IOP Conf. Series: Materials Science and Engineering **199** (2017) 012093 doi:10.1088/1757-899X/199/1/012093

Bi-level Optimization Method of Air-conditioning System Based on Office Building Energy Storage Characteristics

Qingze WANG[1], Xingying CHEN[1,2, a], Li JI[1,2], Yingchen LIAO[1,2] and Kun YU[1,3]

[1]College of Energy and Electrical Engineering, Hohai University, Nanjing 211100, China
[2]Jiangsu Engineering Research Center for Distribution & Utilization and Energy Efficiency, Nanjing 211100, China
[3]Nanjing Hehai Science and Technology Ltd, Nanjing 210098, China

[a]Corresponding author : xychen@hhu.edu.cn

Abstract. The air-conditioning system of office building is a large power consumption terminal equipment, whose unreasonable operation mode leads to low energy efficiency. Realizing the optimization of the air-conditioning system has become one of the important research contents of the electric power demand response. In this paper, in order to save electricity cost and improve energy efficiency, bi-level optimization method of air-conditioning system based on TOU price is put forward by using the energy storage characteristics of the office building itself. In the upper level, the operation mode of the air-conditioning system is optimized in order to minimize the uses' electricity cost in the premise of ensuring user' comfort according to the information of outdoor temperature and TOU price, and the cooling load of the air-conditioning is output to the lower level; In the lower level, the distribution mode of cooling load among the multi chillers is optimized in order to maximize the energy efficiency according to the characteristics of each chiller. Finally, the experimental results under different modes demonstrate that the strategy can improve the energy efficiency of chillers and save the electricity cost for users.

1. Introduction

With the development of economy, the number of office buildings in city is increasing, while the air-conditioning system is the highest energy consumer in a building. Air-conditioning load has accounted for 30%~50% of the summer peak load in some large and medium-sized cities[1]. The water cooled central air-conditioning system is usually used in office building, which has good cooling effect, and is mainly consist of cooling tower, chillers, air treatment unit, air supply pipe et al.[2]. Among them, the power consumption proportion of chillers is the biggest, which can reach more than 80% of the air-conditioning system[3]. There are two main reasons for the high power consumption of the current office building air-conditioning system: 1) The unreasonable setting temperature; 2) The unreasonable load rate distribution among the multi chillers[4][5]. Therefore, to improve energy efficiency of air-conditioning system and save the electricity cost for users, how to take co-optimization between the setting temperature and load rate distribution, has important significance.

Air-conditioning load belongs to a temperature control load (TCL), with the energy conversion and storage characteristics[6]. Many scholars have carried on related researches on the optimization of air-conditioning system. The research in [7] measured and analyzed the effect of pre-cooling and indoor temperature resetting strategy applied to a medium density office and found the power load of air-conditioning decreased a lot without causing people's discomfort. The research in [8] analyzed the effect of the demand response control strategy on the whole building energy consumption, and the results showed that the pre-cooling strategy can reduce by 10~20% of the overall cost. The research in [9] made a research on shifting strategy of air-conditioning by using actual measurement and fast evaluation software for demand response and the results showed that the pre-cooling strategies of index-type and step-type are more effective. These researches are mainly based on the actual measurement and building energy consumption software, which lack of air-conditioning system energy consumption model and neglect the performance differences of chillers to optimize the cooling load distribution.

TOU price, as an important measure of demand response, has been gradually popularized and promoted. The air-conditioning system controller with the function of advanced computing capability is proposed in [10], which can provide the best ratio of comfort / cost and reduce the energy consumption. In[11]， according to the predicted value of the outdoor temperature and the electricity price signals to control the air-conditioning system, the multi-objective optimization method is offered in this paper.

Based on the above considerations, the office building is used as energy storage device in this paper. The bi-level optimization method of central air-conditioning system is put forward considering TOU price. In the upper level model, to minimize the cost of office building, the pre-cooling time and setting temperature of air-conditioning system is optimized. In the lower level model, the load rate of each chiller is optimized to maximize the COP (Coefficient of Performance). At last, the case verifies the effectiveness of the proposed strategy.

