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Research on Energy-saving Optimization of HVAC System in Power Plant in Smart Grid Operation

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Abstract: With the rise of smart grid, traditional power plants are facing challenges and opportunities of energy saving and emission reduction. This paper studies the energy-saving optimization strategy of HVAC (heating, ventilation, and air conditioning) in power plant under smart grid environment. Firstly, the energy consumption model of HVAC system and indoor environment heat balance model are established, and the key factors affecting energy consumption are analyzed. Then, an optimal operation strategy based on time-of-use electricity price (TOU) is proposed, and model predictive control (MPC) is used to reduce the operation cost by adjusting the operation strategy on the premise of ensuring environmental comfort. In addition, the feasibility of participating in grid demand response (DR) is discussed. By adjusting the temperature set point and implementing graded load shedding, the load regulation service is provided for the grid and economic compensation is obtained. The case study shows that the optimization strategy can effectively reduce the power consumption and electricity bill of HVAC system and improve the operation efficiency of equipment, which proves the feasibility and economic benefits of energy saving and emission reduction in smart grid environment.

Keywords: Smart Grid; Energy-saving Optimization; HVAC System; Power Plant.

1. Introduction

As one of the main sources of energy consumption and carbon emissions, the power industry's energy saving and emission reduction work is particularly important [1]. As a new generation power system, smart grid has realized the efficient, reliable and sustainable development of power system by introducing advanced information technology and communication technology [2]. However, the operation of smart grid also brings new challenges and opportunities to traditional power plants. How to realize efficient operation, energy saving and emission reduction of power plants in smart grid environment has become a hot and difficult issue in current research.

Heating, ventilation, and air conditioning (HVAC) is an important part of the power plant, which is mainly responsible for providing suitable temperature, humidity and air quality for the production process and staff of the power plant [3]. However, HVAC system is also one of the main sources of power plant energy consumption, and its energy consumption accounts for the proportion of total power plant energy consumption. Therefore, the energy-saving optimization of HVAC system not only helps to reduce the operating cost of power plants, but also significantly reduces carbon emissions, which has important economic and social benefits.

2. Modeling and Analysis of HVAC System

2.1. System Energy Consumption Modeling

The total power consumption P_{HVAC} of HVAC system is mainly composed of the power consumption of refrigeration unit, water pump, cooling tower fan, air supply/return fan and other equipment [4-5]. In order to simplify the analysis and grasp the main contradiction, the power consumption of its core-refrigeration unit is taken as the key modeling object. The power consumption of refrigeration unit is closely related to its operating efficiency (COP) and refrigeration load.

A commonly used simplified model formula is:

$$P_{chiller} = \frac{Q_{cooling}}{COP(\tau)} \tag{1}$$

Among them, $P_{chiller}$ ——Real-time power consumption of refrigeration unit (kW). This is the core energy consumption index that needs to be analyzed and optimized.

$Q_{cooling}$ ——Real-time cooling capacity (kW) required by the system. This value is determined by the internal heating value of the plant, outdoor meteorological parameters, the characteristics of the envelope and other factors.

$COP(\tau)$ ——Performance coefficient of refrigeration unit, which is a function of time τ . COP value is not constant, which is mainly influenced by the following two factors:

Partial load ratio (PLR): the ratio of actual cooling capacity to rated cooling capacity of refrigeration unit. Usually in the range of 40%-80% load rate, COP is the highest.

Condensation temperature/cooling water temperature: The lower the temperature, the higher the COP . This is related to the outdoor wet bulb temperature and the operation state of the cooling tower.

According to this model, there are two ways to reduce $P_{chiller}$: 1) reduce the refrigeration demand $Q_{cooling}$ on the premise of meeting the process requirements; 2) Optimize the operation strategy to make the refrigeration unit run in the high COP range as much as possible.

2.2. Indoor Environmental Heat Balance Model

In order to estimate the cooling demand $Q_{cooling}$, it is necessary to establish a simplified heat balance model for the core areas such as the main building or control room [6-7].

$$C = \frac{dT_{in}}{dt} = Q_{gain} - Q_{cooling} + H(T_{out} - T_{in}) \quad (2)$$

Among them, C ——Indoor comprehensive heat capacity (kWh/°C). It reflects the heat absorbed or released by indoor air, walls, equipment and other objects with a temperature change of 1 °C.

T_{in} ——Indoor temperature (°C).

t ——Time (h).

Q_{gain} ——Total indoor heating value (kW). Including process equipment cooling, lighting cooling, personnel cooling, etc., can be regarded as a relatively stable value or measurable value.

H ——Total thermal conductivity of building envelope (kW/°C). Reflects the infiltration/exudation heat caused by indoor and outdoor temperature difference.

T_{out} ——Outdoor temperature (°C).

This model reveals the dynamic process of indoor temperature change. By forecasting T_{out} (weather forecast) and known Q_{gain}, this model can be used to calculate in advance the $Q_{cooling}$ needed to maintain T_{in} within the allowable range in the future, thus providing a basis for pre-optimization control.

