

An orderly charge and discharge control method of considering electric vehicle V2G and photovoltaic complementation in residential area

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Abstract. In order to resolve the problems of distribution network overload and increased peak-valley difference caused by large-scale electric vehicles' disordered charging, taking the residential community as the research object, an orderly charging method of electric vehicles (EVs) based on power line carrier communication was proposed, and a model of ordered charge and discharge control and load peak regulation considering the complementary of EVs V2G and photovoltaic (PV) was established. It makes full use of the ability of EVs to cut peaks and valleys and restrain the fluctuation of PV output, alleviates the load pressure of the distribution network and reduces the cost of network transformation, which not only brings great benefits to the owners of EVs and power supply operators, but also promotes the consumption of new energy.

1 Introduction

With the rapid development of distributed generation technology, a large number of distributed PV power generation has been installed in residential areas. The randomness and intermittency of the injected power bring new challenges to the operation of the distribution network [1]. With the increasing popularity of EVs and the continuous improvement of residential charging facilities, on the one hand, large-scale disorderly charging of EVs will form the phenomenon of load peak on top of load peak of distribution network, which will aggravate the burden of distribution network. On the other hand, it is expected to combine EVs with PV energy through V2G technology to slow down the load fluctuation of the distribution network and promote the penetration and absorption of PV energy.

There have been many related studies on the charging control methods of photovoltaic power generation and EVs access to distribution network. Reference [2] has studied the optimal scheduling methods of EVs PV charging stations with the aim of reducing the power purchase cost and the circulating quantity of battery pack as the optimization goals. Reference [3] has studied the joint scheduling of distribution systems with distributed PV and EV charge and discharge. Reference [4] has proposed a new optimization model of time-of-use electricity price in the case of considering distributed PV power. Reference [5] studied the charging and discharging model of EV in V2G mode. Reference [6] studied the cooperative load control problem of wind power, PV power generation and EV.

According to the charging characteristics of EVs and the characteristics of PV power generation, taking residential area as the research object and aiming at maximizing power supply benefits, this paper considers the complementary of EVs and PV power generation through V2G technology, has established a model which takes into account the economic interests of both grid operators and EV users, and verifies this through simulation, and its effectiveness is verified by simulation

2 The models of EVs and PV in residential area

2.1 The stay and SOC distribution of private EVs

According to reference [6], the return time of private EVs approximately satisfies the normal distribution $t \sim N(17.6, 3.4)$, and the daily mileage approximately obeys the log-normal distribution $d \sim \log N(3.2, 0.88)$. According to the driving rules of private EVs, the travel of 400 EVs in the residential community has been simulated. It is assumed that 90% of the vehicles have travel needs, and the distribution of 24-hour vehicle residence (Figure 1) and the SOC state distribution (Figure 2) in the residential community are obtained. As can be seen from the figure, the number of electric cars staying in the community keeps increasing in the afternoon. After 17:00, there are enough EVs and sufficient discharge power in the community to PV in V2G peak clipping and valley filling.

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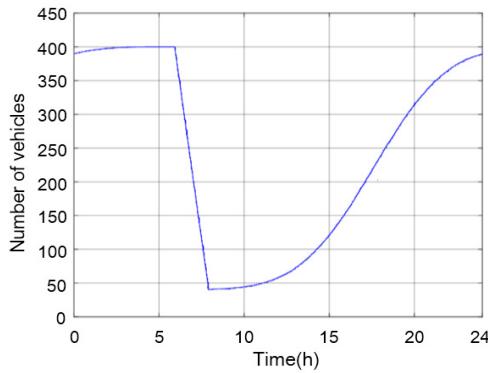


