PAPER • OPEN ACCESS

Research on Scheduling Model and Control Strategy of Ice Storage Air Conditioning in Urban Power Grid

View the article online for updates and enhancements.

Research on Scheduling Model and Control Strategy of Ice Storage Air Conditioning in Urban Power Grid

Liming Meng[1], Lei Chen[1], Tuo Jiang[1], Fei Xu[1], Xingchen Yao[1], Ling Hao[2], Shuai Yang[3]

[1]Dept.of Electrical Engineering, Tsinghua University, Beijing, China

[2]School of Mechanical and Vehicle Engineering, Beijing Institute of Technology, Beijing, China

[3]State Grid Anhui Maintenance Company, China

Corresponding author: Meng Liming (1992), male, graduate, research direction for the integrated electric energy systems,

E-mail: mlm16@mails.tsinghua.edu.cn.

Abstract. In this paper, a two-layer scheduling model for ice storage central air conditioning is established: the system level optimization control of the upper layer and the energy management system of the lower massive decentralized air conditioning system. The system level consists of thermal power, hydropower, wind turbines and ice storage air conditioning polymerization models, with the goal of minimizing the abandonment of wind and water, generating the scheduling results of generator set and ice storage air conditioning, and delivering them to the lower energy management system; After receiving the scheduling result issued by the upper layer, the large-scale ice storage air-conditioning is dispatched by the load aggregator, and the minimum scheduling deviation is targeted, and the direct load control is performed under the condition that the user comfort is satisfied to complete the upper-level scheduling plan. Through simulation examples, it is proved that the ice storage air-conditioning realizes the effectiveness of the disposal of abandoned water and abandoned wind under the premise of ensuring user comfort.

1. Introduction

The demand for electricity in Chongqing's power grid and the proportion of power supply to the grid are increasing, which is the main factor for the seasonal supply and demand balance of power grid load. At the same time, the peak and valley of electricity consumption for air conditioning loads are synchronized with the peak of power supply and the valley of power supply, which further increases the peak-to-valley difference of the power grid. At the same time, there are many rivers in Chongqing with abundant traffic and large water resources. However, due to the small electricity load during the low valley period, the contradiction of water abandonment is prominent. By optimizing the dispatching, the contradiction between the abandoned water and the abandoned wind can be alleviated to some extent, but there is no practical method for real-time dispatching of the power grid specifically for the abandoned water and abandoned wind consumption service.

This paper proposes waste water and wind abandonment dispatching method based on ice storage air-conditioning system, with the minimum dispatch deviation and minimum abandoned water and wind as the optimization target, to realize the abandoned water and wind abandonment. The model

considers system power balance, line transmission capacity, power system tidal current distribution and power system up and down rotation standby to build power system operation constraints; It also considers thermal power unit operating characteristics, hydropower unit operating characteristics, wind turbine operating characteristics to construct power system unit characteristics constraints, the thermal coupling of the ice storage device, the heat balance, the capacity of the cold storage system and other factors constitute the operation constraints of the ice storage system; Besides, it also includes the thermal equivalent model of the building and other thermal structural constraints. Through comprehensive and detailed modeling of the power system containing the ice storage device, the the ability to reduce the abandoned water and wind can be maximized.

2. System level optimization control
Because the massively distributed ice storage air conditioning is difficult to directly participate in the generator set dispatching with the unit, the massive ice storage air conditioning is concentrated, and a large volume ice storage air conditioning polymerization model is used instead of the mass ice storage air conditioning to participate in the scheduling. The parameters come from the parameters and operating status of the massively dispersed ice storage air conditioner.

2.1. Operating characteristics

$$W_{t+1} = s * W_t + Q_{x,t} * \Delta t - Q_{r,t} * \Delta t \tag{1}$$

Where W_t is the hourly cooling capacity of the cold storage equipment; s is the hourly cooling loss coefficient of the cold storage equipment.

2.2. Cold storage constraint
The following analysis of ice storage air conditioning is based on the comfort of the user.
   (1) Cool storage period
   Time-dependent cold storage constraint:

$$0 \le Q_{x,t} \le Q_{x,t}^{\max} \tag{2}$$

Cooling upper limit constraint:

$$W_r \le W^{\max} \tag{3}$$

   (2) Cooling time:

$$0 \le Q_{j,t} \le Q_j^{\max} \tag{4}$$

$$0 \le Q_{r,t} \le Q_r^{\max} \tag{5}$$

$$Q_{j,t} + Q_{r,t} = Q_{k,t} \tag{6}$$

   Although a single ice storage air conditioner generally cannot simultaneously produce ice and carry out unit refrigeration, for a large number of ice storage air conditioners, air conditioning for unit refrigeration and produce ice are often present at the same time, so the polymerization air conditioning model can be regarded as being capable of simultaneous cooling and ice storage.

3. Wind power and hydropower consumption regulation model

3.1. Objective function：

$$\min \Delta Q = \sum_{j=1}^{N_h} |(Q_{\max,j} - \sum_{t=1}^{T} Q_{jt}\Delta t)| + \sum_t |P_{w,f,t} - \sum_{k=1}^{N_W} P_{w,k,t}| \tag{7}$$

3.2. Restrictions
(1)   Power balance constraint:

$$\sum_{i=1}^{N_t} P_{G,i,t} + \sum_{j=1}^{N_h} P_{h,j,t} + \sum_{k=1}^{N_w} P_{w,k,t} = P_{D,t} \tag{8}$$

$P_{G,i,t}$ for the thermal power unit output; $P_{h,j,t}$ for the hydropower unit output; $P_{w,k,t}$ for the wind farm output; $P_{D,t}$ for the ice storage system electrical load. The network loss and network restrictions are not considered, and the system is capable of accepting a certain proportion of wind power to enter the network in full.