2. Energy consumption model of air-conditioning system

2.1. Cooling load calculation of office building

In this paper, the heat balance method is used to establish the energy consumption model of air-conditioning system to describe the relationship between air-conditioning cooling load and indoor temperature, outdoor temperature[12].

$$q_{sys} + Ah_i(T_{io} - T_i) + mC_p(T_o^{'} - T_i) + E = 0 \tag{1}$$

$$MC_m \frac{\partial T_{io}}{\partial t} + Ah_o(T_{io} - T_o) + Ah_i(T_{io} - T_i) = 0 \tag{2}$$

Where, q_{sys} is the cooling load sent to the indoor by air-conditioning in order to counteract the heat; $Ah_i(T_{io} - T_i)$ is convection heat from the external heat storage material to the indoor air, where A is the area of the surface of the external heat storage material, h_i is the convection coefficient between external heat storage material and indoor air, T_i is temperature of indoor air and T_{io} is temperature of external heat storage material. $mC_p(T_o - T_i)$ is the heat that infiltrates into the indoor through the door, cracks etc. Where $m = al\Delta P^{1/n}$, ΔP is pressure difference inside and outside the envelope, n is air-tightness coefficient, associated with the degree of tightness doors and windows and is between 1 and 2. The good air-tightness is close to 2, the worse air-tightness is close to 1. l is the gap length of doors and windows. a is leakage coefficient of unit length gap. C_p is the specific heat ratio of the air . E is the total heat generated by the internal heat source of the building, which is assumed to be a constant. $MC_m \frac{\partial T_{io}}{\partial t}$ is the heat change caused by temperature change of external heat storage material, where M is quality of external heat storage material, and C_m is specific heat ratio of external heat storage material; $Ah_o(T_{io} - T_i)$ is convection heat from external heat storage material to the outdoor air, where h_o is the convection coefficient between external heat storage material and outdoor air, and T_o is outdoor temperature.

From the research, the trigonometric function curve can be fitted well by the outdoor temperature variation, supposed that the outdoor temperature is $T_o = T_o^{'} + \Delta T_o^{'} \sin(\omega t + \varphi)$. The temperature change of the heat storage material and the change of the cooling load is shown as (3) and (4), respectively.

$$T_{io}(\omega t)_1 = \frac{\lambda_o}{\lambda_i + \lambda_o} T_o^{'} + \frac{\lambda_o}{\lambda_i + \lambda_o} T_i + \frac{\lambda_o \Delta T_o^{'}}{\sqrt{(\lambda_i + \lambda_o)^2 + \omega^2 \tau^2}} \sin(\omega t + \varphi - \beta_1) + C_1 e^{\frac{-(\lambda_i + \lambda_o)\omega t}{\omega \tau}} \tag{3}$$

$$\begin{aligned} q_{sys}(\omega t)_1 = -\rho C_P q_v \{ & \frac{E}{\rho C_P q_v} + \frac{m C_p (T_o^{'} - T_i)}{\rho C_P q_v} + \frac{\lambda_i \lambda_o}{\lambda_i + \lambda_o} (T_o^{'} - T_i) + \frac{\lambda_i \lambda_o}{\sqrt{(\lambda_i + \lambda_o)^2 + \omega^2 \tau^2}} \\ & \cdot \Delta T_o^{'} \sin(\omega t + \varphi - \beta_1) + C_1 \lambda_i e^{\frac{-(\lambda_i + \lambda_o)\omega t}{\omega \tau}} \} \end{aligned} \tag{4}$$

Where, C_1 is constant; $\beta_1 = \tan^{-1}(\omega\tau / (\lambda_o + \lambda_i))$, whose value is from 0 to $\pi / 2$; $\omega = 2\pi / 24h$; $\tau = MC_m / \rho C_p q_v$ is time constant based on ventilation rate during the night, where ρ is air density; $\lambda_o = h_o A / \rho C_p q_v$ is the coefficient of convective heat transfer between heat storage material and outdoor air; $\lambda_i = h_i A / \rho C_p q_v$ is the coefficient of convective heat transfer between heat storage material and indoor air.

