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A novel control strategy of space heating equipment for peak shaving based on operating data

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ABSTRACT

With the penetration of renewable generation and terminal electrification, there is a huge demand of peak shaving for power system. Heating equipment are recognized as flexible resources for peak shaving, since there are numerous controllable variables and great power in heating systems, and buildings have significant thermal inertia.

This paper proposed a novel control strategy based on operating data to coordinate distributed space heating equipment across numerous residential households. Heating characteristics of each households, thermal inertial of indoor air, and power characteristics of heating equipment were obtained based on operating data analysis. Thereafter, load shifting potential under different scenarios were determined through historical operating data and current operational status. Based on the principle of minimal impact on indoor air and fairness, target heating equipment was adjusted by remote control instructions. Additionally, local adjustment by users has priority over remote control to assure thermal comfort requirements, and participation in regulation brings subsidies to users. A case study shows the strategy can produce 8% peak shaving and 27% reduction of peak-valley ratio under the same heating cost.

Moreover, the purpose of regulation could be modified according to specific needs, including the cost saving of induvial heating, and the reduction of peak power of the grid.

Keywords: space heating, load shifting, control strategy, operating data

1. INTRODUCTION

The mismatches between the supply and demand sides of the grid system require additional methods to maintain the stability and reliability. Additionally, the increasing penetration of renewable energy, which heavily depend on the weather condition and other factors, poses greater challenge for energy system[1]. The terminal electrification further amplifies the fluctuation and peak-valley ratio, and reduce grid stability and asset utilization of power plant equipment. In the future power system, in addition to whether the power generation is sufficient, how to deal with the volatility and uncertainty of renewable power and loads is also an important issue[2]. Thus, demand side management have gradually receiving great attention.

Buildings play an important role on the demand side management, since the total energy consumption of buildings has accounted for about 30% of the total energy consumption[3]. Especially in heating system, due to the thermal inertial, buildings could act as massive thermal storage body. Buildings can provide significant flexibility potential for electricity. On the premise of ensuring that the indoor temperature is within a certain range, regulation of heating equipment in response to grid requests is an effective method of demand response.

The increasing demand for electricity for heating in China, coupled with the large scale "coal-to-electricity action" [4], which is replace traditional coal burning stoves to heat pumps and other clean heating methods, provides a great potential for load shifting. Many research focused on the DR in public buildings[2, 5], and lack operating characteristics. Further research is urgently needed on the DR of rural residential heating electric heating equipment based on operating data.

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This study proposed a novel control strategy of space heating equipment for peak shaving based on operating data, and presented a case study of 70 households using split-type air-to-air heat pumps (AAHP).

2. METHOD

2.1 Control strategy

The prime principle of peak shaving based on electric heating equipment is to ensure that the indoor temperature is within a certain range. By control the operating mode of heating equipment, the peak load could be reduced and the valley load could be increased, thereby achieving peak shaving and load shifting.

The implementation flow of operating data-based optimal scheduling strategy is shown as Fig. 1.

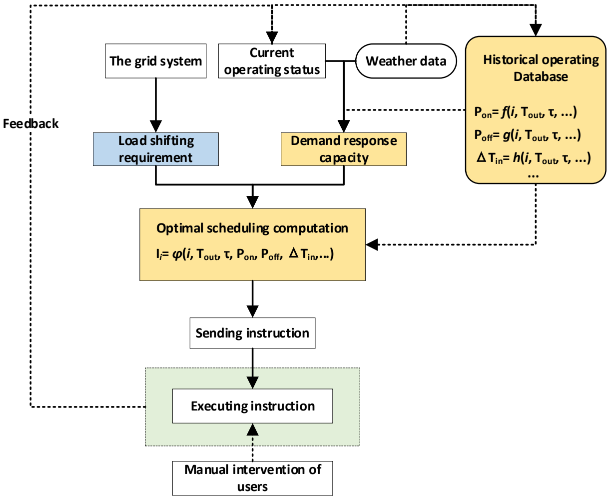


Fig. 1. Implementation flow of operating data-based optimal scheduling strategy

The methodology for the control strategy is based on four key components:

a) The load shifting requirement. This could be any demand given by the grid, which may include renewable energy.

