Optimal Configuration of Energy Storage Capacity on PV-Storage-Charging Integrated Charging Station

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Abstract. The rational allocation of a certain capacity of photovoltaic power generation and energy storage systems (ESS) with charging stations can not only promote the local consumption of renewable energy (RE) generation, but also participate in the energy market through new energy generation systems and ESS for arbitrage. In this paper, a system operation strategy is formulated for the optimal storage and charging integrated charging station, and an ESS capacity allocation method is proposed that considers the peak and valley tariff mechanism. First, the system modeling of the photovoltaic storage and charging station is carried out, the topology structure is analyzed and the cost model of photovoltaic power generation and ESS and dispatching is established; second, the energy flow of the photovoltaic storage and charging station is analyzed and the system operation strategy is formulated; then, the optimal model of ESS capacity configuration is established with the goal of obtaining the maximum benefit from the photovoltaic storage and charging station under the peak and valley electricity price environment; finally, the optimal ESS capacity configuration of the photovoltaic storage and charging station is analyzed based on specific cases and the impact of the change of ESS price on the optimal capacity configuration is discussed.

Keywords: PV-Storage-Charging Integrated system, Capacity configuration, Time-of-use tariffs, Economy

1. Introduction

With the extensive evolution of electric vehicles in countries around the world, our government has given more attention to the development of charging infrastructure. At present, the electricity that powers electric vehicles actually still relies on the conversion of conventional coal energy (about 75% to 80%) and does not fundamentally reduce carbon emissions. Under such circumstances, in recent years, the State has vigorously promoted the development of new energy generation, directly establishing charging equipment linked to RE generation systems, and achieving local consumption of RE has become a trend. Therefore, the rational configuration of a certain capacity of solar electricity generation and ESS along with the charging station can not only reduce the charging station's power...
purchase cost and self-use, and obtain greater economic benefits, but also suppress the randomness of charging load, promote the nearby consumption of RE power generation and the development of low-carbon electric vehicles. However, energy storage is expensive, and how to reasonably allocate optical storage capacity of PV-Storage-Charging Integrated Charging Station (PSCS) has important research significance. Current research on energy storage capacity allocation is mainly divided into the following 2 aspects.

The first category is configuration of the capacity of the ESS for smoothing load fluctuations [1-4]. Literature [2] presents a sizing method for distributed PV distribution systems equipped large-scale centralized PV power stations for accurate allocation of ESS capacity: by analyzing the probabilistic statistical laws and stochastic processes of short-term forecast errors of PV output and short-term forecast errors of load, the interval estimation method is used to derive the capacity allocation function of ESS. Literature [3] introduces an approach for ESS with centralized solar power. The method aims to improve the stability of PV output and uses statistical methods to determine the energy capacity by considering the effects of various weather conditions. Literature [4] aims to suppress PV and wind power output volatility by combining spectral analysis and low-pass filtering to determine the optimal ESS rated power and capacity.

The second category is ESS capacity allocation for economic purposes [5-12]. The literature [8] considers economic indicators such as energy cost, cost of capital, etc., using entropy weight and similarity ranking preference techniques to evaluate optimal capacity allocation. Literature [9] proposed an optimal configuration method aiming at the minimum construction and operation cost of ESS and the maximum consumption of photovoltaic and wind power. Literature [10] proposes two iterative search algorithms based on constraints to determine the optimum capacity of ESS with the objective of system reliability and economy.

In summary, there have been many studies on PSCS in recent years, but there are fewer studies on energy storage capacity allocation involving optical storage and integrated power plants. In this paper, we systematically model the PSCS, analyze the topology structure, establish the cost model of photovoltaic power generation and ESS dispatching costs, formulate the energy flow strategy of the PSCS under various working situations, and establish the energy storage capacity allocation model with the goal of optimal economy. Through specific examples, the analysis determines the optimum ESS capacity of the PSCS and analyzes the operation of the PSCS under optimum ESS capacity, and analyzes the impact of changes in energy storage price on the optimal ESS capacity.

2. Modeling of PSCS

2.1 Structure for PSCS

The structure of the PSCS is shown in Fig. 1. It consists of PV generator sets, energy storage units, power networks, charging piles, monitoring systems, etc.
2.2 PV Annual Cost Model
The cost of photovoltaic power generation mainly depends on three factors, such as the cost of spare parts, installed capacity, policy subsidies, etc. After the construction is completed, only the necessary maintenance is required, and there is no additional cost for photovoltaic power generation, which can be generated only by light. Therefore, the annual cost of PV power generation is shown as Eq. 1.

\[ C_{pv} = L_{pv}P_{pv,m}E_{pv} \]  

(1)

\[ L_{pv} = \frac{r(1+r)^z}{(1+r)^z - 1} \]  

(2)

Where, \( L_{pv} \) is the annual value of the PV cost factor; \( P_{pv,m} \) is the PV installed capacity; \( E_{pv} \) is cost of PV by unit capacity; \( r \) is the discount rate; \( z \) is the equipment life.

