Regulation capacity evaluation for air conditioners considering operating status and occupant comfort

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Abstract. In recent years, the load peak-valley difference is increasing rapidly and needs more regulation capacity to reduce it. However, traditional generating units are phasing out for low carbon goal and cannot provide enough regulation capacity for the power system. Besides, Air conditioners (ACs) account for about 40% of the electricity consumption of the power system during peak period in summer. Due to the thermal inertia of rooms, indoor temperature will not be greatly affected, when ACs are controlled temporarily to provide regulation capacity. To fully realize the regulation potential, it is of significantly importance to accurately evaluate the regulation capacity of ACs, where the real-time operating status and occupant comfort are two key factors. Therefore, this paper proposes a regulation capacity evaluation method for ACs considering operating status and occupant comfort. The equivalent thermal parameter (ETP) model based on the AC operating characteristics is developed firstly. On this basis, the regulation capacity for the individual AC is evaluated considering operating status and user comfort, and the regulation capacity of aggregated ACs can be obtained by summing. Finally, the effectiveness of the proposed method is proved by cases.

1. Introduction
In recent years, the electricity consumption continues to increase rapidly. According to the data released by the National Bureau of Statistics, the total electricity consumption reached 7,486.61 billion kWh in the world at 2019 [1]. The load peak-valley difference is also increasing rapidly and needs more regulation capacity to reduce it. However, traditional generating units are phasing out for low carbon goal and cannot provide enough regulation capacity for the power system. Therefore, maintaining the balance between supply and demand becomes more and more difficult.

To relieve the pressure of electricity generation and transmission during peak load period, demand response (DR) is a widely used method to shave the peak load. DR guides users to change their electricity consumption behaviors, by reducing the power consumption or shifting the load to other periods [2, 3]. During the hot summer, the air conditioners (ACs) electricity consumption increases quickly, accounting for more than 40% in total electrical loads [4]. Benefit from the thermal inertia of air in the room, the indoor temperature will not vary a lot if the ACs are turned off for a short time. Therefore, ACs are ideal flexible loads which have huge regulation potential to provide the regulation capacity for the power system. What’s more, with the rapid development of 5G technology, controlling lots of ACs distributing within a wide area becomes possible [5].
To maximize the utilization of ACs’ regulation potential, the electric power dispatching center needs to master the exact regulation ability of ACs. It is of great importance to evaluate the regulation capacity of ACs precisely [6]. There are several parameters influencing the regulation capacity of ACs, including building structure, rated power, and operating status. Besides, occupant comfort can’t be ignored, either. For different users, the maximum acceptable temperatures are not the same. To keep the motivation of participating in DR, the room temperature must quit participating in DR at once if the temperature reaches the comfort boundary.

There are many researches about the evaluation of ACs’ regulation capacity. Reference [7] presented a direct load control to investigate the potential of providing intra-hour load balancing services using aggregated ACs. Reference [8] established the model of aggregated ACs regulation capacity, considering the users comfort and wishes, so as to explore the maximum response potential of ACs. Reference [9] defined the indexes of aggregated ACs, including regulation capacity, response time, duration time and ramp rate, operating reserve performance is evaluated based on the indexes.

However, the existing research mostly evaluated the regulation capacity of aggregated ACs directly, ignoring the real-time operating status of ACs. For a certain room and its AC, the regulation capacity mainly depends on the difference between current temperature and the boundary temperature. When DR starts, the indoor temperature distributes randomly in the temperature range instead of a constant value. If the real-time temperature higher than the room set temperature, the regulation capacity will be lower than the expectation value. Furthermore, when the indoor temperature reaching the maximum acceptable temperature, most existing control methods will make the AC continuing operating at the maximum temperature, which has serious impact on users’ comfort.

Therefore, to evaluate the precise regulation capacity provided by ACs, and guarantee the occupant comfort, this paper analyzes the operation characteristic of ACs, and develops the equivalent thermal parameter (ETP) model of rooms. Then, the regulation capacity of an individual AC is evaluated considering the AC operating status and occupant comfort. On the one hand, for both operating and standby state of ACs, the regulation capacity is calculated respectively. And the effect of real-time temperature is also considered. On the other hand, to minimize the impact of DR on users’ comfort, the AC will begin cooling and reset the original set temperature, once the temperature reached the maximum acceptable temperature. Based on the result of the individual AC, the regulation capacity of aggregated ACs can be calculated precisely. At last, the influence of ACs status and occupant comfort on regulation capacity is proved by cases.

![Figure 1. The AC operation mechanism.](image)

2. Modelling of ACs based on thermodynamic process

2.1. Operation characteristic of the AC

In order to maintain the relative stability of the indoor temperature, the ACs can only keep switching statuses between operation and standby statuses, which are shown as Figure 1. Therefore, the indoor
temperature fluctuates within a range of the set temperature $T_{set}$, and the temperature range depends on the deadband $T_{db}$. When the AC is operating, the AC begins cooling and the temperature will continue decreasing until it is lower than boundary $T_{set} - T_{db}$. At this time, the power of AC reaches rated power $P_{rated}$. Once the temperature is lower than boundary, the AC will turn to the standby status. If the AC is on standby, the power is near to 0. Because the AC stops cooling, the indoor temperature will increase slowly, and the rise rate is mainly associated with the heat insulation of the room. The standby status will keep on before the temperature beyond $T_{set} + T_{db}$. Therefore, the on/off process will loop all the time when the AC is running.

