Research on Large-scale Air-conditioning Loads Participating in Peak Shaving

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Abstract. As a type of the elastic load, the demand-side controllable air-conditioning load can respond to electricity demand based on incentives or electricity prices. By adopting a reasonable control strategy for the optimal combination of controllable air-conditioning load groups, the air-conditioning loads of large-scale buildings can be guided to execute various dispatch commands of the power grid in the best response to electricity consumption. This paper constructs an air-conditioning load model. On this basis, a day-ahead dispatch model of the power grid with the extensive participation of central air-conditioning loads is established. The case shows that the participation of large-scale air-conditioning load in demand response can effectively reduce the peak load and realize the economic operation of the system.

1. Introduction
The sharp increase in air-conditioning load has increased the burden on the power grid. If peak electricity consumption simply depends on expanding the scale of investment and increasing installed capacity to meet, the cost of power generation will continue to rise. Therefore, economic and technical measures of power demand side management are adopted to effectively manage the air-conditioning load during peak hours. It is of great significance to improve the efficiency of energy consumption and to ensure the safe operation of the power grid. Intelligent power use methods such as power visualization and load optimization control can be used to monitor the user's air-conditioning equipment. Then the demand response incentive mechanism is used to guide users to participate in grid peak reduction and valley filling. Summarizing the current status of the implementation of direct load control projects for air-conditioning loads at home and abroad, it is found that foreign air-conditioners already have a mature operating system through direct load control projects. In contrast, the implementation of direct load control projects for air conditioners in other regions of my country except Taiwan Province is still in its infancy. Therefore, it is necessary to study the direct load control technology of air-conditioning load adapted to the current environment of our country.

2. Air-conditioning load model
Public buildings generally use a set of central air-conditioning systems for cooling. The central air-conditioning system of a public building mainly includes one or more refrigeration units and a corresponding number of chilled water pumps, cooling water pumps and cooling towers. It may also include terminal equipment such as air-conditioning units, fan coil units, and fresh air units, in which the chiller completely provides the cooling required for cooling public buildings.

For a public building, during the cooling period, the central air-conditioning refrigeration unit continues to provide cooling to keep the room temperature lowered. During the shutdown period, the central air-conditioning refrigeration unit stops working. Due to the heat release of the heat sources
inside and outside the building and the heat storage effect of the inner wall of the building, the room temperature continues to rise. Therefore, the following two formulas respectively express the heat balance relationship of the indoor air in public buildings during the period between the shutdown period and the cooling period at any time.

\[
C_a V_k \rho_a \frac{dT_{in}}{dt} = q_{cl} dt + q_{nw} dt - q_x
\]

(1)

\[
C_a V_k \rho_a \frac{dT_{in}}{dt} = q_{cl} dt + q_{nw} dt - q_x - q_{ch} dt
\]

(2)

Where \( C_a \) is the specific heat of air at a constant pressure, taking 0.28 J/kg • ℃; \( V_k \) is the volume of refrigeration space in public buildings, which can be calculated as the product of public building area, floor height and number of floors above ground; \( \rho_a \) is the air density, taking 1.29 kg/m³; \( T_{in} \) is the temperature inside the house; \( q_{cl} \) is the instantaneous heat gain of public buildings; \( q_{nw} \) is fresh air load; \( q_x \) is the heat storage of the enclosure structure; \( q_{ch} \) is the hourly cooling capacity of the central air-conditioning refrigeration unit.

Then the thermodynamic equations of the central air-conditioning system in public buildings during the shutdown period and the refrigeration period can be derived.

\[
X_k \frac{dT_{in}}{dt} + B_k T_{in} - A_k = 0
\]

(3)

\[
X_k \frac{dT_{in}}{dt} + B_k T_{in} - (A_k - q_{ch}) = 0
\]

(4)

and

\[
A_k = \sum K_{F_i} (T_{in} + T_{o}) + \sum K_{F_c} F_{out} + q_{l} F_{c} C_{s} C_{n} C_{cl} + 1000 n_1 n_2 n_3 n_4 n_5 n_6 n_7 + N_1 + C r n \phi q_{e} + n \phi q_{e} + 1.01 G_k^{n} + 38.5 G_k^{n}
\]

(5)

