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Article

Research on temperature control optimization method of ice storage refrigeration system empowered by Internet of Things in digital transformation environment

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Abstract: Aiming at the problem of high energy consumption and low level of intelligent operation and maintenance of ice storage cold air conditioning system, this paper analyzes the intelligent operation and maintenance design of ice storage cold air conditioning system empowered by Internet of Things (IoT) technology. In order to optimize the control of temperature during the operation of ice storage cold air conditioning system and achieve the goal of minimizing the operation energy consumption, this paper adjusts the inertia weight of particle swarm optimization algorithm, introduces the artificial immunity idea to form the immune particle swarm algorithm, and strengthens the algorithm's ability of local optimization. Through the AI-PSO algorithm to optimize the ice storage air conditioning system PID controller parameters to solve the objective function. The optimization results of the ice storage air conditioning system show that under different ratios of rated demand loads, the optimization results of the AI-PSO algorithm have smaller fluctuation values and the system consumes less energy. In the same cooling cycle, the AI-PSO algorithm is 27.29% and 8.08% smaller than the mainframe-first and ice-melting-first control methods, respectively, with significant peak-shaving and valley-filling effects, and better energy-saving effects and control quality. Compared with the host-first and ice-melting-first methods, the method has better temperature control effect and economic benefits.

Keywords: ice storage cooling system; particle swarm optimization algorithm; intelligent operation and maintenance; system energy consumption; internet of things technology

1. Introduction

In recent years, China is gradually increasing the share of new energy power generation such as wind power and photovoltaic in the country's total power generation capacity [1-2]. However, due to the intermittent and unstable nature of new energy generation such as wind and photovoltaic, it brings great challenges to the real-time balance of supply and demand in the power system [3-4]. The policy of guiding demand-side flexible loads to synergize with new energy generation (i.e., demand response) by adopting time-sharing tariffs or real-time tariffs in various regions is an important technological path to ensure the effective consumption of a high proportion of new energy in the future [5-7]. In this context, the ice storage refrigeration system makes full use of the price advantage of time-sharing tariffs by cooling energy storage during trough tariffs and releasing cooling during peak tariffs, which reduces the cost of energy supply and absorbs the fluctuations of electric loads, and is of positive significance for the development of new energy generation in the country [8-11].

With the development and application of the Internet of Things (IoT), the Ice Storage and Refrigeration System empowered by IoT has realized the intelligent management of the system [12-13]. The IoT-enabled ice storage refrigeration system, which has no mechanical moving parts, is characterized by no noise, no vibration, long service life, and high work reliability [14-15]. In particular, it does not require a refrigeration mass, eliminating the possibility of ice storage refrigeration harming the human body and polluting the environment. In the context of digital transformation, the IoT-enabled ice storage refrigeration system will in turn develop in a more intelligent direction [16-17]. The digital transformation of the system can realize the use of big data, cloud platforms and other technologies to achieve the automatic collection and optimization of energy consumption data, optimizing the system temperature control, improving the energy utilization rate and reducing the overall energy consumption [18-20].

This paper analyzes the types and characteristics of cold storage media, combines the temperature control optimization requirements of ice storage refrigeration system, describes the working principle of ice storage air-conditioning system, analyzes its operation mode as well as applicability characteristics. It analyzes the intelligent operation and maintenance of ice storage cooling system empowered by Internet of Things from the aspects of schedule optimization control and fault rule warning. A typical control method of ice storage air conditioning system is proposed, and the key components model of ice storage system is established, and the optimization objectives are set and constraints are provided to form a multi-objective global optimization mathematical model for the ice storage system. The AI-PSO algorithm is used to solve the problem, and the AI-PSO algorithm is used to optimize the PID controller parameters of the ice storage system. Simulation experiments of the ice storage and cold system are carried out to compare and analyze the system energy consumption results of the system under different strategies.

2. Internet of Things (IoT) enables intelligent temperature control of ice storage and refrigeration systems

2.1. Cooling medium

Cold storage systems are mostly distinguished according to the type of cold storage medium, which can be mainly categorized into water, ice and eutectic salt cold storage systems, and the main technical characteristics of the three types of medium are shown in Table 1.

Table 1. The main technical characteristics of the three kinds of cold medium

Cryogenic medium	Temperature parameter	Technical characteristics	
Water	Return water temperature difference/ 6~12℃	Merit	Low investment, low technical requirements, low maintenance and low maintenance cost, the water temperature of the storage water can be consistent with the water supply of the system, which can be used directly
		Shortcoming	The cooling device is larger and colder. The insulation and waterproof measures require high.
Ice	Water supply temperature/ accessibility 0℃	Merit	The unit storage device is small, and it is suitable for a large number of cold buildings to be released in the short term.
		Shortcoming	At least one two-condition cold water unit is configured, and the cop is reduced under the ice condition.
Eutectic salt	Phase transition temperature/ 6~8℃	Merit	The cooling device is between water and ice.
		Shortcoming	The requirement for phase change materials is high, and the equipment investment is higher, and the application is less.

2.2. Ice storage air-conditioning systems

Ice storage technology utilizes the process of water transforming from a liquid to a solid state to store cold, and when refrigeration occurs the stored ice is transformed from a solid state back to a liquid state, and the phase change process releases the stored cold, which is supplied to the indoor air-conditioning system to achieve cooling. This technique actually utilizes the properties of latent heat of phase change for the purpose of storing and releasing cold [21].

2.2.1. Conventional system operating principles

Conventional ice storage air-conditioning system is shown in Figure 1, which consists of three subsystems, namely, cooling water circulation system, solution circulation system and chilled water circulation system.

Cooling water system: the cooling water system is an important part of the ice storage cold air conditioning system, consisting of refrigeration units, cooling towers and cooling water pumps. Its working principle is that the cooling water cooled down by the cooling tower absorbs the heat of the refrigeration host through the condenser, thus maintaining the normal operation of the refrigeration host. After absorbing the heat of the cooling water is pressurized and sent back to the cooling tower through the heat and humidity exchange with the outdoor air and cooling, so the cycle repeats.

Solution system: The solution system is a key component of the ice storage air-conditioning system, consisting of ice storage device, double-condition refrigeration unit and plate heat exchanger and other components, different operating conditions can be realized through the control valve. Glycol solution is the commonly used refrigerant, the purity of the solution is 10%, the freezing point is -12.6℃, the low freezing point nature can ensure that the glycol solution is always in liquid state to meet the demand of the system working temperature.