(2) System backup constraint

$$\sum_{i=1}^{N_t} (P_{G,i,\max} - P_{G,i,t}) + \sum_{j=1}^{N_h} (P_{h,\max,j} - P_{h,j,t}) \geq k_d P_{D,t} + k_w \sum_{k=1}^{N_w} P_{w,k,t} \tag{9}$$

$P_{G,i,\max}$ is the maximum output power of the thermal power unit; $P_{h,\max,j}$ is the maximum output power of the hydropower unit; k_d、 k_w is the load fluctuation coefficient and the wind power fluctuation coefficient.

(3) Thermal power output upper and lower limits

$$P_{G,i,\min} \leq P_{G,i,t} \leq P_{G,i,\max} \tag{10}$$

(4) Thermal power output climbing constraint

$$-r_{di}\Delta t \leq P_{G,i,t} - P_{G,i,t-1} \leq r_{ui}\Delta t \tag{11}$$

(5) Hydropower generation capacity constraint

$$P_{h,\min,j} \leq P_{h,j,t} \leq P_{h,\max,j} \tag{12}$$

(6) Hydropower conversion relationship

$$P_{h,j,t} = A\eta_j Q_{jt} h_{jt} \tag{13}$$

A is the hydroelectric conversion constant; η_j is the hydropower station efficiency; h_{jt} is the reservoir head height.

(7) Daily flow integral constraint

$$Q_{\min,j} \leq \int_{t=1}^{T} Q_{jt}dt \leq Q_{\max,j} \tag{14}$$

$Q_{\min,j}$、 $Q_{\max,j}$ are the minimum and maximum water allocation of the reservoir on the dispatch day, that is, the upper and lower limits of the daily flow integral.

(8) Wind turbine actual output constraint

$$0 \leq P_{w,k,t} \leq P_{w,f,t} \tag{15}$$

$P_{w,f,t}$ is the maximum output that can be scheduled for the predicted wind farm.

3.3. Wind speed probability distribution
In order to consider the uncertainty of wind power and hydropower output, the probability function is used to describe its output. The wind speed sequence of the wind farm obtained with the wind gauge obeys the two-parameter Weibull distribution

Distribution function:

$$F(V) = P(v \leq V) = 1 - \exp[-(\frac{V}{c})^k] \tag{16}$$

Probability density function:

$$f(V) = (\frac{k}{c}) * (\frac{V}{c})^{k-1} \exp[-(\frac{V}{c})^k] \tag{17}$$

Where c and k are the scale parameters and shape parameters of the Weber distribution, respectively;

Wind power characteristic function:

$$P(v) = \begin{cases} 0, 0 \leq v \leq v_c \\ a_0 + a_1 v + a_2 v^2 + a_3 v^3, v_c \leq v \leq v_N \\ P_N, v_N \leq v \leq v_0 \end{cases} \tag{18}$$

Where, v_c and v_N are respectively the cut-in and rated wind speeds, and $P(v_c) = 0$, $P(v_N) = P_N$ are satisfied; v_0 is the cut-out wind speed;

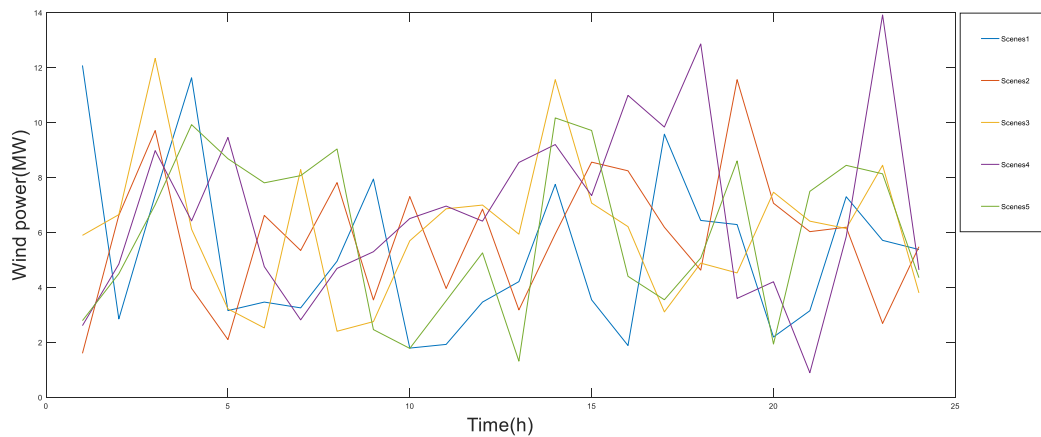Wind power output curve based on scene method:

Figure 1. Curves of wind power prediction.

3.4. Probability distribution of inflow runoff of a single hydropower station
We use the Pearson type III distribution function to describe the long-term probabilistic characteristics of hydropower station inflows.

