Application of extraction steam graded heat storage in peak shaving of condensing units

Siyu Zou 1a, Puyan Zheng 2b, Qunzhi Zhu 3c, Tianyu Bai 4d, Qingyuan Wei 5e, Guoqing Wei 6f

1-6College of Energy and Mechanical Engineering, Shanghai University of Electric Power, Shanghai, China

aemail: zousiyude@163.com, bemail: 1997000014@shiep.edu.cn,

cemail: zhuqunzhi@shiep.edu.cn, demail: 459694916@qq.com,

eemail: 840223335@qq.com, eemail: 3166461641@qq.com

* Corresponding author: Puyan Zheng, bemail: 1997000014@shiep.edu.cn

Abstract: In order to alleviate the peak shaving pressure of power grid and further improve the deep peak shaving capacity of coal-fired units, this paper applies staged heat storage to condensing units. Under the condition of constant boiler load, the heat of regenerative steam extraction is stored to reduce the electrical load output of the unit. Taking a 660MW ultra-supercritical unit as an example, 30%THA, 40%THA and 50%THA were taken as the initial conditions of heat storage respectively to discuss the peak shaving range and power regeneration efficiency of different extraction steam positions for heat storage. The results show that the "storage 1# HP heater extraction steam" scheme with "two-stage three tank" heat storage and release structure has the largest peak shaving range of 37.3%~56.9% under 50% initial conditions. When the "two-stage three tank" heat storage and release structure selects the "storage 1# HP heater extraction steam" scheme under 40% initial working condition, the "power regeneration efficiency" reaches the highest——78.3%. And the "power regeneration efficiency" of "two stage three tank" storage structure are always higher than the "single-stage" storage structure.

1. Introduction

Coal-fired thermal power generation is the main form of power production in China. In 2020, the national power generation capacity was 7623.6 billion kW·h, of which thermal power was 5174.3 billion kW·h, accounting for 67.9% [1]. Thermal power generation has the advantages of stable power output, mature technology and relatively low production cost. However, its biggest disadvantage is serious pollution and large emissions of greenhouse gases such as CO2 [2]. In order to achieve the goals of "peak carbon dioxide emissions" and "carbon neutrality", new energy power generation such as wind power and solar power will play a vital role [3,4]. By the end of 2020, the national installed capacity of grid connected wind power has increased by 34.6%, and the installed capacity of grid connected solar power has increased by 24.1% [1]. However, wind power and solar power have great randomness and volatility [5-7]. With the development of China’s economy entering the new normal, the total power consumption tends to grow steadily, but the peak valley difference of power consumption is becoming larger and larger. The above two points lead to great pressure on peak shaving of power grid [8,9]. Because of the large proportion of coal-fired generating units in China, coal-fired units have become the main force of...
peak shaving at present[10, 11].

Most coal-fired units in China have a minimum boiler steady combustion load factor of 50% [12], below which can lead to unstable combustion and even fire suppression. Adding oil will reduce the minimum stable combustion load, but long-term oil operation will greatly increase the cost [13]. Reforming the boiler to reduce the minimum stable combustion load is also a way. If the boiler load remains unchanged, it is easier to realize peak shaving by using energy storage technology [14]. Common energy storage technologies are divided into power storage and heat storage, but at present, large-scale commercial power storage technology is not mature and the cost is very high [15]. Heat storage technology is mostly used for peak shaving of cogeneration units [16-18], and there is little research and application of heat storage technology for peak shaving of condensing units.

WOJCİK J D et al. [19] studied the application of "single-stage single tank" heat storage mode to store steam heat energy at different positions in 375MW subcritical unit, and analyzed the advantages and disadvantages of the scheme from the aspects of peak shaving range and energy efficiency utilization. WANG Y et al. [13] proposed to adopt the "single-stage double tank" heat storage form to store the heat of main steam and all regenerative extraction steam, so as to improve the operation flexibility of coal-fired power plant and significantly reduce the wind abandonment rate. STEVANOVIC V D et al. [20] explored the method of using "single-stage" steam heat storage to increase the flexibility of the system. During heat storage, the exhaust steam of high-pressure cylinder is injected into the steam accumulator from the reheat pipe, and the condensed water is heated during heat release, so as to bypass two low-pressure heaters.

