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SIMULATION RESEARCH ON THE GRID CONNECTED GENERATION SYSTEM OF SOLAR THERMAL POWER GENERATION

by

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Objective: To improve the efficiency and stability of the solar thermal power generation system, and promote the optimization and development of solar thermal power generation grid connection. Methods: The working principle of the heat exchanger in the heat storage system is analyzed. Combined with the technological requirements of the system, the mathematical model of the heat exchanger is established by the mechanism modelling method. According to the inherent characteristics and control requirements of the heat storage system, the control schemes are proposed. The control strategies of different control algorithms, such as single-loop control, Smith predictive compensation control, cascade-Smith control, and feedforward-cascade-Smith control, are designed and adopted. The simulation model is established to obtain step response waveforms of different control systems. The advantages and disadvantages of different control strategies are comprehensively analyzed and compared. Results: After introducing the superheated steam mass-flow disturbance, the error of the single-loop control system increases. After adjusting the system to restore the oscillation state, the system error is high (10.24%). Smith predictive compensation control system fluctuates, with a peak time of 548 seconds and a peak temperature of 366 °C. The cascade-Smith control system fluctuates, with a peak time of 620 seconds, a peak temperature of 398 °C, and a maximum deviation of 31 °C. The feedforward-cascade-Smith control system is disturbed, with a peak time of 606 seconds, a minimum temperature of 347 °C, and a maximum deviation of 4 °C. Compared with the cascade-Smith control system, the disturbance deviation of the feedforward-cascade-Smith control system is reduced by 87%. Conclusion: The feedforward-cascade-Smith control system proposed has the advantages of strong anti-interference ability, good stability, and small steady-state error, which has a certain significance for the development of concentrating solar power technology.

Key words: *solar energy, power generation, grid connection, simulation. control*

Introduction

Energy is an important material basis, which is not only related to the development of national economy, but also necessary for people's life. In the primitive society, the era of wood for fire developed to the modern era of fossil resources, and then to the modern era of new energy such as solar energy and water energy. The development of energy in each era is closely related to the development of social productivity, and the development of productivity must rely on the

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supply of energy [1, 2]. In the face of the rapid development of social productivity, the increasing demand for energy, the lack of fossil energy to provide social development, and the rapid depletion of fossil energy, countries have increased the use of new energy research. The demand for energy has become an important indicator of a country's economic development and national living standards [3, 4]. Electric energy is the most important primary energy, which is mainly composed of thermal power, hydro power and nuclear power [5]. Among them, thermal power generation still accounts for a high proportion in China, and the coal combustion as the main body of thermal power generation has caused serious irreversible pollution the earth's environment [6]. At the same time, the emission of GHG makes the environment temperature rise constantly, the melting of glaciers at the north and south poles causes the sea level to rise, and the land area of human life is threatened [7]. Although hydro power will not cause too much environmental pollution, it still has a potential threat to the ecological environment, limited by the region. Moreover, the development of hydroelectric power in China has come to an end [8]. Nuclear energy is a relatively clean energy. However, if there is a nuclear leak, it will cause unimaginable disaster. Moreover, the waste after nuclear power generation is not easy to deal with.

In 2020, the total consumption of coal should be controlled under 2.72 billionns of standard coal. The proportion of coal consumption will decrease by 57.3%, and the proportion of non-fossil energy will increase to 15.2%. By 2050, global clean energy accounting for 80% of primary energy is to be achieved. Not only the emissions of harmful gases and GHG are to be reduced, but also the temperature rise is to be controlled within two degrees Celsius [9]. In view of the aforementioned situation, China's State Grid proposes the concept of global energy interconnection, connecting *one pole one equator*, and developing the Arctic wind energy and solar energy near the equator [10]. Therefore, the development and utilization of wind energy and solar energy is the main direction of future development. In fact, any form of energy comes from solar energy, and solar power generation has unique advantages, such as large reserves, wide distribution, clean energy, and relatively simple construction, no noise. However, it also has many disadvantages, such as low power generation efficiency, high cost, easy to be affected by the environment, unable to output good waveform, and low power quality.

