Study on Optimal Operation for Concentrating Solar Power Plants Considering Wind Power Reduction

Guochun Yuan, Panfeng Guo

1 College of Electrical Engineering and New Energy, China Three Gorges University, Yichang, Hubei, 443002, China
2 Hubei Provincial Key Laboratory for Operation and Control of Cascaded Hydropower Station, Yichang, Hubei, 443000, China
*Corresponding author’s e-mail: 397038289@qq.com

Abstract. Concentrating solar power (CSP) generation units, which can generate electricity without any pollutant emissions, is one of the most attractive alternatives to fossil fuels. However, the main disadvantage of the CSP device is the high investment cost. In order to improve the economic feasibility, it is necessary to properly design the thermal energy storage (TES) device to optimize its economic benefits. In this paper, considering the operation requirements of power system, the optimal co-allocation model of solar energy field and TES device is established to weigh the investment cost and wind power reduction. Through a case study, the effectiveness of using energy storage to improve wind power consumption is verified on the basis of considering the constraints of the actual operation of the system, solar radiation and wind energy uncertainty.

1. Introduction

In recent years, CSP devices have attracted the attention of some researchers. In the literature [5-7], TES can significantly improve the energy value, auxiliary service value and capacity value of CSP equipment. In reference [1], an optimization method is proposed to maximize the profit of CSP equipment in the power market. The work of these published CSP devices focuses on operational optimization. However, the deployment and distribution of SF and TES in CSP devices have not been deeply studied. According to reference [11], CSP equipment is usually designed by minimizing horizontal cost (LCOE). This method only considers the production of a single CSP device, but ignores the impact on the whole power system. The flexibility of CSP equipment has great potential advantages, which can reduce the turn-on / shutdown of traditional equipment and reduce the loss of wind power, especially in coal-fired power generation systems. Therefore, when allocating SF and TES, the energy flow of CSP device and its influence on the whole power system should be taken into account.

In this manuscript, an optimal co-allocation model of SF and TES for CSP devices in wind power integrated power system is established to deal with the trade-off between investment costs and benefits. Considering that the actual operation constraints take into account the interaction between hourly changes, the uncertainty of solar radiation and wind energy is characterized by a set of scenarios.
2. Mathematical Model of CSP device

2.1. Basic structure of CSP device
In general, CSP equipment can be divided into three independent modules: solar field module SF, thermal storage module TES and power block module (PB). The following is a brief description of these three modules: the light field module SF subsystem is a sunlight collector that can heat cold fluids. It consists of one or more solar collector assembly rings, each arranged in parallel. In the solar collector assembly, sunlight is concentrated on the receiving tube through a U-shaped curved mirror, which makes the heat transfer fluid (HTF) reach high temperature. Compared with other renewable energy technologies, a bright spot of CSP equipment is schedulability. Using the TES subsystem, CSP devices can send heat from noon to low radiation periods or reach peak loads at night. The TES subsystem consists of two lines and a large number of heat storage materials. One tank is designed to store hot fluids and the other to store depleted cold fluids. In the process of storage, a small part of the heat energy will be lost in the hot water tank. In the hot molten salt storage system, the round trip efficiency is > 98%. The power block subsystem consists of traditional steam cycles and generators, which have the ability to convert heat into electricity. The heat generated by the high temperature HTF is transferred to the water, generating superheated steam to drive the turbine. Steam cycle technology is also widely used in traditional equipment, such as fossil fuels, nuclear power and biomass equipment. The difference between CSP devices is that their heat comes from radiation, not from nuclear reactions or biomass.

2.2. Mathematical constraints of CSP Model
The flow chart of the CSP device is shown in figure 1. In the CSP device, the SF, TES and PB subsystems are combined with the heat flow. In the SF, sunlight is converted into heat energy. Thermal energy can then be stored in the TES subsystem. In the PB subsystem, heat is converted into electricity. Therefore, the three blocks of CSP device must comply with its technical limitations. The detailed operation model is described by the following equation.

\[ P_{\text{solar}} + P_{\text{chge}} = P_{\text{bge}} + P_{\text{bge}} \]  
\( (1) \)

Solar energy is defined as direct normal radiation (DNI). As described in (2), the output of SF is limited by solar energy. The size of the SF is usually measured by the solar multiple. Constraint (4) states the upper and lower limits for reducing solar energy.