Probability density function of inbound runoff:

$$\varphi(I) = \begin{cases} \dfrac{1}{\beta^\alpha \Gamma(\alpha)} (I - \delta)^{\alpha-1} e^{-\frac{I-\delta}{\beta}}, \delta \leq I < +\infty \\ 0, -\infty < I < \delta \end{cases} \tag{19}$$

Where: I is the inflow of the hydropower station; $\Gamma(\alpha)$ is the Gamma function, α、β、δ is the shape parameter, the scale parameter and the position parameter. Take α = 6.45，β=120，δ =40.

Pearson type III distribution function:

$$F(I) = \begin{cases} \dfrac{1}{\beta^\alpha \Gamma(\alpha)} \int_\delta^I (t - \delta)^{\alpha-1} e^{-\frac{t-\delta}{\beta}} dt, \delta \leq I \leq +\infty \\ 0, -\infty < I < \delta \end{cases} \tag{20}$$

$$V_i^{\min} \leq V_{i,t} \leq V_i^{\max} \tag{21}$$

$V_{i,t}$ is the water storage capacity of the hydropower station reservoir
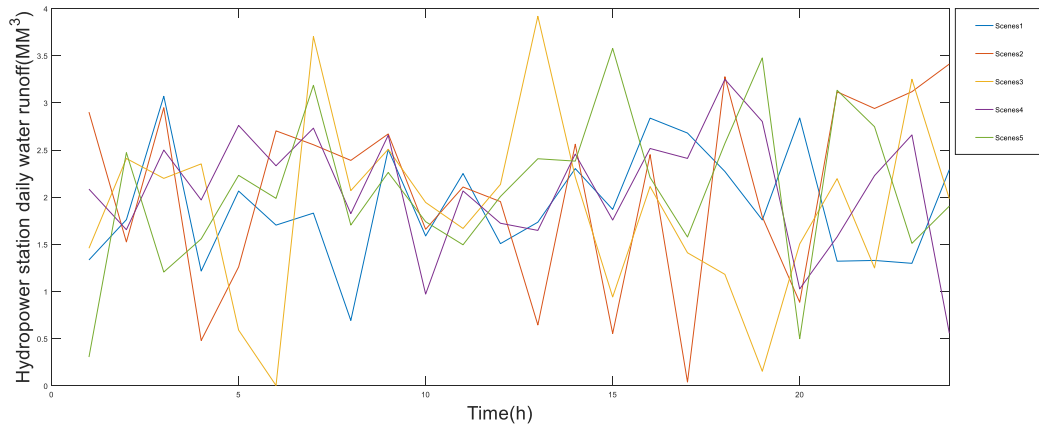
Generate a water runoff curve based on the scene method:

Figure 2. Curves of hydropower station daily water runoff.

4. Integrated energy management for massive decentralized air conditioning systems

At the system level, the unit and the ice storage air conditioning polymerization model are optimized to generate a scheduling plan, and the timetable for the cooling power, ice storage power and melting power of the aggregate ice storage air conditioner is obtained. The dispatch plan is then assigned by the load aggregator to the air conditioner under jurisdiction.

There are four states for each ice storage air conditioner: unit refrigeration, unit ice storage, ice melting and cooling and shutdown (assuming cooling, ice storage, ice melting, shutdown can not be performed simultaneously for each unit). When the unit is not under control, it is cooled by p_i.

The Δx minute is a control cycle, and each hour is a scheduling cycle.

$$Q_z = \sum q_{zi} * x_{ij1} \tag{22}$$

$$Q_x = \sum q_{xi} * x_{ij2} \tag{23}$$

$$Q_r = \sum q_{ri} * x_{ij3} \tag{24}$$

Where, x_{ij1}, x_{ij2}, x_{ij3}, x_{ij4} are unit 0-1 state variables, and the state variable is 1, respectively, indicating that the unit is in unit refrigeration, unit ice, ice melting, and shutdown; when the state variable is 0 , respectively, the unit is not cooling, the unit is not livestock ice, does not melt ice for cooling, no shutdown. Since the unit has and can only be in one of the states at each moment, there are the following constraints:

$$x_{ij1} + x_{ij2} + x_{ij3} + x_{ij4} = 1 \tag{25}$$

Consider unit constraints and does not affect user comfort for each ice storage air conditioner

4.1. Unit constraint

$$W_{t+1} = s * W_t + Q_{x,t} * \Delta t - Q_{r,t} * \Delta t \tag{26}$$

$$0 \le Q_{x,t} \le Q_{x,t}^{\max} \tag{27}$$

$$W_r \le W^{\max} \tag{28}$$

$$0 \le Q_{j,t} \le Q_j^{\max} \tag{29}$$

$$0 \le Q_{r,t} \le Q_r^{\max} \tag{30}$$

4.2. User comfort constraint

By studying the thermodynamic model of air conditioning units, the relationship between air conditioning power, temperature and time is established. The simplified thermal equivalent parameter

model is used to study the room temperature variation under the control of ice storage air conditioning, as shown in the following figure.
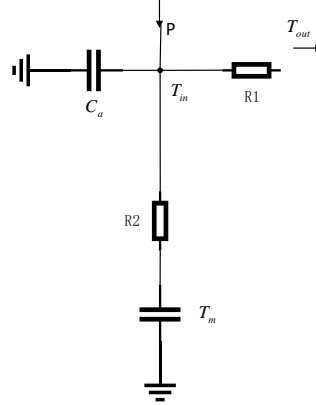

Figure 3. Thermal dynamics model of air conditioning unit.