Figure 1. Residence distribution of EV in the community

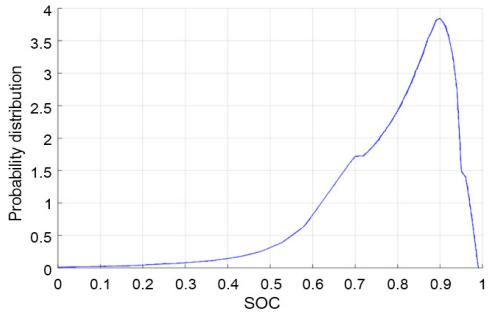


Figure 2. SOC distribution of EV after return

2.2 The model of EVs responding to V2G participation

The difference between peak and valley electricity price is used to attract EV users to participate in V2G peak-valley clipping. According to the price elasticity coefficient of power demand side response and the V2G data survey of EV users' participation, the relationship between users' V2G participation and arbitrage returns is shown in equation (1).

$$\lambda = \begin{cases} 0, & \Delta p < 0.3 \\ 1.0 \times \Delta p - 0.1, & 0.3 \leq \Delta p < 0.6 \\ 2 \times \Delta p - 0.7, & 0.6 \leq \Delta p < 0.8 \\ 0.9, & 0.8 \leq \Delta p \end{cases} \quad (1)$$

In the above equation, λ is the EV users' percent of participation, Δp is the net income of EVs for V2G discharge 1kWh and its unit is yuan /kWh.

2.3 The model of PV power generation system

The sunlight has a strong characteristic of time regularity. Studies have shown that the solar light intensity meets Beta distribution at a certain moment [7].

$$f(r(t)) = \frac{\Gamma(\alpha + \beta)}{\Gamma(\alpha)\Gamma(\beta)} \left(\frac{r(t)}{r_{\max}(t)} \right)^{\alpha-1} \left(1 - \frac{r(t)}{r_{\max}(t)} \right)^{\beta-1} \quad (2)$$

In the above equation, Γ is the Gamma function, $r(t)$ is the intensity of sunlight, α and β are shape parameters of Beta distribution.

The output function of the PV power generation system is expressed as:

$$P_s(t) = r(t)A\eta(1 - k_T\delta T) \quad (3)$$

In the above equation, A is the total area of the P power generation array, η is the photoelectric conversion efficiency, k_T is the temperature coefficient provided during the production of PV cells, δT is the prediction error of battery temperature.

3 The profit model of V2G charging and discharging for EVs

Grid operators could save distribution network costs through V2G peak shaving and valley filling. EV users could obtain certain economic benefits through the charging and discharging price difference and subsidies from operators. The key is that only the proper user participation could be able to maximize the benefits of grid operators.

3.1 Orderly charging and discharging profit model of EVs

A mathematical model was established with the maximization of total revenue of power supply operators as the objective function, and the V2G participation of EVs (λ) and the peak load percentage (ϕ) as the optimization variables to establish the objective function of the orderly charge-discharge revenue model of EVs V2G, as shown in equation (4).

$$C_{\max} = C_{\text{save}} - C_{\text{sup}} \quad (4)$$

In the above equation, C_{save} is the reduced capacity expansion cost, operation and maintenance cost and peak regulation income of the distribution network after reducing the peak load; C_{\max} is the subsidy cost paid to EV users to encourage EV to participate in V2G discharge. Among them:

$$C_{\text{save}} = C_T + \Delta P_{I_{o-T}} + 0.4\Delta P_{K-T} + C_{\text{line}} + \Delta P_{L_{ine}} + C_M + C_{su} \quad (5)$$

In the above equation, C_T is the transformer investment and installation cost saved; $\Delta P_{I_{o-T}}$ is the no-load loss cost of transformer saved; ΔP_{K-T} is the transformer load loss cost saved; C_{line} is the cost of line investment and installation saved; $\Delta P_{L_{ine}}$ is the line loss cost saved; C_M is the annual operating cost of medium and low voltage distribution network; C_{su} is the cost of peak regulation subsidy.