Therefore, to ensure the continued efficient and stable operation of the solar thermal power generation system, the mathematical model of the heat exchanger of the key equipment is established. According to the working mode and the adjustment method of the solar thermal power storage system, the control scheme is designed and the control strategy is optimized based on the principle of the basic control method. Also, by analyzing the simulation results, the correctness of the algorithm is checked. By applying this method, the stability, anti-interference ability, and dynamic response ability of the power generation system can be improved. This simulation experiment is greatly significant to the optimization and application of the thermal power generation grid connection.

Method

The solar thermal power generation system

Solar thermal power generation technology collects solar thermal energy through large-scale array parabolic mirrors or dish mirrors. The water in the heat collector is heated to produce superheated steam, which is supplied to the steam turbine to drive the generator to generate electricity. The water or superheated steam heated by solar energy is stored by the heat storage system, and it can still drive the steam turbine to generate electricity for a period of time after the sun sets. Therefore, the heat storage system is a key part of the solar thermal power generation system, and also an important factor of the thermal power generation efficiency. The heat storage system can

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adjust the load, reduce equipment capacity and investment costs. Also, it can improve the equipment utilization rate and solar energy utilization efficiency, as well as enhance the reliability and economy of the solar thermal power generation system [11]. The energy flow direction of the solar thermal power generation system is shown in fig. 1. The heat storage system has the function of buffering energy, reducing system fluctuations and improving efficiency.
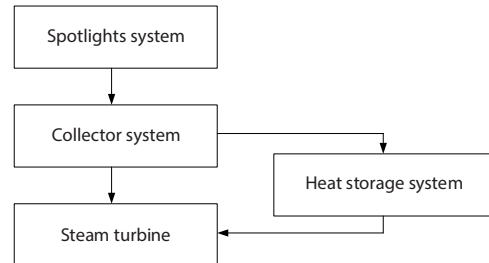

Figure 1. The energy flow direction of the solar thermal power generation system

Mathematical model of the power generation system

The heat storage system is mainly composed of a heat exchanger, reboiler, steam regenerator, and oil storage tank. When the heat storage system is in the heat absorption mode, the heat collector generates superheated steam after absorbing solar energy. After heat exchange through the heat exchanger, the high temperature superheated steam heats the heat transfer oil, and the high-grade energy enters the high temperature oil storage tank for storage [12]. After the superheated steam passes through the heat exchanger, the steam pressure changes less, and the temperature changes more. Under rated conditions, the temperature will be reduced by about 140 °C. This part of the steam will enter the steam regenerator for storage. When the heat storage system is in the heat release mode, the stored steam will continue to enter the reboiler for overheating before entering the steam turbine for power generation. The energy for superheating the steam of the reboiler is provided by the high-temperature oil tank.

The heat exchanger is the key equipment for the heat storage system to absorb high-grade energy. Its working principle is shown in fig. 2. Considering that steam is easy to produce scale, it needs to be stored in a low temperature heat storage system after heat exchange. The pressure drop cannot be too large. The heat transfer oil is relatively clean in the closed system, and its own pressure is small. Therefore, the shell side fluid of the heat exchanger chooses heat transfer oil, and the tube side fluid chooses superheated steam.
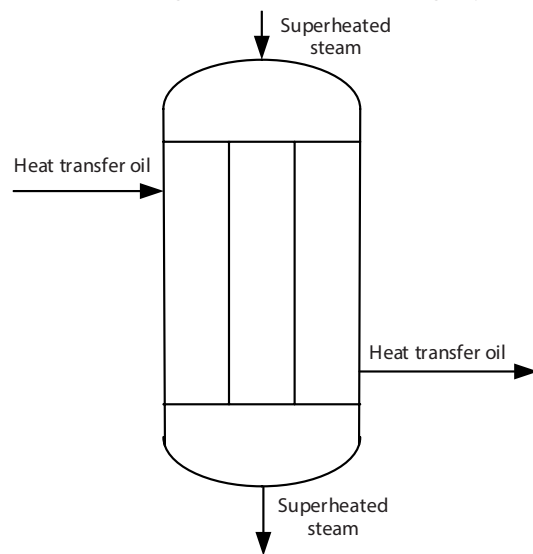