Chilled water system: It is composed of chilled water pump, plate heat exchanger and end. The chilled water flows through the heat exchanger to absorb the cold quantity transferred by the low-temperature glycol solution, and then sends the cold quantity to the air-conditioning end for cooling.

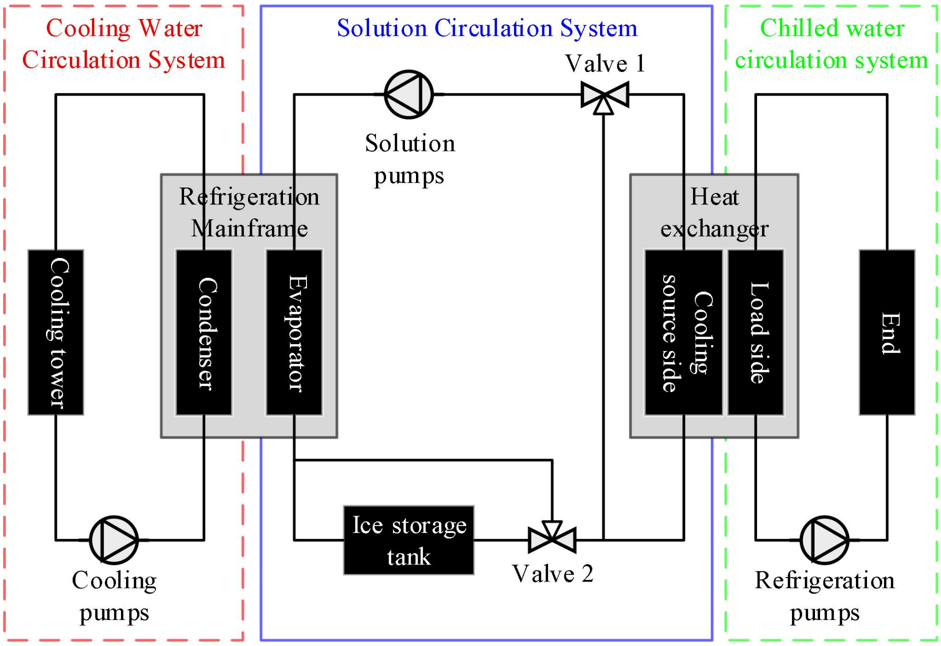

Figure 1. Conventional ice storage air-conditioning system

2.2.2. Modes of operation

The ice storage system can realize four different working modes by controlling the switching and adjusting of the electric valve, including ice storage in the host computer, separate cooling supply in the host computer, joint cooling supply in the host computer and ice storage tank, and separate cooling supply in the ice storage tank. These different working modes have different operation methods and application scenarios, and can be selected and adjusted according to actual needs.

2.2.3. Applicability analysis

The economy of ice storage air-conditioning in the cold and heat source system is mainly affected by the following two factors: firstly, the power policy of the power supply department has a great influence on it, such as whether the electricity price adopts the peak-valley time-sharing system, whether the difference in the price of electricity in peak and valley hours is large, and whether there is a corresponding preferential policy for the price of electricity, and so on. Secondly, the air-conditioning cold load characteristics of the user's building also has a great impact on it, such as whether the air-conditioning cold load is in a part-load state of the time is more, whether the average load in the unit cycle is less than the peak load is more, whether the power peak and peak hours and the load of the peak section of the overlap is higher and so on.

2.3. Ice storage system intelligent operation and maintenance

The intelligent operation and maintenance cloud platform empowered by IOT provides one-stop energy management and intelligent operation and maintenance solutions and services for centralized air-conditioning systems, which can carry out all-around management and monitoring of the air-conditioning system, realize the visualization of all-area sensory data, and use big data analysis to conduct deep mining of the system's operation data to save the use and management costs.

The following focuses on the application of intelligent operation and maintenance cloud platform in the intelligent operation and maintenance of ice storage cooling system from the perspective of optimization control and fault diagnosis.

2.3.1. Schedule optimization control

The schedule for the operation mode of the ice storage air-conditioning system was formulated on the basis of the local peaks and valleys ladder tariff, and the changes in the actual air-conditioning load were not taken into account at the initial stage of formulation. After the system has been running for some time, it is found that: as the outdoor temperature rises and the air-conditioning load increases, the ice storage capacity of the ice storage tank will be consumed in advance when the system is operated according to a fixed schedule. As the outdoor temperature drops and the air-conditioning load decreases, when the system is operated according to a fixed schedule, the ice storage capacity of the ice storage tank will be too much, resulting in a waste of energy. Based on the data collected by the intelligent operation and maintenance cloud platform, the schedule optimization control algorithm is developed to predict the building load on the 2nd day in advance, and adjust the operation mode schedule according to the predicted load, so that the ice storage capacity of the ice storage tank is just used up while shortening the operation time of the host as much as possible, and achieving the purpose of the lowest electricity cost of the air conditioning system operation.

The schedule optimization control algorithm is mainly composed of three parts: data processing module, system modeling module, and control optimization module.

Data processing module: It is used to obtain the real-time data of the power grid, weather station and air conditioning system and perform data pre-processing operations on them, including data cleaning, feature extraction, standardization and other steps, to provide effective data input for the subsequent system modeling and control optimization.

System modeling module: Based on the historical data of the system (external environmental variables, controllable variables, state parameters, etc.), a neural network is used to establish a system prediction model, including a duplex mainframe model, a base-loaded mainframe energy consumption model, a pump and cooling tower model and an ice storage tank model. The equipment energy consumption model is shown in equations (1) to (7). Namely:

$$P_{\mathrm{ch1}} = f_1\left(Q_{\mathrm{ch1\_c}}, Q_{\mathrm{ch1\_i}}, t_{\mathrm{cwr}}, t_{\mathrm{chw1}}\right) \tag{1}$$

$$P_{\mathrm{ch2}} = f_2\left(Q_{\mathrm{ch2}}, t_{\mathrm{cwr}}, t_{\mathrm{chw2}}\right) \tag{2}$$

$$P_{\mathrm{chp1}} = f_3\left(N_{\mathrm{ch1}}, f_{\mathrm{chp1}}\right) \tag{3}$$

$$P_{\mathrm{chp2}} = f_4\left(N_{\mathrm{ch2}}, f_{\mathrm{chp2}}\right) \tag{4}$$

$$P_{\mathrm{cdp1}} = f_5\left(N_{\mathrm{ch1}}, f_{\mathrm{cdp1}}\right) \tag{5}$$

$$P_{\mathrm{cd2}} = f_6\left(N_{\mathrm{ch2}}, f_{\mathrm{cdp2}}\right) \tag{6}$$

$$P_{\mathrm{ct}} = f_7\left(N_{\mathrm{ch1}}, N_{\mathrm{ch2}}, t_{\mathrm{cwr}}\right) \tag{7}$$