Based on this simplification, we can establish the relationship between air conditioning power and room temperature:

$$T_{in}^{t+1} = T_{out}^{t+1} - (T_{out}^{t+1} - T_{in}^{t})\varepsilon \tag{31}$$

$$T_{in}^{t+1} = T_{out}^{t+1} - \frac{q_x}{A} - (T_{out}^{t+1} - \frac{q_x}{A} - T_{in}^{t})\varepsilon \tag{32}$$

T_{in}^{t} is the indoor temperature at time t; T_{out}^{t+1} is the outdoor temperature at the time $t+1$; ε is the heat dissipation function, $\varepsilon = e^{-\tau/Tc}$ is the control time interval, T_c is the time constant, and q_x is the rated cooling power of the air conditioner at time x.

The load control process must meet the user comfort requirements specified in the contract, that is, the room temperature interval $[T_{\min}, T_{\max}]$, and the user's room temperature should not exceed the interval. When the room temperature is closer to $T_{\min}$, the corresponding air conditioning load can be shut down for a longer duration.

Assume that the average rated cooling power of the x-stage air conditioner is $\bar{q}$, and the ambient temperature is set to a constant value T_{out} during the control period. According to the thermodynamic model of the air conditioning unit, combined with the room temperature control interval $[T_{\min}, T_{\max}]$, the load control cycle τ_c can be solved, as well as the time when the air conditioner is turned on and off, τ_{on}, τ_{off} as shown below:

$$T_{\max} = T_{out}(1 - \varepsilon^{\tau_{off}}) + T_{\min}\varepsilon^{\tau_{off}} \tag{33}$$

$$T_{\min} = (T_{out} - \bar{q}/A)(1 - \varepsilon^{\tau_{on}}) + T_{\max}\varepsilon^{\tau_{on}} \tag{34}$$

$$\tau_c = \tau_{off} + \tau_{on} \tag{35}$$

The load aggregator also needs to meet the user comfort specified in the contract while performing direct load control, and the room temperature cannot exceed the range $[T_{\min}, T_{\max}]$. Due to the difficulty in real-time measurement of room temperature and the delay of information transmission, it has a certain impact on real-time load control. Therefore, based on the thermodynamic model of air conditioning, this paper replaces real-time room temperature with duration to characterize the direct load control decision model. The continuous shutdown time of the air conditioner is:

$$\tau_i^{off}(i) = [\tau_i^{off}(i-1) + (x_{ij2} + x_{ij4}) * \Delta x] * (x_{ij2} + x_{ij4}) \tag{36}$$

(1) According to the thermodynamic model of the air conditioner, it can be concluded that the continuous shutdown time of the air conditioner cannot exceed τ_{off} .

Because the air conditioner and its environment have certain thermal storage characteristics, there is a certain relationship between the temperature changes in the entire control interval. The energy storage in the previous period can be used as the output for the later period of time, but the output at each moment cannot exceed The cumulative energy storage size of all previous periods, this relationship can also be characterized by time, from which the constraints of the DLC can be derived:

$$\frac{\sum (x_{ij1} + x_{ij3}) * \Delta x}{\sum (x_{ij2} + x_{ij4}) * \Delta x} \geq \frac{\tau_{on}}{\tau_{off}} \tag{37}$$

Since the ice storage air conditioner can be respectively used for electric refrigeration and ice melting refrigeration, respectively, corresponding to different sets of opening times respectively, since the electric cooling power of the ice storage is generally greater than the melting cooling power, the opening time of the electric cooling is smaller than the opening time of the melting and cooling, That is, for the sake of simplicity, it is only necessary to consider the opening time of the melting ice supply, so that the opening time is greater than the melting ice opening time without affecting the user's comfort. which is:

$$\frac{\sum (x_{ij1} + x_{ij3}) * \Delta x}{\sum (x_{ij2} + x_{ij4}) * \Delta x} \geq \frac{\tau_{on水}}{\tau_{off}} \geq \frac{\tau_{on电}}{\tau_{off}} \tag{38}$$

Objective function:

Ice storage air conditioning and dispatching plan have the smallest deviation

$$f = \min |Q_{j,t} - \sum q_{z,i,j} * x_{z,i,j}| + |Q_{r,t} - \sum q_{r,i,j} * x_{r,i,j}| + |Q_{x,i,j} - \sum q_{x,i,j} * x_{x,i,j}| \tag{39}$$

5. Simulation study

Assume that there are 20 ice storage air conditioners, 5 thermal power units, one hydropower station, and one wind farm participating in direct load control. The information of each unit is as follows:

Table 1. Thermal power station basic information

	Maximum power / MW	Minimum power / MW	Maximum climbing ability / (MW / h)
1	200	100	50
2	350	175	70
3	300	150	80
4	200	80	50
5	500	200	130

Table 2. Hydropower station basic information

	Maximum power / MW	Head height/m
6	300	12

Table 3. Ice storage air conditioning parameters

	Cooling power / MW	Melting power / MW	Ice storage power / MW	Maximum ice storage capacity / MWh
1	100	100	100	1000
2	100	100	100	1000
3	100	100	100	2000
4	100	100	100	2000
5	100	100	100	2000
6	100	100	100	2000

7	100	100	100	2000
8	100	100	100	3000
9	100	100	100	4000
10	100	100	100	5000
11	200	200	200	1000
12	200	200	200	1000
13	200	200	200	2000
14	200	200	200	2000
15	200	200	200	2000
16	200	200	200	2000
17	200	200	200	2000
18	200	200	200	3000
19	200	200	200	4000
20	200	200	200	5000

The parameters of the polymerized ice storage air conditioning model are determined according to a large number of ice storage air conditioners within the jurisdiction of the load aggregator. The output of each unit is as follows:

Ice storage:

Figure 4. Generator set scheduling results with ice storage.