Previous studies tend to use the heat storage and release structure of "single-stage single tank" or "single-stage double tank". The advantage is that the heat storage and release process is simple, but it reduces the stored heat level to a certain extent, so that the stored heat cannot crowd out the high-pressure heater extraction steam in the heat release process to improve the utilization of the stored heat. And energy efficiency evaluation is rarely carried out for a storage and discharge cycle. In this paper, staged heat storage is applied to the deep peak shaving of condensing units based on the principle of energy cascade utilization. Aiming at the peak shaving process of a heat storage and discharge cycle, the peak shaving range and peak shaving energy efficiency of graded heat storage peak shaving scheme are studied. In particular, "two-stage three tank" heat storage and release structure and the evaluation indexes —— "power regeneration efficiency" are proposed.

2. Materials and Methods

2.1. Design of graded heat storage and release scheme for condensing unit

2.1.1. Principle of extraction steam heat storage and peak shaving

Extraction steam heat storage and peak shaving refers to store the heat of steam turbine extraction steam in the heat storage device during the low power consumption period to reduce the power generation power of steam turbine, and use this part of heat to heat feed water or condensed water during the peak power consumption period. The regenerative steam extraction is crowd to increase the power generation of the steam turbine, so as to respond to the needs of peak shaving of the power grid.

During heat storage, the extraction steam can be directly led out from the regenerative extraction steam pipe and reheat pipe. The heat release of extraction steam can be composed of superheated steam heat release, saturated steam condensation heat release and condensed water heat release, as shown in "abcd" in Figure 1 (a).

The "single-stage" heat storage system often uses a single or double tank to store thermal energy at one temperature level. After the storage medium absorbs heat, the temperature will increase, as shown in Figure 1(a), and the outlet temperature of the storage medium reaches “Tg” and is stored.

If graded heat storage is used, the heat exchanger will be divided into two parts (as shown in Figure 1(b)), the heat exchanger shall be set separately for the heat release of superheated steam, and the heat storage medium is divided into two parts after absorbing the heat from condensed water exothermic
and saturated steam condensation exothermic, one part will be stored at “Tf” temperature, and the other part will continue to heat up along the “fh” direction in Figure 1(a), and finally stored at “Th” temperature. So the graded heat storage can store thermal energy at different temperature levels, which facilitates the graded utilization of energy.

2.1.2. Design of heat storage and release scheme

Design of "two-stage, three-tank" heat storage and peak shaving system for condensing units based on the principle of graded heat storage, with two high-temperature tanks (H1 and H2) and one low-temperature tank (L), as shown in Figure 2.

In the process of heat storage, the high pressure extraction steam is drawn out and condensed to subcooled water in the two heat exchangers EX1 and EX2 after full exothermic discharge into the condenser heat well; the low temperature heat storage medium is pumped out from the L tank and absorbed in the heat exchanger EX2 and divided into two streams, one flowing into the H2 tank to be stored (Tf), the other through the heat exchanger EX1 to continue to be heated, and then into the H1 tank to be stored (Th). According to the different sources of heat storage, there can be different heat storage solutions, 1#, 2#, 3# high-pressure heater extraction steam as a source of heat storage solutions are called...
"storage 1# extraction steam" "storage 2# extraction steam" "storage 3# extraction steam" scheme.

Three heat exchangers EX3, EX4 and EX5 are set up in the heat release process. H1 tank with high temperature heat storage medium flows into L tank after exotherm through EX3, EX4 and EX5 in turn, which can simultaneously discharge 1#, 2# and 3# high-pressure heater extraction steam and low-pressure heater extraction steam to increase power generation. H1 and H2 tanks release the heat storage medium at the same time, which is called "exothermic stage 1", and the power generation increases the most; H1 tank is finished exothermic, and H2 tank continues exothermic stage, which is called "exothermic stage 2", and the power generation increases less.

