Energy Management Strategy of Photovoltaic Charging Station for Electric Vehicles in Commercial Area

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Abstract. Aiming at the problem of orderly charging in the electric vehicle charging stations based on photovoltaic power generation, a set of real-time energy management strategy is put forward in different period of time. The strategy is based on the premise of considering constraints and the principle of minimizing the operating cost of the charging station, taking into account factors such as photovoltaic utilization rate, real-time electricity price and battery loss. Taking the commercial area photovoltaic charging station as an example, Monte Carlo sampling method is used to provide basic behavior data of electric vehicles, and the effectiveness of the strategy is verified by Python programming.

1. Introduction

In recent years, electric vehicles have played a significant role in energy conservation, emission reduction and environmental protection. More and more countries are vigorously developing the electric vehicle industry. The photovoltaic (PV) electric vehicle charging station can realize the organic combination of local consumption of clean new energy and electric vehicle charging, effectively improving economic and environmental benefits [1].

However, if the electric energy charged by an electric vehicle is from a thermal power plant, merely replacing the direct emission of greenhouse gases with indirect emissions, it cannot solve the greenhouse effect fundamentally. In addition, the disordered charging of electric vehicles will also bring problems to the power grid. For example, during peak hours of grid load power consumption, a large number of electric vehicles flooding into charging stations will put more pressure on the distribution network that has already been heavily burdened [2, 3]. Therefore, electric vehicle charging stations should make full use of new energy sources such as PV and wind power to achieve the maximum in-situ consumption of new energy sources. At the same time, according to the real-time electricity price information, formulate a suitable charging strategy to minimize the operating costs such as purchasing electricity, and orderly charge the electric vehicles [4].

An energy strategy for real-time management in different time period is proposed in this paper. The strategy is dynamically planned based on PV power generation, real-time electricity price and current electric vehicle charging status at each moment. It can make full use of solar power and orderly charge the electric vehicles, which is independent of data prediction. In addition, the strategy algorithm is simple and the calculation time is short, which brings the maximum benefit to the charging station while protecting the environment and reducing the indirect emission of greenhouse gases.

2. Analysis of the Behaviours of Electric Vehicles

2.1. Driving rules of electric vehicles

According to the statistics obtained by the US Department of Transportation's Survey of American Residents Travel (NHTS) in 2009, the time distribution of the traditional fuel vehicles leaving and entering the family parking lot fits well with the lognormal distribution [5]. It can be inferred that the behaviors of the family electric vehicle are consistent with that of the traditional fuel car. After entering the home parking lot for half an hour, it enters the charging station of the commercial area, and leaves the charging station of the commercial area for half an hour before entering the family parking lot. The time probability distribution function of an electric car driving into a charging station is given as:

$$f_{T1}(x) = \frac{1}{(x-0.5)\sigma_{T1}\sqrt{2\pi}} \exp\left[-\frac{(\ln(x-0.5)-\mu_{T1})^2}{2\sigma_{T1}^2}\right] \tag{1}$$

Where $\mu_{T1} = 2.23$, $\sigma_{T1} = 0.30$.

The time probability distribution function of an electric car leaving a charging station is given as:

$$f_{T2}(x) = \frac{1}{\sigma_{T2}\sqrt{2\pi}} \exp\left[-\frac{((x+0.5)-\mu_{T2})^2}{2\sigma_{T2}^2}\right] \tag{2}$$

Where $\mu_{T2} = 17.31$, $\sigma_{T2} = 3.36$.
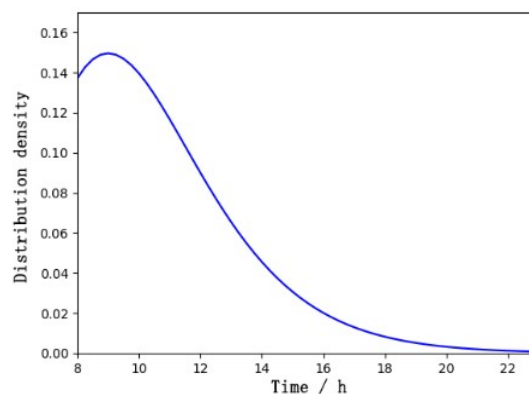
The time distribution is shown in Figures 1 and 2.