b) The limitation of operating mode control, especially the maximum time of turning off heating equipment. This is closely related the properties of buildings and affect the assurance of thermal comfort of users.

c) The corresponding power of turning on or off a heating equipment and how it is affected by the ambient temperature.

d) User's engagement in regulation. Since the heating equipment serves users, the biggest issue in the regulation process is whether it meets the needs of users and whether it causes dissatisfaction. In the process, the user's regulatory behavior should be collected and considered to ensure that their needs are met.

The following three components must be analyzed through actual operating data to reveal the mathematical model of building thermal inertia and indoor thermal environment under different conditions, as well as the inherent correlation and dynamic variation rules between characteristic parameters related to power peak shaving potential.

2.2 Data analysis

Database was established through historical operating data. Fundamental parameters of heating system were extracted through database, namely power of heating equipment, P_{on} and P_{off}; and temperature change of indoor air after turn off the heating equipment, ΔT_{in}.

Power of heating equipment when turn on, power of heating equipment when turn off, and temperature change of indoor air after turn off of each heating equipment are all influenced by outdoor temperature (T_{out}) and time (τ). The function between them can be obtained through historical data analysis:

$$P_{on}=f(i,T_{out},\tau) \tag{2-1}$$

$$P_{off}=g(i,T_{out},\tau) \tag{2-2}$$

$$\Delta T_{in}=h(i,T_{out},\tau) \tag{2-3}$$

2.3 Optimal scheduling computation

Based on the parameters obtained from the aforementioned data analysis, combined with the current operating status of heating equipment and load shifting requirements, the control strategy I of each equipment can be obtained.

2.4 Executing instruction

When receiving instruction, heating equipment will execute it through judging process, as shown as Fig. 2.

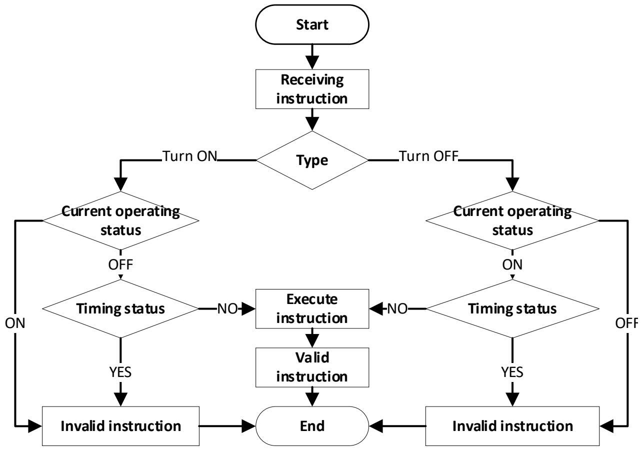


Fig. 2. Instruction executing process of heating equipment

Only when the device is in the opposite operating status to the instruction, and it is not in a timing status, can the instruction be executed and considered valid. For example, when the instruction is turned on, and the heating equipment is turned off and not in a timing status, the heating equipment could be turned on and complete the instruction.

It is worth noting that in order to ensure users' heating requirements, users have the highest priority for control the heating equipment any time.

3. CASE STUDY

Long-term operating data of 70 households through a whole heating season were obtained in a rural village in Beijing. Each household has 3 air-to-air heat pumps (AAHP) for heating.

First, AAHPs were not continuously operating. As shown in Fig. 3, the highest proportion of operating AAHPs during a day is 0.28 at 6:00, which means only 60 AAHPs were turning on at the same time. The proportion reaches its lowest point at noon, around 13:30. Operation status of three AAHPs in a typical household in ten days are shown in Fig. 4. Three AAHPs were working in different patterns. One AAHP was turned off all the time, one AAHP was turned on for few hours regularly, and one AAHP was turned on continuously.