2.2. Studied system and scheme evaluation index

2.2.1. Studied system

Taking a 660MW ultra-supercritical primary reheat unit as an example, EBSILON is used to build a static simulation model for peak shaving of the unit, and 30% THA, 40% THA, and 50% THA are used as the starting conditions of heat storage, and each peak shaving scheme is simulated and calculated. Table 1 gives a comparison of the data between the simulation results and the heat balance diagram, and it can be seen that the simulation error is within the acceptable range.

|                | Actual value | Simulation | Error | Actual value | Simulation | Error | Actual value | Simulation | Error |
|----------------|--------------|------------|-------|--------------|------------|-------|--------------|------------|-------|
| Power generation (MW) | 330.004      | 330        | 0.0%  | 264.007      | 264        | 0.0%  | 197.994      | 198        | 0.0%  |
| Main steam pressure (Mpa) | 15.8         | 16         | 1.3%  | 12.9         | 13.1       | 1.6%  | 9.93         | 10.06      | 1.3%  |
| Main steam temperature (℃) | 600          | 600        | 0.0%  | 600          | 600        | 0.0%  | 583          | 583        | 0.0%  |
| Main steam flow (t/h)     | 838.48       | 848.52     | 1.2%  | 679.19       | 689.539    | 1.5%  | 520.25       | 526.766    | 1.3%  |
| Reheat steam pressure (Mpa) | 2.052        | 2.074      | 1.1%  | 1.668        | 1.688      | 1.2%  | 1.282        | 1.291      | 0.7%  |
| Reheat steam temperature (℃) | 590          | 590        | 0.0%  | 575          | 575        | 0.0%  | 560          | 560        | 0.0%  |
| Reheat steam flow (t/h) | 723.84       | 730.075    | 0.9%  | 591.74       | 598.93     | 1.2%  | 457.39       | 461.908    | 1.0%  |

2.2.2. Scheme evaluation index

Taking a certain operating condition as the starting point, the power generation is the lowest when heat is stored and the power generation is the highest when heat is discharged under the condition of constant boiler load, so as to determine the range of peak shaving. In this study, the operating conditions of peak shaving are studied by simulation with EBSILON software, and the peak shaving range of the unit is determined.

The power generation efficiency of a condensing unit is the ratio of the electrical energy output of the unit to the chemical energy input to the fuel. Since the heat storage process stores the heat energy of the pumped steam, the generation efficiency of the unit must be lower than the normal generation condition during heat storage. Similarly, the exothermic process returns the stored thermal energy to the thermal system, so the power generation efficiency must be high. This index cannot reflect the impact of peak shaving on the energy efficiency of the unit during the whole heat storage and discharge cycle. In the peak shaving process, the heat storage process stores thermal energy by reducing power generation, and the heat release process converts the stored thermal energy into electrical energy again. In order to reflect the energy efficiency utilization of the whole heat storage and discharge process, the concept of "power regeneration efficiency" is proposed in this paper: the ratio of the increased power generation by heat discharge to the reduced power generation by heat storage. The greater the value, the higher the energy conversion efficiency of heat storage and peak shaving. The calculation is as Eq. (1).
where, $\eta_{e,re}$ is power regeneration efficiency. $\Delta W_{\text{dischg}}$ is increased power generation from exothermic processes. $\Delta W_{\text{chg}}$ is power generation reduced by heat storage process.

In Eq. (1), when the heat storage time is $t_{\text{chg}}$, the reduced power generation $\Delta W_{\text{chg}}$ due to heat storage is shown as Eq.(2)

$$\Delta W_{\text{chg}} = (P_{\text{stor}} - P_{\text{chg}}) \cdot t_{\text{chg}} \times 1000$$

where, $P_{\text{stor}}$ is power generation at starting conditions. $P_{\text{chg}}$ is power generation during heat storage. $t_{\text{chg}}$ is heat storage time.