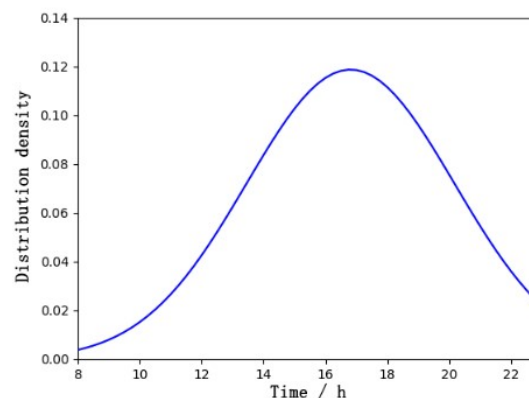**Figure 1.** Time when the car enters the charging station.

Figure 2. Time when the car leaves the charging station.

2.2. Classification of electric vehicles

We can classify electric vehicles based on whether the electric car can reach the target SOC before the departure time. When the owners arrive, they can set the charging target *SOC* and the time they leave. From this, the minimum continuous charging time T_{min} can be calculated under the maximum rated charging power.

$$T_{min} = \frac{\left(SOC_{obj} - SOC_o\right)Q_N}{P} \tag{3}$$

Where SOC_{obj} is the Charging target, SOC_0 is the initial SOC, P is the rated charging power of electric vehicle, and Q_N is the Battery rated capacity. The adjustable coefficient μ can be introduced to measure whether the electric vehicle can achieve the target SOC before leaving the charging station, and then determine the type of electric vehicle. The adjustable coefficient μ can be expressed as:

$$\mu\ (t) = \frac{\left(t_{out} - t_{ari}\right)}{T_{min}} \tag{4}$$

The larger the value of μ, the larger the adjustment margin of the electric vehicle. When $\mu>1$, it is defined as a flexible charging type, and when $\mu<1$, it is a rigid charging type.

Due to the adjustment margin of the flexible charging type is large, the concept of the latest charging time is produced. That is, only start charging electric vehicle at the maximum charging power before the latest charging time can the target SOC be reached. The latest charging time is given as:

$$t_{late} = t_{out} - T_{min} \tag{5}$$

3. Energy management strategy for PV charging stations

3.1. Restrictions

3.1.1. The Restrictions of Charge Power. According to formula (4), it is judged whether each electric vehicle is rigid or flexible at each moment. The restrictions of charging power of the kth management period are as follows:

$$\begin{cases} P_{min,k} < P_k < P_{max,k} \\ P_{min,k} = \left(N_g + N_{lr}\right)P \\ P_{max,k} = \left(N_g + N_r\right)P \end{cases} \tag{6}$$

Where $P_{min,k}$ and $P_{max,k}$ are respectively the minimum and maximum charging power of the electric vehicle, N_g and N_r are respectively the number of rigid and flexible charging vehicles, and N_{lr} is the number of the flexible charging vehicles which latest charging time is just in this management period.

3.1.2. The Restrictions of Battery pack. The restrictions of the SOC and the charging power of the battery pack can be expressed as:

$$\begin{cases} 1-D \le SOC_k \le 1 \\ P_{bk} \le P_{bn}\eta_{dd} \\ P_{bmin} \le P_{bk} \le P_{bmax} \\ \Delta P_{bmin} \le P_{bk} - P_{b(k-1)} \le \Delta P_{bmax} \end{cases} \tag{7}$$

Where D is the maximum depth of discharge of the battery, P_{bn} is the rated power of a bidirectional DC-DC converter, η_{DD} is the conversion efficiency of bidirectional DC-DC converter, P_{bmin} and P_{bmax} are respectively the minimum and maximum charging limit of the battery pack, and ΔP_{bmin} and ΔP_{bmax} are respectively the minimum and maximum charging amount.

3.1.3. The Restrictions of Distribution Network Power and System Power Balance. The charging power supplied by the distribution network is limited by the rated capacity of the distribution transformer and the AC-DC converter. The charging station also needs to balance the system power balance. So the restrictions are given as:

$$
\begin{cases}
P_{g,\,lim} = \min\ (P_T\eta_T, P_{AD}\eta_{AD}) \\[2mm]
P_{gk}\eta_{AD} + P_{pvk}\eta_{DD} = \dfrac{P_k}{\eta_{DD}} + \dfrac{P_{bk}}{\eta_{DD}} \\[2mm]
P_{gk}\eta_{AD} + P_{pvk}\eta_{DD} = \dfrac{P_k}{\eta_{DD}} + P_{bk}\eta_{DD}
\end{cases}
\tag{8}
$$

Where $P_{g,lim}$ is the minimum charging power provided by the distribution network, P_{AD} and η_{AD} are the rated capacity and conversion efficiency of the distribution transformer, P_{gk} is the amount of power purchased from the power grid, P_{pvk} is the power generation of PV system, P_k is the charging power to the electric vehicle , P_{bk} is charging power of the battery.

