Multi-Objective Energy-Saving Control Strategy for HVAC Systems Under Complex Climatic Conditions

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Abstract: This article focuses on the energy-saving regulation of HVAC system under complex climate conditions. At present, climate change makes HVAC systems face challenges, and it is difficult for traditional control strategies to take into account multiple objectives. This article analyzes the influence of complex climate on load, equipment and operation, designs multi-objective energy-saving strategies, establishes an energy-saving-comfort-stability model and solves it with NSGA-II. The simulation results show that the strategy can reduce energy consumption and maintain good comfort and stability in different climate scenarios, but there is still room for optimization in some scenarios. After technical, economic and environmental feasibility analysis, it is adjusted and optimized. The research results provide an effective way for energy-saving regulation of HVAC system in complex climate, which is helpful to realize the synergistic improvement of energy saving, comfort and system stability.

1. Introduction

As the main component of building energy consumption, HVAC system has attracted much attention [1]. Futhermore, climate change leads to frequent extreme weather events, and the climatic conditions in different regions become more complex and diverse, which brings great challenges to the efficient and stable operation of HVAC systems [2]. Under this background, it is of great significance to study the multi-objective energy-saving control strategy of HVAC system under complex climate conditions to reduce building energy consumption and realize sustainable development [3].

Judging from the research status, many achievements have been made in the field of energy-saving regulation and control of HVAC system. Some studies focus on single-objective optimization, such as simply pursuing energy saving and ignoring indoor comfort, or focusing on comfort but failing to effectively control energy consumption [4-5]. Other studies have focused on specific climatic conditions, but with the increase of climate complexity, the universality of these strategies is limited. Under complex climate conditions, the load characteristics and equipment performance of HVAC system will change significantly, and it is difficult for traditional control strategies to take into account multi-objective requirements such as energy saving, comfort and system stability [6]. Based on this, the purpose of this study is to construct a set of multi-objective energy-saving control strategies for HVAC systems under complex climatic conditions. Through in-depth analysis of the influence mechanism of complex climate on HVAC system, a multi-objective energy-saving regulation model is established and solved by effective optimization algorithm, so as to realize the collaborative optimization of energy saving, comfort improvement and stable operation of the system. This will not only help to promote technological innovation in HVAC field, but also provide strong theoretical and practical support for building energy conservation, which is of great practical significance for alleviating energy pressure and promoting the sustainable development of the construction industry.

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2. Influence of complex climatic conditions on HVAC system

Complex climatic conditions cover a variety of extreme or special climatic conditions, such as extreme cold, extreme heat, high humidity and changeable temperature and humidity, which significantly affect the operation of HVAC system [7]. The complex climate first changed the load characteristics of HVAC system. In winter in extremely cold areas, in order to maintain the appropriate indoor temperature, the system needs to provide a lot of heat, and the heating load increases greatly. In the hot and humid environment, in addition to cooling to reduce the indoor temperature, dehumidification is also needed, which makes the cooling load and wet load of the system increase significantly [8]. This load change is not simple and linear, and its fluctuation range and frequency are affected by climate complexity, which brings difficulties to system load forecasting.

Complex climate also has a negative effect on the equipment performance of HVAC system. Taking the compressor as an example, under extreme temperature, its performance parameters such as compression ratio and volumetric efficiency change, which leads to the increase of compressor energy consumption and the decrease of refrigeration or heating capacity [9]. In high humidity environment, the surface of heat exchanger is prone to condensation, which affects the heat transfer efficiency and reduces the overall performance of the system. In addition, the changeable climatic conditions make the equipment start and stop frequently or run under non-rated working conditions, which accelerates the wear and tear of the equipment and shortens its service life.

Moreover, the complex climate increases the difficulty of HVAC system operation control. The traditional constant parameter control strategy is difficult to adapt to the rapid change of load in complex climate, and it is easy to lead to the decrease of indoor comfort or the increase of energy consumption [10]. In order to achieve accurate regulation, it is necessary to monitor the climate parameters in real time and adjust the system operation mode and parameters in time. This requires higher response speed and intelligence of the control system.