In Eq. (1)~(7), P_{ch1} is the power of duplex main engine, kW. $Q_{\mathrm{ch1\_c}}$ is the refrigeration working load of duplex main engine, kW. $Q_{\mathrm{ch1\_i}}$ is the ice working load of duplex main engine. kW. t_{cwr} is the cooling tower return water temperature, °C. t_{chw1} is the duplex main machine discharge water temperature, °C. P_{ch2} is the power of the base load host, kW. Q_{ch2} is the load of the base load host, kW. t_{chw2} is the temperature of the discharge water from the base load host, °C. P_{chp1} is the power of chilled water pump of duplex host, kW. N_{ch1} is the number of operating units of duplex host. f_{chp1} is the operating frequency of the chilled water pump of the main engine in dual condition, Hz. P_{chp2} is the power of the chilled water pump of the main engine in kW. N_{ch2} is the number of the main engine operating in base load. f_{chp2} is the frequency of operation of the chilled water pump of the base load mainframe, Hz. P_{cdp1} is the power of the cooling water pump of the mainframe in duplex condition, kW. f_{cdp1} is the frequency of operation of the chilled water pump of the mainframe in duplex condition, Hz. P_{cdp2} is the power of the base load main engine cooling water pump, kW. f_{cdp2} is the operation frequency of the base load main engine cooling water pump, Hz. P_{ct} is the power of the cooling tower, kW.

Ice storage tank has refrigeration and ice-making 2 kinds of working conditions. 2 kinds of working conditions under the ice storage tank ice storage volume proportion of the change rule is different, so for the refrigeration conditions and ice-making conditions respectively to establish the ice storage tank model, see formula (8), (9). That is:

Refrigeration conditions:

$$S(\tau)=g_1\left(Q_{\mathrm{tank}}(\tau-1),S(\tau-1),t_{\mathrm{wb}}(\tau-1)\right) \tag{8}$$

Ice making conditions:

$$S(\tau)=g_2\left(Q_{\mathrm{ch1\_i}}(\tau-1),S(\tau-1),t_{\mathrm{wb}}(\tau-1)\right) \tag{9}$$

In Eqs. (8) and (9), $S(\tau)$ is the ratio of the volume of ice storage volume in the ice storage tank at the moment of τ. $Q_{\mathrm{tank}}(\tau-1)$ is the cooling capacity of the ice storage tank at the $\tau-1$ moment, kW. $S(\tau-1)$ is the proportion of the ice storage volume of the ice storage tank at the $\tau-1$ moment. $t_{\mathrm{wb}}(\tau-1)$ is the outdoor wet bulb temperature at the moment of $\tau-1$, °C. $Q_{\mathrm{ch\_i}}(\tau-1)$ is the refrigerating capacity of the ice condition of the main dual-stage mechanism at the moment of $\tau-1$, kW.

Control optimization module: this module can be based on the system prediction model in the future within a certain time span of the system prediction results, the use of optimization algorithms to solve the optimal combination of control sequences, in order to achieve the goal of the lowest system electricity costs.

2.3.2. Fault rule warning

Failure rule warning is a method of online detection of state abnormalities and operational failures of HVAC equipment based on the HVAC equipment expert rule base established by the “IFELSE” judgment logic. Failure rule diagnosis is characterized by wide coverage, strong versatility and flexible deployment, and can realize most of the fault diagnosis of air conditioning system.

3. Ice storage system temperature control optimization strategy

3.1. Regulation of a typical ice storage air-conditioning system

Ice storage air-conditioning systems include air-conditioning mainframes, chilled water pumps, cooling water pumps, cooling towers, cold storage water pumps, cooling water pumps, heat exchangers, ice storage tanks and so on.

Compared with conventional air-conditioning systems, ice storage air-conditioning systems add ice storage tanks, heat exchangers and other devices. Ice storage air-conditioning system will be in the power load is very low at night, that is, the use of electricity during the trough period, the use of electric chiller refrigeration, the cold in the form of ice storage. During the daytime when the electric load is high, that is, during the peak period of electricity consumption, the stored cold volume is released to meet the demand of the air-conditioning load of the building. At the same time, in the spring and fall when the air conditioning usage is small, reduce the opening of the electric chiller and try to melt ice to release cold to meet the air conditioning load. The use of ice storage air-conditioning systems is a method of “shifting the electricity load” or “balancing the electricity load”.

3.2. Mathematical modeling of key system components

3.2.1. Refrigerated water pump model

Circulating water pump speed frequency control is the use of frequency converters to adjust the motor supply frequency, as a way to regulate the speed of the pump, the mathematical relationship can be expressed as equation (10):

$$n = 60f\frac{1-s}{m} \tag{10}$$

Where n is the rotor speed, r/min. 60 is the conversion factor, f is the frequency of power supply, Hz. s is the rotation rate between stator and rotor. m is the number of pole pairs of the motor winding. From the formula (10), the rotational speed n and frequency f is proportional to the change of f can be realized by the speed control of the pump.

By the similarity law of the pump is not difficult to find, the pump flow and impeller diameter or shaft speed is obviously positively correlated, that is, with the impeller diameter or shaft speed changes, the flow rate is synchronized by an equal proportion of change. Then the pump flow and speed of the relationship between the existence of such as formula (11):

$$\frac{Q}{Q_m} = \frac{n}{n_m} \tag{11}$$

In the formula, n represents the rotational speed of the pump, r/min. Q represents the flow rate of the pump, m^3/h .

