Evaluation of Air-conditioning Load Adjustability Based on Load Plasticity

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Abstract. The air-conditioning load is an important part of the power system's peak load, significantly impacting the power grid's safe and stable operation. Therefore, it is necessary to evaluate the air-conditioning load's adjustment potential, providing a reference for the power grid to formulate a reasonable dispatch plan, participate in the demand-side response, and alleviate the insufficient power-side regulation capacity caused by the large-scale access of intermittent renewable energy. This paper mainly obtains the air-conditioning load curve under different conditions through the characteristics of residents' electricity usage behavior and analyzes the adjustable air-conditioning load capacity based on load plasticity.

1. Introduction

The current rapid growth in power demand has brought considerable challenges to maintaining the balance of power supply and demand. The increasing number of air conditioners has made the summer cooling load and winter heating load the main components of the two seasons' peak load [1]. Flexible load provides a variety of flexible ways to solve this problem. It relieves the power supply pressure during peak hours, improves power equipment utilization during low valleys, and actively participates in active power regulation when the system frequency fluctuates, thereby reducing the operating cost of the system and promoting the carbon peak and carbon-neutral target process [2][3].

Thermostatically controlled loads (TCLs) are a class of controllable loads with good thermal energy storage characteristics. They have gradually become one of the main research objects of flexible loads due to their rapid response, energy storage, and high controllability [4]. The temperature control load mainly includes air conditioners, refrigerators, water heaters. The air-conditioning load has become the focus of temperature control load research due to its high load ratio and considerable regulation potential.

Literature [5] proposed a two-tier optimal dispatch and control model for air-conditioning load based on direct load control. By optimizing the control strategy of air-conditioning load within its jurisdiction, the actual air-conditioning load output is as consistent as possible with the dispatching plan. Literature [6] Load aggregators integrate many household water heaters and air conditioners as demand response resources and participate in the demand bidding market through direct load control. Their control strategies can tap the demand response potential of multi-family water heaters and air conditioners to a certain extent. Literature [7] proposes a method for constructing an energy-efficient power plant by considering the comfort constraints of the home temperature control load, using the
state queue response control model to control the state of the heat pump load switch. Most of the above have studied the load changes under different control strategies. Although it maintains the indoor temperature in a comfortable range, it doesn’t consider the air conditioning load's actual demand and power usage habits by the user’s electrical behavior characteristics. As a result, the actual adjustment effect deviates from the expected. Load plasticity means that the flexible load is affected by its internal and external factors, making the load curve different, presenting different load characteristics. Its ability to participate in the adjustment is also different. The load plasticity size determines the load's size that the flexible load can adjust up and down under different conditions—the greater the load plasticity, the stronger the adjustment ability after receiving the dispatch. The existing research mainly uses more complicated calculation methods to obtain the plasticity of different flexible loads, but the process is relatively cumbersome [8]. This paper mainly considers the actual use demand, and power usage habits of the air-conditioning load by its power consumption behavior characteristics. The load plasticity can be more directly obtained through the load curve and effectively evaluate the load's adjustable capacity. It can provide references for formulating reasonable scheduling plans and participating in the demand-side response.

2. Air-conditioning load modeling and the characteristics of residents’ electricity usage

At present, air-conditioning load modeling mainly includes modeling methods based on equivalent thermal parameters and modeling methods based on cooling load calculations [9][10]. In this paper, the second-order equivalent thermal parameters model (ETP) for air-conditioning units suitable for home users and small industrial and commercial users is used to study the air-conditioning load [11]. The ETP equivalent model is shown in Figure 1. The research object is fixed-frequency air conditioning, and the control strategy mainly involves the start-stop decision-making of the air-conditioning.

![Figure 1. Equivalent thermal parameter model of air-conditioning load unit](image)

In the Figure 1, $C_n$ is the solid specific heat capacity, J/°C; $C_a$ is the gas specific heat capacity, J/°C; $\dot{Q} = \eta P$ is the operating heat ratio of the air conditioning load; $R_1$ is the indoor air thermal resistance, $R_2$ is the indoor solid thermal resistance; $T_{out}$ is the outdoor air temperature, °C; $T_m$ is indoor solid temperature, °C; $T_{in}$ is the indoor air temperature, °C.