3.2. Energy Management Strategy

The energy management strategy proposed in this paper is based on the PV output in one day. In order to ensure the real-time management of the charging station without causing the system to start and stop too often, we set the management period to 15 minutes.

3.2.1. The Charging Strategy from 8am to 6pm. From 8am to 6pm, it is a period of sufficient PV power during the day and PV power generation should be fully used. During this period, we divided the charging strategy into the following three cases:

1) If the power in the time k satisfies $P_{pv}\eta_{DD}\eta_{DD} \geq P_{max,k}$, the electric vehicles in the charging station will be charged with the maximum charging power $P_{max,k}$, and the remaining PV power is charged to the battery pack. So the electricity purchased from the power grid is zero, then the charging power of the battery pack at time k is:

$$
P_{bk} = (P_{pvk}\eta_{DD} - \frac{P_{max,\,k}}{\eta_{DD}})\ \eta_{DD}
\tag{9}
$$

2) If the power in the time k satisfies $P_{min,k} \leq P_{pv}\eta_{DD}\eta_{DD} \leq P_{max,k}$, the electric vehicles in the charging station will be charged with the minimum charging power $P_{min,k}$, and the remaining PV power is charged to the battery pack. Then the electricity purchased from the power grid is zero, and the charging power of the battery pack at time k is:

$$
P_{bk} = (P_{pvk}\eta_{DD} - \frac{P_{min,\,k}}{\eta_{DD}})\ \eta_{DD}
\tag{10}
$$

When the battery pack is fully charged, if there is still residual PV power, we will charge the vehicle according to the latest charging time t_{late} until the PV power is used up.

3) If the time k satisfies $P_{pv}\eta_{DD}\eta_{DD} \leq P_{min,k}$, we divided into three cases as follows:

a. When the sum of the PV power and the battery pack discharging power can satisfy the minimum charging power of the electric vehicles, we don't need to buy electricity from the power grid, and the discharging power of the battery pack is given as:

$$P_{bk}\eta_{DD} = \frac{P_{min,\ k}}{\eta_{DD}} - P_{pvk}\eta_{DD} \tag{11}$$

b. When the sum of PV power and battery pack discharging power cannot meet the minimum charging power of the electric vehicles, it is necessary to purchase electricity from the power grid. At this time, the discharging power of the battery pack is:

$$P_{bk} = P_{bmax} \tag{12}$$

The electricity purchased from the power grid is given as:

$$P_{gk} = \left(\frac{P_{min,\ k}}{\eta_{DD}} - P_{pvk}\eta_{DD} - P_{bk}\eta_{DD} \right) / \eta_{AD} \tag{13}$$

c. When the discharging depth of the battery pack is less than or equal to 0.2, the battery pack will not be able to charge the electric vehicles. In this case, make full use of the PV power, and the other power is purchased from the power grid.

$$P_{gk} = \left(\frac{P_{min,\ k}}{\eta_{DD}} - P_{pvk}\eta_{DD} \right) / \eta_{AD} \tag{14}$$

3.2.2. The Charging Strategy from 6pm to 11pm. During this period, there is no PV power generation, we divided into three cases as follows:

1) When the battery pack discharging power can meet the minimum charging power of the electric vehicles, then it is not necessary to purchase electricity from the distribution network.

$$P_{bk}\eta_{DD} = \frac{P_{min,\ k}}{\eta_{DD}} \tag{15}$$

2) When the sum of the discharging power of the battery pack cannot meet the minimum charging power of the electric vehicle:

$$P_{bk} = P_{bmax} \tag{16}$$

$$P_{gk} = \left(\frac{P_{min,\ k}}{\eta_{DD}} - P_{bk}\eta_{DD} \right) / \eta_{AD} \tag{17}$$

3) When the discharging depth of the battery pack is less than or equal to 0.2, battery pack cannot be discharged, the electricity purchased from the power grid is

$$P_{gk} = \left(\frac{P_{min,\ k}}{\eta_{DD}} \right) / \eta_{AD} \tag{18}$$

3.3. Profit Function of PV Charging Station

In the operation of the PV charging station system, the cost mainly comes from two aspects. One is the cost of purchasing electricity, and the other is the life loss of the battery pack. The cost of purchasing electricity from the power grid can be expressed as:

$$f_g = \sum_{k=1}^{T} pr_k \left(P_{gk} \cdot \Delta t \right) \tag{19}$$

Where T is the number of management periods, pr_k is the electricity price of the grid at this time, p_{gk} is the electric power purchased, and Δt is the duration of the management period.