Where \( F_i \) is the area of the external wall or roof; \( T_{o} \) is the hourly value of the temperature for the external wall and roof cooling load; \( F_c \) is the area of the outer window; \( K_{c} \) is the heat transfer coefficient of the outer window. \( q_{l} \) is the maximum amount of heat received by the external window; \( C_{s} \), \( C_{n} \), \( C_{cl} \) are the correction coefficient of the external window glass type, the internal shading coefficient, and the cooling load coefficient respectively; \( N_1 \) to \( N_7 \) are the installation factor, load factor and utilization rate of electric heating equipment; \( N_{s} \) is the installed power of electric heating equipment; \( n_1 \) to \( n_7 \) are the simultaneous utilization rate of the lighting equipment, the heat storage coefficient of the lighting equipment, the coefficient of the power consumption of the rectifier, and the installation coefficient of the lighting equipment. \( N_{s} \) is the installed power of the lighting equipment; \( C_{s} \) is the cooling load coefficient of human body's sensible heat dissipation; \( n \) is the total number of people in public buildings; \( q_{c} \) is the amount of latent heat dissipation of each adult man; \( \phi \) is the clustering coefficient; \( q_{o} \) is the amount of latent heat dissipation of each adult man; \( G_{k}^{n} \) is the amount of fresh air; \( S_i \) is the heat transfer coefficient of the inner wall; \( F_{in} \) is the equivalent inner wall area.

So far, the modeling of the central air-conditioning system in public buildings has been established.

3. Air conditioning control strategy

The refrigeration units of the cold storage central air-conditioning system of public buildings include dual-mode refrigeration units and base-load units. Generally, the cold storage type central air-conditioning system of public buildings adopts the following operating modes when there is no
regulation in summer. During the low electricity price period from 00:00 to 8:00 in the evening, the
dual-condition refrigeration unit runs at rated load for refrigeration. All the produced cold capacity is
stored in the form of ice (or other phase change materials) in the cold storage tank, and the cooling load
required for indoor cooling is provided by the base load unit. In other periods, the base load unit first
provides the cooling load required for indoor cooling, and the unsatisfied load is then provided by the
cold storage tank.

With the above working methods, there is a problem that the cold storage in the cold storage tank of
the dual-mode unit during the low electricity price period at night cannot be fully or almost completely
released in other periods, resulting in a waste of energy. In view of this, this article adopts the constant
ratio control method to regulate and control the cold storage central air-conditioning in public buildings.
The specific control strategy is that the operation mode of the refrigeration unit of the central air-
conditioning system remains unchanged during the 8-hour low electricity price period in the evening.
In other periods, the base load unit and the ice storage tank jointly provide the cooling load required for
indoor cooling, and the ratio of the cooling capacity released by the ice storage tank to the total cooling
capacity required by public buildings at each moment is always a constant value $k$. With this control
scheme, it is possible to select an appropriate value of $k$ daily to release all or almost all of the cold
energy stored in the cold storage tank, while effectively reducing the total electricity consumption of
public building air conditioning loads during peak electricity consumption. This public building cold
storage central air-conditioning control strategy satisfies the following formula.

$$\frac{1}{4} \sum_{i=33}^{96} q_{x,i} = (1-LF) Q_{x,i}$$

Where $i$ is the scheduling period (This article divides a day into 96 periods, and assumes that all the
power variables and cooling capacity variables discussed in the article are constant in one period.); $q_i$
is the total cooling capacity required by the public building during the i-th period; $q_{j,i}$ is the actual
cooling capacity of the base load unit during the i-th period; $q_{x,i}$ is the actual cooling capacity of the
cold storage tank in the i-th period; $LF$ is the percentage of remaining cold capacity of the cold storage
tank after the end of the day; $Q_{x,i}$ is the total cold storage capacity of the dual-condition refrigeration
unit during the 8-hour low price period of the evening of the day.

4. Large-scale air-conditioning load participates in load scheduling

4.1 Objective Function
The goal of large-scale public building central air-conditioning load participating in the day-a-day
dispatch of the power grid is to minimize the total cost of system operation. On the premise that the
deviation between the total load value of the regional power grid after regulation and the dispatching
command of the regional power grid is sufficiently small, it is necessary to meet the conventional unit
operation constraints, human thermal comfort requirements, and the remaining cold capacity
requirements of the cold storage tank of the cold storage air conditioning system.