Therefore, the I/O characteristic between the frequency and flow rate of the chilled water pump can be expressed as equation (12):

$$G_p(s) = \frac{f}{Q} = K_p \tag{12}$$

3.2.2. Modeling of charge-cooling regulator valves

For the charge-cooling control valve, there is a valve gain k_v and also a certain time constant τ_v . Therefore, the transfer function of the valve can be expressed as the following equation:

$$G_v(s) = \frac{k_v}{\tau_v s + 1} \tag{13}$$

Generally speaking, control valves can be divided into four types of models according to the flow characteristics of the fluid: equal percentage, linear, parabolic and fast-opening. With equal percentage flow characteristics of the valve in the opening of the smaller flow change is small, the flow can be adjusted smoothly. And in the large opening degree has a high sensitivity to accurately regulate the flow. Therefore, with equal percentage flow characteristics of the valve in the regulation of performance excellence, and thus is widely used in the field of engineering.

Data center chilled water system cooling regulator valves are mostly used in equal percentage regulator valves, and their flow characteristics can be expressed by equations (14) and (15):

$$\Phi = \Phi_0 R_V^h \tag{14}$$

$$R_V = \frac{\text{Maximum control flow rate}}{\text{Minimum control flow}} = \frac{Q_{\max}}{Q_{\min}} \tag{15}$$

Where Φ represents the flow coefficient at a specific opening. R_V is the adjustable ratio, which represents the ratio of the maximum flow rate to the minimum flow rate that can be controlled. h is the relative opening. Φ_0 is the initial flow coefficient.

3.2.3. End piping models

The presence of a pressure difference in a pipe causes the fluid to flow, and the higher the pressure difference between pipe sections, the faster the water will flow and the more flow will pass through the pipe section. The relationship between flow rate and pressure difference between pipe sections can be expressed by the following equation:

$$Q = \frac{\Delta P}{R_f} \tag{16}$$

$$R_f = \frac{8\eta l}{4\pi r^2} \tag{17}$$

Where R_f is the hydraulic resistance. η is the liquid viscosity, l is the pipe length, and r is the pipe radius. It follows that I/O of flow and differential pressure is a typical proportional link.

In the pipeline sidewalls without changes in the uniform flow section of the resistance to flow is called along the resistance or friction resistance. Along the resistance caused by the fluid flow process energy loss or head loss, along the resistance uniformly distributed throughout the uniform flow section, and with the length of the pipe section is proportional to the relationship between the h_f expressed. Hazen-William formula is widely used in water distribution network hydraulic calculation, the form of the following formula:

$$h_f = \frac{10.667 l}{C^{1.852} d^{4.87}} q^{1.852} \tag{18}$$

Where C is the Hazen-William coefficient. d is the inner diameter of the pipe, m. l is the length of the pipe section, m. q is the flow rate, and m^3/s.

With the rapid change of the pipeline wall along the course of the energy loss will be concentrated in some specific areas, this concentration occurs in a specific area of energy loss or resistance is called local loss or local resistance, also known as the local head loss. Local resistance or local loss often occurs in the pipe section cross-section of the sudden change, the import and export of the pipe, as well as bends and other locations, with h_i said. Distribution network hydraulic calculation, generally do not consider the local head loss.

3.3. Establishment of mathematical model for multi-objective global optimization

In this paper, the following assumptions are used in the multi-objective global optimization solution:

(1) The ice storage cooling air conditioning system studies mainly the energy-consuming equipments measured by the cold source, which are mainly double-condition refrigeration units, glycol circulation pumps, chilled water pumps, chilled water pumps, cooling water pumps, and cooling towers, and the remaining equipments consume negligible energy or are not taken into account.

(2) It is considered that the total cooling load borne by the refrigeration unit at each moment is distributed equally among the chillers. After study, this condition is the optimal load distribution for parallel operation of refrigeration units.

(3) Each cycle the unit stores ice from 0:00 to 8:00, the building works from 9:00 to 18:00, the ice storage tank and the chiller do their best to supply the building with cold at this stage, and the rest of the time the building does not need to be supplied with cold and does not consume any energy, and the equipment does not work for the rest of the time.

(4) The ice storage working condition of the refrigeration unit at night is operated at an average load rate according to the amount of ice storage and the working time of the ice storage.

3.3.1. Determination of the objective function

The optimized regulation of ice storage and cold air conditioning system aims to solve the problems of optimizing energy allocation, balancing the peak and valley differences of the power grid, and saving operating costs. Therefore, in order to improve the operation energy efficiency of the air conditioning system and balance the two optimization indexes of system energy consumption and operation cost, this paper takes the minimum operation energy consumption and the minimum operation cost as the objective function, and optimizes the operation strategy of time-by-time cooling supply during the operation cycle of the ice storage air conditioning system under the guarantee of the demand of the building load and the constraints of the system. According to the calculation results of the building load prediction model, with the objective of minimizing the operation cost and energy consumption of the air conditioning system, the ice storage volume at night, the next day daytime refrigeration unit and the ice storage tank time-by-time cold distribution are obtained. The specific mathematical model of the optimization objective is as follows:

Optimization objective one is the energy consumption of the ice storage air conditioning system, i.e., minimizing the sum of the energy consumption of the chiller unit, cooling tower, cooling water pump, glycol circulating water pump, and chilled water pump during the operating cycle of the ice storage air conditioning system. See the following formula:

$$f_1 = \sum_{i=1}^{n} \left(P_{ch}(i) + P_{ct}(i) + P_{mq}(i) + P_{my}(i) + P_{md}(i) \right) \tag{19}$$

Where i -current moment.

Optimization objective two is the operating cost of the ice storage air conditioning system (yuan), according to the time-sharing tariff policy, the operating cycle cost of the ice storage air conditioning system, i.e., the sum of the product of the total energy consumption at each moment of the operating cycle and the electricity price at the corresponding moment, is shown in the following equation:

$$f_2 = \sum_{i=1}^{n} \left(\left(P_{ch}(i) + P_{ct}(i) + P_{mq}(i) + P_{my}(i) + P_{md}(\mathrm{i}) \right) * E(i) \right) \tag{20}$$

Where E - time-sharing electricity price, yuan/kWh.

Therefore the multi-objective optimization model is the sum of two optimization objectives. Due to the nature of different objectives, units of measurement and different quantities, the actual data of each objective needs to be processed, and this paper adopts the objective weighting method, see the following formula. Then it is synthesized into a multi-objective global optimization model. Eq:

$$Z_{\min} = A_1 * f_1 + A_2 * f_2 \tag{21}$$

where A_1, A_2 are the weights of individual objectives, $A_1 + A_2 = 1$, which can be adjusted according to the optimization to be achieved.