The above model can be simplified to obtain the calculation formula of indoor temperature $T_{in}$ and air-conditioning power:

$$T_{in,t+1} = T_{out,t+1} - (T_{out,t+1} - T_{in,t})e^{-\Delta t/R C}, S_{AC} = 0$$

$$T_{in,t+1} = (\eta PR + T_{in,t} - T_{out,t+1})e^{-\Delta t/R C} + T_{out,t+1} - \eta PR, S_{AC} = 1$$

Where $T_{in,t}$ and $T_{in,t+1}$ represent the indoor temperature at time $t$ and $t + 1$ respectively; $T_{out,t+1}$ is the outdoor temperature at time $t + 1$; $e^{-\Delta t/R C}$ is the heat consumption parameter; $R$ is the equivalent thermal resistance, $C$ is the equivalent heat capacity; $\eta$ is the air-conditioning load efficiency; $P$ is the rated power of the air-conditioning load; $S_{AC}$ is the air-conditioning start-stop state variable. 1 means start, and 0 means stop.
According to the time of using air-conditioning load and typical scenarios, the air-conditioning load can be divided into household load, commercial office load and special air-conditioning load. The three types of air-conditioning load comparison are shown in Table 1.

| Air-conditioning load type | Home | Business | Office | Special area |
|---------------------------|------|----------|--------|--------------|
| Typical scene             | Residential area | Mall | Office building | Hospital |
| Electricity time          | Most 18:00—the next morning | 9:00-22:00 | 9:00-17:00 | Specific time, all day |
| Small part all day        | 9:00-22:00 | 9:00-17:00 | Specific time, all day |

During regulation, special air-conditioning loads are generally not involved. Commercial office air-conditioning load is relatively fixed due to the relatively fixed switching time and is less affected by electricity usage habits, while household air-conditioning load is more susceptible to users' electrical usage behavior characteristics [12]. Therefore, this article mainly takes household air conditioners as the research object, considers the influence of residents' electrical usage behavior characteristics on their load curves, and studies the plasticity of air conditioning load within the range of the upper and lower limits of certain indoor temperatures. Since residents’ daily travel activities have a relatively large impact on their load, this paper mainly studies the residential air-conditioning load curve on working days and non-working days based on family structure. There are mainly three types of family structure in residential areas: Working type, elderly type and mixed type, so they do not use air conditioning for a certain period. Besides, the time to leave home and arrive home will be different because of the different commuting times. The elderly and children spend much time at home. This part is home users. Therefore, the residential air-conditioning load curve is different on working days and non-working days, and the difference in the air-conditioning temperature setting value will also affect the size of its load.

The calculation steps of air-conditioning load plasticity are as follows:

1. It uses the load calculation method to obtain information such as the air-conditioning load power and indoor temperature at a specific time. The outdoor temperature is directly obtained by measurement.

2. Determine the upper and lower limits of the air-conditioning operating temperature according to the scheduling requirements. Due to the short time scale, a higher upper limit of operating temperature and a lower limit of operating temperature can be set for emergency dispatch. User comfort can be appropriately sacrificed to solve emergencies as much as possible. For economic dispatch, because the problem is not serious and the time scale is long, the user comfort should be ensured as much as possible. The operating temperature range of the air conditioner should not be expanded at this time.

3. Calculate air-conditioning load's maximum and minimum operating power allowed according to the operating temperature range. If the calculated operating power to reach the upper limit of temperature is negative, it means that even if the air conditioner is stopped, the indoor temperature will not rise to the upper limit of temperature within a period of time. At this time, the allowable minimum operating power of the air conditioner load can be taken as 0. Suppose the calculated power to reach the lower temperature limit is greater than the rated operating power of the air conditioner, it means that even if the air conditioner is running at the maximum power, the indoor temperature will not drop to the lower temperature limit during this time. At this time, the air-conditioning load's maximum allowable operating power is the air-conditioning load's rated operating power.

4. The maximum and minimum operating power allowed by all air-conditioning loads is added to obtain the maximum operating power allowed by the large-scale air-conditioning load. At this time, the difference between the allowable maximum operating power and the load curve and the difference between the load curve and the minimum operating power is the air-conditioning load's plasticity. The range between the maximum and minimum operating power is the plastic range of the large-scale air-conditioning load. The flow chart of air-conditioning load plasticity calculation is shown in Figure 2.
3. Case study applications

There are 1000 air-conditioning loads. The rated cooling power is 2kw; the average cooling energy efficiency ratio is 2.7; the equivalent heat capacity is 0.18kWh/℃; the equivalent thermal resistance is 5.56℃/kW [13]; the simulation time interval Δt = 0.02h. In this paper, a typical month in the summer of 2019 in Shanghai is selected as the real-time outdoor temperature. Through the relationship between the indoor and outdoor temperature and power of the air conditioner, the air conditioning load curve of working days and non-working days can be obtained, and the plasticity of the air-conditioning load within a certain range of temperature upper and lower limits can be analyzed.

