MODELLING AND CONTROL OF SOLAR THERMAL POWER GENERATION NETWORK IN SMART GRID

by

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The thermal storage system is an essential part of the trough solar thermal power generation system. Due to the strong randomness, intermittency, and volatility of solar energy resources, to further improve the system's overall reliability to meet the needs of variable operating conditions, the paper optimizes the control strategy of the trough solar heat storage system. Taking the molten salt heat storage medium in the oil/salt heat exchanger, the core equipment of the heat storage system, as the critical research object, the article adopts proportional, integral, and differential (PID) control theories. It builds the system in the MATLAB/Simulink simulation environment mathematical model. We use the critical proportionality method to determine many critical parameters in the control system, tune the proportional coefficient, integral time, and other physical quantities in the PID controller, and analyze the proportional control, proportional-integral control, PID controls the respective dynamic response characteristics of these three different control systems. The simulation and comparative analysis results show that: compared with the other two control methods, PID control can effectively weaken the heat storage system oscillation caused by external disturbance, its dynamic response speed is faster, the adjustment time is shorter, and it can meet the requirements of operational stability. The paper adopts PID control, which reduces the control difficulty of the trough solar heat storage system and improves the adaptability to changes in external meteorological resources. The research results have particular guiding significance at the academic and engineering levels.

Key words*: power generation network, differential control, heat storage system, critical proportionality method, parameter tuning, solar energy*

Introduction

Solar thermal power generation is a new type of renewable energy. The solar thermal technology with energy storage ensures the reliability of the grid operator to a certain extent. The solar thermal power station with a large-scale thermal storage system (TSS) has a high degree of flexibility and can participate in the dispatch of the power system when the grid needs it. Compared with the large-scale batteries configured in photovoltaic power stations and used for long-term grid energy storage applications, heat storage systems' cost is much lower. The unit capacity cost is only 1/15 of the former [1]. The large-scale application of TSS is an obvious advantage of solar thermal power generation. Even in the case of low solar radiation intensity such as rainy days, the system can still maintain the energy required for power generation and

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adjust the system output according to the power generation plan within a specific range to better adapt to the grid's needs. Besides, solar resources' daily dynamic change trend is roughly the same as the load, which has natural peak-shaving characteristics.

Research status of the heat storage system

Due to the intermittent and fluctuating nature of solar energy resources, scholars use the heat storage system to maintain the stability of the output of the concentrating heat collection system, which is not only required by the rotating equipment in the back-end heat conversion system but also can enhance the adaptability of the power grid. Besides, the heat storage system can further improve the controllability in operation while satisfying the concentrated solar power (CSP) station's efficient operation. Therefore, the TSS optimal control is a crucial link in the entire solar thermal power generation system's control process. The correct control strategy plays an essential role in improving the solar thermal power generation system's practicability and maintaining its long-term stable output. Some domestic and foreign scholars have also carried out more scientific research in this field.

Some scholars take the solar TSS heat exchanger as the research object and control the oil temperature by proportional-integral (PI). They used the pole configuration method to design a PI parameter self-tuning controller, and compared two feedforward control structures on this basis, and found that series feedforward can better compensate for the influence of disturbances. Some scholars designed LQG and GPC adaptive controllers based on modelling and analyzing different operating points of CSP stations. However, the control system integrator will cause the system to oscillate, and the use of an integrator with saturation characteristics can effectively weaken the oscillation. Some scholars have proposed a model-based predictive adaptive control scheme, which better solves the traditional CSP plant control process. The high order model must be used to eliminate the low frequency resonance in the feedback process, and the high order model has the problem of slow online parameter identification. Some scholars explained the complete application of fuzzy logic controllers in CSP systems and optimized the genetic algorithm's fuzzy rules. Compared with other control algorithms, the fuzzy control strategy shows better control effect under different weather conditions.

