Research on Optimal Control Strategy of Ice Storage Air Conditioning System

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**Keywords**: Ice storage air conditioning, Optimal control, Trust region algorithm, Minimum cost.

**Abstract**. Ice storage air conditioning technology is a very valuable power demand side management technology. This paper establishes the goal of minimizing the operating costs of ice storage air conditioning system for the whole day. The cooling capacity of air-conditioning refrigeration and ice melting refrigeration in ice storage air conditioning systems and the total cooling capacity requirement of ice storage air conditioning systems are limited to the optimization of constraints in model. The paper applies trust region algorithm to solve the established optimization model, and uses MatLab to program. The simulation results of the example verify the correctness of the proposed model and the programming procedure.

**Introduction**

A prominent contradiction in the supply and demand of electricity is the huge peak-to-valley gap in the load curve. Ice storage air conditioning system is the first time to make ice in the low season, and an air conditioner that utilizes melting ice for refrigeration at the peak. According to statistics from the Beijing Municipal Electric Power Bureau, 41% of Beijing's total electricity consumption in summer is for air conditioning and refrigeration [5]. If demand-side management of urban air conditioning and refrigeration systems is conducted, theoretical calculations and experiments show that if ice storage air conditioners can be universally promoted, the load during peak hours can be shifted around 41%, and over 30% of the low valley power can be fully utilized. The realization of "pick load shifting" in the power grid can save the power system investment in power generation and power supply, and save operating costs.

Therefore, it is necessary to study the establishment of an optimal control model under the constraints of the existing load curve, peak-valley electricity price, and cooling demand, so as to achieve a reasonable conversion of energy at different peak-valley times, so that the total cost of expenditure can be minimized to reach the win-win result with the user and power supply system, and the ideal effect of both social and economic benefits.

**Literature Review**

Tamblyn[1] (1985) used temperature sensors, flowmeters and other measuring instruments to draw accurate cooling load curves and establish a functional relationship between cooling load and ambient temperature and internal load for load forecasting. Stethman[2] (1989) proposed the optimal control of the ice storage system and conducted a simulation analysis of a 9,200-square-meter building in San Diego, USA, and found that the optimized control saved 42% of the operating cost compared to the cold-stand. Ferrano[3](1990) used an artificial neural network to predict the total cooling load of the next day and combined it with a real-time expert system for the control of an ice-storage air-conditioning system in Miami.

This paper aims to study the operation principle and control strategy of ice storage air conditioning. Under the background of time-based electricity price, with the goal of minimizing the
total cost, the optimization model of ice storage air conditioning operation is studied and established, and the optimized model is solved by applying the optimization algorithm. Give example calculations and analysis. This article hopes to provide reference for promoting the large-scale implementation of ice storage air-conditioning technology.

Modeling and Analysis

Parameter Hypothesis

**Peak-valley Electricity Price.** The electricity price parameter in the model is based on the real-time peak-valley electricity price in Beijing and is simplified to some extent\[4\].

The simplified results are:

1. From 23:00-7:00, the price is ¥0.4/MWh.
2. From 7:00-10:00 and 15:00-18:00 and 21:00-23:00, the price is ¥0.8/MWh.
3. From 10:00-15:00 and 18:00-21:00, the price is ¥1.3/MWh.

**Cooling Capacity.** The cooling capacity of an air conditioner refers to the total amount of heat removed from a confined space per unit time when the air conditioner performs cooling. The cooling capacity of the air conditioner should be slightly greater than the cooling load of the room. The cooling capacity is related to the environment temperature. In this report, Beijing is taken into consideration\[6\].

The temperature changes in Beijing during the summer day can be simplified as shown below.

1. High temperature range, i.e. 30°C and above, includes 10 to 19 o’clock.
2. Intermediate temperature range, i.e. 28°C to 30°C, includes 8 to 10 and 19 to 23 o’clock.
3. Low temperature range, i.e. 28°C or below, includes 23 to 8 o’clock.

In this paper, a 1000m² house was selected as the study object. Under normal circumstances, the normal room cooling load recommended value is 1.5-2.5W/m². In this paper, when calculating cooling capacity for lower range, 1.5W/m² is taken which is Q=1000×1.5=1500W. When calculating cooling capacity for intermediate range, 2.0W/m² is taken which is Q=1000×2=2000W. When calculating cooling capacity for high range, 2.5W/m² is taken which is Q=1000×2.5=2500W.

![Figure 1. Cooling capacity required at various times in a 1000m² house.](image)

**Power Consumption.** (1) Electricity consumption of electric cooling

The power consumption and cooling capacity are numerically multiplied, and the cooling capacity \( Q_i \) is three times the power consumption \( Q'_i \), i.e. from this formula \( Q_i = 3Q'_i \)[7], the power consumption of the electric cooling \( Q'_i \) in each period can be obtained.

