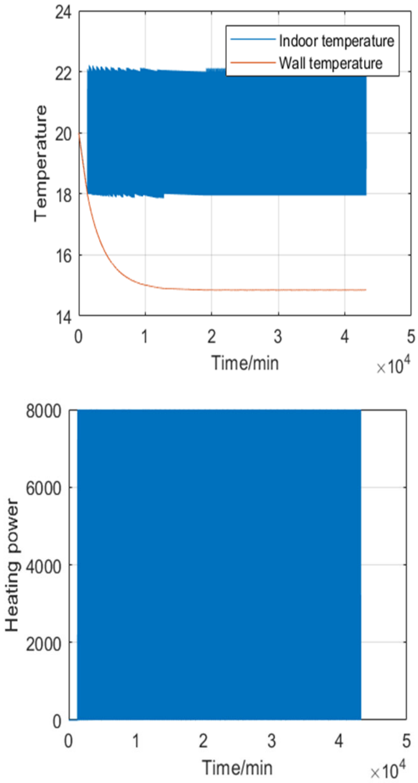

Figure 7. The steady state period at outdoor temperature of -25°C

Conclusion: i.e., the steady state solution varies greatly when parameters such as R1,R2 are varied.

The following table demonstrates the statistical results of characteristic quantities of electricity behaviour of electric heating loads in a typical household. From the table we can get a conclusion that the lower the outdoor temperature, the higher the electricity consumption for electric heating operation.

Table 1. Statistical results of characteristic quantities of electricity behaviour of electric heating loads in a typical household (initial indoor temperature of 20°C)

outdoor temperature	Average heating time/min	Average cooling time/min	Cycle time/min	Average duty cycle/%	Daily electricity consumption/kWh	Average daily power consumption/kW	Daily electricity cost/yuan
0°C	339	1102	240	0.236	45.2	1.883	20.427
-5°C	434	1007	240	0.298	57.866	2.411	26.133
-10°C	519	922	240	0.367	69.2	2.883	30.944
-15°C	607	834	240	0.414	80.933	3.372	36.234
-20°C	696	745	240	0.487	92.8	3.867	41.856
-25°C	786	655	240	0.538	104.8	4.367	47.093

2.2. Model analysis based on iterative computation of differential equations

Due to the thermal inertia of the building, downward power regulation can be obtained by switching off the electric heating equipment in the heating state, and the duration of downward regulation is limited to the lower limit of the temperature control interval; upward power regulation can be obtained by switching on the electric heating equipment in the off state, and the duration of upward regulation is limited to the upper limit of the temperature control interval [4].

Taking the electric heating load of a single household as the object, the outdoor temperature is -15°C, the initial indoor temperature is 20°C, and the initial state of the electric heating equipment switch is on, calculate the duration of upward and downward power regulation of a typical household's electric heating load at each point of the 24h within a day (at 1min intervals), and plot the results of the calculations. The electric heating equipment needs to be switched on and off several times during a day (24h), where the durations of up-regulation and down-regulation are the maximum consecutive lengths of time that it can be switched on and off during a day. We take the data of the last day of stabilisation to analyse, and obtain that the up-regulation of power refers to the time when the switch is turned on for heating from the lower limit of the temperature range, gradually increasing the heating power of the electric heating to reach the upper limit of the temperature, and on the contrary, the down-regulation of power refers to the time when the switch is turned off from the upper limit of the temperature range, gradually decreasing the heating power of the electric heating equipment until it reaches the lower limit of the temperature-controlled range. The change of indoor temperature with time is calculated based on the provided parameters and model to obtain the dynamic equation of indoor temperature as equation (4):

$$\frac{\theta_{in}(t+\Delta t)-\theta_{in}(t)}{\Delta t}=-\frac{\theta_{in}(t)-\theta_{wall}(t)}{R_1 C_{in}}+\frac{P_{heat}(t)}{C_{in}} \quad (4)$$

Where C_{in} is the equivalent heat capacity of the indoor air; R_1 is the equivalent thermal resistance of the indoor air and the inside of the wall; θ_{in} , θ_{wall} are the indoor temperature and wall temperature respectively; $P_{heat}(t)$ is he heating power of electric heating equipment.