The domestic research on solar thermal power generation technology started relatively late. During the *Thirteenth Five-Year Plan* period, the National Energy Administration of China announced the first batch of 20 solar thermal power generation demonstration projects and plans to start production and grid connection before the end of 2018. Among them, there are many solar thermal power generation projects equipped with perfect sensible heat storage systems. As far as the thermal storage subsystem of solar thermal power generation is concerned, most of the research focuses on thermal storage materials and TSS economic calculations. Some scholars optimize the project economy by designing and optimizing the solar TSS capacity configuration. Some scholars discussed the progress and application of molten salt heat transfer and heat storage technology at home and abroad and gave a correlation formula for calculating molten salt heat transfer. Some scholars have analyzed the impact of TSS on CSP stations. The research results show that the heat storage system has dramatically improved the heat collection efficiency and annual power generation, and the cost of the network has also been reduced. Simultaneously, it is optimized with the lowest electricity as the goal, and the whole system is configured. Heat storage capacity. Based on the heat release model of the thermal storage stacked bed, some scholars used numerical simulation analyze the influence of parameters such as flow velocity, initial temperature, and porosity of the thermal storage material on the system's heat release rate during the heat release process.

Compared with the research mentioned earlier on heat storage materials or economy, solar heat storage systems' control work is still lacking. The control of the heat storage system can further adapt to the randomness and volatility of solar resources, thereby increasing the dispatchability of CSP stations in the actual operation and maintenance process. The heat storage system is the link between the front-end optical field and the back-end power generation system. By effectively strengthening the control research of the heat storage system, on the one hand, CSP can be used as the flexible power source of the power grid to participate in the dispatch of the power system. On the other hand, it can be organically coupled with other new energy sources to build a micro-energy grid that can complement each other. The total output is stable, clean, and efficient. The heat storage system's control goal is mainly to generate system responses under different working conditions according to the load side's specific needs so that the CSP station can finally output relatively stable electric energy. The difficulty of this kind of control lies in the uncertainty and random fluctuation of the external light, resulting in uneven heat absorption of the front-end concentrating heat collector, causing changes in the thermal characteristics of the internal working fluid under different working conditions, thereby increasing the difficulty of control [2]. Therefore, in response to the previous problems, this paper adopts a PID controller to establish a control strategy that meets the trough solar thermal power generation and storage system requirements. Use MATLAB/Simulink software to research optimization control of the heat storage system and carry out parameter setting and simulation analysis. The results obtained have particular academic and engineering application value.

Physical model of the heat storage system

The structure of the trough solar thermal power generation system using double tank molten salt sensible heat storage is shown in fig 1. The heat storage system comprises critical equipment such as oil/salt heat exchanger, high temperature molten salt heat storage tank, low temperature molten salt heat storage tank, and molten salt pump. When storing heat, the heat-conducting oil working fluid is heated by the heat collector to absorb solar energy, enters the oil/salt heat exchanger in the heat storage system, exchanges heat with low temperature molten salt and heats it into high temperature molten salt, and then undergoes melting. The salt is pumped to the high temperature molten salt tank for storage. After the heat is released, the temperature of the heat-conducting oil decreases, and it flows back to the trough collector to repeat the aforementioned process. When there is no sunshine at night, and the back-end heat conversion system needs to generate electricity, the heat storage system releases the heat energy stored in the high temperature molten salt [3]. This process is also carried out in the oil-salt heat exchanger. The high temperature molten salt releases heat to the low temperature heat

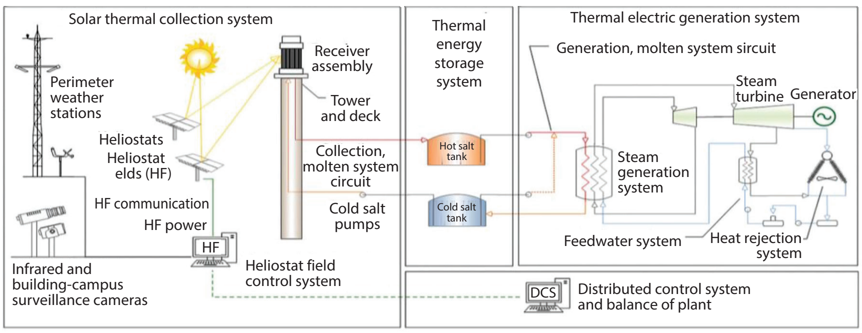

Figure 1. Structure diagram of trough solar thermal power generation system

transfer oil, which turns into low temperature molten salt. The heated heat transfer oil further exchanges heat with the power generation working fluid in the back-end conventional island unit evaporator through the heat transfer oil pump. Heats the power cycle working liquid into steam that meets individual quality requirements to realize heat energy conversion. From the aforementioned analysis, it can be seen that the oil/salt heat exchanger is the core component of the entire heat storage system, and it is also the key to achieving energy cascade storage and release utilization.