When the central air-conditioning load and the conventional unit combination participate in the
power grid control, the actual peak cut of the central air-conditioning load can be equivalent to the output
of the virtual unit. The combined control decision model aims to minimize the total cost of system
operation. The total cost includes the power generation cost of the conventional unit, the startup cost of
the conventional unit, the environmental pollution control cost caused by the power generation of the
conventional unit, and the compensation cost of the central air-conditioning system in public buildings.
The objective function is
Where \( z_{f,i} \) and \( w_{f,i} \) are signs indicating whether the \( f \)-th public building is open during the morning and evening peak shaving period; \( u_{z,f,i} \) and \( u_{w,f,i} \) are signs indicating whether the air-conditioning system of the \( f \)-th public building are controlled by the marking quantity of the \( l \)-th gear during the morning and evening peak shaving period; \( P_{d,f,l,i} \) is the total load value during the \( i \)-th period when the central air-conditioning system of the \( f \)-th public building is controlled by the \( l \)-th gear; \( c_f \) is the unit compensation price for the air-conditioning system participating in the grid peak cut; \( FDC_{m,i} \) is the power generation cost of the \( m \)-th generator set during the period \( i \), and \( FDC_{m,i} = c_{2,m} F_{D,i} + c_{1,m} F_{D,m} + c_{0,m} u_{m,i} \); \( FDC_{m,i} \) is the output of the \( m \)-th generator set during the period \( i \); \( c_{2,m} \), \( c_{1,m} \) and \( c_{0,m} \) are all coefficients for the characteristics of unit power generation cost; \( u_{m,i} \) is the start and stop status of the \( m \)-th generator set during the period \( i \); \( M \) is the total number of generator sets in the area; \( ST_{m,i} \) is the start-up cost of the \( m \) generator set during the period \( i \); \( e_n \) is the pollutant emissions of the \( m \)-th generator; \( EC \) is the treatment price of the pollutants discharged by the generator. The first item of the formula (9) is the sum of the adjusted and compensated electricity charges of the central air-conditioning system of all public buildings that participate in peak shaving in this area during the morning and evening peak shaving periods. The second item is the sum of the power generation cost, start-up cost and environmental pollution control cost of the conventional generator set that provides all loads in the area throughout the day.

4.2 Restrictions

The constraint conditions of the central air-conditioning load and the conventional unit combination control decision model are as follows.

1) Power balance constraint

In any \( i \)-th period, the sum of the output of all generating units in the area is equal to the difference between the total load forecast of the area and the sum of the dispatchable capacity of the central air-conditioning system of all public buildings participating in the grid peak reduction in the area.

\[
\sum_{m=1}^{M} FDC_{m,i} = \begin{cases} 
  p_{z,i} - \sum_{j=1}^{44} \sum_{l=1}^{4} v_{z,f,i} \mu_{f,j} P_{d,f,l,i} & i = 1,2,\ldots,44 \\
  p_{z,i} - \sum_{j=45}^{54} \sum_{l=1}^{4} v_{z,f,i} \mu_{f,j} P_{d,f,l,i} & i = 45,46,\ldots,54 \\
  p_{z,i} - \sum_{j=55}^{55} \sum_{l=1}^{4} v_{z,f,i} \mu_{f,j} P_{d,f,l,i} & i = 55,56,\ldots,78 \\
  p_{z,i} - \sum_{j=79}^{84} \sum_{l=1}^{4} v_{z,f,i} \mu_{f,j} P_{d,f,l,i} & i = 79,80,\ldots,84 \\
  p_{z,i} - \sum_{j=85}^{96} \sum_{l=1}^{4} v_{z,f,i} \mu_{f,j} P_{d,f,l,i} & i = 85,86,\ldots,96 
\end{cases}
\]

Where \( p_{z,i} \) is the predicted value of the total load in the \( i \)-th period of time.

2) Deviation constraint

The maximum sum of the total load value of the air-conditioning system in the area after regulation during all peak-shaving periods and the deviation of the power grid’s dispatching instructions shall satisfy the following inequality.

\[
\begin{align*}
\sum_{i=1}^{96} \left[ p_{z,i} - \left( \sum_{f=1}^{F} \sum_{j=1}^{4} v_{z,f,i} \mu_{f,j} P_{d,f,l,i} + \sum_{f=1}^{F} \sum_{j=45}^{54} v_{w,f,i} \mu_{f,j} P_{d,f,l,i} \right) \right] \leq \Delta P \\
\end{align*}
\]
Where $p_{s,i}$ is the total load dispatch command of the central air-conditioning system of public buildings in the area from the power grid during the i-th period; $\Delta P$ is the maximum allowable deviation.