Figure 2. Working principle of the heat exchanger

The research object is the shell and tube counterflow single-pass heat exchanger. The mass-flow of the hot fluid and the mass-flow of the cold fluid are set to G_1 and G_2, respectively. The initial temperatures are set to T_{1i} and T_{2i}. The end temperatures are set to T_{1o} and T_{2o}. The specific heat capacity is set to C_1 and C_2, respectively. Ignoring the heat loss, according to the law of conservation of energy:

$$q = G_1 c_1 \left(T_{1i} - T_{2o} \right) = G_2 c_2 \left(T_{2o} - T_{2i} \right) \tag{1}$$

where q is the energy exchanged per unit time, subscript 1 – superheated steam, i – the initial inlet, 2 – the low temperature heat transfer oil, and o – the terminal outlet. The energy q exchanged per unit time:

$$q = KF\Delta T \tag{2}$$

where K is the heat transfer coefficient in the heat transfer process, F – the area, and $\triangle T$ – the temperature difference.

The basic expression of the static characteristics of the shell and tube counterflow single-pass heat exchanger:

$$\frac{T_{1o} - T_{1i}}{T_{2i} - T_{1i}} = \frac{1}{\dfrac{G_1 c_1}{KF} + \dfrac{1}{2}\left(1 + \dfrac{G_1 c_1}{G_2 c_2}\right)} \tag{3}$$

The increase coefficient of each channel is further derived. To facilitate analysis, the following settings are made. The specific heat capacity of the heat exchanger fluid partition is negligible. The heat transfer area, heat transfer coefficient, and specific heat capacity remain constant. The temperature of each point in the same section is the same. Starting from the heat dynamic equilibrium equation, the mathematical model of the distributed parameter object is established. The cylinder of length $\mathrm{d}z$ is taken as the micro-element. The energy conservation relationship of the micro-element in a certain period of time:

$$G_1 c_1 T_1(l,t) - G_1 c_1 \left[T_1(l,t) + \frac{\partial T_1(l,t)}{\partial l}\mathrm{d}l\right] + KA\mathrm{d}l\left[T_2(l,t) - T_1(l,t)\right] = M_1 c_1 \mathrm{d}l \frac{\partial T_1(l,t)}{\partial l} \tag{4}$$

where l is the length of the heat exchanger, A – the circumference of the inner tube, $A\mathrm{d}l$ – the surface area of the micro-element, M_1 – the fluid mass per unit length of the hot fluid, and $M_1\mathrm{d}l$ – the mass of the micro-element:

$$\left(\frac{M_1}{G_1}\right)\frac{\partial T_1(l,t)}{\partial l} = \frac{\partial T_1(l,t)}{\partial l}\left(\frac{KA}{G_1 c_1}\right)\left[T_2(l,t) - \partial T_1(l,t)\right] \tag{5}$$

By analyzing the cold fluid, the energy balance equation of the cold fluid is obtained:

$$\left(\frac{M_2}{G_2}\right)\frac{\partial T_2(l,t)}{\partial l} = \frac{\partial T_2(l,t)}{\partial l}\left(\frac{KA}{G_2 c_2}\right)\left[T_1(l,t) - \partial T_2(l,t)\right] \tag{6}$$

The boundary expression of time and space is shown:

$$\begin{cases} T_1(l,0) = T_1(l), T_2(l,0) = T_2(l) \\ T_1(0,t) = T_{1i}(t), T_1(1,t) = T_{1o}(t) \\ T_2(0,t) = T_{2o}(t), T_2(1,t) = T_{2i}(t) \end{cases} \tag{7}$$

By discretizing the equation, the corresponding discrete state space model can be obtained. The dynamic performance of the heat exchanger can be expressed by an empirical equation. The transfer function is used to describe the inlet temperature of the hot fluid and the cold fluid as well as the impact of the inlet temperature on the outlet temperature of the hot fluid:

$$G(s) = \frac{K}{Ts + 1} \tag{8}$$

where K is the increase coefficient, T – the ratio of the heat exchanger capacity and the flow of the cold fluid, and s – the symbol of the Laplace operator.

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The transfer function is used to describe the impact of the flow of the hot fluid and cold fluid on the temperature of the hot fluid outlet:

$$G(s) = \frac{K}{(T_1 s + 1)(T_2 s + 1)} e^{-\tau_2 s} \tag{9}$$

The calculation of T_1 and T_2:

$$T_1 = \frac{\dfrac{W_1}{G_1} + \dfrac{W_2}{G_2}}{2} \tag{10}$$

$$T_2 = \frac{\dfrac{W_1}{G_1} + \dfrac{W_2}{G_2}}{8} \tag{11}$$

where W_1 is the hot fluid capacity, W_2 – the cold fluid capacity, G_1 – the hot fluid-flow, and G_2 – the cold fluid-flow.

