Scheduling Strategy of PV-Storage-Integrated EV Charging Stations considering Photovoltaic Output and User Demand Uncertainty

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Abstract. The PV-Storage-Integrated EV charging station is a typical integration method to enhance the on-site consumption of new energy. This paper studies the optimization of the operation of PV-Storage-Integrated charging stations. Firstly, considering the uncertainty of photovoltaic output and user's charging demand, a photovoltaic output model and a user charging behavior model were constructed. Secondly, the optimal economic operation model of the PV-Storage-Integrated EV charging stations is proposed based on the cost of purchasing power from the distribution network and the life loss cost model of the battery cycle. The constraints such as the charging and discharging power of the battery and the SOC range of the energy storage battery are considered. Finally, optimal scheduling schemes in different typical scenarios are analyzed, and the results show the effectiveness of the proposed optimal scheduling scheme.

Keywords: PV-Storage-Charging, Integrated Charging Station, Photovoltaic Output, Uncertainty

1. Introduction

With increasingly serious environmental problems, new energy electric vehicles have been vigorously developed [1, 2]. With the substantial increase in the number of EV, their disorderly charging has had a huge influence on the operation of distribution networks [3,4]. Meanwhile, China's primary energy generation side of the coal is still dominated, while the electric car is still rely on fossil fuels. As a renewable and clean energy source, photovoltaics can also be produced in urban areas [5,6]. By integrating photovoltaic power generation systems, energy storage systems and charging facilities on-site, not only can photovoltaic consumption be increased, but the dependence of electric vehicles on the grid can also be reduced. Therefore, it is necessary to conduct research on reasonable optimization scheduling strategies.

At present, many scholars have conducted research on electric vehicle photovoltaics storage charging stations. Some concentrate on the PV charging’s structure. [7,8] design the system structure...
of photovoltaic-based charging station in order to promote the consumption of photovoltaic energy. [9] introduces the structure of the DC microgrid including electric vehicle charging and renewable energy generation. [10] designs an independent photovoltaic docking station and shows that the electric vehicle using photovoltaic system to store energy may be the best way to improve the consumption of clean energy. [11] discusses the charging strategy of collaborative electric vehicles and renewable energy microgrids and analyzes the service availability under different charging strategies. Taking into consideration the randomness of electric vehicle charging, [12] mentions a real-time operation strategy of PVCS and realizes the maximization of photovoltaic energy in the charging station. [13,14] propose an energy management algorithm under constraints to maximize the profit of electric vehicle charging stations. Considering the battery degradation cost of electric vehicles, [15] proposed an optimal charging strategy to minimize the user's charging cost.

In view of the above research, currently, there is no scheduling scheme that considers the photovoltaic output of the PV-Storage-Integrated EV charging stations and the uncertainty of power demand. Regarding the issue above, this paper builds a model of photovoltaic output and user charging behavior based on uncertainty. Combining the cost of purchasing power from the distribution network and the life cycle cost model of battery recycling, the optimal economic of the integrated storage and charging station is proposed.

2. Uncertainty Modeling of PV Output and User Charging Needs

2.1. Photovoltaic Power Scene Generation

The output power of PV battery pack is proportional to light intensity, which can be shown in formula (1):

\[
P_{\text{PV}} = \begin{cases} 
    p_{\text{PV},a} \eta_v \eta_h, & \text{if } \eta_v \eta_h > 0 \\
    p_{\text{PV},a} \eta_v \eta_h, & \text{if } \eta_v \eta_h < 0 
\end{cases} 
\]  

(1)

Where, \( p_{\text{PV},a} \) and \( \eta_h \) are the rated power and rated light intensity of the photovoltaic cell group, respectively. The output of photovoltaic cells is affected by many factors and has a strong uncertainty. In this paper, a typical photovoltaic output scenario is generated based on historical data, and the nuclear density estimation method is used to generate a photovoltaic output probability density function for each period of 24 hours a day based on historical data, namely:

\[
f(x') = \frac{1}{nh} \sum_{t=1}^{n} K \left( \frac{x' - x_t'}{h} \right) 
\]  

(2)

Where, \( n \) is the quantity of days of historical records; \( t \) represents the time period; \( h \) is the bandwidth of the core density estimate; \( x_t' \) is the photovoltaic output of the i-th day t time period in the historical data.