3. Design of multi-objective energy-saving regulation strategy

3.1. Optimal control measures of operation parameters

According to different working conditions in complex climate, the operation parameters of HVAC system are optimized from many aspects. In refrigeration mode, the flow and temperature of chilled water are dynamically adjusted according to the changes of outdoor temperature and indoor load. When the outdoor temperature is low and the indoor load is small, properly increase the chilled water temperature and reduce the pump speed to reduce the flow, thus reducing the energy consumption of the pump. In the heating mode, the heating efficiency is improved by adjusting the flow and temperature of hot water and the air volume of the air side heat exchanger. Futhermore, the start-stop time of the equipment is set reasonably, and the intelligent start-stop control strategy is adopted to avoid the ineffective operation of the equipment. For example, in the transitional season, according to the indoor and outdoor temperature difference and personnel activities, the start and stop of equipment are accurately controlled to reduce unnecessary energy consumption. Table 1 lists the optimization strategies corresponding to different climatic conditions.

Table 1 Summary of Operational Parameter Optimization Strategies

Climate Condition	Chilled Water Temp. Range (° C)	Chilled Water Flow Adjustment Ratio	Hot Water Temp. Range (° C)	Hot Water Flow Adjustment Ratio	Equipment Start/Stop Criteria

Extreme Heat	10-12	0.6-0.8	-	-	Indoor/outdoor temp. difference & load
Extreme Cold	-	-	55-60	0.7-0.9	Indoor/outdoor temp. difference & load
Transition Season	12-14	0.5-0.7	-	-	Occupancy & temp. difference

3.2. Construction of multi-objective energy-saving regulation model

The regulation model is constructed with energy saving, indoor comfort and system stability as multi-objectives. The goal of energy saving is to minimize the system energy consumption. Let the total energy consumption of the system be E, and reduce the equipment running time and energy consumption by optimizing the operation parameters $x_i(i = 1,2,\cdots,n)$, which can be expressed as:

$$E = \sum_{j=1}^{m} P_j t_j (x_i) \quad (1)$$

Where: P_j is the power of the j device, $t_j(x_i)$ is the running time of the j device under the operating parameter x_i, and m is the total number of devices. The indoor comfort target is quantified by the predicted average thermal sensation index (PMV), and the PMV value is controlled between -0.5 and 0.5 by comprehensively considering indoor temperature, humidity, wind speed and human activity intensity, so as to ensure the thermal comfort of indoor personnel.

The system stability goal is achieved by limiting the fluctuation range of equipment operation parameters, such as setting the compressor frequency change rate as Δf and the pump flow change range as ΔQ. Set the allowable maximum change rate as $\Delta f_{\max}$ and the maximum change range as $\Delta Q_{\max}$, and meet the following requirements:

$$[\Delta f| \le \Delta f_{\max} \quad (2)$$

$$[\Delta Q| \le \Delta Q_{\max} \quad (3)$$

In this way, parts wear and failure caused by frequent equipment adjustment can be avoided, and the reliability of system operation can be improved.

Here, a multi-objective function F is established, and the objectives are weighted and summed, and the weights w_1, w_2 and w_3 are adjusted according to the actual needs and importance, namely:

$$F = w_1 E + w_2 |PMV| + w_3 \left(\frac{|\Delta f|}{\Delta f_{\max}} + \frac{|\Delta Q|}{\Delta Q_{\max}}\right) \quad (4)$$

The multi-objective function is solved by optimization algorithm, and the optimal combination of operation parameters is found to realize multi-objective collaborative optimization.

3.3. Application of multi-objective optimization algorithm

Non-dominated sorting genetic algorithm -II(NSGA-II) is selected to solve the multi-objective energy-saving regulation model. NSGA-II has the advantages of fast non-dominated sorting, congestion calculation and elite reservation strategy, and can quickly search Pareto optimal solution set in complex multi-objective space.