The optimally generated ice storage air conditioning polymerization model scheduling plan is as follows：
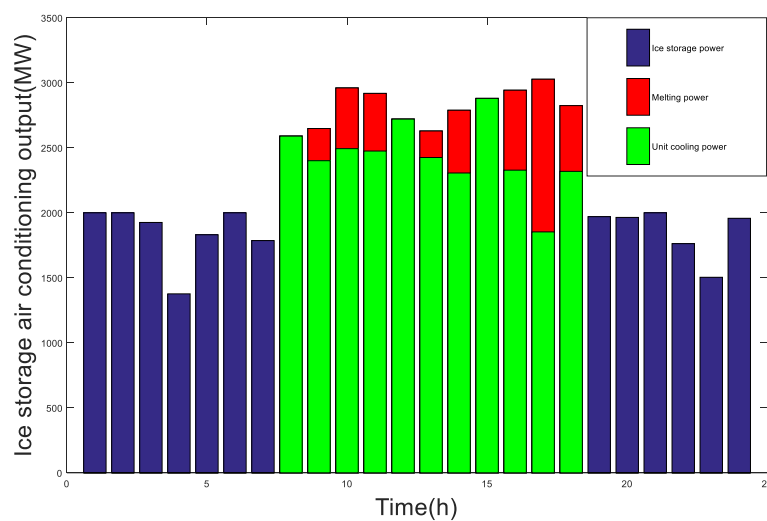

Figure 5. Scheduling results of ice storage air conditioning.t.

No ice storage:

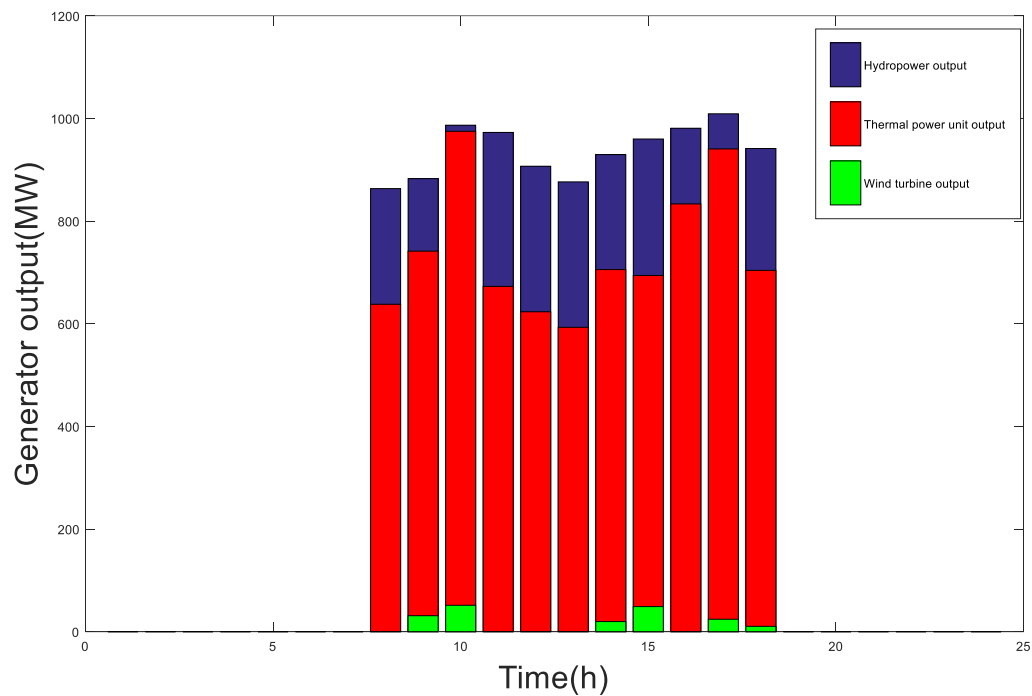

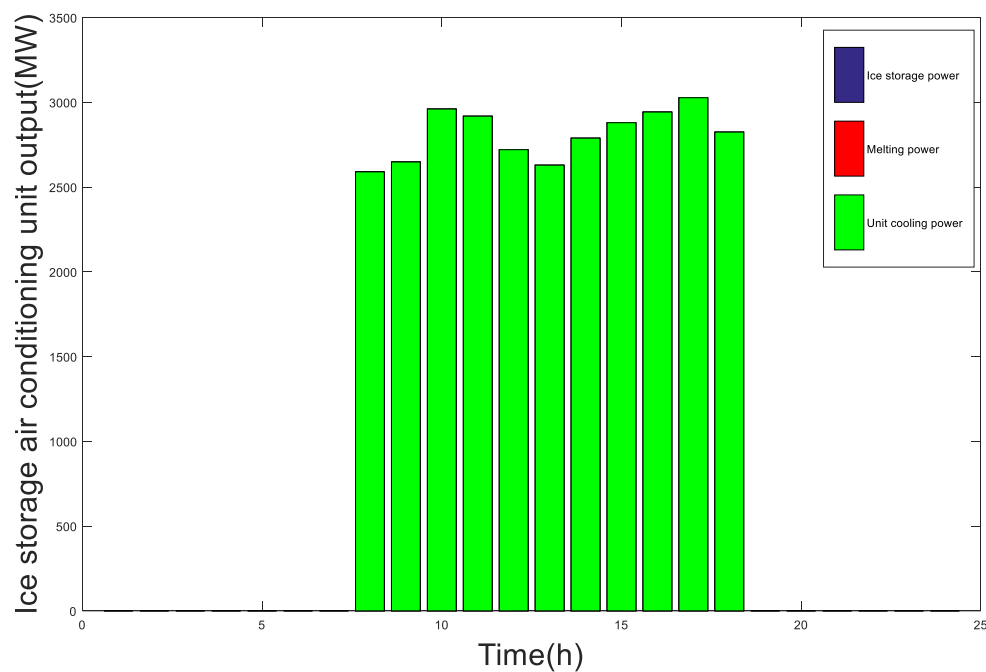Figure 6.Generator set scheduling results without ice storage.

Figure 7. Scheduling results of ice storage air conditioning.

Wind power output:
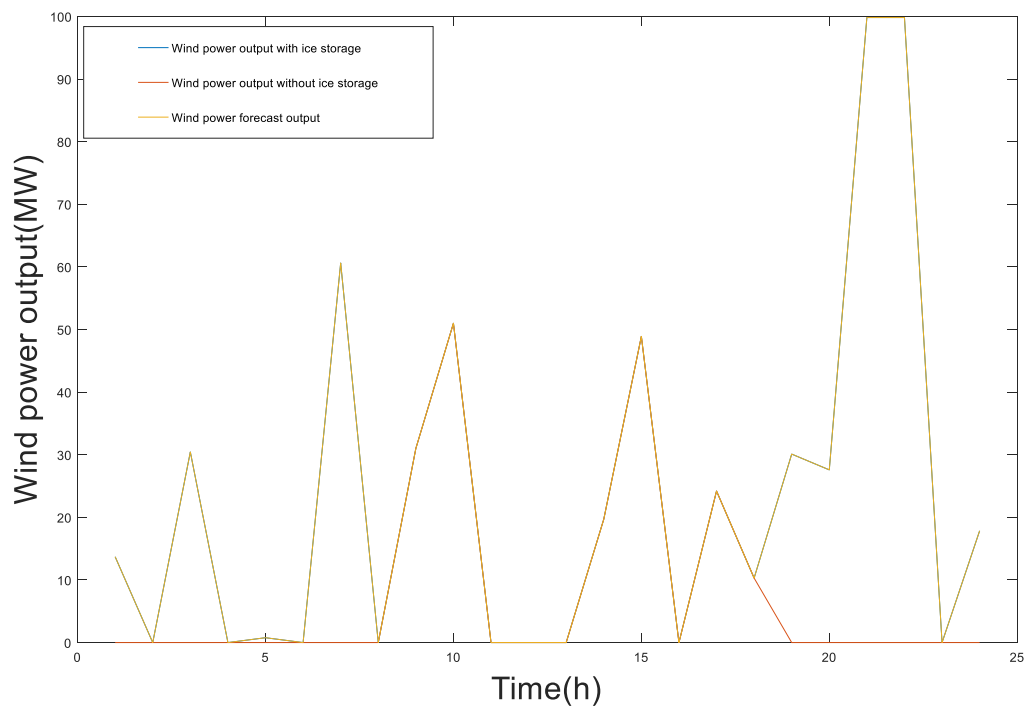
Figure 8.Wind power consumption.

It can be seen that there is less wind power consumption when there is no ice storage, and the wind is relatively large. When there is ice storage, the wind power is almost completely absorbed.

