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A Control Method for District Cooling System Participating in Secondary Frequency Modulation of Power Grid

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Abstract. In this paper, in order to use the district cooling system for secondary frequency regulation of the power grid, this paper first established a thermodynamic model of the district heating system, and then proposed a two-step regulation method for the power demand response of the power grid, and in the second step, a control method based on Q-learning was specifically applied to ensure that high-quality frequency regulation services are provided and the temperature comfort of the terminal buildings is guaranteed. This effectively achieves the goal of using the district heating system for secondary frequency regulation of the power grid.

Keywords: secondary frequency modulation, Q-learning, District Cooling System, demand-side response.

1. Introduction

The rapid development of renewable energy such as wind power and photovoltaics has reduced society's dependence on traditional fossil energy, but the randomness and volatility of its output have brought new challenges to the safe and stable operation of the power system. In order to alleviate the power fluctuation problem caused by the access of new energy to the distribution network. A large number of energy storage technologies have emerged.

With the wave of digital revolution set off by modern information technology. Relying on advanced information and communication technology, we can achieve demand-side response by adjusting the power consumption of the power system through demand-side resources, thereby providing secondary frequency regulation services for the power system. Utilizing a large number of loads with energy storage characteristics such as air conditioners, refrigerators, water heaters, heat pumps, etc., by short-term switching or changing control parameters, they participate in the multi-time scale active power dispatch of the power system without obvious perception by users.

As an ideal regulation resource, the building thermostatic control load has received more attention at the moment when a high proportion of new energy is connected. As a centralized cooling equipment, the regional cooling system has great regulation potential. A regional cooling system can cover multiple buildings, and its power regulation is obviously easier to achieve than large-scale distributed air conditioners with the same regulation capability. District cooling systems account for a large proportion of the total urban electricity consumption in summer. Due to the thermal inertia of buildings, temporary adjustments to their power distribution usually have a negligible impact on the temperature comfort of buildings.

In this case, the district cooling system, as a high-energy-consuming object on the demand side, can provide direct active power regulation for the power grid, thereby realizing secondary frequency regulation. This advantage can effectively avoid communication and coordination problems in distributed resource regulation. At the same time, due to the large thermal inertia in pipelines and buildings, the temperature impact caused by power regulation is small. Therefore, district cooling systems have great advantages in providing regulation services.

The district cooling system consists of complex thermodynamics, including water cooling supply at the initial end, cold transportation in the pipeline, and cold consumption in the terminal building. At present, existing research on district cooling systems mainly focuses on their operation optimization to minimize energy costs or improve system cooling efficiency. Neri et al. [1]

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proposed a topology optimization of a DCS to successfully save the total life-cycle cost of the DCS. Yu et al. [2]proposed a method of control barrier function and safe deep reinforcement learning to provide regulation services. However, these studies have not focused on the huge potential of district cooling systems in secondary frequency regulation of power grids.

We know that the resources that provide secondary frequency regulation for the power grid must be adjusted to the specified power within a few seconds based on real-time control signals to meet the needs of maintaining the balance of the power system. For the district cooling system, its control methods can be divided into quality regulation by adjusting the circulating chilled water temperature, quantity regulation by adjusting the circulating chilled water flow rate, and quality-quantity regulation that combines the two. In order to use the district cooling system for secondary frequency regulation of the power grid, this paper first established a thermodynamic model of the district cooling system, including the modeling of the pipe temperature, and then proposed a two-step adjustment method for the power grid power demand response, and specifically designed a Q-learning-based control method to ensure that the temperature comfort and experience of the terminal building are guaranteed while providing high-quality secondary frequency regulation of the power grid [3]. This effectively achieves the goal of using the district cooling system for secondary frequency regulation of the power grid.

2. Establishment of Thermodynamic Model for District Cooling System

We first establish a thermodynamic model of the regional cooling system. It is known that cooling power multiplied by efficiency equals flow multiplied by specific heat capacity multiplied by temperature difference. The formula is as follows:

$$P_t^{\mathrm{cool}} \times \eta = m_t c^{\mathrm{w}} (T_t^{in} - T_t^{\mathrm{out}}) \tag{1}$$

In the formula, P_t^{cool} is the real-time heating power, m_t is the regional cooling pipe flow per unit time, c^{w} is the specific heat capacity of water, T_t^{out} is the real-time outlet water temperature, T_t^{in} is the real-time return water temperature, and η is the cooling efficiency.