Using operational parameters as genetic codes, the population continuously evolves through genetic operations such as selection, crossover, and mutation. Let the population size be N and the kth generation population be P_k. In each iteration process, the objective function value F_i of the individual i of the population is calculated, and the non-dominant sorting and crowding degree are calculated.

In the process of non-dominant sorting, the population P_k is divided into different non-dominant frontiers $F_1, F_2, \cdots$. Among them, the individual in F_1 is the current optimal non-dominant individual. The calculation of crowding degree is to keep the diversity of population. The formula for calculating the crowding degree I_i of individual i is:

$$I_i = \sum_{j=1}^{n} \frac{|f_{j,i+1} - f_{j,i-1}|}{f_{j,max} - f_{j,min}} \quad (5)$$

Where $f_{j,i}$ is the function value of individual i on the target j, $f_{j,max}$ and $f_{j,min}$ are the maximum and minimum values of the target j in the population respectively.

Here, outstanding individuals are retained to enter the next generation, and after many iterations, a series of optimal solutions to meet different needs are obtained for decision makers to choose appropriate control schemes according to actual conditions.

4. Strategy assessment and optimization

4.1. Construction of assessment index system

In order to comprehensively evaluate the effect of multi-objective energy-saving control strategy of HVAC system under complex climate conditions, a comprehensive assessment index system covering energy-saving effect, comfort and system stability is constructed. The energy saving effect takes the energy consumption reduction rate as the main index, that is, the ratio of the difference between the system energy consumption before and after adopting the regulation strategy and the original energy consumption, which reflects the effectiveness of the strategy in energy saving. Comfort is measured by the deviation between the actual PMV value and the target range (-0.5 to 0.5). The smaller the deviation, the higher the comfort. The stability of the system is evaluated by the fluctuation coefficient of key operating parameters of the equipment, such as the fluctuation amplitude of compressor frequency, water pump flow and other parameters in unit time. The smaller the fluctuation coefficient, the more stable the system is.

4.2. Strategy assessment based on simulation

Using professional HVAC system simulation software, a system model is constructed which conforms to the complex climate characteristics. Set different climate scenarios, including extreme cold, extreme heat, high humidity and other typical working conditions, and simulate the multi-objective energy-saving control strategy. During the simulation process, the data of various assessment indexes are recorded in real time. In the scenario of simulating an extremely hot climate, the energy consumption data, the indoor PMV value and the fluctuation of equipment operation parameters of the system before and after the implementation of the control strategy are recorded. The simulation results are shown in Table 2 and Figure 1:

Table 2 Assessment Results of Multi-Objective Energy-Saving Strategy

Climate Scenario	Energy Reduction Rate (%)	PMV Deviation	Equipment Parameter Fluctuation Coefficient
Extreme Cold	18.5	0.08	0.06
Extreme Heat	22.3	0.12	0.07
High Humidity	16.7	0.10	0.05