3.3.2. Determination of constraints

(1) Constraints on the total amount of ice melted in ice storage. If the daytime ice storage tank melting ice volume is less than the nighttime ice storage volume, that is, part of the ice is not used up in the cycle, due to the ice storage tank ice preservation process there is a loss of energy, and ultimately lead to a waste of cold. Therefore the total amount of ice stored during the operating cycle should be less than the capacity of the ice storage tank, and the total amount of ice melted in the ice tank should be less than the expected total amount of ice stored in the ice tank, and should be greater than 98% of the total amount of ice stored. I.e.:

$$Q_{ice,st} \le 53935 \tag{22}$$

$$Q_{ice,st} * 0.98 \le Q_{tank} \le Q_{ice,st} \tag{23}$$

Where $Q_{ice,st}$ -Total ice storage in ice storage tank, kWh. Q_{tank} -Total cooling supply in ice storage tank, kWh.

(2) Refrigeration unit maximum cooling capacity constraints. The cooling capacity of the refrigeration unit should not exceed the maximum capacity, i.e., its load ratio does not exceed 1 and is not less than zero. I.e.:

$$0 \le x(i) \le 1 \tag{24}$$

(3) Maximum ice melting rate constraint. Ice storage tank of the maximum melting rate and the remaining ice volume, this paper according to measured data and equipment parameters to calculate the melting ice working conditions of the ice storage tank by time the maximum melting rate, that is, the ice storage tank each moment of the cooling capacity should be less than its maximum melting rate. That is:

$$b(i) \le b(i)_{\max} = 13080 \frac{B_e(i)}{53935} \tag{25}$$

Where b -ice storage tank hour-by-hour cooling supply, kW. B_e -remaining ice volume, kWh.

(4) System cooling quantity constraint. Building cold load by the refrigeration unit and ice storage tank together, in order to make the building load supply and demand matching, the unit time of the two to provide the cold volume should be equal to the moment of the building cold load. That is:

$$Q_{ch}(i) + b(i) = Q(i) \tag{26}$$

3.3.3. Determination of multi-objective optimization algorithm

(1) Particle Swarm Optimization Algorithm

Particle swarm optimization algorithm (PSO) can achieve the solution of complex nonlinear functions. In order to get the optimal value of the multi-objective optimization model, particle swarm optimization algorithm is chosen to solve the problem [22].

The basic PSO algorithm optimization steps are as follows:

Step 1: Set the values of each parameter of the algorithm and randomly initialize the velocity and position of the particle population.

Step 2: Evaluate the adaptation value of each particle, judge the individual optimal pbest of the particle's current position, and update the particle global optimal gbest.

Step 3: Judge the iteration termination condition, output the optimal solution if the condition is satisfied, otherwise continue to the next step.

Step 4: Eq. (27) and Eq. (28) update the particle velocity, position, and turn to step 2. Eq:

$$v_{id}^{t+1} = w v_{id}^{t} + c_1 r_1 \left(P_{id}^{t} - x_{id}^{t} \right) + c_2 r_2 \left(P_{gd}^{t} - x_{id}^{t} \right) \tag{27}$$

$$x_{id}^{t+1} = x_{id}^{t} + v_{id}^{t} \tag{28}$$

(2) Artificial immune particle swarm algorithm

The inertia weight descent strategy adopted in this paper can better meet the requirements of PSO algorithm for inertia weights in the iterative process. Although the above improved PSO algorithm has a more suitable update rate, it still cannot get rid of the problem of easy convergence to local optimum.

AI algorithm is a learning algorithm that imitates the natural defense mechanism of human body so as to solve the problems of data processing, fault diagnosis, and optimal control. In order to optimize the temperature control of the IoT-enabled ice storage system, the introduction of artificial immunity ideas in the PSO algorithm can retain the high adaptability particles in the optimization process while expanding their diversity, guide the search process and inhibit the degradation phenomenon so that it is easier to converge to the global optimum, thus effectively solving the problem of uncertainty uptake in the model parameters. The improvement of PSO algorithm by using AI algorithm mainly introduces four behavioral ideas of immune memory, self-regulation, vaccination and immune selection in human immune system. The following improvements can be made by imitating the above four behaviors:

a. mimic the immune memory behavior to store quality particles, i.e., the particles with the highest fitness value generated in each iteration are stored as memory particles.

b. Mimic self-regulatory behavior to replace unavailable particles by detecting N new particles after each iteration, and replacing them with the previous generation of memorized particles if one of the particles' position vector X has a dimension that is not in the specified value range.

Before mimicking the behavior of vaccination and immune selection, M randomly generated compliant particles are required, and then N new particles are newly picked among the $M+N$ particles according to affinity strength and concentration. When the value of particle fitness increases, its affinity is stronger, so the inverse of fitness function can be taken to express the affinity, i.e.:

$$A_i = 1 / J_i \tag{29}$$

Then the probability of selection determined by affinity is:

$$H_{i1} = A_i / \sum_{k=1}^{N+M} A_k \tag{30}$$

The concentration of particles can be approximated as:

$$C_i = 1 / \left(\sum_{k=1}^{M+N} \left| J_i - J_k \right| \right) \tag{31}$$

Then the probability of selection determined by concentration is:

$$H_{i2} = C_i^{-1} / \sum_{k=1}^{N+M} C_k^{-1} \tag{32}$$

In summary, the probability that a particle is selected is:

$$H_i = \alpha H_{i1} + (1-\alpha) H_{i2} \tag{33}$$

where $i = 1, 2, \cdots, M+N, \alpha \in [0,1]$ is the weighting factor. The $M+N$ particles are sorted according to the H_i size, and the first N particles with larger H_i are selected.

c. Improve the PSO algorithm by mimicking the behavior of vaccination, i.e., select a certain particle from N new particles, and then replace the value of the corresponding dimension of the selected particle with a certain dimensional component from the position vector of the previous generation of memorized particles $X(t)$.

d. Improve the PSO algorithm by mimicking the behavior of immune selection, i.e., to check whether each dimension of the position vector of the vaccinated particles meets the constraints, and if not, then discard them, or else find the fitness value. If the obtained fitness value is smaller than before vaccination it is discarded, otherwise probability calculation is performed, i.e., a value is generated using rand() and compared with the threshold p. If it is greater than, the parent particle is replaced with the vaccinated particle, otherwise it is discarded.