Control strategy of the heat storage system

Single-loop control system

The single-loop control system consists of an actuator, a controller, a detection transmitter, and a controlled process. It is a feedback control system that controls a controlled variable. It is the most basic control method in the process control system with the simplest structure [13]. In the heat exchanger control system, the outlet temperature of the heat transfer oil of the heat exchanger is the controlled variable. When the solar radiation changes, the flow of superheated steam produced by the collector changes accordingly. The heat exchanger deviates from the set value after being disturbed. The controlled variable of heat transfer oil outlet temperature is detected by the temperature sensor of the detection element and converted into a signal that can be compared with the set value by the transmitter. The detected transmission signal is deviated from the set value. According to the deviation calculation, the heat exchanger control system generates a corresponding control signal to drive the oil pump to change the speed to change the heat transfer oil flow, so that the controlled variable returns to the set value.

Smith predictive compensation control system

When there is a pure lag link in the system, the lag time is large and the system control is not timely, the predictive compensation control can add the assumed model to the feedback control system according to the industrial process characteristics of the large lag. Then, the controlled quantity of the control lag is reflected on the controller in advance, and the controller acts in advance. Thereby, the influence caused by time lag is significantly reduced or compensated, the transition time and overshoot of the system are effectively reduced, and the control quality of the system is improved. Smith prediction is a common predictive compensation control. Smith predictive compensation concept is to parallel a compensation link on the generalized controlled object, eliminating the adverse effects of pure time lag on the system. In the process of heat exchanger control of the solar thermal power storage system, there are two time lag links, namely the large time lag in the heat transfer oil temperature control channel of the heat exchanger and the small time lag in the variable frequency pump control. In this case, the Smith predictive compensation controller can be added to the system's main loop and the flow control loop in the cascade control system to improve the control accuracy of the system.

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Cascade-Smith control system

To improve the quality of control, the cascade control strategy is considered. Cascade-Smith control system adopts a fixed value control method. The heat transfer oil temperature controller plays a leading role in the system, and the variable frequency pump flow controller plays an auxiliary role. While overcoming the pressure disturbance of the heat transfer oil, it is manipulated by the temperature controller to form a complete heat transfer oil outlet temperature-flow cascade control system. The system has two closed loops, the main loop and the secondary loop, where the main loop is the external temperature control loop and the secondary loop is the internal flow control loop. The temperature control loop of the system is fixed value control. The input of the temperature controller is the given value of the solar thermal power generation process, and the output is the given value of the flow controller. The output of the flow controller directly acts on the variable frequency pump. In addition, the set value of the flow controller is provided by the output of the temperature controller, which changes as the output of the temperature controller changes. Therefore, the flow control loop of the cascade control system is a servo system.

Feedforward-cascade-Smith control system

The feedforward control is conducted according to the change of the disturbance amount. When there is interference in the system, the controller directly calculates the control signal according to the measured interference size and direction offset or reduce the impact of the disturbance on the controlled variable. After the disturbance occurs, the controller has already produced a control effect before the controlled quantity has changed. Therefore, there is no deviation in the controlled variable. The feedforward control is an open-loop control, and there is no feedback to the controlled variable, and the compensation effect is not tested. Therefore, the feedforward control cannot eliminate the error eventually. Moreover, the accuracy of feedforward control is limited by various factors, and it is difficult to obtain good control quality. Thus, feedforward control and cascade-Smith control can be combined to form a feedforward-cascade-Smith control system.

Simulation experiment of grid-connected generation system of solar thermal power generation

When the control system is simulated in MATLAB/SIMULINK environment, the sub-module of the model library is used to establish the simulation model. The parameters of each module are set and the solver is selected. The control system simulation time is divided into the 50 seconds, 1000 seconds, and 1500 seconds according to the system response time. The simulation algorithm uses ode45 solver, and the simulation step size selects the variable step size. After the parameter setting is completed, the simulation experiment is performed on the control system. The simulation time is set to 1000 seconds. At 500 seconds, a superheated steam flow step signal with an amplitude of 1 is added, and the interference of the superheated steam flow change of the heat exchanger to the system is introduced.

