Smoothing of Power Consumption in Air Conditioning Systems with Ice Storage: A Receding-Horizon Optimization Approach

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Abstract. The peak of power load brings great challenges to the safety, stability, and economical operation of the modern power system. Building air conditioning refrigeration is one of the main reasons for the peak load. In this paper, we make use of an ice storage tank to smooth the air conditioning load as far as possible so as to achieve the purpose of peak filling. A mathematical model of quadratic programming is established to characterize the trade-off between the lowest energy storage cost and smoothness via a receding-horizon optimization approach. Numerical examples are given to analyze the relationship between ice storage cost and peak filling effect.

1. Introduction

With the dual pressure of energy and environment, the development of efficient smart grid has attracted more and more attention from academia, government and industry [1-3]. Smart grid is built on the basis of integrated, high-speed two-way communication network, through the application of advanced sensing and measurement technology, advanced equipment technology, advanced control method and advanced decision support system technology, to achieve the power grid reliable, safe, economic, efficient, environmentally friendly and safe use of the target. The development of smart power grid makes the power consumption side more and more controllable. Lays the foundation for large-scale access to renewable energy. The control and optimization of power consumption side will be the key technology of smart power grid development in the future.

In China, an important factor contributing to the current power supply crunch is the rapid increase in building energy consumption. Air conditioning energy consumption accounts for the majority of building energy consumption, and it’s growing rapidly. If the peak power consumption caused by air conditioning can be adjusted effectively, China’s power investment will be reduced effectively and good benefits will be achieved.

Great progress has been made in the control and optimization of air conditioners in recent 10 years. Coordinated control among variable frequency air conditioner and constant frequency air conditioner has been designed in [4] for primary frequency control and secondary frequency control. Considering the market environment, a novel bilayer interaction strategy to solve the problem of air conditioning aggregators participating in demand response [5]; A fuzzy logic and neural networks control is designed...
The general air-conditioning system is limited by the user experience and the adjustment ability is limited. Air conditioning ice storage technology, in the day when the power load is high, that is, the peak period of power consumption, makes the cold storage medium melt ice, and releases the stored cold quantity, so as to meet the requirements of building air conditioning or production process. Force shifting peak load and valley load balancing power load, strengthening the Management of Demand Side Management of power grid. As a result of the transfer of the refrigerating unit power consumption time, the role of the transfer of peak power load. The refrigerating unit is operated during the off-peak period of power at night to store the cooling capacity. During the peak period of power consumption during the day, the refrigerating unit is used to supply all or part of the air-conditioning load with the stored cooling capacity, and the refrigerating machine is not turned on or not turned on. It has an obvious "peak shifting and valley filling" effect on urban power grid and remarkable social benefits. Model-free adaptive dynamic programming [8] is proposed to solve the optimal regulation of ice-storage air conditioning systems. Optimal control was applied to minimize the cooling cost of air conditioning system with ice storage tank in [9]. Reference [10] introduces the concept and development status of ice storage air conditioning. Particle swarm optimization (PSO) is used to solve the problem of minimum cost operation of ice storage air conditioning [11]. In [12], the authors studied the optimization problem of ice storage air conditioning aiming at the maximum utilization efficiency and circulation cost of ice storage tank. The above-mentioned work [5-9] on ice storage air-conditioning system assumes that there is only one ice storage tank in the system. The current work does not consider the cold loss of the ice storage tank, and the cost of using the ice storage tank cannot be accurately described.

In this paper, we consider using ice storage tanks to smooth the energy usage of air conditioning systems. A mathematical model of quadratic programming is established to characterize the tradeoff between the lowest energy storage cost and smoothness. Numerical examples are given to analyze the relationship between ice storage cost and peak filling effect.

2. Problem Formation and Optimal Method

Consider an air-condition system with ice-storage, the ice-storage tank can be modelled by the following discrete-time system:

\[ S(k+1) = S(k) + T_o p(k) - T_o \varepsilon S(k) \]  \tag{1}

where \( k = 1, 2, \ldots \), \( S(k) \) denotes the quantity of residual cooling at time \( k \), \( T_o \) is control period, and \( p(k) \) denotes the charge or discharge rate of the cooling, i.e., \( p(k) > 0 \) means storing cooling, \( p(k) < 0 \) means releasing cooling and \( p(k) = 0 \) means the cold storage tank is idle. \( p(k) \) constraints by

\[ p_{\min} \leq p(k) \leq p_{\max} \]  \tag{2}

where \( p_{\max}(k) \) and \( p_{\min}(k) \) are the maximum and minimum cold storage rate. \( S(k) \) constraints by