\[ P_{\text{solar}} = \eta_S \left( A_{SF} \times \text{DNI} \times \eta_{\text{cos}} \right) \]  
\( (2) \)

\[ S_{SF} = \eta_S \eta_{\text{bge}} A_{SF} \times \text{DNI} / P_{\text{max}} \]  
\( (3) \)

\[ 0 \leq P_{\text{bge}} \leq A_{SF} \times \text{DNI} \]  
\( (4) \)
2.3. Mathematical constraints of TES Model
At present, the commonly used heat storage device is a large heat storage tank for short-term heat storage, which uses water as the storage medium and stores heat according to the difference of water density at different temperatures and the principle of stratification of cold and hot water. For the operation cost of the heat storage device, the heat dissipation loss is mainly considered. Therefore, the following expression can be obtained for the heat storage transformation of the heat storage device.

\[ \Delta H_t = (1 - \mu_{loss}) \cdot H_{i,t-1} + Q_{ch,t} \cdot \eta_{ch,ref} - Q_{dis,t} / \eta_{dis,ref} \]  

In the formula: \( H_t \) and \( H_{i,t-1} \) represent the heat storage of the heat storage tank at \( t \) time and the previous time respectively; \( \mu_{loss} \) indicate the heat loss rate of the heat storage tank; \( Q_{ch,t} \) indicate the heat storage efficiency of the heat storage tank over a period of time; \( \eta_{ch,ref} \) indicate the heat release efficiency of the heat storage tank for a period of time; \( \eta_{dis,ref} \) indicate the heat release efficiency of the heat storage tank.

3. Establishment of objective function
The optimal scheduling of integrated energy system considering wind power consumption usually takes the lowest total coal consumption cost of the system as the scheduling goal. In order to test the effect of energy storage device on abandoned wind absorption, the abandoned wind cost is added to the cost, so the objective function of the optimal scheduling model can be expressed as follows:

\[
\min C_{total} = \sum_{t=1}^{T} \left( F_1 + F_2 \left( P_{c,t}, P_{ch,t}, P_{h,t} \right) + \sum_{i=1}^{N} C_{w,i} \right) 
\]

In the formula, \( C_{total} \) is the total investment cost, \( F_1 \) is investment cost function of the conventional thermal power unit, \( F_2 \) is investment cost function of the CHP unit, \( P_{c,t} \) is the electric energy output of the conventional unit at the \( t \) time, \( P_{ch,t} \) is the total electric energy output, \( P_{c,t} \), \( P_{ch,t} \) and \( P_{h,t} \) is the total thermal energy output, the total heating power and the TES storage and release power of the CHP unit at the \( t \) time, respectively, and \( C_{w,i} \) is the abandoned air cost of the fan at the \( t \) time.

4. Case study
4.1. The basic situation of testing power system
IEEE-30 bus power system is taken as an example to simulate the common distribution of SF and TES of CSP devices. The test system includes 500MW of wind power and nine coal-fired units with a total capacity of 1550 MW. In addition, three CSP devices with a total capacity of 330MW have been added to the test system, and the relevant parameters are shown in Table 1.

| Unit type   | Installed capacity /MW | Quantity |
|------------|------------------------|----------|
| conventional unit | 1550                  | 9        |
| CSP unit   | 330                    | 2        |

4.2. Analysis of simulation results
The hourly power outputs under different settings is shown in figures 2 and 3. Without energy storage, the output curve of wind power and conventional thermal power and cogeneration units is shown in figure 2, and the abandoned wind appears in the system. At this point, the abandoned wind power is 289MWh. A heat storage device is installed at the CSP unit, and the heat storage capacity is 110MWh. After adding heat storage, the curve of wind power output and conventional thermal power and cogeneration units is shown in Figure 3, and the abandoned wind power is reduced to 213 MWh. As can be seen from the diagram, when the wind power output is too large, the power load will be less abandoned wind, at this time, the CSP unit uses the heat storage device for heating, reducing the unit output (including electric energy output and thermal energy output), thus increasing the space for wind power consumption; when the wind power output is small and the power load is large, the CSP unit increases the power output, in addition to meeting the heat load demand, the remaining heat can be stored in the heat storage tank. That is, the heat storage device releases heat when there is abandoned wind, and stores heat when there is no abandoned wind.

**Figure 2** The hourly power outputs without TES

**Figure 3** The hourly power outputs with TES

5. Conclusion

The integrated energy system is a complex and diverse system with various energy forms, with the CHP unit as the core, including a variety of energy supply units and energy storage units, which can realize the comprehensive utilization of many kinds of energy, and has the characteristics of flexible scheduling, high energy efficiency, environmental protection and safety.

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