The pre-cooling period is $t_p \sim t_1$, the internal heat gain is 0, where there is air infiltration, and the cooling load is obtained from the heat balance equation:

$$\begin{aligned} q_{sys}(\omega t)_2 = -\rho C_P q_v \{ & \frac{m C_p (T_o^{'} - T_i)}{\rho C_P q_v} + \frac{\lambda_i \lambda_o}{\lambda_i + \lambda_o} (T_o^{'} - T_i) + \frac{\lambda_i \lambda_o}{\sqrt{(\lambda_i + \lambda_o)^2 + \omega^2 \tau^2}} \\ & \cdot \Delta T_o^{'} \sin(\omega t + \varphi - \beta_1) + C_1 \lambda_i e^{\frac{-(\lambda_i + \lambda_o)\omega t}{\omega \tau}} \} \end{aligned} \tag{5}$$

During $t_2 \sim t_p + 24$, the internal heat gain is 0, air-conditioning system is off, ventilation rate of ventilation system is q_v , as a constant, and air infiltration heat can be neglected. The wall temperature can be got from the heat balance equation, as (6):

$$T_{io}(\omega t)_2 = \frac{1 + \lambda_o}{\lambda_o} T_o^{'} - \frac{1}{\lambda_o} T_i + \frac{(1 + \lambda_o) \Delta T_o^{'}}{\sqrt{\lambda_o^2 + \omega^2 \tau^2}} \sin(\omega t + \varphi - \beta_2) + C_2 e^{\frac{-\lambda_o \omega t}{\omega \tau}} \tag{6}$$

2.2. Power calculation of air-conditioning system

In order to ensure the cooling capacity of the air-conditioning system, office buildings are usually equipped with multiple chillers. Suppose that the number of chillers is n , cooling capacity of central air-conditioning can be calculated as follows:

$$L_{cool}(t) = \sum_{i=1}^{n} COP_i(t) \alpha_i(t) P_{N,i} \tag{7}$$

Where, $\alpha_i(t)$ is the load rate of the i_{th} chiller at time t ; $P_{N,i}$ is rated power of the i_{th} chiller; COP reflects the operation condition of chillers, and is the important index of energy efficiency of air-condoning. The relationship between COP and load rate is:

$$COP_i(t) = a_i + b_i \alpha_i(t) + c_i [\alpha_i(t)]^2 \tag{8}$$

Where, a_i , b_i and c_i are coefficient, which is related to the characteristics of chiller.

During the working time, the formula (9) can be established from the heat balance equation.

$$q_{sys}(t) = \gamma L_{cool}(t) \tag{9}$$

Where, γ is dissipation factor, generally 0.8~0.9, and 0.8 is taken in this paper.

Formula (10) can be obtained from the formula(7), (8)and(9).

$$q_{sys}(t) = \gamma \sum_{i=1}^{n} (a_i \alpha_i(t) + b_i[\alpha_i(t)]^2 + c_i[\alpha_i(t)]^3) P_{N,i} \tag{10}$$

Power consumption of air-conditioning system can be obtained from formula(10).

$$P_{air}(t) = \sum_{i=1}^{n} \alpha_i(t) P_{N,i} \tag{11}$$

2.3. Calculation of thermal comfort

In this paper, the PMV-PPD index in ISO 7730 is used to describe and evaluate the thermal comfort of human. The PMV index is divided into seven levels. The relationship between temperature sense and PMV index is as shown in Table1.