The battery pack will have a lifetime loss when the charging is too fast or deep discharge, so an over-speed-charging penalty factor α and an over-depth-discharging penalty factor β can be introduced. In general, when the SOC is lower than a certain value (generally 20% of the maximum capacity) or a single charge power exceeds a certain value (generally 20% of the maximum capacity), it will have a significant impact on the lifetime of the battery. So the cost of the battery pack is:

$$\begin{cases} f_{deep,\ k} = \alpha \cdot P_{bk}, & \text{if } SOC < 0.4 \\ f_{v,\ k} = \beta \cdot P_{bk}, & \text{if } \dfrac{P_{bk}}{Q_b} > 0.2 \\ f_b = \displaystyle\sum_{k=1}^{T} (f_{deep,\ k} + f_{v,\ k}) \end{cases} \tag{20}$$

The charging station earns profit by charging the user, so the profit of the charging station can be expressed as:

$$f_{ac} = \sum_{k=1}^{T} p_k \cdot pr_{s,\ k} \cdot \text{Vt} \tag{21}$$

Where f_{ac} is the earnings of the charging station, p_k is the charging power to the electric vehicles, and $pr_{s,k}$ is the price of the unit power which charge the users in the time k.

In summary, the profit function of an electric vehicle charging station is:

$$f = f_{ac} - f_b - f_g \tag{22}$$

4. Simulation

In order to verify the effectiveness of the proposed strategy, a PV charging station in a large commercial office area was chosen as an example. The charging station is open from 8am to 11pm. Assuming that it can accommodate 10,000 electric vehicles at the same time, the maximum rated charging power of each electric vehicle is 7 kw·h, the battery capacity of a single electric vehicle is 48 kw·h, the rated capacity of the charging station battery is 150,000 kw·h. Assuming that the maximum discharge depth D of the battery pack is 0.8, and the initial SOC is 0.2, the over-discharging penalty factor α is 0.02, and the over-discharge penalty factor β is 0.01;the conversion efficiencies of the DC-DC converter and the AC-DC converter are both 0.97; the initial SOC distribution of vehicles fits well with the lognormal distribution which the standard deviation is 0.1 and the mean is 1. The initial SOC are all greater than 0.2 and less than 1. The target SOC of each electric is set to 1. The time each electric vehicle enters the charging station and the time to leave the charging station are sampled by the Monte Carlo method.

The real-time electricity price of the grid and the charges to the owners of electric vehicles are shown in Table 1.

Table 1. The electricity price and the charges.

Time	The electricity price	The charges
8：00 -12：00	0.869	1.0
12：00-17：00	0.687	1.0
17：00-18：00	0.869	1.0
18：00 -21：00	0.869	1.2
21：00 -23：00	0.678	1.2

According to the energy management strategy of the PV charging station proposed in this paper, the Python programming is used to simulate the operation of the PV charging station under two typical cases of strong and weak lighting. The charging power to the vehicle, the power of the PV power generation, the charging and discharging power of the battery pack, and the electrical energy purchased from the power grid are calculated. In addition, the economic losses of the battery pack and the profit of the entire charging station are calculated.

The outputs are shown in Figure 3 and Figure 4. When the light is strong, PV power generation and battery power generation can meet the power output of the entire charging station before 7pm, without purchasing power from the power grid. In the case of weak lighting, electricity needs to be purchased after 6 pm.
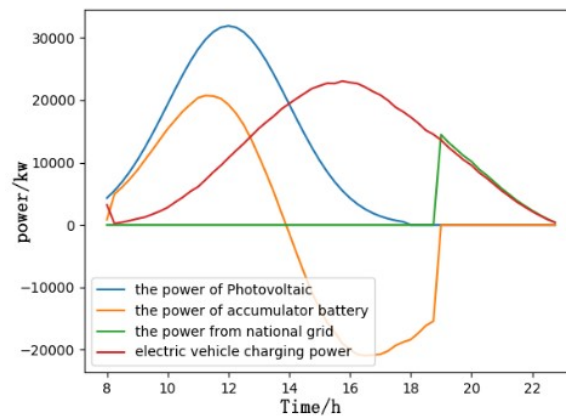

Figure 3. The power curve under strong light.
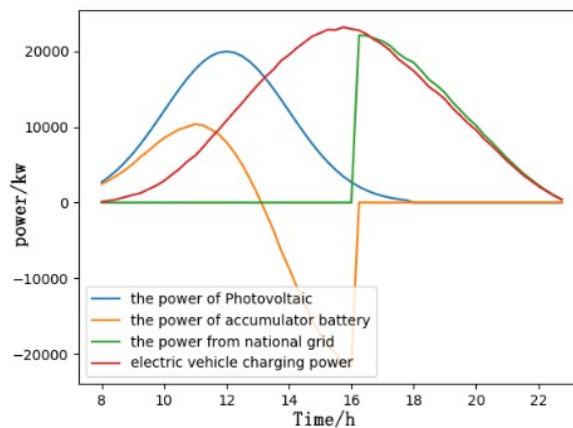

Figure 4. The power curve under weak light.