2.2. Room thermodynamic modelling

The time of DR is uncertain, and in order to find out the real-time operating status of AC, ETP model is widely used to describe the real-time temperature dynamic process [10, 11], which can be expressed by

$$\frac{dT_a}{dt} = \frac{1}{C} (Q_{gain} + Q_{loss})$$

(1)

$$Q_{gain} = Q_{AC} + Q_{sun} + Q_{loads}$$

(2)

$$Q_{loss} = (T_a - T_{out}) / R$$

(3)

where $T_a$ and $T_{out}$ indicate the indoor temperature and the ambient temperature, respectively. $C$ is the heat capacity of room, which denotes the capacity of heat storage, and the temperature of the room is more difficult to change if the room has the larger heat capacity; $R$ represents heat resistance of the room, which is heat insulation ability of the room; $Q_{AC}$ represents the cooling capacity of ACs, which is related to the rated electrical power and energy efficiency ratio (EER) of ACs; $Q_{sun}$ is the heat from the sun exposure. $Q_{loads}$ corresponds to the heat generated by all kinds of electrical appliances in the room.

For a room with certain heat capacity and heat resistance, the room temperature is influenced by gain and loss of heat. The heat gain mainly consists of AC cooling, sun radiation and heat produced by electrical appliances. The heat loss is related to the difference between indoor temperature and ambient temperature, and the greater the temperature, the heat loss is more rapid.

3. Regulation capacity evaluation of ACs

ACs usually are used to shave the peak load, so as to relieve tight supply and demand of the electricity power. According to the operating characteristic of the AC, it’s obvious that the regulation capacity comes from the standby status. The regulation capacity is equal to response power multiples duration time. If the AC is under operation state, the response power is its rated power. If the AC is under standby state, it seems that the response power is zero, but the time of standby will prolong. Therefore, it is important to calculate the response duration time of ACs. However, the existing research mostly ignores the real-time status and occupant comfort, resulting in inaccurate calculation of the duration time during regulation process.

If the parameters of the room and AC are determined, the duration time depends on the maximum temperature rise. As shown in Figure 2 and Figure 3, when the DR event begins, the AC’s status may be operating or standby, and the real-time temperatures are different. Therefore, the regulation capacity needs to calculate according to AC’s status, respectively.

When the DR starts, if the AC is operating, the AC will switch to standby status, and the power decreases from $P$ to 0 quickly. If the temperature reaches the higher boundary but the DR is still continuing, the AC will be operating to ensure the occupant comfort instead of continuing
participating in DR. If the AC is under standby state, the power can’t shave any more. However, the indoor temperature is able to reach the maximum acceptable temperature until the AC begins cooling again, so the stand-by time will prolong.

Figure 2. The response process of AC on operation.

Therefore, the response duration time is influenced by the maximum temperature rise \((T_{\text{max}} - T_s)\). \(T_s\) is the temperature when DR begins, and the \(T_{\text{max}}\) is the highest temperature acceptable to the user.

Based on the ETP model, the real-time room temperature is shown as

\[
T_{\text{air}}(t) = R P_{\text{cool}} + T_{\text{out}} + [R P_{\text{cool}} + T_{\text{air}}(t - \Delta t) - T_{\text{out}}] e^{-\frac{\Delta t}{R C}}
\]

where \(T_{\text{air}}(t)\) and \(T_{\text{air}}(t - \Delta t)\) are the room temperature at time \(t\) and \((t - \Delta t)\), respectively; \(P_{\text{cool}}\) represents the cooling power of AC; \(\Delta t\) is the calculation cycle.

If the DR starts, we need to calculate the electricity consumed during the DR event.

\[
t_{\text{off}} = R C \ln \frac{T_s - T_{\text{out}}}{T_{\text{max}} - T_{\text{out}}}
\]

\[
t_{\text{on}} = \begin{cases} 0 & t_{\text{off}} \geq t_{\text{DR}} \\ t_{\text{DR}} - t_{\text{off}} & t_{\text{off}} < t_{\text{DR}} \end{cases}
\]

where the \(t_{\text{DR}}\) is the duration time of DR; \(t_{\text{on}}\) and \(t_{\text{off}}\) represents the operating time and standby time, respectively.