3. Energy-saving Optimization Strategy in Smart Grid Environment

One of the core features of smart grids is the introduction of Time of Use Electricity Price (TOU) and Demand Response (DR) mechanisms [8]. This strategy utilizes these signals to achieve the lowest total operating cost of the HVAC system while ensuring the safety and comfort of the power plant production environment [9].

3.1. Optimal Operation Strategy based on TOU

TOU signal provided by smart grid is $P(\tau)$ (yuan /kWh), which is usually high in peak hours and low in low hours. The optimization objective function can be set to minimize the total electricity bill in a period:

$$\min \sum_{\tau=1}^{N} \left(P_{HVAC}(\tau) \cdot P(\tau) \cdot \Delta t\right) \quad (3)$$

The system operation needs to meet two core constraints: one is temperature constraint, which means that the indoor temperature $T_{in}(\tau)$ must be maintained between the set minimum and maximum values τ at any time to ensure compliance with production process requirements and personnel health environment; The second is equipment constraint, which requires that the operating parameters of each equipment in the HVAC system, including power output, start stop frequency, and medium flow rate, must not exceed their designed safety limits to ensure long-term stability and safe operation of the equipment.

Model predictive control (MPC) strategy is adopted to realize the optimal operation of HVAC system. Firstly, based on the weather forecast, the outdoor temperature T_{out} forecast data for the next 24 hours is obtained as the external disturbance input of the system. Then, with the goal of minimizing the total operating cost, the optimization model is solved in the 24-hour rolling time domain to generate the optimal operation plan of the refrigeration unit. For example, the factory building is precooled in advance during the low electricity price period, and the indoor temperature is regulated to the allowable lower limit to accumulate cold energy, so as to reduce the output of the unit during the peak electricity price period and allow the indoor temperature to rise moderately within a safe range, thus reducing the peak load and the energy consumption cost; Finally, the controller only executes the first time step instruction in the optimization result, and updates the prediction model at the next moment according to the actually measured indoor and outdoor temperature and disturbance information, and re-optimizes the rolling to form closed-loop feedback, so as to realize the dynamic and adaptive adjustment of the system operation.

3.2. Participate in Power Grid DR

The power plant energy management system (EMS) can automatically start the preset HVAC control strategy after receiving the emergency load reduction instruction by participating in the power grid DR [10]. On the one hand, by adjusting the temperature set point, the temperature control range of the core area is temporarily relaxed, and the cooling demand is rapidly reduced; On the other hand, according to the regional importance, load shedding is carried out by stages, air conditioning and ventilation in non-critical areas are suspended, and the operating environment of the main equipment room and the control room is given priority, so that the power consumption (P_{HVAC}) of the HVAC system is significantly reduced in a few minutes, and reliable auxiliary services for load regulation are provided for the power grid, at the same time, the power plant is helped to obtain corresponding economic compensation, and the economic benefits of overall energy-saving optimization are further improved.

4. Case Study and Verification

In order to verify the effectiveness of the above modeling and optimization strategy, a one-month case study was conducted for the HVAC system in the centralized control room and electronic equipment room of a 600MW coal-fired power plant in a coastal area. The refrigeration in this area is undertaken by a centrifugal refrigeration unit with rated cooling capacity of 300 rt. Hourly data of typical summer weeks in this region are collected, including outdoor temperature, indoor temperature set value (originally fixed at 24°C), power consumption of refrigeration unit and time-of-use electricity price signal (peak: 1.2 yuan /kWh, flat section: 0.8 yuan /kWh, low valley: 0.4 yuan /kWh).

Compare the following two scenarios:

1) Scenario 1 (benchmark): The original fixed temperature setpoint control strategy.

2) Scenario 2 (Optimization): The optimization strategy based on MPC is applied to allow the indoor temperature to fluctuate dynamically within the comfort range of 22 C-28 C in response to the electricity price signal.

Figure 1 below shows the dynamic change process of indoor temperature and power consumption of refrigeration unit on a typical day under the optimization strategy. As shown in the figure, the optimized system strengthens refrigeration in advance during the low electricity price period

(0:00-8:00), lowers the room temperature to the allowable lower limit (22°C), and uses the building heat capacity for "cold storage". During the peak hours of electricity price (10:00-12:00, 18:00-21:00), the cooling power of the system is greatly reduced, and the room temperature is allowed to slowly rise from 22°C to 28°C, thus significantly reducing the electricity load during the peak hours. This move successfully shifted the demand for electricity from high-cost period to low-cost period.