The PID-based control theory

The PID controller is a standard controller in the process of power production. Many pressure, temperature, and force circuits are realized by PID control. According to the input deviation value, the PID controller uses PID functional relationships to perform operations. They represent the current, past, and future information of the controlled quantity in the dynamic control process. The system uses the calculation result to control the amount contained. The control process is rapid, the overshoot is small, and there is no steady-state error, showing a good control effect. The slight disturbance of the system parameters has little influence on the control effect and has strong robustness and good adaptability.

Basic principle of PID controller

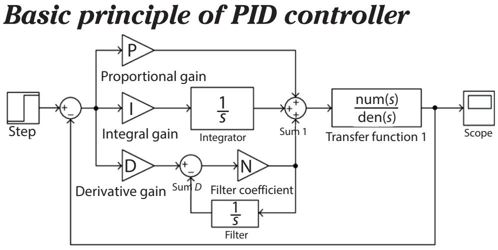

Figure 2. The PID control system structure diagram

The structure of the PID control system is shown in fig. 2. The PID controller is linear. The input signal is the deviation, $e(t)$, between the given value, $r_{\rm in}(t)$, and the actual value, $y_{\rm out}(t)$:

$$e(t) = r_{\rm in}(t) - y_{\rm out}(t) \tag{1}$$

The PID control process is to perform PID operations on $e(t)$, respectively:

$$u(t) = K_p \left[e(t) + \frac{1}{T_i} \int_0 e(t) \mathrm{d}t + T_d \frac{\mathrm{d}e(t)}{\mathrm{d}t} \right] \tag{2}$$

$$G(s) = \frac{U(s)}{E(s)} = K_p \left[1 + \frac{1}{T_i s} + T_d s \right] \tag{3}$$

where $u(t)$ is the output of the control system, used to control the creation of the actuator, $G(s)$ – the transfer function of the PID control system, K_p – the proportional coefficient, T_i – the integral time constant, and T_d – the derivative time constant. The parts of each correction link of the PID controller are as follows.

Proportion link

The proportional coefficient mainly affects the system response speed. The larger the proportional coefficient value, the faster the system response speed. However, if the amount is too large, system overshoot and oscillation will occur, resulting in system instability. Proportional adjustment is a differential adjustment, and there is a steady-state error. When the proportional coefficient is small, it will lead to a slow system response and severe steady-state mistake. Since the proportional coefficient sets the controller performance boundary, the larger the coefficient value, the better the effect.

Integration link

The integral link can eliminate the steady-state error in the system control process. Even a small steady-state mistake can cause a substantial increase in the output of the integrator. The smaller the integral time constant, the stronger the necessary action, and the stronger the system's steady-state stiffness and anti-disturbance ability.

Differentiation link

The differential link can improve the dynamic performance of the system. It reflects the changing trend of the signal. Suppressing deviations from changing in all directions can reduce overshoot and increase the dynamic stiffness of the system. But the differential link reduces the gain margin and is very sensitive to high frequency noise, so the differential coefficient cannot be too large [4]. From the comparison of the effects of the three parameters of the PID controller, the three parameters will directly affect the system's overall control effect. Therefore, if we want to get a better control effect, we must select the appropriate controller parameters according to the scientific method, carrying out the necessary parameter tuning work.

The PID controller parameter tuning

Different components of the PID controller have other effects, and the performance of the control system can be fine-tuned through parameters in the later stage. However, in the system's initial design, the control effects of each component must be considered. Improper parameter settings will make the system perform poorly during actual operation, be more sensitive to disturbances, and have low adaptability to operating conditions. The PID parameter tuning methods are mainly divided into two categories. One is the theoretical calculation method. The article first establishes the mathematical model of the system. It then derives the set standards according to the system's requirements for response time, overshoot, and steady-state error, and finally sets the parameters through theoretical calculations. This method is cumbersome to calculate and relies on the system's mathematical model, so the calculated results generally need to be applied through actual engineering debugging. The other is the engineering tuning method.We directly tune through authentic engineering experience. This method does not require an accurate system model, is convenient and straightforward, and is widely used in engineering. In this paper, the engineering tuning method is used to optimize the heat storage system's control.