(2) Power Consumption of Melting Refrigeration Device

The amount of power consumed by the melt-thawing refrigeration device is linearly related to the power consumption of the electrical cooling under the same cooling load condition. Under the same cold load condition, the ratio of the power consumed by melting ice cooling and the power consumption of electric cooling is generally 0.28[7]. It is assumed here that this ratio increases by 0.05 every four hours starting from 0.2, yielding the following proportional coefficients:
From 7 to 11 o’clock, this value is 0.2;
(2) From 11 to 15 o’clock, this value is 0.25;
(3) From 15 to 19 o’clock, this value is 0.3;
(4) From 19 to 23 o’clock, this value is 0.35.

Model Establishment

After analyzing the various physical parameters above, the objective function is:

\[ M = \sum_{i=1}^{24} Q_i^* k_i + \sum_{j=1}^{23} Q_j^* k_j + M_0 \]  

(1)

The first part, \( \sum_{i=1}^{24} Q_i^* k_i \), is the cost of electric cooling for air-conditioning. This value is obtained by multiplying the electricity consumption per hour of electric cooling \( Q_i^* \) with the electricity price \( k_i \), in the corresponding time period. Considering that the power consumption \( Q_i^* \) is approximately estimated to be one-third of the cooling capacity \( Q_i \), the formula is developed as \( \sum_{i=1}^{24} Q_i^* k_i = \sum_{i=1}^{24} k_i a_i * Q_i / 3 \). In this equation, \( a_i \) is the proportional coefficient of the total cooling capacity in \( i \) hours.

The second part, \( \sum_{j=1}^{23} Q_j^* k_j \), is the cost of melting ice. It is agreed that the ice-melting refrigeration is only 7 am to 23 pm. As with air-conditioner electric refrigeration, the cost of melting ice is obtained by multiplying the electricity consumed per hour of electric cooling \( Q_j^* \) by the electricity price \( k_j \) corresponding to the time period. Assume that the proportion coefficient of electrical refrigeration to the total cooling capacity within the \( j \)th hour is \( a_j \), and the ratio of the melt ice cooling and the electrical cooling power consumption under the same cooling capacity in the \( j \)th hour is \( s_j \), then the equation becomes

\[ \sum_{j=1}^{23} Q_j^* k_j = \sum_{j=1}^{23} k_j * (1-a_j) * s_j * Q_j / 3. \]  

(2)

The third part, \( M_0 \) is the total cost of ice storage. As agreed in the above, ice storage operations will only be conducted during the period from 23 o’clock in the evening to 7 o’clock in the morning. The total amount of ice storage can be expressed by the total refrigeration capacity of ice melt \( Q_m \). The amount of ice melt refrigeration can correspond to the power consumption needed to produce the ice, and it can be expanded to obtain \( M_0 = Q_m / 5 * k \).

In summary, the objective function can be expanded to:

\[ M=\sum_{i=1}^{24} k_i a_i * Q_i / 3 + \sum_{j=1}^{23} k_j * (1-a_j) * s_j * Q_j / 3 + Q_m / 5 * k \]  

(3)

Based on the objective function, the following constraints are obtained:

\[
\begin{align*}
0 & \leq Q_i \leq Q_{i_{max}} \\
Q_j & = Q_m \\
Q_i + Q_j & = Q_{m_0}
\end{align*}
\]

(4)

Among them: The cooling capacity for the user at a certain moment is \( Q \) and the total cooling capacity of ice melting after ice storage is \( Q_m \).

In the first part, the cooling capacity of the air-conditioner electric refrigeration in the ice storage air-conditioning system is limited by the rated power and rated cooling capacity of the electric refrigeration device. The cooling capacity in each period \( Q_i \) should not be greater than the maximum cooling capacity \( Q_{i_{max}} \) that the electric refrigeration device can produce.

In the second part, in order to ensure that the system achieves the lowest cost, it is assumed that
the amount of ice stored at night is consumed during the day’s cooling process. Therefore, the total refrigerating capacity $Q_j$ of the ice-melting refrigeration system in the ice-storage air-conditioning system should be equal to the total refrigerating capacity $Q_m$ of the ice-melted ice at night, i.e.

$$Q_m = \sum_{i=1}^{24} (1-a_i) * Q_i$$

Among them, $Q_m$ is the total cooling capacity of ice melting after ice storage.

In the third part, the total cooling capacity of the ice-storage air-conditioning system is composed of the cooling capacity $Q_i$ of the electric cooling and the cooling capacity $Q_j$ of the melted ice. The sum of these two parts should be equal to the total demand for cooling capacity in the environment.