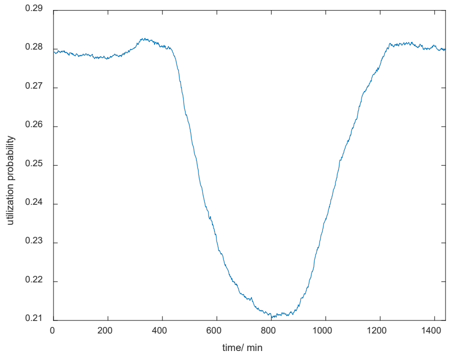
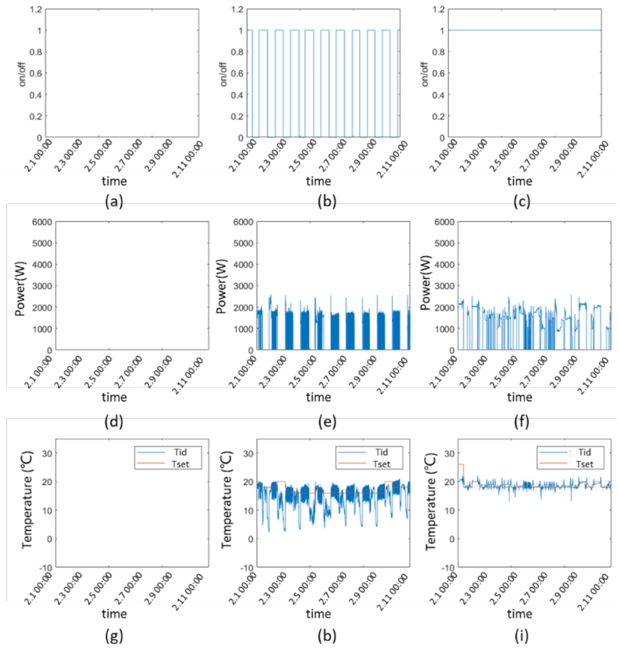


Fig. 3. Utilization probability of AAHPs

3.1 Indoor temperature after turn off the AAHPs

The indoor temperature drops after turn off AAHPs is shown in Fig. 5. The average indoor temperature at the time of turn off was 16 ℃. From the temperature change curve, it can be seen that the temperature drops by 3.6 ℃ within 30 minutes, and the room temperature is still acceptable. To ensure that the indoor temperature is within a certain comfort range and avoid overly complex control strategy in this case, statistics and fitting are conducted based on the temperature drop trend of each AAHP. Therefore, in this case, the upper limit of turn off time is set to 30 minutes, corresponding to a temperature decrease of 3.6 ℃.



(a) (b) (c)

(d) (e) (f)

(g) (b) (i)

Fig. 4. Operation status of three AAHPs in a typical household from February 1, 2022 to February 11, 2022

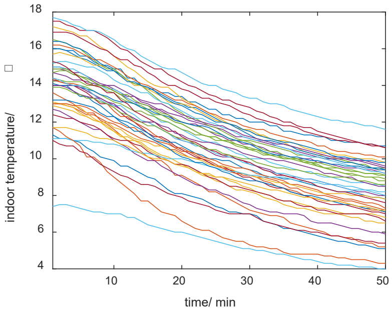


Fig. 5. Indoor temperature drops after turn off AAHPs

3.2 Power of turn on and turn off

Operating power of one AAHP and average power of multiple AAHPs can be seen from Fig. 6. It can be clearly seen that during the initial start-up stage, due to factors such as building thermal inertia, the operating power is relatively high and tends to stabilize after half an hour.