3) Participation constraint

The central air-conditioning system can only be controlled by a certain level control scheme in a day.

$$\sum_{j=1}^{3} u_{z,j} \leq 1$$ (12)

4) Generator output constraint

$$u_{n,i} p_{\min,m} \leq u_{n,i} \leq u_{n,i} p_{\max,m}$$ (13)

Where $p_{\min,m}$ and $p_{\max,m}$ are the minimum and maximum power generation of the m-th generator respectively.

5) Generator ramp rate constraint

$$|p_{n,i} - p_{n,i-1}| \leq PP_m \cdot \Delta I$$ (14)

Where $PP_m$ is the ramp rate of the m-th generator; $\Delta I$ is the time interval of scheduling.

6) Minimum opening and shutdown time constraints of the generator

$$\begin{cases} (u_{n,i-1} - u_{n,i}) (u_{n,i-1,\text{on}} - u_{n,i,\min,\text{on}}) \geq 0 \\ (u_{n,i} - u_{n,i-1}) (u_{n,i-1,\text{off}} - u_{n,i,\min,\text{off}}) \geq 0 \end{cases}$$ (15)

Where $u_{n,i-1,\text{on}}$ and $u_{n,i-1,\text{off}}$ are the cumulative start-up time and time of the m-th generator during the i-1 period; $u_{n,i,\min,\text{on}}$ and $u_{n,i,\min,\text{off}}$ are the minimum continuous start-up and shutdown time of the m-th generator.

The air conditioning load and conventional unit combination control model composed of formulas (9)-(15) is a nonlinear single-objective mixed integer programming problem. This model can be converted into a mixed integer linear programming model, and then solved by the CPLEX software package.

5. Case study

This article takes the central air-conditioning load of all public buildings in a certain area on a certain day as the research object. After studying the adjustment strategy proposed in this paper, the effect of reducing the grid load in the morning and evening peak hours of the region's power consumption is studied, and the economics of the adjustment plan is analyzed. The research area includes three parts: the industrial area, the business area and the residential area. The air-conditioning load control in this article is aimed at all 22 public buildings in the business district that adopt central air-conditioning refrigeration methods, including 5 shopping mall buildings, 13 office buildings and 4 hotel buildings. Assume that the outdoor temperature during the morning peak shaving period is 34.1°C, and the outdoor temperature during the late peak shaving period is 30.9°C.

In order to reduce the total load of the power grid in the morning and evening peak power consumption in the area that day, given that the load dispatching commands $p_{s,z}$ and $p_{s,\omega}$ of the central air-conditioning system of public buildings in the morning and evening peak shaving periods in this area are 22500kW and 7800kW respectively. Set the maximum allowable regulation deviation $\Delta P$ for all peak shaving periods throughout the day as 20kW. In this paper, three different types of public buildings of shopping malls, office buildings and hotels are divided into three different types of public buildings to set compensation electricity prices, respectively 0.32 yuan / kWh, 0.3 yuan / kWh and 0.34 yuan / kWh. Four conventional generator sets are used to supply power to all loads in the area. The unit parameters of each generator are shown in Table 1, and the unit price for the treatment of pollutants discharged by the generator unit is 34.1 yuan/ton.
Table 1. Parameters of generators.

|     | c_2     | c_1     | c_0     | FD_{max}/MW | FD_{min}/MW |
|-----|---------|---------|---------|-------------|-------------|
| #1 GU | 0.00398 | 19.70   | 450     | 162         | 25          |
| #2 GU | 0.00211 | 16.50   | 680     | 130         | 25          |
| #3 GU | 0.00679 | 22.27   | 370     | 85          | 20          |
| #4 GU | 0.00679 | 22.27   | 370     | 85          | 20          |
| #5 GU | 0.00413 | 25.92   | 660     | 55          | 10          |

|     | ST/yuan | PP/MW/h | I_{min,on}/h | I_{min,off}/h | e/ton/MW |
|-----|---------|---------|--------------|---------------|----------|
| #1 GU | 4340    | 81      | 2            | 2             | 0.82     |
| #2 GU | 3472    | 65      | 2            | 2             | 0.78     |
| #3 GU | 1550    | 63.75   | 1            | 1             | 0.63     |
| #4 GU | 1550    | 63.75   | 1            | 1             | 0.63     |
| #5 GU | 496     | 41.25   | 0.5          | 0.5           | 0.55     |