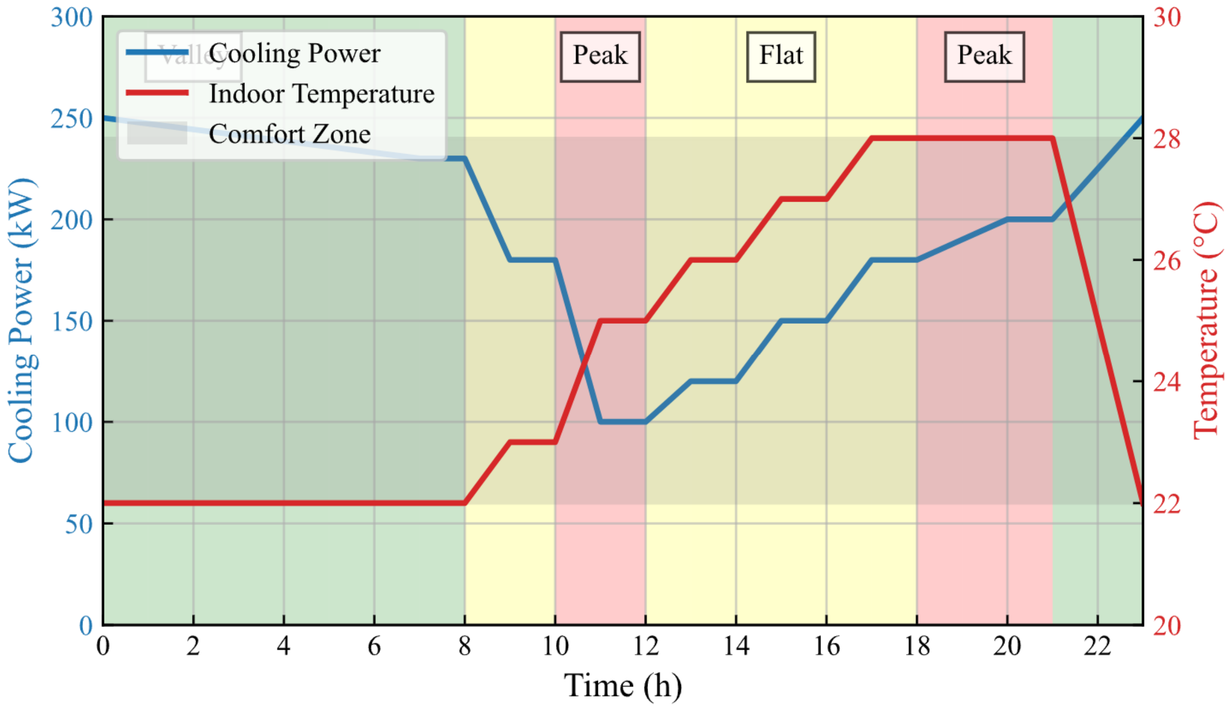

Figure 1. Dynamic response of temperature and power consumption

Table 1 below compares the running data of two scenarios in a typical week. The total power consumption is reduced by 5.6%, which is mainly due to the optimization strategy to make the refrigeration unit run in the high efficiency (high COP) range for more time. The total electricity bill dropped by 27.6%, much higher than the decrease of power consumption. This fully proves the huge cost advantage brought by the optimization strategy through demand side management (peak shaving and valley filling), and its economic benefits mainly come from the saving of electricity charges, rather than the simple energy saving. The improvement of average COP proves that the optimized operation strategy effectively improves the operation efficiency of the unit. The room temperature under the two strategies fully meets the requirements, which proves the effectiveness of the optimization strategy under the premise of ensuring environmental comfort.

Table 1. Comparison between energy saving and economy

Index	Scenario 1 (benchmark)	Scenario 2 (Optimization)	Rate of change
Total power consumption (kWh)	28,500	26,900	-5.6%
Total electricity charge (yuan)	22,300	16,150	-27.6%
Average COP	4.1	4.5	+9.8%
Room temperature compliance rate	100%	100%	0

Combining HVAC system with smart grid environment, by establishing mathematical model and adopting model predictive control optimization strategy, significant energy saving and cost reduction effects can be achieved on the premise of ensuring environmental requirements. This strategy not only reduces the operating cost of the power plant itself, but also provides support for the stable operation of the power grid by participating in the demand response, which verifies the feasibility and superiority of the method proposed in this study.

5. Conclusion

Aiming at the energy-saving optimization problem of HVAC system in power plant in smart grid operation, this paper puts forward a set of optimization strategies combining MPC and DR mechanism. By establishing the energy consumption model of HVAC system and the indoor environment heat balance model, the key factors affecting the energy consumption of refrigeration units are analyzed, and a dynamic regulation method based on time-of-use electricity price signal is designed. The case study shows that the total power consumption of centralized control room and electronic equipment room in a 600MW coal-fired power plant in a coastal area is reduced by 5.6%, the total electricity bill is greatly reduced by 27.6%, and the COP is increased by 9.8%. At the same time, the room temperature compliance rate reached 100%, ensuring the production environment and personnel comfort. These results show that the combination of HVAC system and smart grid environment, through mathematical modeling and intelligent control strategy, can not only effectively reduce the operating costs of power plants, but also provide support for the stable operation of power grids by participating in demand response, which has remarkable economic and social benefits.

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