3.2 Orderly charging and discharging profit model of EVs taking into account PV consumption

After the PV power generation system is connected in, the V2G discharge power of EVs can be divided into two parts: one part participates in the form of peak clipping, valley filling and energy storage arbitrage; the other part participates in the form of eliminating PV power output

fluctuations. Taking the optimal EV V2G participation (λ), percentage of peak load (ϕ) and distributed PV installation capacity as the optimization variables, the objective function of the mathematical model of EV orderly charge-discharge earnings considering PV energy consumption and V2G is shown in equation (6).

$$C_{\max} = C_{\text{save}} + C_{PV-\text{earn}} - C_{\text{sup}} - C_{PV-\text{sup}} \quad (6)$$

In the above equation, $C_{PV-\text{earn}}$ is the annual net income of PV power generation; $C_{PV-\text{sup}}$ is the subsidy cost of EVs participating in the regulation of photovoltaic output fluctuation. Among them:

$$C_{PV-\text{earn}} = p_{PV} * Q_{PV} - C_{PV} - C_{PV-M} - C_{EV-re} \quad (7)$$

In the above equation, p_{PV} is the on-grid price of PV power; Q_{PV} is the annual PV power generation; C_{PV} is the equivalent annual cost of PV investment; C_{PV-M} is the annual operation and maintenance cost of PV equipment; C_{EV-re} is the cost attached to EVs to suppress fluctuations in PV output.

4 Sequential charge and discharge control method for EVs in residential quarters

This article adopts the method of combining peak-valley time-of-use electricity price and power carrier communication to realize the orderly charging and discharging of EVs.

4.1 Peak and valley time price

The peak and valley electricity prices are used to guide users to actively change their electricity consumption behaviors, to perform V2G discharge during peak periods and charge during valley periods, so as to achieve the purpose of peak shaving and valley filling. The peak and valley electricity prices of residential areas are shown in Table 1.

Table 1. Electricity price table of residential quarters

Type	Time	Price
Peak	6:00-22:00	p_p
Valley	22:00-6:00	p_v

In the Table 1, p_p is the peak period electricity price, p_v is the price of grain time.

4.2 Orderly charging control method based on power line carrier communication

The orderly charging scheme of EVs based on power carrier communication is to obtain the total load level of the distribution system in real time by each charging pile through the mode of carrier broadcast communication. According to the total load level of the system, EVs with appropriate conditions are selected for orderly charging in the load valley period. The system is shown in Figure 3.

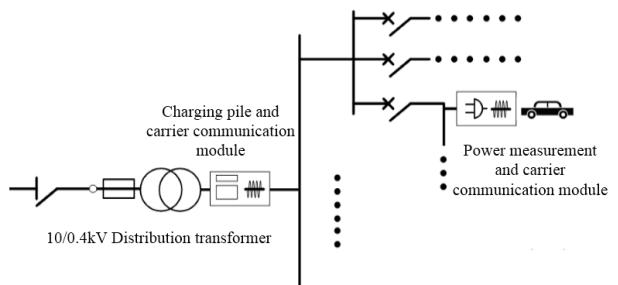


Figure 3. Schematic diagram of power carrier communication

The implementation process of orderly charging and discharging of EVs based on power line carrier communication is as follows:

(1) Install the power measurement and carrier communication transmission module at the main switch of the distribution transformer, and set the power limit threshold.

(2) Install the carrier communication receiving module at each charging pile.

(3) The power measurement module measures the total power of the bus at a certain time interval, and sends the measured value and the maximum power limit threshold through carrier communication.

(4) The carrier receiving module on the charging pile receives the carrier information.

(5) When the EV is connected to the charging pile, the control strategy as shown in Figure 4 is used to control the EV for orderly charging.