It is known that the power dissipation of a room is affected by the room volume, the difference between the indoor set temperature and the outdoor temperature, and the heat transfer coefficient. The power dissipation formula of the $i-th$ building can be expressed as:

$$Q_i = V_i \times \Delta T_i \times k_i \tag{2}$$

Q_i is the power dissipated by $i-th$ building (W). V_i is the volume of the $i-th$ building (m^3). ΔT_i is the difference between the indoor set temperature and the outdoor temperature of the $i-th$ building (℃). k_i is a heat transfer coefficient that reflects the thermal insulation performance of the $i-th$ building.

According to the law of conservation of power, when the indoor temperature of a building is constant, the cooling power is equal to the heat absorption power, that is, formula (1) is equal to formula (2), and the formula can be expressed as:

$$P_t^{\mathrm{cool}} \times \eta = \sum_{i=1}^{n} Q_i \tag{3}$$

In the formula, n is the total number of buildings.

According to the relationship between inflow and outflow, the regional cooling pipeline flow satisfies that the total flow is equal to the sum of the flow of each building. The formula is as follows:

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$$m_t = \sum_{i=1}^{n} m_{i,t} \tag{4}$$

$m_{i,t}$ represents the regional cooling pipe flow per unit time in the $i-th$ building, where there are n buildings in total.

From the specific heat capacity formula $Q = cmT$, we can see that the total $m_t c^{\mathrm{w}} T_t^{out}$ is the sum of the $m_{i,t} \times c^{\mathrm{w}} \times T_{i,t}^{out}$ of the n buildings from 1 to n. The formula is as follows:

$$m_t c^{\mathrm{w}} T_t^{out} = \sum_{i=1}^{n} m_{i,t} \times c^{\mathrm{w}} \times T_{i,t}^{out} \tag{5}$$

The real-time indoor temperature $T_{i,t}^{\text{indoor}}$ modeling analysis of the $i-th$ building is as follows, which is determined by two parts: the heat exchange with the outdoor environment, and the cooling energy obtained from the district cooling pipe. The constraints are as follows:

$$D_i \frac{\mathrm{d}T_{i,t}^{\text{indoor}}}{\mathrm{d}t} = \frac{T_{i,t}^{\text{indoor}} - T_t^e}{R_i} - \eta_i m_{i,t} c^{\mathrm{W}} (T_{i,t}^{\text{in}} - T_{i,t}^{\text{out}}) \tag{6}$$

In the formula, D_i is defined as the heat capacity of air and objects in the $i-th$ building (J/°C), R_i is the thermal resistance of the $i-th$ building, T_t^e is the real-time ambient temperature, η_i is the heat exchange efficiency of the $i-th$ building.

In the district cooling system model, the flow rate of the district cooling pipeline $m_{i,t}$ must satisfy the real-time water output equal to the real-time water return, that is, satisfy the following constraints:

$$m_{i,t} = m_{i,t-1} + \sum_{i=1}^{n} \mu_i (T_{i,t}^{\text{indoor}} - T_{i,t-1}^{\text{indoor}}) \tag{7}$$

In the formula, $m_{i,t}$ is the regional cooling pipeline flow, $m_{i,t-1}$ is the regional cooling pipeline flow at the previous moment, and parameter μ_i is the coefficient of the $i-th$ building.

The temperature difference $\Delta T_{t,i}$ is equal to the real-time indoor temperature value minus the set temperature value, expressed as:

$$\Delta T_{t,i} = T_{t,i}^{\text{set}} - T_{t,i}^{\text{indoor}} \tag{8}$$

In the formula, $T_{t,i}^{\text{set}}$ is the temperature setting value corresponding to the $i-th$ building, $T_{t,i}^{\text{indoor}}$ is the real-time indoor temperature value of the $i-th$ building.

The entire process of secondary frequency modulation using the regional cooling system is shown in the “Fig. 1”.