It is assumed that the working time in Shanghai is 8 o'clock and off-work time is 17:00. Statistics show that Shanghai's commute time accounts for about 40% within one hour and about 60% for more than one hour. Users turn on the air conditioner when they arrive home and turn it off when they leave home. And there is still a certain percentage of residential users who do not go out to work. For non-working days, most users rest at home. Due to some special work or exceptional circumstances, there are also a small number of out-of-home users. Ensure that the user's comfortable temperature zone is [23, 25]°C. The difference in the temperature setting of the air conditioner will also affect its load. Take a non-working day as an example, compare the air-conditioning load when the air-conditioning set temperature is 24°C and 26°C.

It can be seen from Figure 3 that there is a relatively large difference in the air conditioning load curve between working days and non-working days, and the power consumption on non-working days is significantly higher than that on working days. For workdays, users will go home and turn on the air conditioner from 17:00 onwards. Since the indoor temperature at the initial start-up time has not yet reached the user's requirements, the load rises quickly, reaching the peak of electricity consumption at 19:00-20:00. After the user's indoor temperature gradually reaches the comfort zone, the load gradually decreases. And the outdoor temperature at night gradually decreases, the load tends to stabilize from 21:00 with a slight drop. At 8:00 a.m., there was a significant drop in the load due to going out to work. At 12:00-14:00, the load increased due to the high outdoor temperature. For non-working days, as residents get up and move around, the load rises at a relatively fast rate from 7:00 a.m. Between 12:00-15:00, the outdoor temperature reaches its peak, so its load also reaches its peak.
Figure 3. Comparison of air conditioning load curves between working days and non-working days

Figure 4. Comparison of load curves of air conditioners with different set temperatures on non-working days.

It can be seen from Figure 4 that only changing the set temperature will not affect the trend of the load curve. The air conditioner with a high set temperature consumes less power than a low set temperature. Appropriately increasing the set temperature can effectively reduce the load power. This effect is evident at the peak of the load.

Take the time when the user is at home on a working day as an example, set the temperature to 24°C, and analyze the air-conditioning load plasticity in the range of 22°C-27°C. As shown in Figure 5, the solid line in the figure is the load curve, and the dashed line is the maximum and minimum allowable power in the temperature range of 22°C-27°C.

Figure 5. Load plasticity within a certain temperature range

It can be seen from Figure 5 that at the initial opening time of the air conditioner, since the indoor temperature has not yet reached the user's requirements, the air conditioner load is almost inflexible. Because there are also some home users during working days, and they also have a certain amount of adjustment. As the room temperature gradually approaches the temperature comfort zone, its plasticity becomes considerable. It can bring about 120kW of plasticity at 27°C and about 200kW of plasticity at 22°C. At this time, the air conditioner's load power can be increased or decreased, and adjustment is very flexible. The size of plasticity reflects its load adjustment ability. Around 8 o'clock, as users shut down, part of the air-conditioning load can no longer participate in the regulation, and the plasticity is gradually weakened. Until all users shut down, the load loses its plasticity. Suppose the air-conditioning load's two-way adjustment capability can be fully utilized. In that case, the air-conditioning load power can be appropriately adjusted when the intermittent renewable energy fluctuates to maintain the system power balance, which improves the system operation's safety.

4. Conclusion

This paper mainly focuses on the air-conditioning load curve and the size of load plasticity under different electrical usage behavior characteristics and analyzes the air-conditioning load adjustability.
Firstly, the load curves of 1000 air conditioners during working days and non-working days obtained by Monte Carlo simulation are compared and analyzed. Then, we take a non-working day to illustrate the influence of the air conditioner's temperature settings on its load curve. Finally, the load plasticity of the upper and lower limits of the working users' temperature during the working day at home according to the dispatch needs is studied, and the adjustable ability of the load is analyzed. This article can be known that the load plasticity, that is, the adjustable load ability, is related to its internal factors and related to the user's electrical usage behavior characteristics and external environmental conditions.

Acknowledgments
This paper was supported by the State Grid Shanghai Electric Power Research Institute(Project No: B30940200008)

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