Results

Single-loop control simulation results

The single-loop control simulation waveform is shown in fig. 3. The temperature of the heat transfer oil reaches its maximum value at 147 seconds. Due to the large pure lag time

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of the system, the control signal cannot accurately control the outlet oil temperature, and the system enters periodic oscillation. After introducing the superheated steam mass-flow disturbance, the system error increases after the 530 seconds. After adjusting the system to restore the oscillation state, the system error is higher, being 10.24%, which does not meet the technological requirements for the normal operation of the heat storage system.

Smith predictive compensation control system

Smith predictive compensation control simulation waveform is shown in fig. 4. When Smith predictive compensation control is adopted, the peak time of the heat transfer oil temperature control system of the heat exchanger is 144 seconds, and the adjustment time is 320 seconds. After the superheated steam interference signal is introduced, the system fluctuates, with a peak time of 548 seconds and a peak temperature of 366 °C.

Cascade-Smith control system

The cascade-Smith control simulation waveform is shown in fig. 5. When cascade-Smith control is used, the peak time of the heat transfer oil temperature control system of the heat exchanger is 123 seconds, and the adjustment time is 199 seconds. After introducing the superheated steam interference signal, the system fluctuates, with a peak time of 620 seconds, a peak temperature of 398 °C, and a maximum deviation of 31 °C.

Feedforward-cascade-Smith control system

The feedforward-cascade-Smith control simulation waveform is shown in fig. 6. When feedforward-cascade-Smith control is adopted, after the superheated steam interference signal is introduced, the system is disturbed, with a peak time of 606 seconds, a minimum temperature of 347 °C, and a maximum deviation of 4 °C. Compared with the cascade-Smith control system, the disturbance deviation of the feedforward-cascade-Smith control system is reduced by 87%.
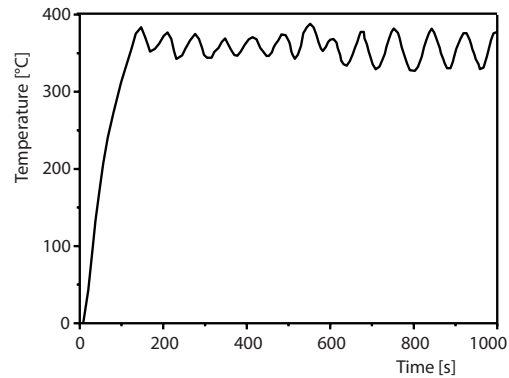

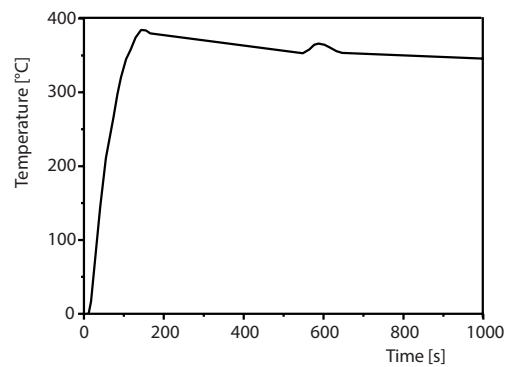**Figure 3 Single-loop control simulation waveform**

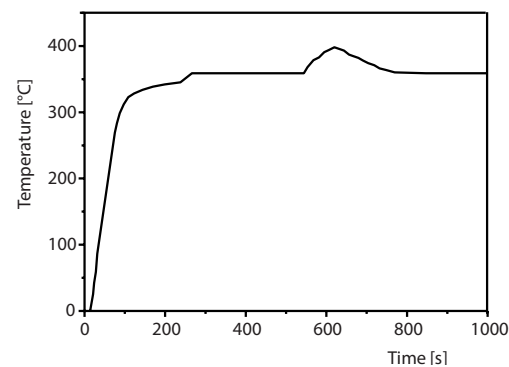**Figure 4. Smith predictive compensation control simulation waveform**