3. Two operating Modes of District Cooling System

The regional cooling system adopts two control methods, the first is the normal control method, and the second is the power response control method.

The first method is that in normal operation, when there is no power demand response from the power grid, the regional cooling system adopts the normal control method, and uses the power

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conservation that the cooling power is equal to the heat absorption power to maintain the indoor temperature at the set value [4].

The second method adopts the power response control method when the power grid issues a power demand response. Power regulation is achieved through a two-level control process. The regulation requires two steps. The first step is to quickly adjust the cooling power of the cooling station in the regional cooling system to fill or weaken the difference between the actual power and the target power, thereby achieving rapid power regulation to achieve the goal of secondary frequency regulation. The second step is to reasonably distribute the changed regional cooling pipeline flow among the buildings to ensure that the indoor temperature of each building can still be maintained within the specified temperature range as much as possible [5].

Under the power response control mode, the change in the flow rate of the regional cooling pipeline is equal to the flow rate at the next moment minus the flow rate at the current moment, and the formula is expressed as:

$$m_{t+1}^{\text{cool}} = m_t^{\text{cool}} + \Delta m_t^{\text{cool}} \tag{9}$$

According to the law of conservation of power, the power gap between the actual operating power and the target power can be determined as:

$$\Delta P_t^{cool} = P_t^{\text{target}} - P_t^{cool} \tag{10}$$

Since different buildings require different cooling energy to maintain indoor temperature comfort, under the power response control mode, we track the distribution of regional cooling pipe flow $\Delta m_{i,t}$ between buildings as the real-time regional cooling pipe flow change value, and the formula is expressed as :

$$m_{i,t+1} = m_{i,t} + \Delta m_{i,t} \tag{11}$$

In step 1, the total regional cooling pipeline flow is adjusted to fill or weaken the difference between the actual power and the target power. At this time, the system should meet the three constraints of flow constraint, temperature constraint and power constraint:

$$\begin{cases} m_{t+1}^{cool} = m_t^{cool} + \Delta \mathrm{m}_t^{step\,1} \\ T_{t+1}^{cool,out} = T_t^{cool,out} - \dfrac{T^{cool,in} - T_t^{cool,out}}{m_{t+1}^{cool}} \times \Delta \mathrm{m}_t^{step\,1} \\ \Delta P_{t+1}^{cool} = c^w m_{t+1}^{cool} T_{t+1}^{cool,out} - c^w m_t^{cool} T_t^{cool,out} \end{cases} \tag{12}$$

In step 2, we introduce a reward function r_i to evaluate the implementation effect of the i-th building. The reward function includes two measurement objects: the power gap value $\Delta P_{t,i}^{heat}$ and the building temperature difference value $\Delta T_{t,i}$. We define as follows:

$$r_i = -\beta_1 \times (\Delta P_{,}^{cool})^2 - \beta_2 \times \Delta T_{t,i} \tag{13}$$

Where β_1 and β_2 are weight factors that balance the two objectives

The total reward function r_total is equal to the sum of the reward functions of the n buildings from 1 to n.

$$r\_total = \sum_{i=1}^{n} r_i \tag{14}$$

The temperature change value $\Delta T_{t+1,i}$ in the i-th building at the next moment is as follows:

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$$\Delta T_{t+1,i} = c^{w} \times \frac{m_{t+1,i}}{m_{t+1}^{cool}} \times (m_{t+1}^{\text{cool}} - m_{t,i}) \times \frac{T_t^{cool,in} - T_t^{cool,out}}{D_i} \tag{15}$$

Where $m_{t+1,i}$ is the regional cooling pipe flow of the i-th building, m_{t+1}^{cool} is the total regional cooling pipe flow of the building.

4. Application of Q-learning Algorithm in Step 2

In step 2, we need to reduce the regional cooling pipe flow of each building to ensure that the total flow reduction of each building meets the requirements to achieve secondary frequency modulation, and at the same time, meet the range requirements of the comfortable temperature of each building.

In formula (15), we introduced a reward function r_total to evaluate the implementation effect. The measurement factors include two measurement objects: power gap value and building temperature difference.