Table 1. The relationship between temperature sense and PMV index

temperature sense	hot	warm	slightly warm	neutral	slightly cool	cool	cold
PMV index	+3	+2	+1	0	-1	-2	-3

In China, the range of PMV is -1≤PMV≤+1 according to design conditions of air-conditioning system in <Standard for design of heating ventilation and air-conditioning> (GB 50019-2003). The calculation of PMV is very complex. To simplify the calculation, the PMV value is calculated by the dimensionless index of evaluating thermal environment proposed in [13].

$$PMV = 0.13(1 + K_1)T_i + 0.13K_2T_{io} - 5.97 \tag{12}$$

$$K_1 = \sum_{j=1}^{5} A_j \Big/ \sum_{j=0}^{5} A_j \tag{13}$$

$$K_2 = A_o \Big/ \sum_{j=0}^{5} A_j \tag{14}$$

Where, A_j is the area of j_{th} surface of the room.

3. Bi-level optimization model of air-conditioning system

3.1. Bi-level optimization model

The Bi-level optimization model of air-conditioning system is as shown in Figure 1.In the upper level model, the building is used as energy storage device. And during the period of low price, air-conditioning can pre-cool thermal mass, while during the period of high price, the cold can be released to room to reduce the cooling load of air-conditioning system considering the TOU price.

In the lower level model, the distribution mode of cooling load among the multi chillers is optimized in order to maximize the energy efficiency according to the characteristics of each chiller.

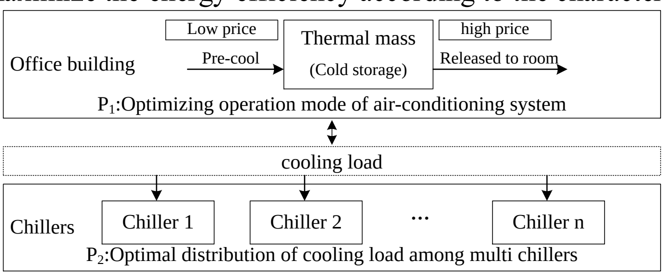

Figure 1. The Bi-level optimization model of air-conditioning system

3.2. Upper level optimization model

3.2.1. Objective function. To save electricity cost, the air-conditioning system should adjust the setting temperature value dynamically according to the change of outer temperature to ensure the users' comfort. So the electricity cost and users' thermal comfort should be considered in the objective function.

$$\min f = \min \sum_{t=t_p}^{t=t_2} \omega p(t) P_{air}^{*}(t) + (1-\omega) PMV^{*}(t) \tag{15}$$

$$P_{air}^{*}(t) = P_{air}(t) / P_{air,B} \tag{16}$$

$$PMV^{*}(\mathrm{t}) = PMV(t) / PMV_{B} \tag{17}$$

Where, ω is the weight coefficient of electricity cost and thermal comfort; $P_{air,B}$ is reference power of air-conditioning system; PMV_B is reference value of thermal comfort; And the reference value is determined in the case of indoor temperature and heat storage material temperature of 26℃.

3.2.2. Constraints. 1) PMV should meet the requirement of standard.

$$-1 \le PMV \le +1 \tag{18}$$

2) Setting temperature of air-conditioning system

$$T_{\min} \le T_{in} \le \mathrm{T}_{\max} \tag{19}$$

Where, $T_{\min}$, $T_{\max}$ are the lower and upper limit of setting temperature, respectively.

3) Electric power for air-conditioning system

$$0 \le P(t) \le P_{\max} \tag{20}$$

Where, $P_{\max}$ is the allowable maximum electric energy consumption of air-conditioning system.

3.3. Lower level optimization model

3.3.1. Objective function. The goal of the lower level model is to make the overall energy efficiency of all chillers highest, so the objective function is:

$$\max \sum_{\mathrm{i}=1}^{n} COP_i(t) \tag{21}$$

Where, n is the number of the chillers.

3.3.2. Constraints. Suppose that the expected load rate of i_{th} chiller is $\alpha_i^e(t)$ at t moment and the expected optimization is η_i^e .The relationship between them is:

$$\eta_i^e(\mathrm{t}) \times W_i^a(t) = \left[\alpha_i(t) - \alpha_i^e(t)\right] W_i^f \tag{22}$$

The expected optimization capacity of each chiller is:

$$W_i(t) = \eta_i^e(t) \times W_i^a(t) \tag{23}$$

1) The expected optimization needs to meet the requirements of the target optimization:

$$\sum_{i=1}^{n} W_i(t) = q_{sys}(t) \tag{24}$$

Where, $q_{sys}(t)$ is the objective optimization capacity at t moment obtained from the upper level.