Besides, the regulation capacity should be different in electricity consumption. Therefore, it’s necessary to calculate the power consumption without DR. If the AC is operating, the operating time \(t'_{\text{on}}\) and standby time \(t'_{\text{off}}\) can be calculated through Equations (7) - (8).

\[
t'_{\text{on}} = R C \ln \frac{T_s - T_{\text{out}} + R P_{\text{cool}}}{T_{\text{min}} - T_{\text{out}} - R P_{\text{cool}}}
\]

\[
t'_{\text{off}} = t_{\text{DR}} - t'_{\text{on}}
\]

If the AC is standby, the operating time and standby time can be calculated through Equations (9) - (10).

\[
t_{\text{off}} = R C \ln \frac{T_s - T_{\text{out}}}{T_{\text{set}} + T_{\text{db}} - T_{\text{out}}}
\]

\[
t_{\text{on}} = t_{\text{DR}} - t_{\text{off}}
\]

The power of the AC \(P_{\text{AC}}\) is equal to the cooling power \(P_{\text{cool}}\) divided by Energy efficiency ratio (EER), which indicates the cooling efficiency of AC. Therefore, the regulation capacity can be expressed by:
After evaluating the individual AC regulation capacity, the total regulation capacity $E_{DR}^{\text{sum}}$ of $n$ aggregated ACs can be calculated by:

$$E_{DR}^{\text{sum}} = \sum_{i=1}^{n} E_{DR}(i)$$  \hspace{1cm} (13)$$

4. Case study
In order to verify the significant impact of operating status and users’ comfort, different cases are simulated. First of all, the simulation parameters are initialized. The equal heat resistance $R$ and the equal heat capacity $C$ obey the normal distribution, and the specific ranges are shown in Table 1. And the set temperature $T_{\text{set}}$ is the random integer selected from [24, 27]. The deadband are set uniformly as 1 °C.

**Table 1.** The fixed parameters initialization.

| Parameters | $R$ (°C/W) | $C$ (J/°C) | Number of ACs | $T_{\text{set}}$ (°C) | Deadband (°C) |
|------------|------------|------------|---------------|---------------------|---------------|
| Values     | [0.006, 0.008] | [300,000, 800,000] | 3000          | [24, 27]            | 1             |

Furthermore, this paper has set up 2 sets of simulations including 5 cases. As shown in Table 2, Case 1, case 2 and case 3 have the same temperature range, but the start temperatures, which mean the average temperature of rooms at the beginning of DR, are different. Then, case 1, case 4 and case 5 have different temperature ranges, which indicate the highest temperatures users can accept.

**Table 2.** The cases information.

| Cases   | Start Temperature (°C) | Temperature range(°C) | Number of ACs |
|---------|------------------------|-----------------------|---------------|
| Case 1  | $T_{\text{set}}$       | [-2, 2]               | 3000          |
| Case 2  | $T_{\text{set}} - 0.4$ | [-2, 2]               | 3000          |
| Case 3  | $T_{\text{set}} + 0.3$ | [-2, 2]               | 3000          |
| Case 4  | $T_{\text{set}}$       | [-1.5, 1.5]           | 3000          |
| Case 5  | $T_{\text{set}}$       | [-2.5, 2.5]           | 3000          |

![Figure 4. The DR comparison between cases with different start temperature.](image)
Figure 4 shows the DR effects of different start temperature. DR begins at 0:45:00, all ACs shave the load quickly, and the aggregated power decreased from 711kW to 0. Then, ACs continuously exit the DR after reaching the maximum acceptable temperature. Case 3 has the highest start temperature, and the aggregated power rose at first, and case 1 is the last one because the lowest start temperature. When DR ended at 1:15, the aggregated power of 3 cases have reached 980kW, 700kW and 1200kW, respectively.

Figure 5 is the result of different maximum acceptable temperatures. The case 4 has the lowest temperature boundary, and the load-shedding only keeps for a short time. At time 1:00, the aggregated power has reached 964kW, which is higher than normal power a lot. However, DR of case 5 lasts longer time. Therefore, the maximum acceptable temperature has significant impact on regulation capacity.

![Figure 5. The DR comparison between cases with different maximum acceptable temperature.](image)

The results of regulation capacity are shown in Table 3. Case 5 has the largest regulation capacity 305.5 kWh, and the case 4 has the minimum regulation capacity, which is only 64.5 kWh. It can be seen that the lower start temperature and higher acceptable temperature will produce larger regulation capacity.

| Cases | Origin | Case 1 | Case 2 | Case 3 | Case 4 | Case 5 |
|-------|--------|--------|--------|--------|--------|--------|
| Average power (kW) | 714 | 299 | 153 | 395 | 585 | 103 |
| Regulation capacity (kWh) | 0 | 207.5 | 280.5 | 159.5 | 64.5 | 305.5 |

5. Conclusions
To realize the efficient DR by ACs, evaluating the regulation capacity precisely is significant. This paper analysed the operating characteristic of the AC and established the ETP model of the room. Then, this paper takes the AC’s operating status and user’s comfort into consideration, the individual AC and the aggregated ACs regulation capacity are evaluated based on the ETP model. Finally, through the performance analysis of two cases, the effectiveness of the proposed regulation capacity method is illustrated.

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