However, the heat release time $t_{\text{dischg}}$ is not equal to the heat storage time $t_{\text{chg}}$, and without considering the heat loss of the storage process, $t_{\text{dischg}}$ can be calculated by Eq. (3).

$$t_{\text{dischg}} = \frac{(h_{\text{h,in}} - h_{\text{h,out}}) D_s t_{\text{chg}}}{(h_{\text{w,in}} - h_{\text{w,out}}) D_w}$$

where, $t_{\text{dischg}}$ is exothermic time. $h_{\text{h,in}}$, $h_{\text{h,out}}$ is enthalpy of extraction steam into and out of the heat exchanger. $D_s$ is extraction steam flow rate. $h_{\text{w,in}}, h_{\text{w,out}}$ is enthalpy of feed water or condensed water out and into the heat exchanger. $D_w$ is feed water or condensed water flow rate.

Then the increase of power generation $\Delta W_{\text{dischg}}$ by the exothermic process is calculated according to Eq. (4).

$$\Delta W_{\text{dischg}} = (P_{\text{dischg}} - P_{\text{stor}}) \cdot t_{\text{dischg}} \times 1000$$

where, $P_{\text{dischg}}$ is power generation during exotherm.

The "generation regeneration efficiency" $\eta_{e,re}$ can be calculated by substituting Eq.(2)(3)(4) into Eq. (1). When the heat storage time $t_{\text{chg}}$ is 1h, the sum of the corresponding heat release time $t_{\text{dischg}}$ and heat storage time $t_{\text{chg}}$ is one cycle of peak shaving.

3. Results & Discussion

3.1. Changes in the scope of peak shaving

Figure 3 shows the variation of the generation load factor with the amount of heat storage extraction steam for different storage starting conditions, and it can be seen that the generation load factor of all storage schemes decreases with the increase of the extraction steam amount, and the peak shaving depth of the "storage 1# extraction steam" scheme is always greater than that of the "storage 2# extraction steam" scheme, and the peaking depth of "storage 2# extraction steam" is always greater than that of "storage 3# extraction steam". This is because the extraction steam location of the "storage 1# extraction steam" scheme is at the 1# high pressure heater extraction steam location, and the extraction of steam at 1# high pressure heater extraction steam location will result in more reduction of turbine work than at 2# high pressure heater extraction steam location, and the reduction of work is equal to the internal work at the turbine level from 1# high pressure heater extraction steam location to 2# high pressure heater extraction steam location. In the same way, the depth of peak shaving of the "storage 2# extraction steam" scheme is greater than that of the "storage 3# extraction steam" scheme.

Different heat storage schemes have the same heat release scheme under the same heat storage initial working condition, so the maximum power generation in the heat release process is equal, as shown by the dotted line in Figure 3. However, the maximum generating power of heat release process under
different initial conditions of heat storage is not equal. Different initial conditions of heat storage lead to different maximum extraction steam, resulting in different peak shaving depth. The lowest peak shaving depths of 30%, 40%, and 50% storage starting conditions reach 26.3%, 31.5%, and 37.3%, respectively, with the 50% starting condition having the largest peaking range.

![Diagram showing power generation load rate with regenerative steam extraction under different initial conditions of thermal storage](image)

**Fig.3** Variation of power generation load rate with regenerative steam extraction under different initial conditions of thermal storage

### 3.2 Comparison of power regeneration efficiency of various schemes

Figure 4 shows the variation of power regeneration efficiency of each heat storage scheme with extraction steam under different initial conditions of heat storage. In most cases, the power regeneration efficiency of the "storage 1# extraction steam" scheme is greater than that of the "storage 3# extraction steam" scheme, while the "storage 3# extraction steam" scheme is greater than that of the "storage 2# extraction steam" scheme. However, when the steam extraction capacity is large under the initial working conditions of 40% and 50% heat storage, the power regeneration efficiency of the "storage 3# extraction steam" scheme is the highest. And the power regeneration efficiency of the "storage 1# extraction steam" scheme has dropped sharply.