The goal of step 2 is to establish a model to ensure that the reward function r_total is maximized while trying to meet the frequency modulation power requirements.

On the basis of the established dynamic model of the regional cooling system, an MDP model of the regional cooling system based on the Q − learning algorithm is established, and the MDP model parameters of the regional cooling system are reasonably selected. The MDP model parameters of the regional cooling system include a state space set S, a discrete action space set a, a state transition probability ε, a reward function R and a discount rate γ. The algorithm uses the Q − learning method to maximize the sum of the reward function. The specific implementation steps are as follows:

4.1 define the states and actions

a) State S: The current heating status of the system, including current temperature $T_{t,i}^{\text{indoor}}$, power gap $\Delta T_{t,i}$, etc.

$$s = \left\{ n, T_{t,i}^{\text{indoor}}, \Delta T_{t,i} \right\} \tag{16}$$

b) Action a: Adjust the flow rate of the heating pipe $\Delta m_{i,t}$ (such as increase, decrease, or remain unchanged).

$$a = \{\Delta m_{1,t}, \Delta \text{m}_{2,t}, ..., \Delta \text{m}_{n,t}\} \tag{17}$$

4.2 initialize the Q table

Initialize the Q value of all state-action pairs to zero. Denoted as $Q(s,a)=0$.

In the Q − learning algorithm, the Q − value is the quality of a state-action pair taking a specific action in a specific state. It represents the expected cumulative reward value that can be obtained by taking this action in this state. The definition of Q − value is based on the Bellman equation, which is updated through continuous iteration to approximate the optimal strategy.

$$Q(s,a) = \sqcup[r_t + \gamma r_{t+1} + \gamma^2 r_{t+2} + \ldots \mid s_t = s, a_t = a] \tag{18}$$

The meaning of the formula symbols is: $Q(s,a)$ is the Q − value of state s and action a ;) r_t is the immediate reward at time step t ; γ is a discount factor, ranging from 0 to 1, used to weigh the importance of future rewards.

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4.3 select actions based on the ε-greedy strategy

In each state, an action is randomly selected with a probability of ε, and the action with the largest current Q value is selected with a probability of 1 − ε.

$$a = \begin{cases} \text{Randomly select an action} & \epsilon > \text{random number} \\ \arg\max_{a'} Q(s,a') & \epsilon \leq \text{random number} \end{cases} \tag{19}$$

4.4 Perform actions and observe results

Perform the selected action a in the system and observe the results, including the new state s' and reward r.

4.5 Update Q − value

Update the Q − value using the following formula:

$$Q(s,a) \leftarrow Q(s,a) + \alpha\left(r + \gamma \max_{a'} Q(s',a') - Q(s,a)\right) \tag{20}$$

The meaning of the formula symbols is: s is the current state; a is the current action; r is a reward after performing action; s' is the next state after performing action; α is learning rate; γ is a discount factor; $\max_{a'} Q(s',a')$ is the maximum Q − value that can be obtained by selecting the optimal action a' in the new state s'.

Q − value update: The new Q − value is equal to the old Q − value, plus one learning step (α) times the error of the current estimate, which is the difference between the immediate reward plus the discounted future Q − value and the old Q − value.

After the grid power response secondary frequency modulation is finally realized, the changed regional cooling pipeline flow can be reasonably distributed among the buildings to ensure that the indoor temperature of each building can be maintained within the specified temperature range as much as possible. This effectively achieves the goal of using the regional cooling system for grid secondary frequency modulation.

5. Conclusions

This paper proposes a strategy that effectively realizes the secondary frequency modulation of the power grid using the district cooling system. By first establishing a thermodynamic model of the district cooling system, including modeling the pipe temperature and indoor temperature, a reasonable model is determined. Then a two-step regulation method for the power demand response of the power grid is proposed. The first step is to adjust the total flow to achieve power response, and the second step is to distribute the flow. For the task of reasonable redistribution of pipeline flow after responding to secondary frequency modulation, this paper specially designs a control method based on Q learning to ensure that while providing high-quality secondary frequency modulation of the power grid, the temperature comfort and experience of the terminal building are guaranteed. Thereby finally achieving the purpose of using the district cooling system for secondary frequency modulation of the power grid.

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