2.2. Uncertainty Analysis of User's Charging Demand

2.2.1. Charging Characteristics of Electric Vehicle Users

The probability density of electric vehicle users' parking time is shown as formula (3), and the probability density of daily driving distance of users is shown in formula (4). Under these distribution, the time users reach the charging station and the amount of charge required can be simulated.


\[ f_i(x) = \begin{cases} 
\frac{1}{\sigma_i \sqrt{2\pi}} \exp \left[ -\frac{(x - \mu_i)^2}{2\sigma_i^2} \right] & \text{if } x_i \leq 24, \\
0 & \text{otherwise} \end{cases} \]

(3)

\[ f_0(x) = \frac{1}{x\sigma_0 \sqrt{2\pi}} \exp \left[ -\frac{(\ln x - \mu_0)^2}{2\sigma_0^2} \right] \]

(4)

2.2.2. Charging Load Model

As the user drives, the state of battery changes as following.

\[ SOC = (1 - d / d_m) SOC_B \]

(5)

In which, \( d \) is the daily mileage of the electric vehicles; \( d_m \) is the maximum mileage of the electric vehicles; \( SOC_B \) is the state of battery before traveling.

The required charging time is:

\[ t_c = \frac{1 - SOC} {P_C} \]

(6)

Where, \( C \) is electric vehicle’s battery capacity and \( P_C \) is charging power.

3. Optimized Scheduling Model

3.1. Optimized Scheduling Model

3.1.1. Objective Function of Optimization Model

The operation cost of the integrated charging station mainly has two parts, the cost of the charging station purchasing electricity from the distribution network and the cost of charge-discharge losses of the energy storage device. This paper minimizes total operating costs and establishes an optimal economic operating model that promotes new energy consumption.

\[ \min F = \sum_{i=1}^{t} pr_c \cdot (P_i \cdot \Delta t) + \sum_{j=1}^{N_d} C_{i,j} \]

(7)

Where, \( F \) is the total operating cost of the PV-Storage-Integrated EV charging stations; \( t \) is the amount of optimized cycles; \( \Delta t \) is the duration of the i-th period; \( P_i \) is the average power supply to the distribution network during the i-th period; \( pr_c \) is the electricity price for the i-th period; \( N_d \) is charge-discharge times of lead-acid battery in the whole period; \( C_{i,j} \) is the life loss cost corresponding to the j-th charge and discharge.

3.1.2. Power Purchase Cost

According to the system power balance relationship, as the storage battery is in a charged state, if the photovoltaic power generation power is less than the sum of the battery pack and electric vehicle charging power, that is:

\[ \frac{P_{in}}{\eta_{in}} + \frac{P_e}{\eta_{el}} - \frac{P_{out}}{\eta_{out}} > 0 \]

(8)

Then the purchase power is:
\[ P_{gr} = \frac{P_{esi} + P_{b}}{\eta_{sd}} - \frac{P_{psi} \eta_{ad}}{\eta_{sd}} \]  (9)

Where, \( P_{esi} \) is the total charging power of the electric vehicle in the i-th period of the station; \( P_{b} \) is the charge-discharge power of the storage battery; \( P_{psi} \) is photovoltaic power, \( \eta_{sd} \) is the efficiency of the DC-DC module; \( \eta_{ad} \) is the efficiency of the AC-DC module.

If the photovoltaic power generation meets the sum of battery and electric vehicle charging power, that is

\[ \frac{P_{esi} + P_{b}}{\eta_{sd}} - \frac{P_{psi} \eta_{ad}}{\eta_{sd}} > 0 \]  (10)

Then the purchased power is:

\[ P_{g} = 0 \]  (11)

Adjust the charging power of the storage battery to maximize the absorption of the remaining power of the photovoltaic power generation:

\[ P_{b} = \left( \frac{P_{psi} \eta_{sd}}{\eta_{ad}} \right) \eta_{ad} \]  (12)

While the storage battery is in the discharge state, if the sum of the photovoltaic power generation and the discharge power of the storage battery is less than electric vehicle demand, then:

\[ \frac{P_{esi} + P_{b} \eta_{ad} - P_{psi} \eta_{ad}}{\eta_{ad}} > 0 \]  (13)

Then the purchased power is:

\[ P_{g} = \frac{P_{esi} + P_{b} \eta_{ad} - P_{psi} \eta_{ad}}{\eta_{ad}} \]  (14)

If the sum of photovoltaic power generation and storage battery discharge power meets the electric vehicle power demand, that is

\[ \frac{P_{esi} + P_{b} \eta_{ad} - P_{psi} \eta_{ad}}{\eta_{ad}} = 0 \]  (15)

Then the purchased power is:

\[ P_{g} = 0 \]  (16)

Also adjust the battery discharge power as follows.

\[ P_{b} = \frac{P_{psi} \eta_{ad} - P_{esi}}{\eta_{ad}} \]  (17)

3.1.3. Life Model of Lead-Acid Battery
When the depth of the charge-discharge cycle of the lead-acid battery is \( R \), the maximum number of cycles of charge and discharge before failure can be expressed as:

\[ N_{ESS} = \alpha_1 + \alpha_2 e^{\alpha_3 R} + \alpha_4 e^{\alpha_5 R} \]  (18)
Where, $\alpha_t - \alpha_s$ is the characteristic parameter of lead-acid battery.