2.3 Energy Storage Cost Model
The number of cycles that occur when the available capacity of the battery decays to a certain degree is called the battery cycle life, which is connected to the temperature, discharge depth, frequent charging and discharge state switching, etc. This paper mainly considers the effect of the discharge depth on the cycle life of the battery, combined with the actual operating conditions, to obtain the calculation of the cost of the battery single discharge loss method.

Take lithium battery as an example, the relationship between the discharge depth of lithium battery and cycle life is shown in Fig. 2, the fitting formula for the cycle life curve is

\[ N_a(D) = aD^b \]  

(3)

Where \( a, b \) is the coefficient and \( D \) is the battery discharge depth.

![Image](image.png)

**Fig 2. Structure diagram of PSCS**

Define the single discharge life loss rate of an energy storage cell as

\[ \lambda% = \frac{1}{N_a(D)} \times 100\% \]  

(4)

As a result, the cost of battery loss due to this energy storage dispatch as

\[ C_d = C_o\lambda\% \]  

(5)

Where \( C_o \) is the purchase cost of ESS.

3. System Operation Mode of PSCS
In the time-of-use tariff model, considering the characteristics of photovoltaic power generation, peak-valley spread and load characteristics, the PSCS can adjust the power exchange with the grid according to different operating conditions, so as to maximize the economic benefits of the PSCS.

Define the difference between the PV power and the charging load power demanded of the
charging station as the net power of the PSCS, recorded as $\Delta P$.

$$\Delta P(t) = P_{PV}(t) - P_{load}(t)$$  \hspace{1cm} (6)

Where $P_{PV}(t)$, $P_{load}(t)$ is the the PV system output power and the charging load requirements power of the PSCS for each time period.

The PSCS operation strategy is shown in Tab. 1, where $SOC_{min}$ indicates the lower limit of safe operating capacity of the ESS; $SOC_{max}$ indicates the upper limit of safe operating capacity of the ESS.

**Table 1. System operation mode of PSCS**

| Operation mode | Electricity price period | Ned load | SOC | Operation strategy |
|----------------|--------------------------|----------|-----|-------------------|
| 1              | Valley                    | $\Delta P(t)<0$ | SOC(t)<$SOC_{max}$ | Power purchase and energy storage charge |
| 2              | Valley                    | $\Delta P(t)>0$ | SOC(t)=$SOC_{max}$ | Surplus electricity sold |
| 3              | Valley                    | $0<\Delta P(t)<P_{B_max}$ | SOC(t)<$SOC_{max}$ | Power purchase and energy storage charge |
| 4              | Valley                    | $\Delta P(t)>P_{B_max}$ | SOC(t)<$SOC_{max}$ | Power purchase and energy storage charge |
| 5              | Peak                      | $\Delta P(t)>0$ | SOC(t)=$SOC_{max}$ | Surplus electricity sold |
| 6              | Peak                      | $0<\Delta P(t)<P_{B_max}$ | SOC(t)<$SOC_{max}$ | Energy storage charge |
| 7              | Peak                      | $\Delta P(t)>P_{B_max}$ | SOC(t)<$SOC_{max}$ | Electricity sold and energy stored charge |
| 8              | Peak                      | $\Delta P(t)<0$ | SOC(t)=$SOC_{min}$ | Power purchase |
| 9              | Peak                      | $-P_{B_max}<\Delta P(t)<0$ | SOC(t)>$SOC_{min}$ | Energy storage discharge |
| 10             | Peak                      | $\Delta P(t)<-P_{B_max}$ | SOC(t)>$SOC_{min}$ | Power purchase and energy storage discharge |

### 4. Economic Optimization Model

#### 4.1 Objective Functions

In this paper, we concentrate primarily on the economic benefits of PSCS, and make the PSCS obtain the maximum economic benefits by optimizing the configuration of ESS capacity. Therefore, with the goal of maximizing benefits, consider the cost of purchasing power from the grid by the charging station, the benefit of selling power to the grid, the benefit of providing charging services, the cost of PV generation, and the cost of ESS loss to establish the objective function as Eq.(7).

$$\max F = C_1 + C_2 - C_3 - C_4$$  \hspace{1cm} (7)

Where $C_1$ is the cost of electricity being sold to the grid from PSCS; $C_2$ is the revenue from the charging service provided by the PSCS to electric vehicle users; $C_3$ is the investment cost of photovoltaic and energy storage equipment, calculated as one year’s cost through the equal annual value method; $C_4$ is the cost of buying electricity from the grid for PSCS.

$$C_3 = \sum_{j=1}^{8760} \rho_{0}(j)P_{G_0}(j)\Delta t$$  \hspace{1cm} (8)

Where $\rho_0(j)$ is the feed-in tariff at the $j$ time; $P_{G_0}(j)$ is the power delivered to the grid by the PSCS at the $j$ time; $\Delta t$ is the duration of 15min(same as below).

$$C_4 = \sum_{j=1}^{8760} \rho_{G}(j)P_{L}(j)\Delta t$$  \hspace{1cm} (9)

Where $\rho_0(j)$ is the electric vehicle charging cost at the $j$ time; $P_{L}(j)$ is the charging load power of the PSCS at the $j$ time.
\[ C_2 = C_{pv} + C_{b} \]  

Where \( C_b \) is the battery dispatch loss cost.

\[ C_4 = \sum_{j=1}^{2760} p(j) P_{G,s}(j) \Delta t \]  

Where \( P_t(j) \) is the purchase price of electricity at the \( j \) time; \( P_{G,s}(j) \) is the power delivered by the grid to the PSCS at the \( j \) time.