In engineering tuning, the critical proportionality method is usually used. This method uses a control system's response curve with only proportional links in the test and measurement process under step input to determine the critical gain and critical oscillation period that the system is close to unstable. It then obtains other parameters of the PID control system by empirical formulas.

The calculation process of the critical ratio method is as follows. First, temporarily remove the integral link and the differential link, that is, set the necessary time constant to infinity and the derivative time continuous to 0. Then, gradually increase the controller's value of the controller's proportional coefficient until the controlled output of the system oscillates with equal amplitude [5]. If K_p is further increased, the system will become unstable, which means that the system has reached a critical state. At this time, the proportionality is the necessary gain K'_p. The distance between the two troughs is the critical oscillation period T_K. Finally, combined with the empirical setting basic formula of proportionality, the PID controller parameters are adjusted reasonably. The empirical setting formula for critical proportionality is shown in tab. 1.

Table 1. Empirical setting formula for critical proportionality

Control law	K_p	T_i	T_d
P control	$0.50K_p'$		
PI control	$0.45K_p'$	$0.83T_K$	
PID control	$0.60K_p'$	$0.50T_K$	$0.125T_K$

The PID control parameter tuning and simulation

Modelling of the heat storage system

In the heat storage system of trough solar thermal power generation, the article takes the molten salt heat storage fluid-flowing in the oil/salt heat exchanger as the critical research object, establishes a mathematical model, and conducts research. According to the empirical formula, we assume that the unit flow rate of the heat storage medium's molten salt in the oil/salt heat exchanger is used as the input. The temperature of the molten salt at the oil/salt heat exchanger outlet after the heat charging and discharging process is completed is the output. Obtain the transfer function $G(s)$ of eq. (4), and use MATLAB/Simulink to build the system simulation model shown in fig. 3:

$$G_T(s) = \frac{4s^2 - 1.2s + 0.36}{240s^3 + 180s^2 + 36s + 0.84} \tag{4}$$

When the system inputs a unit step signal, the unit dynamic response effect we get is shown in fig. 4.

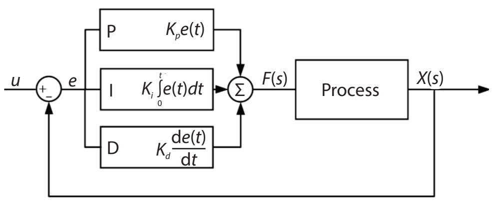

Figure 3. System simulation model

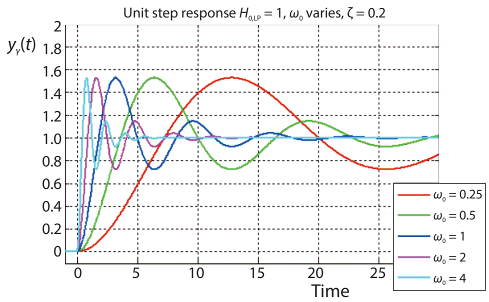

Figure 4. Unit step response curve

It can be seen from fig. 4 that the system has good stability and almost no overshoot in the control process. Still, there is a little error after reaching the steady-state, which is related to the differential adjustment of the proportional control. It is generally believed that the time it takes for the system to get 70.7% of the stable output value is the control system [6]. The response time of the course in fig. 4 is about the 50 seconds. The thermal design's inertia is enormous and the temperature changes slowly, and the response time is generally on minutes. In comparison, the control system responds quickly. It can control the temperature of the heat storage working fluid in the heat storage system to meet the system's control requirements better and ensure the safe, stable, and efficient operation of the system.

Determination of critical proportionality and critical oscillation period

The transfer function model of the system is a built-in MATLAB/Simulink simulation environment. Then we use the locus function draw the root locus diagram of the system's controlled object, as shown in fig. 5.