(3) AI-PSO algorithm to optimize PID controller parameters

The conventional PID control rate is shown in the following equation:

$$u(t) = K_p \left[e(t) + \frac{1}{T_i} \int_0^t e(t) \mathrm{d}t + T_d \frac{\mathrm{d}e(t)}{\mathrm{d}t} \right] \tag{34}$$

where $e(t)$ is the control deviation and $e(t) = r(t) - y(t); u(t)$ is the control output. K_p is the proportionality constant. T_i is the integration time constant. T_d is the differential time constant.

Optimizing the three parameters K_p, T_i, T_d in the PID controller using the AI-PSO algorithm described in the previous section is essentially a search for the optimal parameters based on a certain performance index function.

For PID controllers, the objective function is the function that measures its performance requirements, which is usually categorized into regulation quality type objective function and error integral type objective function. In order to avoid oscillation or regulation time is too long, the control amount is too large, this paper will be the time multiplied by the absolute error integral (ITAE) function as the objective function, that is:

$$ITAE = \int_0^{\infty} \left[k_1 t \,|\, e(t) \,|\, + k_2 u^2(t) \right] \mathrm{d}t \tag{35}$$

Since the smaller the value of the error integral type objective function, the better the system accuracy, it makes the fitness function of the AI-PSO algorithm as shown in the following equation:

$$J = \frac{1}{\int_0^{\infty} \left[k_1 t \,|\, e(t) \,|\, + k_2 u^2(t) \right] \mathrm{d}t} \tag{36}$$

4. Analysis of the results of the optimization of the ice storage system

4.1. Case Selection

In this paper, an ice storage air conditioning unit system is selected as a validation case for an industrial park, which is divided into K1 and K2 zones. The system in K1 zone of the industrial park consists of five 3500kW chillers and the system in K2 zone of the industrial park consists of three 3500kW and four 2500kW chillers.

The PSO and improved PSO algorithms are used to compute the optimal cooling load optimization scheduling problem under summer TOU, respectively, in order to solve the optimal summer scheduling plan of the ice storage air conditioning system and to seek the minimum operating cost.

The input data include the total system cooling load, TOU, operating status of each chiller unit, cooling load, chilled water temperature, ice storage process and ice storage water temperature.

In this case, some of the chiller models are the same as the rated cooling capacity. However, in actual operation, the differences in working conditions, set temperature, working time, flow rate, etc., lead to differences in performance parameters between the same chiller units, and the performance parameters of each chiller of the ice storage air conditioning unit are shown in Table 2.

Table 2. Performance parameters of each equipment in the unit

Industrial park	**Cold number**	α	β	γ	δ	**Rated refrigerating /kw**
K1 region	1	112.36	897.35	-1100.36	850.72	3500
	2	145.01	300.16	30.59	226.41	3500
	3	89.64	652.89	-500.27	409.42	3500
	4	230.85	571.43	80.64	162.05	3500
	5	300.05	420.51	120.91	300.47	3500
K2 region	1	-95.12	780.91	360.85	0	3500
	2	-150.78	620.14	420.95	0	3500
	3	465.14	-100.55	300.51	0	3500
	4	100.92	120.75	-280.78	0	2500
	5	235.45	200.69	290.64	0	2500
	6	320.13	300.11	580.27	0	2500
	7	250.09	150.64	620.94	0	2500

4.2. Analysis of results

In the following, the PSO and AI-PSO algorithms will be used for the comparison of the optimal scheduling problem for the simulation and TOU of the ice storage air conditioning system, respectively, in order to illustrate the superiority of the AI-PSO algorithm.

In order to eliminate chance errors and further verify the stability of the algorithms, the experimental data are optimized using the 2 algorithms at different load rates, respectively. To verify the adaptability and optimization seeking ability of the AI-PSO algorithm under different operating conditions.

4.2.1. Area K1

As mentioned above, at least 25% of the equipment capacity is needed to maintain the basic cooling load. According to the load demand of this industrial park, in order to fit the actual working situation, the rated demand loads of ice storage units are selected at 80% and 40%, respectively.

The number of iterations is selected as 500, and 100 calculations are made to obtain the optimization results of AI-PSO and PSO algorithms for 100 times under different load rates, and the results are compared as follows.

(1) 40% rated demand load

The comparison of 100 times energy optimization results for industrial park K1 is shown in Fig. 2. 40% rated demand load, the optimization results using AI-PSO and PSO algorithms are generally more energy-efficient than conventional strategies in terms of system energy consumption.

During the system operation, the AI-PSO algorithm controls the energy consumption of the system in the range of 3300 $kW \cdot h$ ~ 3400 $kW \cdot h$, and the optimization results of the algorithm have smaller fluctuation values and smoother data output.

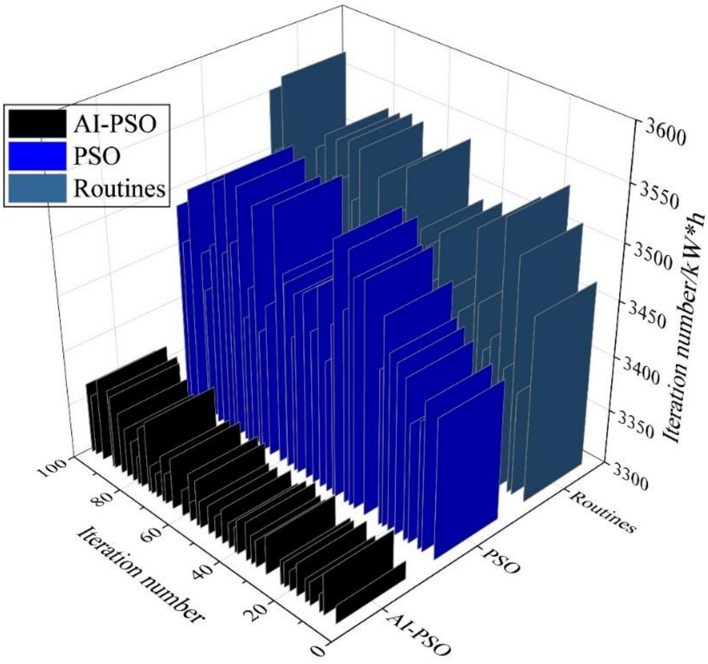

Figure 2. Compared with 100 energy efficiency optimization results in k1 area

(2) 80% rated demand load

Under 80% rated demand load, the comparison of 100 times energy consumption optimization results for industrial park K1 is shown in Fig. 3. AI-PSO algorithm finds the lowest energy consumption results in 24 iterations on average, and PSO algorithm finds the lowest energy consumption results in 71 iterations on average, which gives AI-PSO algorithm a great advantage over PSO algorithm in terms of optimization speed.