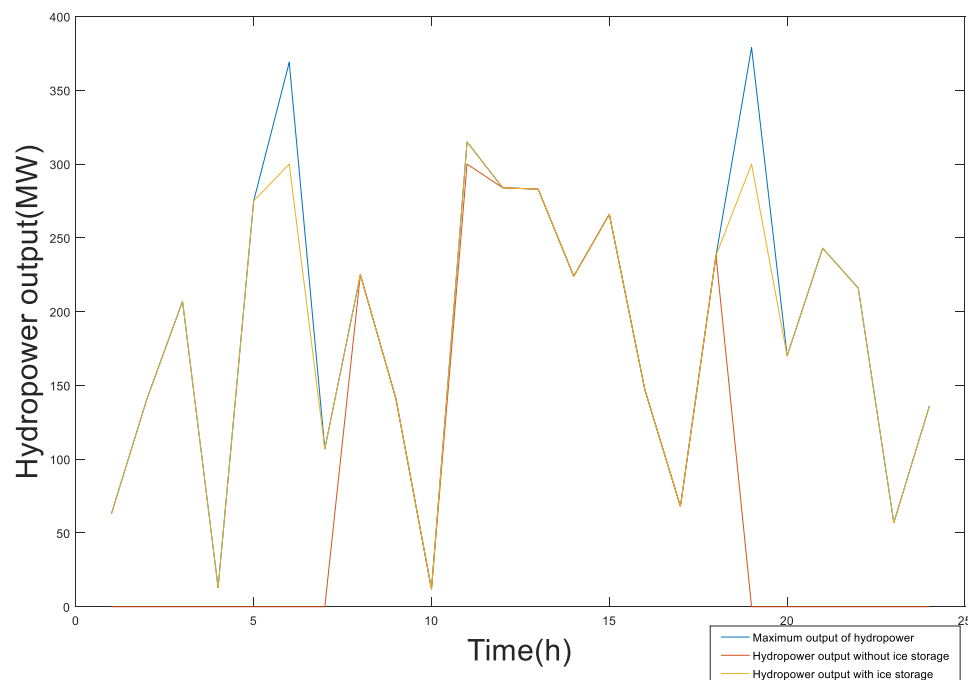Hydropower consumption situation:

Figure 9.Hydropower consumption situation.

Table 4. Abandoned water and wind consumption in different scenarios.

	No ice storage	Ice storage
Abandoning wind and abandoning water/MWh	3277	467
Ice storage/MWh	0	11415

It can be seen that when there is no ice storage, the hydropower part is consumed. When the ice is stored, the water and electricity are largely consumed, and the abandoned water is greatly reduced.

Due to the minimum output constraint of the unit and the climbing slope constraint, the ice storage air conditioner cannot completely eliminate the ice, so in order to completely abandon the wind and abandon the water generation in the case of no ice, choose to ignore the minimum output constraint and the climbing constraint. It is calculated that when the ice is used, the expected value of abandoned wind and abandoned wind power generation in all scenarios is 467 MWh, and the expected value when there is no ice is 3277 MWh, which proves that the ice storage air conditioner can largely abandon the wind and abandon water.

As the amount of ice in the ice storage tank increases, the amount of discarded wind and water drops, but it does not fall after reaching a certain amount. Since the objective function is the minimum amount of abandoned wind and water, when the amount of ice can completely eliminate wind power, the amount of discarded air will not change.

Assume that the scheduling plan is from 12:00 to 13:00 on a certain day: the unit's cooling power is 1050MW, the melting ice cooling power is 870MW, and the unit's livestock ice power is 980MW. The unit is controlled once every 6 minutes. The load aggregator satisfies the dispatch plan by scheduling ice storage air conditioners within the jurisdiction. The calculation results are as follows:
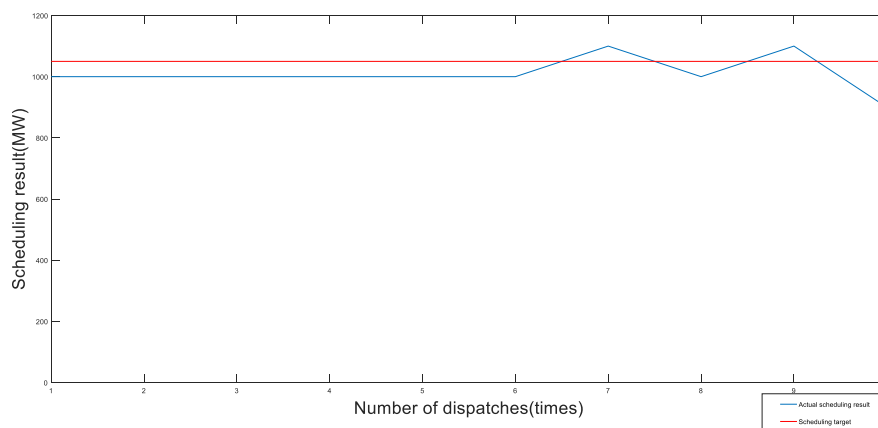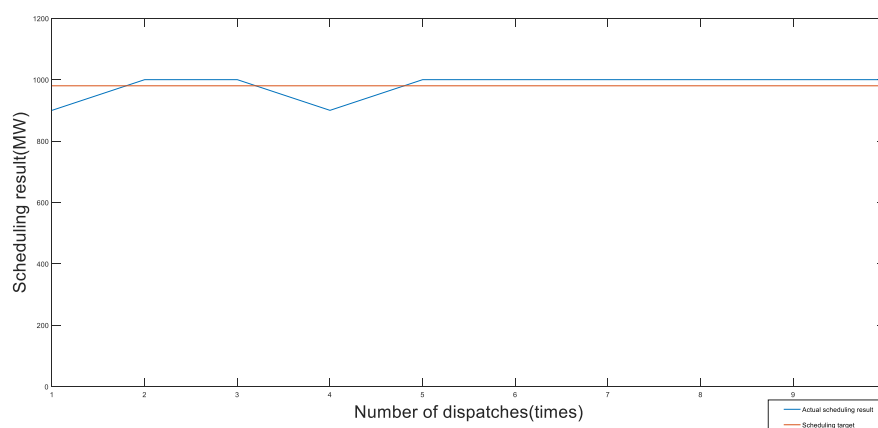