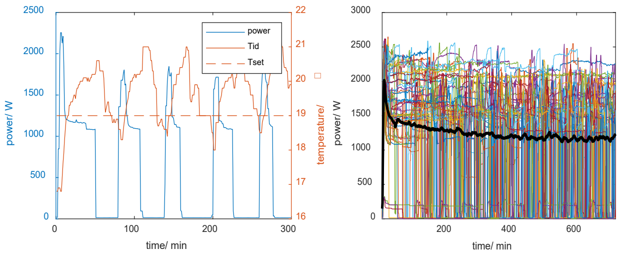


Fig. 6. Operating power of one AAHP and average power of multiple AAHPs

As the outdoor temperature changes within a day, the efficiency of the AAHP will be affected. The power of AAHP on a typical day is shown in Fig. 7, where the black curve represents the average value for all days.

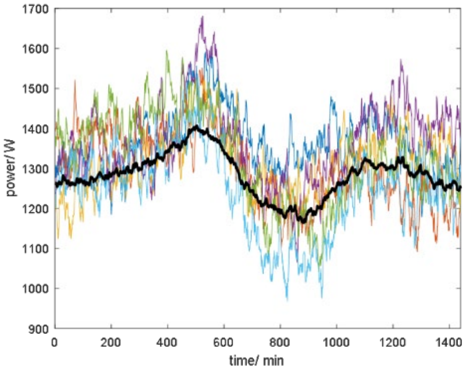


Fig. 7. The power of AAHP on a typical day

It can be seen that as the outdoor temperature increases at noon, the operating power is low. The average operating power is relatively high around 8:00 and 20:00. The operating power is greatly affected by outdoor temperature and time of a day. Hourly operating power can be obtained through the average curve, which is used to calculate the response potential provided by turning off AAHP.

3.3 *Result*

Taking 1200 AAHPs as a case, based on acquired data and the load curve of rural power grids in Beijing mountainous areas before electric heating replacement, load shifting potential was simulated as shown in Fig. 8. Without load shifting, the maximum load increased from 1.3 MW to 1.5 MW, with an overall increase of 28%, i.e., from the grey line to the red line in Fig. 8.

Under the target of ensuring the minimum increase of peak value, the load curve changed to the blue line. The peak valley ratio decreases from 43.70% to 10.74%. Grid capacity can be reduced by 8.25%.

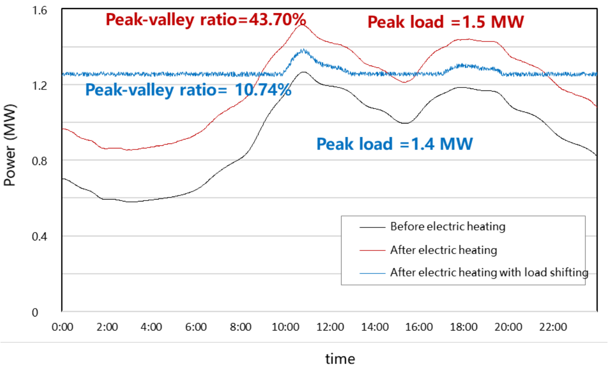


Fig. 8. Simulated load shifting potential

4. *DISCUSSION*

The operating characteristics of heating equipment are significant factors that directly affect the room temperature and response power after regulation. Therefore, based on actual operating data, information on the operating mode can be effectively obtained through analysis.

The establishment of database can be used for demand and load shifting capacity prediction. The case study indicates that great potential lies in the residential heating equipment. Further study concerning about occupants' manual intervention and personal heating requirement is necessary for modification and improvement of the control strategy.

5. CONCULSION

This study verified the thermal inertia and load shifting potential of buildings through 210 AAHPs in 70 households.

Based on weather conditions, building thermal inertia, and actual heating patterns of users, this study proposed a strategy of load shifting. On the premise of ensuring that the indoor temperature is within a certain range, remote control of heating equipment (AAHP) could reduce the daytime peak valley ratio of regional load curve, thereby achieving load shifting.

The strategy could be modified according to different load shifting target, different heating equipment, different heating patterns.

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