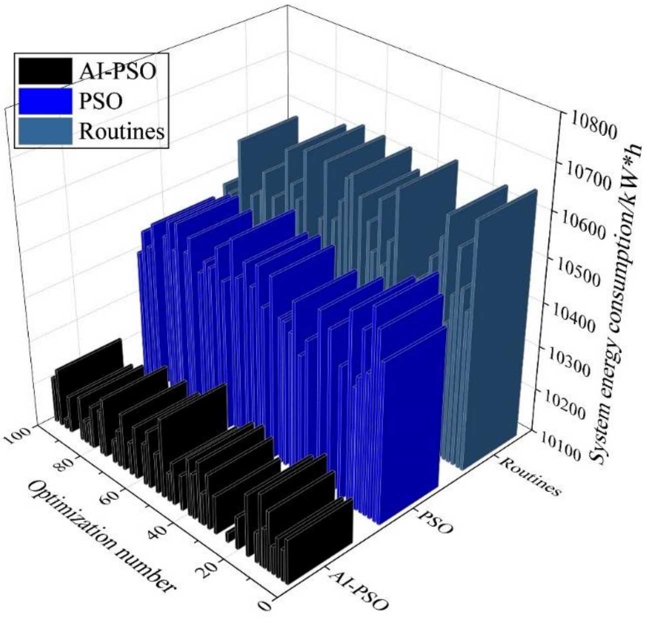

Figure 3. 80% of the rated demand load is found in the k1 area

4.2.2. Area K2

(1) 40% rated demand load

A comparison of the results of 100 energy optimization searches for the industrial park K2 zone is shown in Fig. 4. Since the number of ice storage air-conditioning units in the industrial park K2 area is two more than that in the K1 area, the AI-PSO algorithm is more energy efficient than the PSO algorithm in the optimization process for more units of ice storage air-conditioning units.

At 40% of rated demand load, the AI-PSO algorithm maintains the system energy consumption of K2 zone at 7000 $kW \cdot h$ ~ 7200 $kW \cdot h$. While the system energy consumption of K2 zone under conventional strategy is 7300 $kW \cdot h$ ~7600 $kW \cdot h$.

Due to the increase in the number of units in the system, the corresponding optimization dimension increases and the problem to be solved is more complex, which proves that the AI-PSO algorithm has better advantages in solving the optimal scheduling problem of multiple chillers.

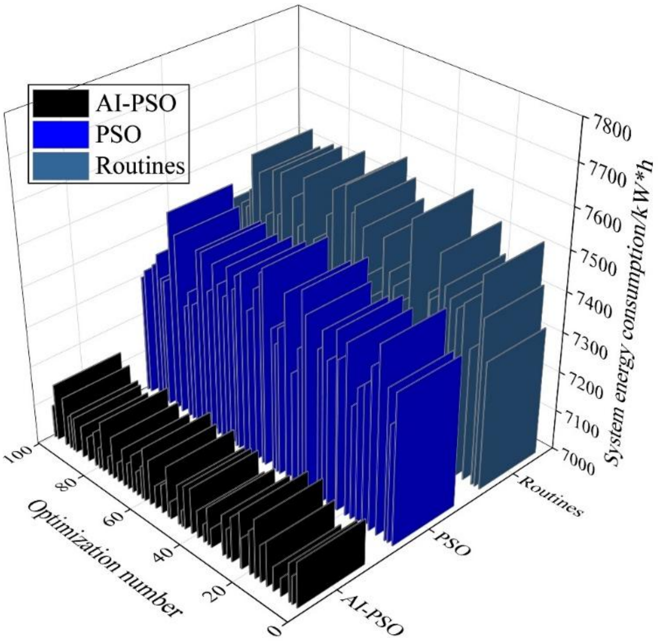

Figure 4. The comparison of 100 energy consumption optimization results in the park

(2) 80% rated demand load

The results of system energy consumption optimization in K2 zone under 80% rated demand load are shown in Fig. 5.

In the experiments of K1 and K2 zones in the case industrial park, the results of total energy consumption under AI-PSO algorithm, PSO algorithm and conventional strategy are compared. Under the three temperature control strategies, the system energy consumption in K2 zone is 12600 $kW \cdot h$ ~13000 $kW \cdot h$, 13100 $kW \cdot h$ ~13500 $kW \cdot h$, and 13200 $kW \cdot h$ ~13600 $kW \cdot h$ in order. It can be found that the average energy saving rate of the algorithm industrial park K2 zone is more obvious than K1 zone, which also shows the excellence of the AI-PSO algorithm for multiple chillers.

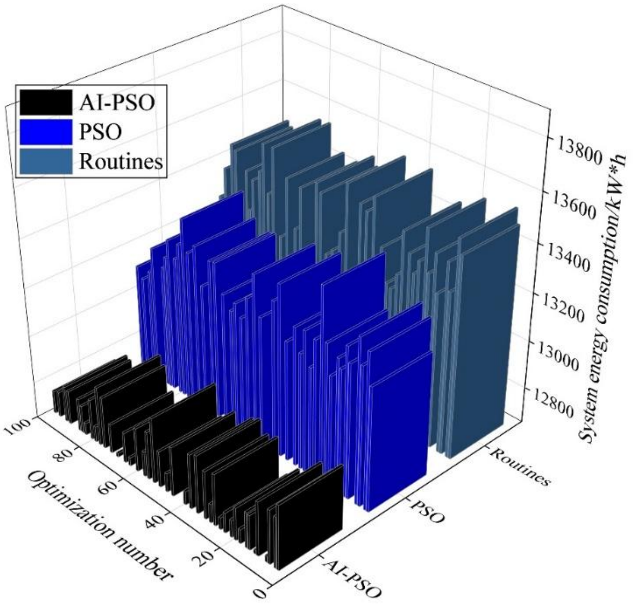

Figure 5. The energy consumption optimization result of the k2 zone system

4.3. Operation under different strategies

4.3.1. Power

The power of the ice storage and air conditioning system at each moment under the AI-PSO algorithm, host priority and ice melting priority control methods is shown in Fig. 6.