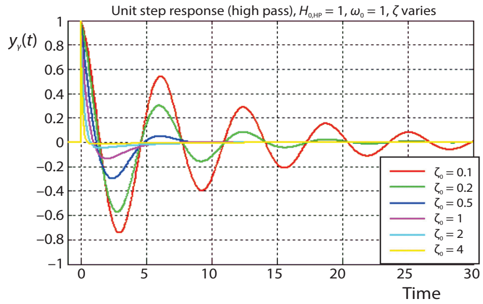

Figure 5. Root locus diagram of the controlled object

It can be seen from fig. 5 that the critical gain K'_p = 23.28, the crossover frequency ω_c = 0.179, and then the critical oscillation period can be obtained:

$$T_K = \frac{2\pi}{\omega_C} = 35.102 \tag{5}$$

At this time, the control system has only proportional control. The proportional gain is 23.28. The controlled object's output is constant amplitude oscillation, and the system is in a critical and stable state. The continuous amplitude oscillation curve output by the system is shown in fig. 6.

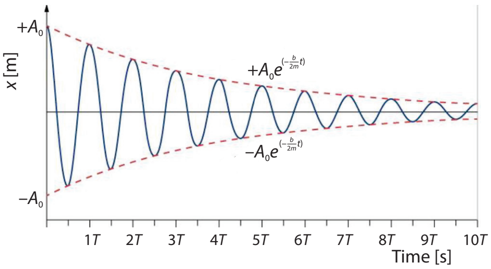

Figure 6. Constant amplitude oscillation curve

The PID controller parameter tuning

Combined with tab. 1, the corresponding parameters of P, PI, PID controller and the transfer function of the control system are obtained through calculation. The P controller: K_p =11.64.

PI controller:

$$K_p = 10.476,\ T_i = 29.135,\ G(s) = 10.476\left(1+\frac{1}{29.135s}\right)$$

$$K_p = 13.968,\ T_i = 17.551$$

PID controller:

$$T_d = 4.388,\ G(s) = 13.968\left(1+\frac{1}{17.551s}+4.388s\right)$$

Analysis of simulation results

We use the feedback function, integrate the controller's mathematical model and the mathematical model of the system, and then simulate through the step function obtain the step response curve, as shown in fig. 7.

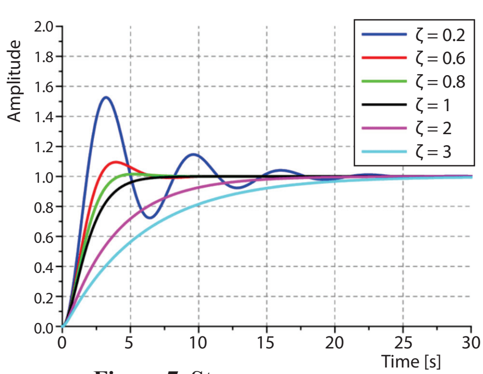

Figure 7. Step response curve

By comparing and analyzing the three control methods in fig. 7, we can get the following results. First of all, the output of proportional control is proportional to the error of the controlled quantity. Once the error occurs, the outcome of the proportional controller is not 0. The output proportional control quantity is input to the controller adjustment system and then output, reducing the error. The action of the proportional adjustment is rapid, and the overshoot is small. But its control weakness is that it cannot eliminate the steady-state error. As the value continues to increase, it will also cause system instability. Secondly, after we introduce the integration link, the steady-state system error can be eliminated. This is because the integral link's existence makes that as long as there is an error in the molten salt temperature of the heat storage system, the output of the integrator will continue to accumulate until the error is zero [7]. While introducing the integral link to eliminate the steady-state error, the extreme essential action will increase the system's overshoot, which is not conducive to system stability. Finally, when we adopt the PID control scheme for the heat storage system, the system overshoot is reduced due to the differential link's effect, and the damping is increased. When subjected to external interference, the differential action can restrain the change of the controlled quantity, thereby better improving the system's dynamic performance. Simultaneously, due to the combined activity of proportional, integral, and derivative, PID control can effectively improve the system's dynamic response speed compared to other solutions.

In the control system of the heat storage unit's oil/salt heat exchanger, the controlled quantity is the temperature of the molten salt at the outlet of the heat exchanger. When the solar radiation intensity changes, if the heat transfer oil flow through the heat exchanger does not change, the molten salt's temperature at the outlet of the heat exchanger fluctuates and deviates from the set value [8]. After detecting the temperature detection element (temperature sensor) at the molten salt outlet, by comparing the transmitter input processor with the set value, the control system can calculate according to the error signal and generate the corresponding control signal to adjust the molten salt pump. Relevant parameters and achieve the ultimate goal: by adjusting the speed variable parameters of the molten salt pump, changing the flow rate of the molten salt, the temperature of the molten salt can be restored to the original set value as soon as possible under the condition of external disturbances, thereby ensuring. The stability and reliability of the entire heat storage system.