The economic losses of the battery during operation are shown in Figures 5 and 6, the battery pack will have loss of life during the process of charging, including the losses caused by over-speed-charging and over-depth-discharging, which will also have an impact on the profit of the charging station.
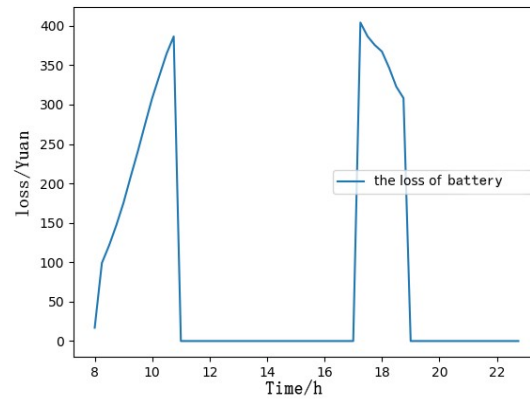
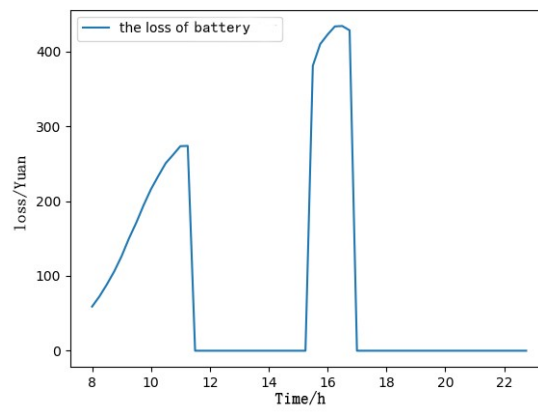**Figure 5.** The loss of the battery under strong light.

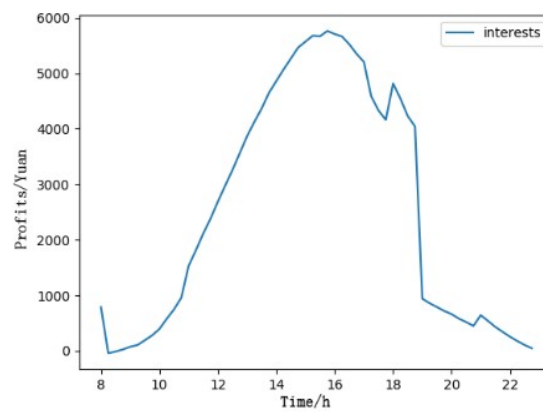**Figure 6.** The loss of the battery under weak light.

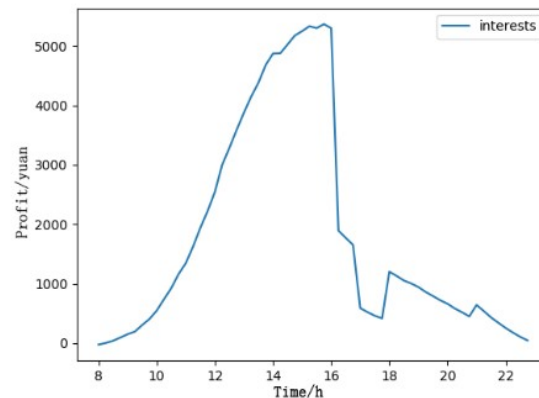**Figure 7.** The profit under strong light.

Figure 8. The profit under weak light.

The yield curves of the charging station are shown in Figures 7 and 8. The benefits of charging station is greatly affected by the light intensity. When the light is weak and the battery pack cannot meet the charging demand of the electric vehicle, the profit of the charging station is obviously reduced, and after the user charges are increased, the income function curve is slightly improved.

5. Conclusion

This paper studies how to coordinate the PV power generation system, battery pack, energy management system and charging device for the PV electric vehicle station located in the commercial area, and proposes a real-time energy management strategy which can charge the vehicles orderly. At the same time the PV system makes full use of the solar energy so that the operating cost of the charging station is reduced and obtains the maximum benefit. The effectiveness of the proposed strategy is verified by an example. The PV power, battery output and charging power of the charging station can be managed in real time under constraints, and the charging station can maximize the profit according to the actual situation. It has a certain effect on the development and promotion of PV charging stations.

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