4.2 Constraints

(1) Power balance constraint

\[ P_{pv}(j) + P_G(j) - P_b(j) - P_t(j) = 0 \]  

Where \( P_G(j) \) is the power delivered by the grid to the PSCS at the \( j \) time; \( P_b(j) \) is the charging power of ESS at the \( j \) time (the discharging is negative power).

(2) Charging state constraints on ESS

\[ SOC_{\min} < SOC(j) < SOC_{\max} \]  

Where \( SOC_{\max} \) and \( SOC_{\min} \) is the maximum and minimum charge rate of the energy storage system, respectively, to avoid overcharge or overdischarge of the ESS.

(3) Charge capacity constraints for ESS

\[ E_a(j + \Delta t) = E_a(j) + P_{a,s}(j) \Delta t \eta_i \]  

Where, \( E_a(j) \) is the capacity of ESS at the \( j \) time; \( P_{a,s}(j) \) is the charging power of ESS at the \( j \) time; \( \eta_i \) is the charging efficiency of ESS.

(4) Discharge capacity constraints for ESS

\[ E_a(j + \Delta t) = E_a(j) + P_{a,o}(j) \Delta t / \eta_o \]  

Where, \( P_{a,o}(j) \) is the discharge power of ESS at the \( j \) time; \( \eta_o \) is the discharging efficiency of ESS at the \( j \) time.

(5) Constraints on ESS charge/discharge power

\[-P_{b,max} < P_b(j) < P_{b,max} \]  

5. Example Analysis

For example, the installed capacity of a PV charging station is 200kW. The demand curve of a typical day’s electric vehicle charging load and PV system output of the PV charging station is shown in the fig. 3.

As is evident from Fig. 3, in the case of low PV power at night, the ESS is mainly recharged during the valley period (23:00-7:00), when the electricity price is low. During the daytime, PV is more powerful (10:00 to 15:00) and the tariff is at the peak of the tariff. Arbitrage by using surplus power when PV is in full supply. Storage begins to supply energy when PV capacity is low to reduce the amount of electricity the system buys from the grid during peak tariff times, thereby reducing the cost of purchasing electricity. It can be seen that even if this paper only considers the economic benefits of the operator, it also helps the grid in certain procedures to achieve peaks and valleys reduction, reducing the grid peak-to-valley gap and easing the pressure on the grid peaking.

Under optimum configuration of the ESS capacity, the annual cost of the system is shown in the Tab. 2.
Table 2. System operation mode of PSCS

| System composition | Charging load | Charging load + PV | Charging load + PV+Stored energy |
|--------------------|---------------|--------------------|---------------------------------|
| Annual commuted cost of system investment/RMB | — | 38189 | 48584 |
| Annual cost of electricity purchased/RMB | 819810 | 573997 | 452361 |
| Annual cost of electricity sales/RMB | — | 46460 | 42969 |
| Cost savings/RMB | — | 254084 | 367834 |

By analyzing the cost operation results of the system in Tab. 2, it is evident that the PSCS saved about 250,000 RMB per year in the case of not configuring ESS, and about 360,000 RMB per year in the case of configuring the optimal capacity of the ESS, compared with only configuring the PV system, saving about 120,000 RMB per year. By configuring the ESS, a significant increase in the revenue of the charging station can be achieved.

Fig 3. PSCS operating state in optimal capacity configuration

The cost of ESS has a large impact on the optimal capacity of ESS, Fig 4 shows how the optimal ESS capacity changes with the cost of ESS. Optimum ESS capacity gradually increasing as the price of storage reduces. When the price of ESS rises to a certain point, called the critical price of ESS, then the configuration of ESS does not help the economics of charging stations, only when the price is lower than the critical price, the configuration of ESS will make sense.

Fig 4. Variation trend of optimal energy storage capacity with different storage battery prices
6. Conclusions
In this study we take into account the annual commuted cost of PV, energy storage investment, energy storage scheduling loss cost, energy storage maximum output constraint and so on to establish the optimal configuration model of ESS capacity with the goal of optimizing the economics of PSCS. The simulation results verify the rationality of the optical storage and charging system configuration and the effectiveness of the system operation strategy. The operation of the PSCS is analyzed in the optimal ESS capacity configuration. The integrated charging station of optical storage can operate scientifically and reasonably according to various working situations, reduce the amount of electricity purchased during the peak period of electricity prices, thus reducing the electricity purchase cost, improving the operational efficiency of the optical storage charging station, and to a certain extent, play the function of auxiliary services in the electricity market, reducing the peak and valley differences on the grid side. The impact of various ESS costs on optimum capacity configuration is analyzed.

Acknowledgements
This work was supported by the State Grid Shandong Electric Power Company Science & Technology Project (NO.52060118005W).

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