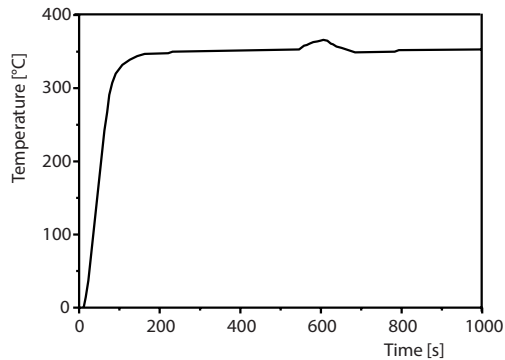**Figure 5. Cascade-Smith control simulation waveform**

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Figure 6. Feedforward-cascade-Smith control simulation waveform

Discussion

The principle of solar thermal power generation is to focus sunlight on the collector through the heliostat field, and the superheated steam generated in the collector drives the steam turbine to drive the generator to generate electricity [14]. The thermal energy required by the solar thermal power generation system depends entirely on the provision of solar light. However, the solar intensity at various points in the day varies greatly and is easily affected by the weather. The solar energy absorbed by the mirror field cannot meet the heat required by the solar thermal power generation system, which in turn causes the unstable power generation of the steam turbine, impacts the power grid, and affects the electricity consumption of users [15]. Therefore, how to ensure the continuous stable and efficient power generation of solar thermal power generation systems is a major problem in the field of solar thermal power generation. Normally, adding a thermal storage subsystem to the solar thermal power generation system can regulate the load and stabilize the operating conditions. However, after the introduction of heat storage, the difficulty of controlling the entire system will increase. Thus, it is necessary to determine a reasonable and feasible heat storage system, establish a heat absorption and release model of the heat storage system, optimize the control strategy of the heat storage system, and accelerate the promotion and development of solar thermal power generation technology.

Based on MATLAB/SIMULINK simulation platform, the temperature control system using different control strategies is simulated. Analysis of the single-loop control simulation results shows that the temperature of the heat transfer oil eventually enters periodic oscillation, and the system error is large. By analyzing the control principle of the single-loop control system, it is not difficult to find that the system has a pure lag link, which causes the control signal output by the controller to not correct the deviation in time. Furthermore, the system enters wide oscillation, affecting the control effect. If the external interference to the variable frequency pump is introduced, the system error will further increase. To reduce the impact of the pure lag link on the system, the feedback control with Smith predictive compensation control are combined. After adding Smith predictive compensation control, compared with the single-loop control system, the anti-interference ability of the system is enhanced, but the adjustment time is longer. Compared with the Smith predictive compensation control system, the control quality of the cascade-Smith control system has been greatly improved, but its anti-interference ability still has room for improvement. Compared with the cascade-Smith control system, the disturbance deviation of the feedforward-cascade-Smith control system is reduced by 90%, and the control quality is significantly improved. It solves the problem of large fluctuations after the introduction of interference signals and enhances anti-interference ability. Magdy *et al.* [16] conducted a preliminary investigation on the control scheme of the solar thermal power storage system. They selected Proportional-Integral-Derivative (PID) control strategy to effectively control the system and increase the anti-interference ability of the system. However, PID control quality is poor in practical applications, often failing to meet the production process requirements. Therefore, in comparison, the feedforward-cascade-Smith control strategy proposed is more advantageous.

In summary, when the feedforward-cascade-Smith control strategy is used to control the temperature of the heat exchanger outlet, the adjustment time of the system is short and there is no steady-state error. The anti-interference ability has been improved, and a better control effect has been obtained. The research has a certain reference value for the follow-up investigation of the solar thermal power storage system.

Conclusion

According to the characteristics of the heat storage system, a key part of the solar thermal power generation system, the feedforward-cascade-Smith control strategy is designed by algorithm fusion. Through simulation analysis, it is found that the control strategy has the advantages of short adjustment time, strong adaptability, good stability, and strong anti-interference ability. The research has a certain reference value for the follow-up investigation of the solar thermal power storage system, with important theoretical significance and application value. However, there are certain deficiencies in the process. Although the control of the heat exchanger of the heat storage system is focused, it is not linked to the reboiler, steam regenerator, and oil storage tank to form a complete system. There is no co-ordinated control strategy for the entire solar thermal power generation system. Therefore, in the later stage, other components will be added to explore the co-ordinated control strategy of the entire solar thermal power generation system, so that the obtained results are more reference value.

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