The reason for the sudden drop in the power regeneration efficiency of the "storage 1# extraction steam" scheme is that when the extraction steam capacity under the initial conditions of 40% and 50% increases, the temperature of the heat storage medium in the H2 tank is lower than the feed water temperature at the outlet of the 2# high-pressure heater, so the heat storage medium in the H2 tank can only crowd out the regenerative extraction steam of the 3# high-pressure heater and the low-pressure heater. This causes H1 tank to increase the supply of heat storage medium per unit time, so as to exclude the high-pressure heater regenerative extraction steam, resulting in a significant reduction in the heat release time of "heat release stage 1". However, "heat release stage 1" has the highest power generation, so the increase of heat release power generation slows down. Although the heat release time
of "heat release stage 2" is relatively prolonged, the increased power generation in "heat release stage 2" is not enough to supplement the reduced power generation in "heat release stage 1", so the increased power generation in the whole heat release process does not increase significantly with the increase of extraction steam.

Fig. 4 shows the variation of power regeneration efficiency with steam extraction rate under different initial conditions of thermal storage.

3.3. Comparison with "single-stage double tank" heat storage and release system

According to the above analysis, in the "two-stage three tank" heat storage and release system, the "storage 1# extraction steam" scheme under the initial working condition of 40% heat storage is the scheme with the highest energy efficiency. Fig. 5 shows the comparison between the "two-stage three tank" and the "single-stage" heat storage and release system under this condition. As shown in Figure 5 (a), the peak shaving range of "single-stage", "two-stage and three tank" storage structure in the heat storage process is the same. With the increase of heat storage extraction steam capacity, the power generation load rate decreases from 40% to 31.5%. However, the power generation load rate of the "two-stage and three tank" structure in the heat release process is higher than that of the "single-stage" structure, because the temperature of the heat storage medium in the "single-stage" structure is lower than that of the feed water at the outlet of 1# high pressure heater, so the extraction steam of 1# high pressure heater cannot be excluded, and only the regenerative extraction steam behind 1# high pressure heater can be excluded, resulting in the power generation load rate in the heat release process is lower than that of the "two-stage and three tank" structure.

As shown in Figure 5 (b), the power regeneration efficiency of the "two-stage three tank" storage structure is higher than that of the "single-stage" structure. Although the reduced power generation under the same heat storage extraction steam capacity is the same, it is also because the temperature of the
heat storage medium of the "single-stage" structure is lower than the temperature of the feed water at the outlet of 1# high pressure heater, so the regenerative extraction steam with high parameters cannot be excluded during heat release, resulting in the increased power generation during heat release is lower than "two-stage three tank" structure, so the power regeneration efficiency in one storage cycle is lower than that of "two-stage three tank" structure.

Fig. 5 Comparison of "storage 1# HP heater extraction" schemes of "single-stage", "two-stage and three tank" storage and drainage structures under 40% initial working conditions

4. Conclusions

In this paper, a peak shaving system with "two-stage and three tank" heat storage and release structure has been proposed and applied to a 660MW ultra supercritical unit. The peak shaving range and power regeneration efficiency of different schemes have been compared. The following conclusions are drawn:

(1) The peak shaving range of "storage 1# extraction steam" scheme is always the largest. The peak shaving range is 26.3%-33% under 30% initial working conditions, and is 31.5% ~ 45.2% under 40% initial conditions, and is 37.3%-56.9% under 50% initial working conditions.

(2) Under the initial working conditions of 30%, 40% and 50%, the power regeneration efficiency of "storage 1# extraction steam" scheme is the highest in most cases, reaching 64.8%, 78.3% and 70.7% respectively. However, when the steam extraction capacity is larger at 40% and 50% initial working conditions, the power regeneration efficiency of the "storage 3# extraction steam" scheme exceeds that of the "storage 1# extraction steam" scheme, and the maximum power regeneration efficiency is 73.9% and 72.1% respectively.

(3) Compared with the "single-stage" storage structure, the peak shaving range and power regeneration efficiency of the "storage 1# extraction steam" scheme of the "two-stage three tank" storage structure under 40% initial working condition are greater than those of the "single-stage" structure. When the heat storage capacity of the "single-stage" structure is 100t/h, the power regeneration efficiency is 69.6%, which is lower than the 77.3% of the "two-stage, three-tank" structure under this condition.

Acknowledgments

This paper is one of the phased achievements of the <Application of Energy Storage Technology in Deep Peak Shaving of Coal-Fired Power Units> project of Shanghai Science and Technology Commission.