**Results and Analysis**

**Operational Results.** In order to represent the proportional relationship between air-conditioning cooling and ice melting better, the calculation results are plotted in a histogram, as shown in the following figure below:

![Figure 2](image)

If the system adopts the above operating mode, the total operating cost is:

$$M = \sum_{i=1}^{24} k_i * a_i * Q_i / 3 + \sum_{j=7}^{24} k_j * (1-a_j) * s_j * Q_j / 3 + Q_m / 15 * k$$

$$= \sum_{i=1}^{9} p_i * k_i * a_i * Q_i / 3 + \sum_{j=2}^{24} p_j * k_j * (1-a_j) * s_j * Q_j / 3 + Q_m / 15 * k$$

Each of these parameters is shown in the following table:

| Time       | Occupied hour $p_i$ | Required cooling capacity $Q_i$ | Electricity price $k$ | ratio $s$ | electrical refrigeration $a_i$ | ice melting and cooling $(1-a_i)$ |
|------------|---------------------|---------------------------------|----------------------|-----------|-------------------------------|----------------------------------|
| 23:00-7:00 | 8                   | 1500                            | 0.4                  | 100%      | 100%                          | 0%                               |
| 7:00-8:00  | 1                   | 1500                            | 0.8                  | 0.2       | 51.71%                        | 48.29%                           |
| 8:00-10:00 | 2                   | 2000                            | 0.8                  | 0.2       | 52.56%                        | 47.44%                           |
| 10:00-11:00| 1                   | 2500                            | 1.3                  | 0.2       | 35.02%                        | 64.98%                           |
| 11:00-15:00| 4                   | 2500                            | 1.3                  | 0.25      | 32.10%                        | 67.90%                           |
| 15:00-18:00| 3                   | 2500                            | 0.3                  | 0.3       | 65.07%                        | 34.93%                           |
| 18:00-19:00| 1                   | 2500                            | 1.3                  | 0.3       | 23.02%                        | 76.98%                           |
| 19:00-21:00| 2                   | 2000                            | 1.3                  | 0.35      | 22.56%                        | 77.44%                           |
| 21:00-23:00| 2                   | 2000                            | 0.8                  | 0.35      | 67.56%                        | 32.44%                           |

The parameters in the above table are brought into the total operating cost $M$, and the cost is reduced through the adjustment of the ice storage air-conditioning system to RMB1657.3.
Analysis. Without the adjustment of the ice storage system, the total operating cost is determined by the cost of one day of operation of the air-conditioning cooling system. In this model, the total cost of operation with the required cooling capacity for the entire day as a reference item is:

\[ M_e = \sum_{i=1}^{24} Q_i / 3 \cdot k_i = \sum_{i=1}^{9} p_i \cdot Q_i / 3 \cdot k_i / 3 \]  

Each of these parameters is shown in the following table:

| Time          | Occupied hours | Required cooling capacity | Electricity price |
|---------------|----------------|---------------------------|-------------------|
| 23:00-7:00    | 8              | 1500                      | 0.4               |
| 7:00-8:00     | 1              | 1500                      | 0.8               |
| 8:00-10:00    | 2              | 2000                      | 0.8               |
| 10:00-11:00   | 1              | 2500                      | 1.3               |
| 11:00-15:00   | 4              | 2500                      | 1.3               |
| 15:00-18:00   | 3              | 2500                      | 0.3               |
| 18:00-19:00   | 1              | 2500                      | 1.3               |
| 19:00-21:00   | 2              | 2000                      | 1.3               |
| 21:00-23:00   | 2              | 2000                      | 0.8               |

The parameters in the above table are brought into the total operating cost, and the total operating cost under the regulation without ice storage air conditioning is RMB6715.26.

It can be seen that the cost of the adjustment of the ice-storage air-conditioning system as described above can significantly reduce the operating cost after the ice-storage refrigeration system is added. In addition, it reduces the power which is generated by the night power system but because the load becomes smaller and is wasted and not consumed, in the meantime, this method can make "peak load shifting" to the power grid, and at the same time, it also increases the system electricity consumption rate and greatly reduces the cost. The investment increases the efficiency and improves the efficiency of the system.

For the specific relationship between the proportions of electricity cooling at various times, we take peak price period as analysis item. When the electricity price is the peak electricity price, the proportion of electric refrigeration in the ice storage air-conditioning system is obviously greater than that when the electricity price is cheap. This is because during the period when the electricity price is high, the use of electrical refrigeration devices should be reduced, and the proportion of refrigeration of ice-melting refrigeration devices should be increased to reduce the operation of the electrical refrigeration devices during the period when the electricity prices are high.

Conclusions

In summary, the total operating cost obtained through the optimization calculation of this model can reasonably demonstrate the principle and results of the ice storage system's cost reduction. However, in this paper, only linear programming is used for this model, which will cause some differences, and the final results will also produce corresponding differences. In addition, there are some factors that have not been taken into account. For example, in this model, only ice storage at night is considered, and the ice storage operation mode is not calculated during the whole day; factors that influence the predicted value of the cooling capacity, etc. Therefore, this conclusion provides a reference value for the optimization strategy of ice-storage air-conditioners in the overall aspect, and it requires further analysis if careful research is to be conducted.

This paper establishes an optimization model that minimizes the cost of the ice storage air conditioning system for the entire day, and uses the load curve, peak-to-valley price, and cooling demand as constraints. And use the appropriate trust region algorithm to solve the example. The
result is compared with the actual situation, and the correctness of the model and program is verified.

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