2) Load rate constraints of chiller

The expected load rate $\alpha_i^e(t)$ of i_{th} chiller can't be lower than the lowest limit of load rate:

$$\alpha_i^0 \le \alpha_i^e(t) \le 1 \tag{25}$$

4. Case study

4.1. Basic information

4.1.1. Building information. The office building locates in Nanjing, China. The building area is 17280m^2, building size is 48m×30m×36m, the thickness of wall is 240mm, the density is 2600kg/m^3, specific heat is 0.96kJ/(kg·K), the convection heat transfer coefficient from external wall to external air in summer is h_o=4.74W/(m^2·K) and the convection heat transfer coefficient to internal air is h_i =2.46W/(m^2·K).The size of the room is 8m×6m×3m, the ventilation rate during night is q_v=450m^3/h and the internal heat gain is E =500W. ΔP is 6.42kg/m^2, n is 1 and l is 2m.The air density is 1.29kg/m^3 and specific heat is 1.005kJ/ (kg·K).

4.1.2. The central air-conditioning system information. The building is equipped with water cooled central air-conditioning, with 3 chillers that has the same rated capacity but different COP curve. The rated capacity is 400kW, and load rate lower limit is 60%. The COP function respectively is:

$$\begin{aligned} COP_1 &= -7.9457a_1^2 + 13.9097a_1 - 0.8151 \\ COP_2 &= -8.1547a_2^2 + 14.6922a_2 - 1.5475 \\ COP_3 &= -5.7545a_3^2 + 9.7558a_3 + 1.1975 \end{aligned} \tag{26}$$

4.1.3. Weather information. The outdoor temperature is fitted by the sine function and the fluctuation is $\triangle T_o^{'} = 3.85$℃ , the average *is* $T_o^{'} = 31.08$℃ and $T_o = 31.08 + 3.85\sin\left(\pi \cdot (t-10)/12\right)$ .The curve of outdoor temperature is as shown in Figure 2.

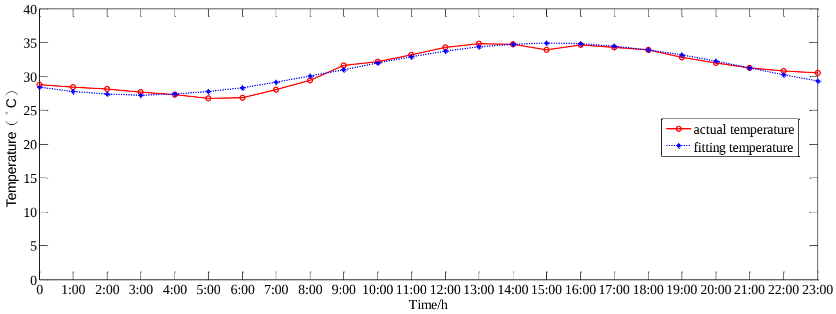

Figure 2. The curve of outdoor temperature

4.1.4. Electricity price information. The TOU price information is as shown in Table 2.

Table 2. The TOU price

period	price/（yuan/kWh）
Valley period（21:00-8:00 the next day）	0.6
Peak period（8:00-21:00）	1.2

4.2. Result analysis

The weight coefficient of electricity cost and thermal comfort is 0.5. The PSO algorithm is used to solve bi-level optimization model and taking the randomness of the PSO algorithm into account, the average value of the 10 calculation results is as the final solution. The following will be analysed from three aspects of electricity cost, thermal comfort, energy efficiency.