Calculation and analysis

We selected M City for the test on April 17, 2019. The weather was sunny and breezy. Based on the Sun's automatic tracking, we read the test data, as shown in tab. 2, through the measurement of radiation sensors, temperature collectors, and other test instruments.

The overall trend of changes in the average solar irradiance of the automatic tracking device and the fixed solar collector is shown in fig. 8. It can be seen from fig. 8 that during the period of 9:00 to 15:00, the average solar irradiance under the automatic tracking device is much higher than that under the fixed device. In the daytime, the maximum solar irradiance under the automated machine can reach 664 W/m^2 around 11:30, and the minimum irradiance is 416 W/m^2. The solar irradiance under the fixed device can reach 546 W/m^2 at the highest around midnight, and the lowest irradiance is 332 W/m^2. It can be seen from tab. 2 that the instantaneous efficiency of the solar collector under the automatic tracking device is higher than that under the fixed device by 14.8% on average, while the theoretical data is 16%. This error is first, the accuracy of the equipment during the experiment is not very accurate. Second, during the measurement process, if we are not very intensive in the period, then the data collected is not very complete. The heat collection effect under automatic tracking is better than the fixed device's impact, and it is feasible.

Table 2. Data related to solar radiation

Time	T_a, [°C]	T_{dr}, [°C]	I, [WM^{-2}]		η, [%]	
			Automatic device	Fixtures device	Automatic device	Fixtures device
9:00	6.00	20.20	506	363	0.6501	0.8325
9:30	6.80	30.10	557	390	0.6383	0.7903
10:00	7.40	47.90	585	462	0.5897	0.7297
10:30	8.10	70.10	631	481	0.5581	0.6681
11:00	8.60	88.70	647	512	0.5194	0.6403
11:30	9.30	104.10	664	527	0.4841	0.6041
12:00	9.60	119.30	611	546	0.4571	0.5572
12:30	11.00	132.90	655	524	0.4451	0.5350
13:00	12.40	145.20	626	511	0.3644	0.5044
13:30	14.60	156.10	550	448	0.3903	0.5003
14:00	15.50	170.00	483	382	0.3841	0.4883
14:30	15.70	160.10	453	348	0.3823	0.4809
15:00	14.10	147.20	416	332	0.3771	0.4679

Conclusion

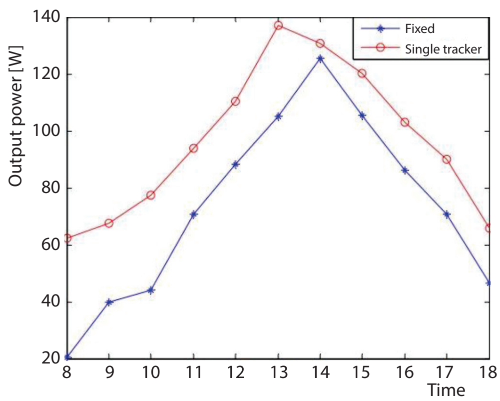

Figure 8. Comparison of solar irradiance between the automatic tracking device and fixed device

The heat storage system is an essential part of the trough solar device, which has a strong coupling effect on the front-end light field and the back-end thermal power conversion system. Regarding the possible disturbance changes in the outside world, this paper establishes a reasonable dynamic simulation mathematical model for the core problem in the trough solar TSS control process, uses PID control law, and uses the critical proportionality algorithm to optimize the control parameters. Combined with the simulation results in the article, we can draw the following conclusions. Compared with the other two control methods, PID control can effectively overcome the heat storage system's oscillation caused by changes in external errors. Its dynamic response speed is faster than P control and PI control and requires shorter adjustment time. We adopt a PID control scheme to ensure that the molten salt parameters at the outlet of the critical equipment *oil/salt heat exchanger* in the heat storage system are maintained within the rated setting range, thereby effectively improving the stability and reliability of the system, Reasonably improve the dynamic performance of the heat storage unit control system. We found that this research has particular guiding significance for the practical application of solar thermal power generation and heat storage engineering.

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