References

[1] China Electricity Council. (2021-01-20). Data list of national electric power industry statistics in 2020. https://cec.org.cn/detail/index.html?3-292820

[2] LOU S, YANG Y, WU Y, et al. (2020) Coal-fired power generation dispatch and coal blending coordinated optimization considering the spatiotemporal characteristics of atmospheric
pollutants diffusion. Proceedings of the CSEE, 40: 6956-6964.

[3] HUANG C, ZHANG P, WANG W, et al. (2021) The upgradation of coal-fired power generation industry supports China’s energy conservation, emission reduction and carbon neutrality. Thermal Power Generation, 50: 1-6.

[4] MENG Z. (2021) Highlight the strategic supporting role of power grid enterprises in the implementation of carbon peak and carbon neutral goals. China Electric Power News, Beijing.

[5] WANG Q, CHEN Z, LI L, et al. (2020) Achievement in ultra-low-load combustion stability for an anthracite- and down-fired boiler after applying novel swirl burners: From laboratory experiments to industrial applications. Energy, 192: 116623.

[6] DENG T, LOU S, TIAN X, et al. (2019) Optimal dispatch of wind power system considering demand response and thermal power deep peak shaving. Automation of Electric Power Systems, 43: 34-41.

[7] SONG C, TIAN X, XU T, et al. (2020) Effect of heat storage device on primary frequency regulation capacity of thermal power unit. Electric Power, 53: 120-128.

[8] DING N, DUAN J, XUE S, et al. (2015) Overall review of peaking power in China: Status quo, barriers and solutions. Renewable and Sustainable Energy Reviews, 42: 503-516.

[9] LI Y. (2019) Research on Multi-point Layout Technology of Energy Storage System in Receiving Power Grid. Xinjiang University, Xinjiang.

[10] ZHAO Y, FAN P, WANG C, et al. (2019) Fatigue lifetime assessment on a high-pressure heater in supercritical coal-fired power plants during transient processes of operational flexibility regulation. Applied Thermal Engineering, 156: 196-208.

[11] XU S, GUO T, WANG Y, et al. (2021) Optimal scheduling of electro-thermal energy integrated system under the background of flexibility retrofit of thermal power unit. Electric Power Construction, 42: 27-37.

[12] ZHANG G, ZHOU K, LU F, et al. (2017) Discussions on deep peaking technology of coal-fired power plants. Thermal Power Generation, 46: 17-23.

[13] WANG Y, LOU S, WU Y, et al. (2020) Flexible operation of retrofitted coal-Fired power plants to reduce wind curtailment considering thermal energy storage. IEEE Transactions on Power Systems, 35: 1178-1187.

[14] ZHOU L, DUAN L, ANTHONY E J. (2019) A calcium looping process for simultaneous CO2 capture and peak shaving in a coal-fired power plant. Applied Energy, 235: 480-486.

[15] CHEN Z, WANG D, JIA H, et al. (2017) Research on optimal day-ahead economic dispatching strategy for microgrid considering p2g and multi-source energy storage system. Proceedings of the CSEE, 37: 3067-3077+3362.

[16] WEI H, LU Y, ZHANG C, et al. (2020) Status and prospect of flexibility regulation technology for coal-fired power plants. Huadian Technology, 42: 57-63.

[17] WANG Z, GUO D, FU J, et al. (2019) Analysis of peak shaving flexibility in heating system after installing heat storage, 61: 311-314+265.

[18] JIN G, GAO Y, ZHANG L. (2021) Research on the effect of heat storage tank reconstruction on decoupling and peaking capacity of chp units. Turbine Technology, 63: 133-136+114.

[19] WOJCIEK J D, WANG J. (2017) Technical feasibility study of thermal energy storage integration into the conventional power plant cycle. Energies, 10: 205.

[20] STEVANOVIC V D, PETROVIC M M, MILIVOJEVIC S, et al. (2020) Upgrade of the thermal power plant flexibility by the steam accumulator. Energy Conversion and Management, 223: 113271.

[21] WANG Z. (2020) Technology and application of flexible deep peak shaving in thermal power plant. China Electric Power Press, Beijing.