When the lead-acid battery is recycled once, the battery life loss as a percentage of the total life is $1/N_{ESS}$; $C_{\text{initial-bat}}$ is investment costs for lead storage batteries; The equivalent economic loss cost $C_i$ is:

$$C_i = \frac{C_{\text{initial-bat}}}{N_{ESS}}$$  \hspace{1cm} (19)

3.2. Constraints
(1) Restriction of battery pack charge-discharge power

$$|P_i| \leq P_{sn} \eta_{dd}$$  \hspace{1cm} (20)

Where, $P_{sn}$ is the rated power of the bidirectional DC-DC converter.

(2) SOC range constraints of energy storage batteries

The life of the battery is affected by the depth of discharge, so the following constraints are imposed on the battery's SOC range.

$$1 - P \cdot SOC_{ni} \leq 1$$  \hspace{1cm} (21)

Where, $P$ is the maximum depth of discharge of the battery pack; $SOC_{ni}$ is the state of charge of the battery pack in the i-th period.

4. Example analysis

4.1. Example Parameter Setting

In the calculation example, 100 private cars were selected. Extract the user's parking moment on weekdays based on the normal distribution $N(17.5, 3^2)$. Extract the user's daily mileage on weekdays based on the distribution $N(4.5, 0.88^2)$. According to the normal distribution $N(16.4, 5^2)$, extract the parking moment of the user on non-working days. Extract the user's daily mileage on non-working days based on the distribution $N(6.2, 5^2)$. The PV-Storage-Integrated EV charging stations has 30 chargers, using the conventional charging method. The rated power of a single charging pile is 10kW. The rated capacity of the photovoltaic system in the station is 200kW. Lead-acid batteries main parameters is in Table 1.

| Type of battery | Maximum charging power / kW | Maximum discharge power / kW | Rated capacity / kW h | Maximum depth of discharge | $\eta_c$ | $\eta_d$ |
|-----------------|-----------------------------|-----------------------------|-----------------------|---------------------------|---------|---------|
| Lead-acid       | 40                          | 40                          | 1000                  | 0.9                       | 0.95    | 0.95    |

The electricity price sold by the power grid to the charging station adopts the time-sharing electricity price, as shown in Table 2.

| Time period | Electricity price/[yuan/(kW·h)]^4 |
|-------------|-----------------------------------|
| 00:00-7:30  | 0.3928                            |
| 22:00-24:00 |                                   |
| 11:30-17:00 | 0.7995                            |
| 21:15-24:00 |                                   |
| 7:45-11:30  | 1.2282                            |
| 17:00-21:00 |                                   |
4.2. Analysis of Optimization Results
The photovoltaic power generation and the user's charging needs are different every day. For the uncertainty of photovoltaic output, this paper selects two typical scenes according to the light intensity; for the uncertainty of user's charging requirements, this paper selects two typical scenes of the user on working days and non-working days.

When the light is strong, the power change of each component in 24 hours on non-working days and working days is shown in Fig.1 and Fig.2.

![Fig 1. The light is strong on non-working days](image1)

![Fig 2. The light is strong, on working days](image2)

When the light is weak, the power change of each component in 24 hours on non-working days and working days is shown in Fig.3 and Fig.4.

![Fig 3. The light is weak on non-working days](image3)

![Fig 4. The light is weak on working days](image4)

When the light is strong, the photovoltaic power is distributed to electric vehicles and battery packs for charging, and the distribution network does not supply power to the charging station. When the grid load is high, the battery pack releases the stored electrical energy. When the grid load is low in the early morning, the electric vehicle charging power is large at this time, and the power of the photovoltaic charging station mainly comes from grid. When the light is weak and electricity price is higher, most of the energy stored is released, and it is charged through the distribution network when the electricity price is the lowest. The charging needs of users on non-working days are higher than those on working days. When the user's charging demand is high, it will cause the battery's charging power to be low during the day.

5. Conclusion
In view of the uncertainty of PV output and user's charging demand, this paper proposes a scheduling strategy for PV-Storage-Integrated EV charging stations. Combined with the cost of electricity purchase and the life-loss cost of battery recycling, the economic cost of the PV-Storage-Integrated EV charging stations is minimized. The analysis of optimization results verifies the rationality of the model.

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