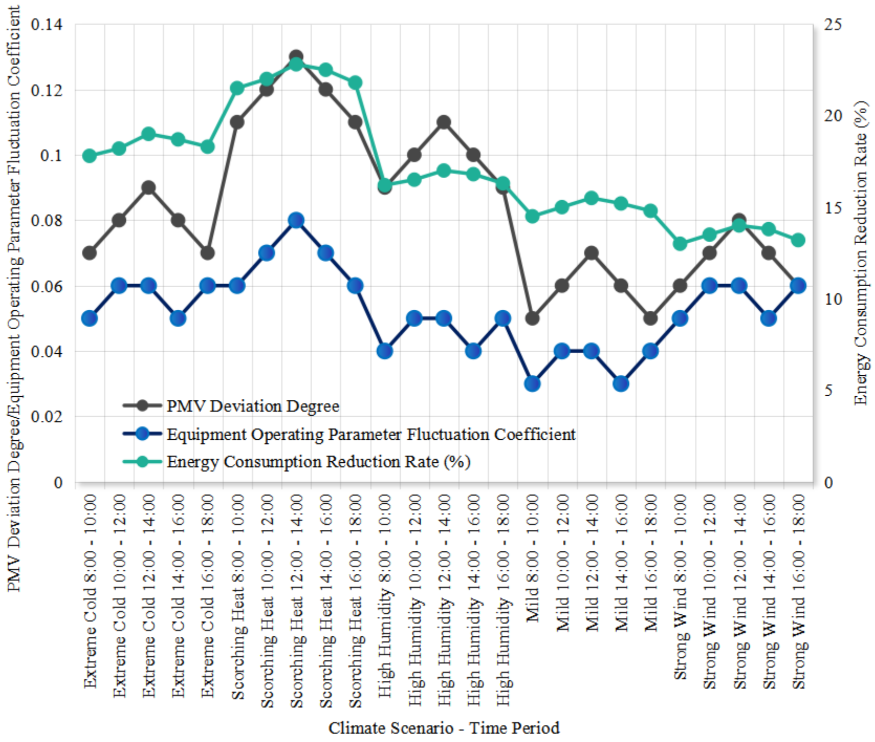

Figure 1 Assessment indicators in different time periods

It can be seen from Table 2 and Figure 1 that the control strategy can reduce energy consumption to a certain extent in different climate scenarios, while maintaining good comfort and system stability. However, there are also some differences. For example, the energy consumption reduction rate is relatively high in the extremely hot scene, but the PMV deviation degree is slightly greater than other scenes, which indicates that the comfort guarantee can be further optimized in the extremely hot conditions.

4.3. Feasibility analysis of strategy

The feasibility of multi-objective energy-saving control strategy is analyzed from three dimensions: technology, economy and environment. Technically, the adopted load forecasting method, operation parameter optimization measures and multi-objective optimization algorithm are all realizable under the current technical level, and have good compatibility with the existing HVAC system. Economically, although the implementation of control strategy may require some initial investment, such as equipment upgrading and control system optimization, in the long run, the reduction of energy consumption will bring significant economic benefits, and the payback period can be determined through cost-benefit analysis. From the environmental point of view, the improvement of energy-saving effect means reducing greenhouse gas emissions caused by energy consumption, which is of positive significance to environmental protection.

4.4. Strategy optimization

Based on the assessment results, the multi-objective energy-saving regulation strategy is optimized. Aiming at the problem that the PMV deviates slightly in the hot scene, the optimization strategy of operation parameters is adjusted, and the indoor temperature and humidity are further finely controlled on the premise of ensuring energy saving. For example, the adjustment curve of chilled water temperature and flow rate is optimized to make it more suitable for indoor load changes in extremely hot climate. Futhermore, the adaptive control strategy is considered to dynamically adjust the weight of each target according to the real-time monitoring climate parameters and indoor environment feedback, so as to better balance energy saving, comfort and system stability. Through continuous optimization, the comprehensive performance of multi-objective energy-saving control strategy in complex climate conditions has been further improved to meet the diversified needs in practical applications.

5. Conclusions

This article discusses the multi-objective energy-saving control strategy of HVAC system under complex climate conditions, aiming at solving the challenges brought by complex climate and realizing the coordinated optimization of energy saving, comfort and system stability.

By analyzing the influence of complex climate on HVAC system, the problems such as the change of load characteristics, the suppression of equipment performance and the increase of operation control difficulty are clarified. On this basis, a set of multi-objective energy-saving control strategies is designed. Based on the load forecasting strategy of climate prediction, machine learning algorithm is used to improve the forecasting accuracy; Optimizing control measures of operation parameters, dynamically adjusting according to different climatic conditions, effectively reducing energy consumption; A multi-objective energy-saving regulation model is constructed, which takes into account energy saving, comfort and system stability, and is solved by NSGA-II algorithm to obtain the optimal operation parameter combination.

After simulation assessment, the strategy shows its effectiveness in different climate scenarios, with obvious energy consumption reduction, guaranteed indoor comfort and good system stability. However, in hot scenes, although the energy consumption reduction rate is considerable, there is still room for improvement in comfort index. The feasibility analysis of technology, economy and environment proves that the strategy is feasible in practice.

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