Figure 10.Scheduling results of unit refrigeration.
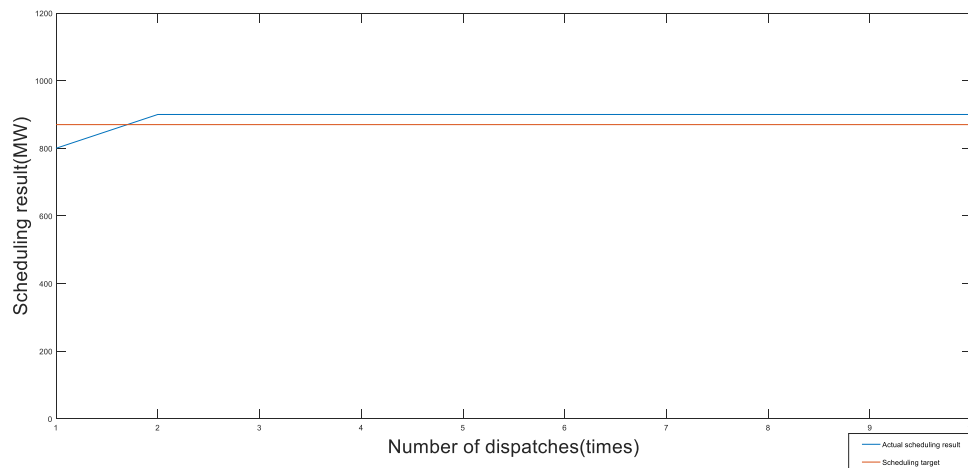

Figure 11. Scheduling results of ice storage.

Figure 12.Scheduling results.of melting ice cooling

Table 5. Error in scheduling results.

Air conditioning units	Scheduling error
Cooling power	4.76%
Ice storage power	2.65%
Melting power	3.91%

6. Conclusion

This paper proposes a waste water and wind abandonment dispatching method based on ice storage air-conditioning system. The simulation example shows that the electric power supply cooling, ice storage and ice melting cooling of ice storage air conditioning are controlled reasonably, and the generator set is optimally dispatched. It can reduce the abandonment of water and the wind without affecting the user's comfort, realize the consumption of abandoned wind and water, can effectively alleviate the power imbalance problem, reduce the peak-to-valley difference of the power load, improve the system operation efficiency, and save user electricity fee. For the ice storage air conditioning control strategy model, the ice storage capacity, the number of controllable air conditioners, and the ice storage margin are important factors influencing the decision-making results. When the number of controllable air conditioners is larger, the control strategy is more flexible, and the scheduling error is smaller. When the ice storage margin is small, the scheduling error is large; when the ice storage is sufficient, the scheduling error can be greatly reduced. The research in this paper is only the beginning. In the future, further study about the uncertainty of the initial state of ice storage air conditioning, the change of ice melting rate, and the power of compressor when considering ice melting and cooling will be made.

References

[1] Gao Zhiwei, Li Qianyu, Li Yang. DLC-based double-layer optimal scheduling and control strategy for air conditioning load[J]. Proceedings of the CSEE, 2014, 34(10): 1546-1555.
[2] Integrated dispatching plan for power generation in user-side interaction mode [J]. Xia Ye, Kang Chongqing, Ningbo, Ding Maosheng. Power System Automation. 2012(01)
[3] Direct load control decision model in power market[J]. Zhang Qin, Wang Xifan, Bie Chaohong, Wang Jianxue. Power System Automation. 2010(09)
[4] Review of demand response research in the electricity market[J]. Zhang Qin, Wang Xifan, Wang Jianxue, Feng Changyou, Liu Lin. Automation of Electric Power Systems. 2008(03)

[5]   Resident direct load control based on fuzzy linear programming[J]. Xu Daolin, Xie Song. Power Demand Side Management. 2007(01)

[6]   An evaluation of the HVAC load potential for providing load balancing service. Lu,Ning. IEEE Transactions on Smart Grid . 2012

[7]   Callaway D S, Hiskens I A. Achieving controllability of electric loads [J]. Proceedings of the IEEE, 2011, 99(1): 184-199.

[8]   Joo Jhi-Young, Marija D I. Adaptive load management (ALM) in electric power systems [C]//International Conference on Networking, Sensing and Control (ICNSC). Chicago: IEEE, 2010: 637-642.

[9]   Lu Ning.An evaluation of the HVAC load potential for providing load balancing service [J]. IEEE Transactions on Smart Grid, 2012, 3(3): 1263-1270.

[10] Yu Na, He Deming, Li Guoqing. Decision Factors and Classification Model of Power Demand Response[J]. Journal of Northeast Electric Power University, 2011, 31(4): 112-116. Yu Na, He Deming, Li Guoqing. Decision factors and Classification model of demand response[J].Journal of Northeast Dianli University,2011,31(4):112-116(in Chinese).

[11] Xu Daolin,Xie Song.Resident direct load control based on fuzzy linear programming[J].Power Demand Side Management,2007,9(1):15-18,34.Xu Daolin,Xie Song.Direct residential load control based On fuzzy linear programming[J].Power DSM,2007,9(1): 15-18,34(in Chinese).

[12] Xu Qingshan, Yang Chenxing, Yan Qingguo. The peaking strategy of electric load before taking into account the thermal balance inertia of large-scale air conditioners[J]. Power System Technology, 2016, 40(01): 156-163.