Table 2. Optimal Combination Control Strategy of Air Conditioning Load.

| Mall 1 | u_{z,1} | u_{z,2} | u_{z,3} | u_{w,1} | u_{w,2} | u_{w,3} |
|--------|---------|---------|---------|---------|---------|---------|
| Mall 2 | 0       | 1       | 0       | 0       | 1       | 0       |
| Mall 3 | 0       | 0       | 1       | 0       | 0       | 1       |
| Mall 4 | 0       | 1       | 0       | 1       | 0       | 0       |
| Mall 5 | 0       | 0       | 1       | 0       | 0       | 1       |
| Building 1 | 0   | 0       | 0       | 1       | 0       | 1       |
| Building 2 | 0 | 0       | 1       | 1       | 0       | 0       |
| Building 3 | 0 | 0       | 1       | 0       | 0       | 1       |
| Building 4 | 0 | 0       | 0       | 0       | 0       | 0       |
| Building 5 | 0 | 0       | 0       | 1       | 0       | 0       |
| Building 6 | 0 | 0       | 0       | 1       | 1       | 0       |
| Building 7 | 0 | 0       | 0       | 1       | 0       | 1       |
| Building 8 | 0 | 0       | 0       | 0       | 0       | 1       |
| Building 9 | 0 | 0       | 0       | 1       | 0       | 0       |
| Building 10 | 0 | 0       | 0       | 0       | 0       | 1       |
| Building 11 | 0 | 0       | 0       | 0       | 0       | 1       |
| Building 12 | 0 | 0       | 0       | 1       | 0       | 0       |
| Building 13 | 0 | 0       | 0       | 0       | 0       | 1       |
| Hotel 1 | 0 | 0       | 1       | 0       | 0       | 0       |
| Hotel 2 | 0 | 0       | 1       | 0       | 0       | 0       |
| Hotel 3 | 1 | 0       | 0       | 0       | 0       | 1       |
| Hotel 4 | 0 | 0       | 1       | 0       | 0       | 0       |

Fig. 1. The total load of the regional power grid before and after the morning peak regulation
Fig. 2. The total load of the regional power grid before and after the evening peak regulation

Table 3. Comparison of system operating costs before and after regulation.

|                  | Generation cost /yuan | Start-up cost /yuan | Pollution control cost /yuan | Compensation for electricity /yuan | Total cost /yuan |
|------------------|------------------------|---------------------|-----------------------------|-----------------------------------|-----------------|
| Before regulation| 958430.07              | 9982                | 98208.2                     | 0                                 | 1066620.27      |
| After regulation | 957212.91              | 9982                | 98000.49                    | 1947.34                           | 1067142.74      |

Fig. 3. Optimal combination output arrangement of generators

It can be seen from the simulation results that after the regulation, the total load of the regional power grid in the morning and evening peak hours has been effectively reduced, and the peak-to-valley difference is reduced. The total electricity saving of central air conditioning in public buildings throughout the day is 6085.44kWh, and the total electricity reduction is 0.74%. In addition, the central air-conditioning load's participation in power grid regulation weakens or even offsets the savings in conventional unit operating costs and environmental pollution control costs caused by peak shaving. Therefore, reasonable setting of the compensation price for demand-side loads directly participating in grid regulation is of great significance to improving the economic efficiency of the combined peak shaving system.

6. Conclusion
This paper mainly conducts a detailed study on the control plan of the central air-conditioning load combination of large-scale public buildings participating in the power grid peak reduction. A comprehensive load model of the air conditioning system was established in this paper. Combining with the traditional generator set model, with the goal of minimizing the total cost of system operation, a day-
ahead dispatching model of the power grid with extensive participation of central air-conditioning loads in public buildings was established. Taking the central air conditioning of 22 buildings in a certain area as the research object, the model's peak shaving effect and economy were simulated and verified. The results show that by setting the compensation price reasonably, the peak load is effectively reduced and the economy of system operation is also improved.

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