IOP Conf. Series: Materials Science and Engineering **199** (2017) 012093 doi:10.1088/1757-899X/199/1/012093

4.2.1. The analysis of electricity cost. In order to explain the effect of pre-cooling strategy under TOU price, the results of the constant temperature mode and the mode without pre-cooling strategy, are compared, as shown in Table 3.

Table 3. Simulation results under different operation modes

The different operation modes	electricity cost(yuan)	PMV
The mode of constant temperature	6141.6	0.8124
The mode without pre-cooling strategy	5662.8	0.9136
The mode with pre-cooling strategy	5583.6	0.9152

It can be known from Table 3 that the electricity cost is the highest but thermal comfort is the best when air-conditioning operates in the mode of constant temperature. Compared with the constant temperature mode, the optimization of setting temperature in the mode without pre-cooling strategy makes the electricity cost decreased by 7.79%. The user's thermal comfort index has been reduced, but did not affect the users' thermal comfort.

Compared with the mode of constant temperature and the mode without pre-cooling strategy, the mode with pre-cooling strategy makes the electricity cost decreased by 9.08% and 1.39%, respectively. The reason is that the TOU price and building storage characteristics are considered in the mode with pre-cooling strategy. Thermal mass is pre-cooled during period of the low price and the cold is stored in the thermal mass in advance; while during period of the high price, the cold stored in the thermal mass is released to the room, thereby reducing the power consumption of the air-conditioning system.

4.2.2. The analysis of thermal comfort. The setting temperature and PMV is as shown in Figure 3 in the different modes.

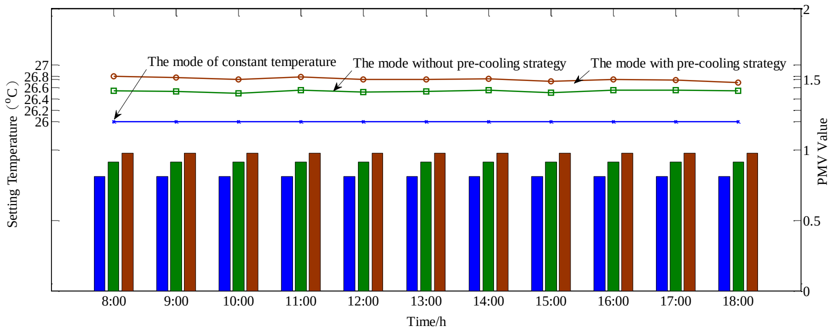

Figure 3. The setting temperature and PMV in different operation modes

It can be known from Figure 3 that the setting temperature is basically floating up and down at 26.5 ℃ in the mode without pre-cooling strategy, while the setting temperature is floating up and down at 26.7℃. Although the setting temperature turn up, but the PMV index is still within the scope of the provisions, which will not cause the body uncomfortable. The pre-cooling strategy makes the setting temperature turn up, because the air-conditioning system pre-cooled the thermal mass during the period of low price and the cold will be released into room so as to reduce the cooling load of air-conditioning system during the working period. In addition, the PMV curve of three operation modes are relatively stable, which demonstrates that the indoor staff do not feel sometimes hot and sometimes cold. Although the optimization strategy reduces the PMV index slightly, the optimized setting temperature is still able to meet the thermal comfort requirements.

4.2.3. The analysis of energy efficiency. The expected load rate of every chiller and the overall COP by solving the bi-level optimization model, are shown in Table 4.

Table 4. The relationship between temperature sense and PMV index

Time	Load rate			Overall COP
	Chiller 1	Chiller 2	Chiller 3	

IOP Conf. Series: Materials Science and Engineering **199** (2017) 012093 doi:10.1088/1757-899X/199/1/012093

8:00	0.70	0.73	0.60	14.8398
9:00	0.73	0.75	0.64	15.0735
10:00	0.77	0.80	0.71	15.3949
11:00	0.81	0.84	0.76	15.5667
12:00	0.83	0.86	0.79	15.6259
13:00	0.86	0.88	0.82	15.6652
14:00	0.88	0.91	0.86	15.6732
15:00	0.89	0.91	0.87	15.6697
16:00	0.86	0.89	0.83	15.6704
17:00	0.85	0.88	0.82	15.6619
18:00	0.72	0.75	0.64	15.0496

It can be known from Table 4 that load rates from high to low are chiller 2, chiller 1, chiller 3, and the distribution of load is according to the degree of new or old. The load rate of relatively old chiller 3 is always lower than that of the chiller 1 and chiller 2. The relatively new chillers take more load, which makes the overall COP maximum and improves the energy efficiency of air-condoning system.