Based on the initial conditions, we start the simulation calculation. By iteratively calculating one step (1 minute) at a time, we can obtain the indoor temperature at each point in time. Depending on the continuity of the indoor temperature in upward or downward adjustments, we can obtain the duration of the upward or downward adjustments by accumulating the segments and thus obtaining the duration of the upward or downward adjustments. The obtained electric heating power curve is processed to obtain the upward and downward adjustable durations of electric heating in a day. The duration of the upward adjustment is 17 min and the duration of the downward adjustment is 24 min, which is demonstrated as Figure 8 [5].

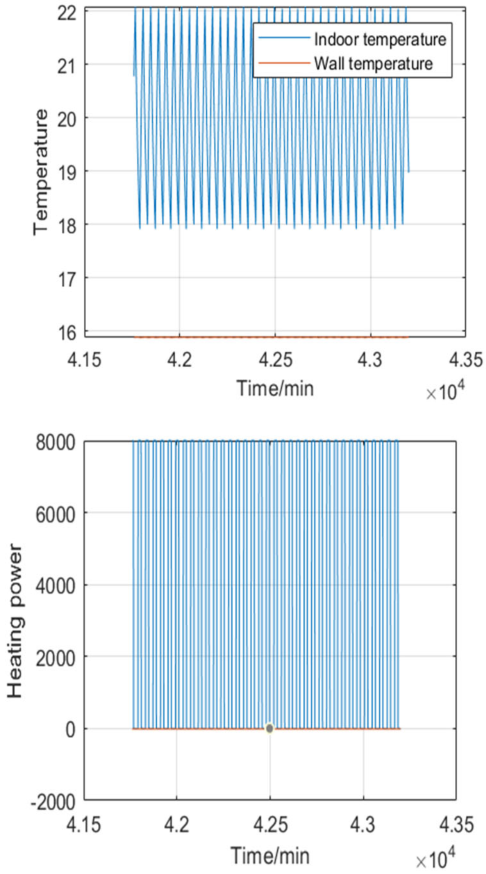

Figure 8. Heating power curve

3. Model Evaluation and Dissemination

In order to address the potential and possible problems of electric heating load participation in grid regulation in a provincial area of 40 million square metres, firstly, under the support of the national policy of clean heating, there are a large number of electric heating loads in the northern region of China and they are developing rapidly, as an important flexible time-shift load, when they reach a certain scale, they will inevitably become a very considerable demand response resource in the operation of the power grid.

However, at present, all kinds of electric heating loads are only in the state of regulation to meet the heating demand, how to deeply explore its regulation potential and incorporate it into the power system scheduling operation still needs to be explored; secondly, electric heating loads participate in the regulation of the need to accurately predict and manage the user's electricity behaviour, which requires a large amount of data support and the application of artificial intelligence algorithms; furthermore, in the wide area, the population density of different areas is different, how to meet the different population densities in the power grid? Secondly, in a wide area, different areas have different population densities, how to satisfy the living needs of households and economic benefits under the situation of different population densities; in addition, the participation of electric heating load regulation needs to solve the problems of insufficient willingness of users to participate, the lack of technical standards, and the difficulty of access, which requires policy support and technical support.

4. Conclusion

In conclusion, the construction of a new energy-based power system is a crucial response to the challenges posed by global climate change. This initiative recognizes the current limitations in power system regulation capacity due to the rapid expansion of new energy sources. To address this issue, innovative approaches to regulate energy consumption, particularly in temperature-controlled loads like air conditioning and electric heating, have been explored in this paper.

The analysis of electricity consumption behavior in typical households, specifically focusing on electric heating loads, sheds light on opportunities for enhancing power system regulation. By strategically controlling electric heating equipment in buildings with thermal inertia, both downward and upward power regulation capabilities can be harnessed. Switching off electric heating equipment in heating states and turning it on during off periods, within temperature control intervals, demonstrates a promising method to optimize power utilization while maintaining user comfort.

In essence, this research contributes valuable insights to the ongoing efforts to develop effective energy regulation methods within the context of new energy-based power systems. These findings have the potential to not only improve energy efficiency but also reduce costs associated with temperature-controlled loads, thereby advancing the goals of sustainability and climate change mitigation.

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