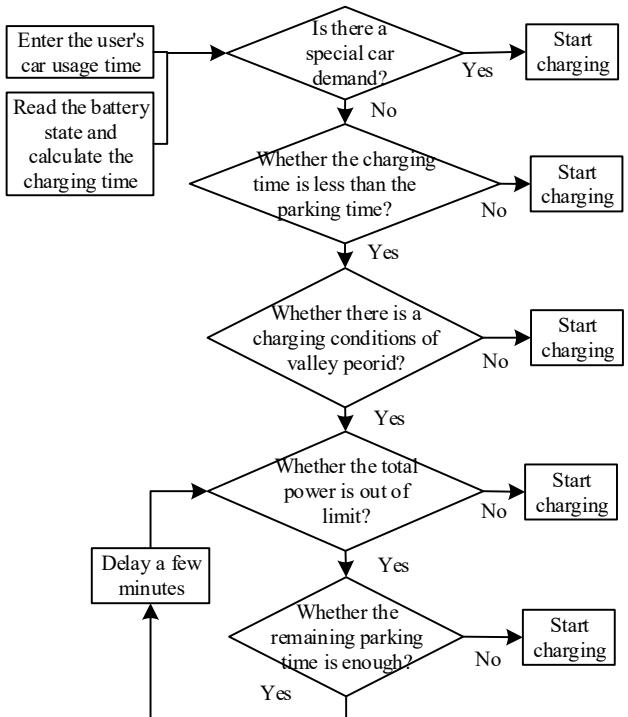


Figure 4. Orderly charging flow chart based on carrier communication

5 Example analysis

A residential community with 750 houses is taken as an example with 400 EVs for simulation. The types of EVs and their related parameters are shown in Table 2. The

average investment of unit distribution capacity is 100 yuan /kVA. The average load loss is 0.004kW/kVA. The unit investment of PV power generation is 4000 yuan /kW. The on-grid price of PV power is 0.75 yuan /kW. Charging price during the valley time is 0.3 yuan /kWh and the price of discharge during the peak time is 1.3 yuan /kWh. Peak shaving subsidy for electric vehicles is 0.35 yuan /kW.

Table 2. EV parameters

Type	Kilometre power consumption kWh/km	Slow charging power/kW	Quick charging power/kW	Proportion
Leaf	15	3	48	50%
E30	18	4.8	58	30%
E6	21	15	120	20%

5.1 Income from orderly charging and discharging of EVs

The average load rate of transformer is 40%, the saved line investment and loss cost are 70% and 30% of the saved transformer investment respectively, and the annual operation cost of distribution network is 15% of the initial investment. According to the above conditions, the simulation and optimization results obtained are shown in Table 3, Table 4 and Figure 5.

As can be seen from Table 3, after orderly charging and discharging regulation of EVs in V2G mode, the original peak load of the community decreases from 3080kW to 2955kW, and the peak load demand is reduced by 125kW. The daily load change curve of the system is shown in Figure 5. It can be seen that after regulation, the system load is smoother and the peaking valley difference is also significantly reduced.

As can be seen from Table 3 and 4, when the percentage of peak load is set to 0.96 and the V2G participation is 0.3, after optimizing the orderly charge and discharge control strategy of EVs, the power grid operator can earn 198,445 yuan per year. It includes 9,955 yuan of revenue from slowing down the transformation and expansion of the distribution network, and 188,490 yuan from EV V2G peak cutting and valley filling.

Table 3. Ordered charge and discharge parameter information

Max load/kW	Min load/kW	The peak valley difference/kW	φ	λ	Average daily peak shaving/kWh
2955	2017	941	0.96	0.3	2065

Table 4. Income information of orderly charge and discharge

Total annual net income/yuan		198445
Reduce the distribution network expansion cost		
Save the annual value of investment/yuan	Saving operation cost/yuan	Total revenue/yuan
2085	7870	9955
Equal annual value of V2G peak shaving revenue		
Peak shaving profit/yuan	EV battery subsidy costs/yuan	Net income of peak shaving of EV /yuan
1017847	527773	301584
V2G net income/yuan		188490