5. Conclusion

Air-conditioning system, as one of the largest power consumption of office buildings, is one of the important means to achieve the demand response of office building users based on the TOU price. The bi-level optimization method put forward in this paper considers outdoor temperature, price information, users' comfort and the performance of chillers, and takes to minimize users' electricity cost and maximize the COP of chillers for the target. Compared with the constant temperature control, the results show that the proposed method can effectively improve the efficiency of chillers and reduce the users' electricity cost.

Acknowledgement

This work is supported by the National Natural Science Foundation of China (No. 51577051), State Grid Corporation of China (key technology research and application for dynamic optimization of public buildings' electricity consumption pattern) and National Development and Reform Commission (the research, development and industrialization for integrated management of smart distribution grid & utilization and enhancing energy efficiency technology based on internet of things).

References

[1] The building energy-saving Center of Tsinghua University. Annual research report on the development of building energy saving in China 2013[M]. Beijing: China architecture and building press, 2013.
[2] LI Canbing, SHANG Jincheng, ZHU Shouzhen, et al. An analysis of energy consumption caused by air temperature-affected accumulative effect of the air-conditioning load [J], Automation of Electric Power Systems, 2010, 34(20):30-33.
[3] SONG Hongkun, TANG Guoqing, LU Yi, et al. Summer air-conditioning load analysis and demand side management measures in Jiangsu province [J]. Power System Technology, 2006, 30 (17): 88-91.
[4] Yordanova S, Merazchiev D, Jain L. A Two-Variable Fuzzy Control Design With Application to an Air-Conditioning System[J]. IEEE Transactions on Fuzzy Systems, 2015, 23(2):474-481.
[5] SUN Xiaoyu, LI Rui. Simulation and analysis of joint operation strategy of chiller [J]. Building Energy Efficiency, 2015 (4): 37-41.
[6] ZHOU Lei, LI Yang, GAO Ciwei. Air-conditioning load polymerization temperature control method and improved control strategy of [J], Proceedings of the CSEE, 2014, 31: 16.
[7] Xu P, Haves P, Piette M A, et al. Peak demand reduction from pre-cooling with zone temperature reset in an office building[J]. Lawrence Berkeley National Laboratory, 2004.
[8] Morgan S, Krarti M. Impact of electricity rate structures on energy cost savings of pre-cooling

IOP Conf. Series: Materials Science and Engineering **199** (2017) 012093 doi:10.1088/1757-899X/199/1/012093

controls for office buildings[J]. Building and environment, 2007, 42(8): 2810-2818.
[9] YIN Rongxin. California hot climates peak strategies of large commercial buildings [D]. Tongji University, a master's degree thesis, 2009.
[10] Thomas A G, Jahangiri P, Wu D, et al. Intelligent Residential Air-Conditioning System With Smart-Grid Functionality[J]. IEEE Transactions on Smart Grid, 2012, 3(4):2240-2251.
[11] ZHANG Yanyu, CENG Peng, LI Zhongwen, et al. Multi objective optimization control algorithm for air conditioning system in smart grid environment [J]. Power System Technology, 2014, 38 (7): 1819-1826.
[12] Thomas A G, Jahangiri P, Wu D, et al. Intelligent Residential Air-Conditioning System With Smart-Grid Functionality[J]. IEEE Transactions on Smart Grid, 2012, 3(4):2240-2251.
[13] YE Hai, WEI Runbo. A simple method for objective evaluation of the thermal environment [J]. Ergonomics, 2004, 10 (3):16-19.