Compared with the mainframe priority control and ice-melting priority control, the ice storage air-conditioning system under the control of AI-PSO algorithm has the peak of energy consumption smoothed out to some extent. In a cooling cycle, the maximum value of power difference between each moment of the ice storage air conditioning system under the AI-PSO algorithm, mainframe priority and ice melting priority control methods are 1475.21 kW, 2028.91 kW and 1604.80 kW, respectively.The maximum value of power difference under the control of the AI-PSO algorithm is the smallest one, which is 27.29% and 8.08% less than that of the other two control methods, shaving peaks and filling peaks, respectively. 8.08%, and the effect of peak shaving and valley filling is significant.

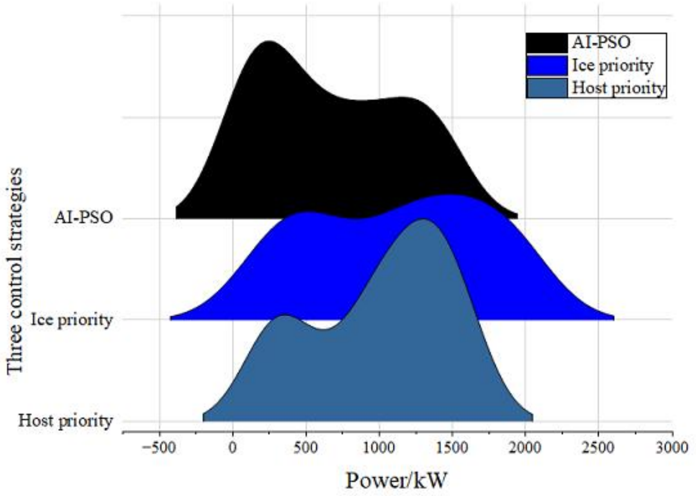

Figure 6. Under different strategies, the power of the ice storage system at all times

4.3.2. Running costs

The operating costs of the ice storage air-conditioning system at each moment under the AI-PSO algorithm, mainframe priority and ice melting priority control methods are shown in Fig. 7.

Calculations show that the total operating costs in one cooling cycle are about 12,200 yuan, 16,000 yuan and 13,700 yuan, respectively.The total operating costs under the control of the AI-PSO algorithm are the lowest, which is 23.75% lower than that of the host-first control and 10.95% lower than that of the ice-melting-first control. The total operating cost is the highest for the host priority control method because of the low utilization of the stored cooling capacity during the low power hours. In the ice-melting priority control method, although the cold capacity stored in the low tariff period is fully utilized, the cold capacity in the ice storage tank is released too early, and the system only relies on the refrigeration mainframe to supply the cold in the high tariff period, which leads to high energy consumption in the high tariff period and a higher total operating cost.

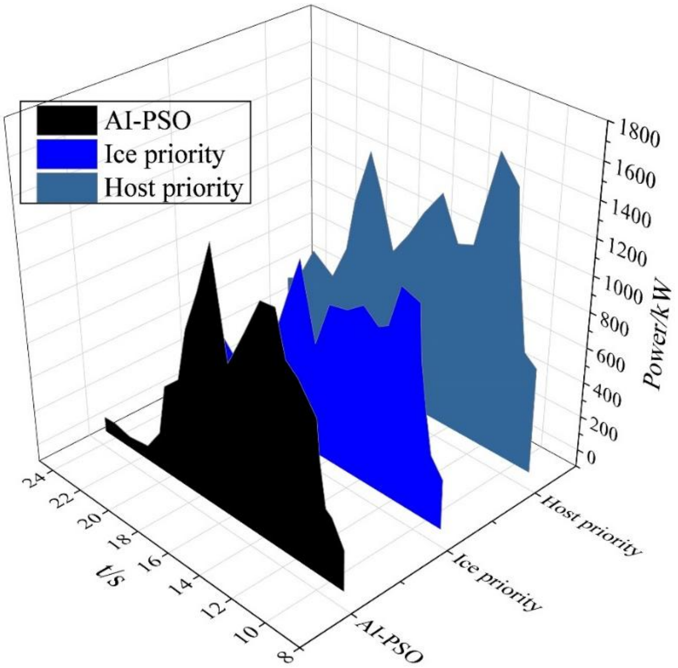

Figure 7. The change of electricity bill when ice storage air conditioning

5. Conclusion

In order to optimize the temperature control of ice storage refrigeration system, this paper proposes to use AI algorithm to improve the behavioral idea of PSO algorithm, and use AI-PSO algorithm to adjust the parameters of the PID controller to solve the multi-objective optimization model of ice storage refrigeration air-conditioning system.Compared with the PSO algorithm and the conventional strategy, the AI-PSO algorithm requires less data, and compared with the PSO algorithm, the number of iterations and the iteration time are respectively reduced. In K1, the number of optimization iterations of the AI-PSO algorithm is reduced by 47 times on average compared to the PSO algorithm. At 40% of rated demand load, the algorithm always controls the system energy consumption in KI zone in the range of 3300 $kW \cdot h$ ~ 3400 $kW \cdot h$, and the AI-PSO algorithm maintains the system energy consumption in K2 zone in the range of 7000 $kW \cdot h$ ~ 7200 $kW \cdot h$. The average energy consumption of the two industrial parks is reduced, which makes it possible to seek for a lower energy consumption operation strategy for the multi-cooler Ice Storage System (ISS) air-conditioning system. The main contribution of this work is the optimization of the parameters of the PID controller using the AI-PSO algorithm with exponentially decreasing inertia weights, so that the temperature can be maintained near the set value to meet the actual indoor load demand and the whole system is less affected by external factors.

Of course, there are some shortcomings in the work of this paper. In the simulation experiment of ice storage refrigeration, only the particle swarm algorithm is compared with the particle swarm algorithm. In the subsequent development, more classical temperature control strategies are simulated and analyzed because they are selected. And this paper mainly focuses on the optimized control solution of the operation strategy, and the development and design of the IoT-enabled ice storage cooling air conditioning system needs to be strengthened. In the subsequent analysis, the development of the operating parameter controller of the ice storage cold air conditioning system is optimized, the control parameters are specified to the system control level, and the multi-objective global optimization algorithm is integrated to establish an intelligent monitoring and control platform for the operating parameters of the ice storage cold air conditioning system.

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