\[ S_{\min} \leq S(k) \leq S_{\max}. \]  \tag{3}

\( Tp(k) \) is the amount of ice stored at the \( k \)-th time slice, \( T \varepsilon S(k) \) is the cooling loss at the \( k \)-th time slice. The cooling demand of the building is expressed in terms of \( L(k) \). In practice, the cooling demand is a predicted sequence. Hence, we assume that \( L(k) \) is already known. The power consumption of the air-condition system denotes by

\[ D(k) = L(k) + p(k). \]  \tag{3}

The objective of this paper is smoothing of power consumption, i.e.,
\[
\min_{P(k)} \sum_{t=1}^{T} \left[ D(k) - \frac{1}{T} \sum_{t=1}^{T} D(k) \right]^2 + \kappa \sum_{t=1}^{M} T_0 \varepsilon S(k),
\]

where \( T \in \mathbb{N} \), and \( \mathbb{N} \) is the set of positive integers. The proposed smooth problem will regard the storage/release cooling of ice-storage tank as the inputs to the model of air condition system with ice-storage tank and minimize the combination of variance of power consumption and the cost of storage/release cooling over future T-period, which is formulated as

\[
\min_{P(k)} \sum_{k=1}^{T} \left[ D(k) - \frac{1}{T} \sum_{k=1}^{T} D(k) \right]^2 + \kappa \sum_{t=1}^{M} T_0 \varepsilon S(k),
\]

s.t.
\[
D(k) = L(k) + p(k)
\]
\[
S(k+1) = S(k) + T_0 p(k) - T_0 \varepsilon S(k)
\]
\[
p_{\min} \leq p(k) \leq p_{\max}
\]
\[
S_{\min} \leq S(k) \leq S_{\max}
\]

Remark 1. The above model is a standard quadratic programming model, and there have been many mature methods to solve this problem. Note that

\[
\left\| D(k) - \frac{1}{T} \sum_{t=1}^{T} D(k) \right\|^2 = \left[ D(k) - \frac{1}{T} \sum_{t=1}^{T} D(k) \right] \left[ I - \frac{1}{T} \mathbf{1}^T \right] \left[ I - \frac{1}{T} \mathbf{1} \right] D
\]

and

\[
\kappa \sum_{t=1}^{M} T_0 \varepsilon S(k) = \kappa \mathbf{1}^T \mathbf{1} S
\]

where \( \mathbf{1} = (1,1,\ldots,1)^T \), \( D = (D_1(k), D_2(k), \ldots, D_T(k))^T \), and \( S = (S_1(k), S_2(k), \ldots, S_T(k))^T \).

3. Simulation Examples

The proposed smooth problem of air conditioning system with ice-storage tank is verified in a simulation example in this section. The cooling demand is given in Figure 1, which is dramatic. The ice storage rate is constrained in \([-40, 60]\) kW, i.e., \( p_{\min} = -40 \), and \( p_{\max} = 60 \). Set \( T_0 = 60(s) \), and \( T = 60 \). The capacity of ice-storage tanks is [0,50].
Figure 1. The predict cooling demand.

Case 1: \( \kappa_i = 20 \). The control effect is shown in Figure 2 and Figure 3.

Figure 2. Energy consumption of an air-conditioning system when \( \kappa_i = 20 \).

Figure 3. Variation of ice storage capacity in ice storage tanks when \( \kappa_i = 20 \).

Case 2: \( \kappa_i = 5 \). The control effect is shown in Figure 4 and Figure 5.
Figure 4. Energy consumption of an air-conditioning system when $\kappa_1 = 5$.

Figure 5. Variation of ice storage capacity in ice storage tanks when $\kappa_1 = 5$.

Case 3: $\kappa_1 = 0.5$. The control effect is shown in Figure 6 and Figure 7.

Figure 6. Energy consumption of an air-conditioning system when $\kappa_1 = 0.5$. 
Figure 7. Variation of ice storage capacity in ice storage tanks when $\kappa_1 = 0.5$.

From these simulations, it can be seen that if the cost of ice storage is very low, the power consumption of air-conditioning system can be almost levelled off.

4. Conclusion
We make use of ice storage tank to smooth the air conditioning load as far as possible so as to achieve the purpose of peak filling. A mathematical model of quadratic programming is established to characterize the trade-off between the lowest energy storage cost and smoothness. Numerical examples are given to analyse the relationship between ice storage cost and peak filling effect.

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