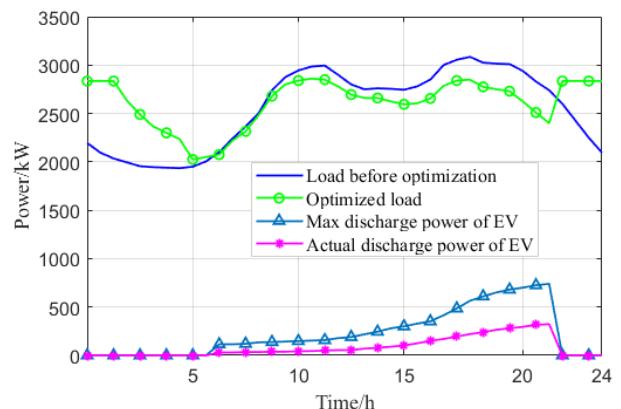


Figure 5. Power and load curves in V2G mode

5.2 Orderly charging and discharging income of EVs taking into PV

Assume that the annual operation and maintenance cost of PV equipment is 60 yuan/kW, and 20% of the gross revenue of PV power generation is taken as the subsidy for EVs to suppress the fluctuation of PV power output. The simulation and optimization results obtained are shown in Table 5, Table 6 and Figure 6.

As can be seen from Table 5, when the orderly charge-discharge strategy of EVs combining PV energy is adopted, the peak load decreases from 2955kW to 2869kW, and the peak load demand decreases by 86kW, compared with the V2G mode only. The daily load change curve of the system is shown in Figure 6. It can be seen that the system load curve is smoother, and the peak load and peaking-valley difference are significantly reduced.

According to Tables 5 and 6, when PV installation capacity is 190kW, EV V2G participation is 0.24, and load threshold is set to 0.93, grid operators can earn an annual income of 313,967 yuan after the orderly charging and discharging strategy of EV combined with PV is adopted. It includes annual income of 17,574 yuan from slowing down the transformation and expansion of distribution network, annual income of 178,490 yuan from EV V2G peak shaving and valley filling, and annual net income of 117,903 yuan from PV power generation system.

Table 5. The V2G charge-discharge parameters of PV mode

Maximum load/kW	The peak valley difference/kW	PV average daily output/kWh	φ
2869	859	843	0.93
Minimum load/kW	Average daily peak shaving/kWh	PV capacity/kW	λ
2010	1666	190/kW	0.24

Table 6. Various costs and benefits of PV and V2G mode

Annual net income/yuan		313967	
Reduce the cost of distribution network expansion			
Save the annual value of investment/yuan	Saving operation cost/yuan	Total revenue /yuan	
3680		13894	17574
Equal annual value of V2G peak shaving revenue			
Peak shaving profit/yuan	EV battery subsidy costs/yuan	Net income of peak shaving of EV	V2G net income/yuan
807800	423574	205736	178490
Annual net income from PV power generation			
Annual value of investment, operation and maintenance/yuan	Annual gross revenue from PV /yuan	PV fluctuations suppress costs/yuan	Net revenue from PV /yuan
88806	258387	51677	117903

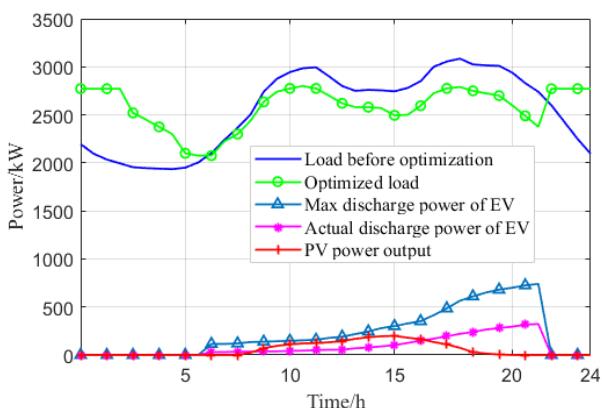


Figure 6. Power and load curves of V2G mode and PV

6 Conclusion

From the perspective of grid operators, this article also takes into account the interests of EV users, has established an orderly charging and discharging control and load peak shaving model for EVs in residential areas that take into account V2G EVs and PV complements, and has conducted the simulations. The conclusions are as follows: (1) EVs reasonably participate in V2G discharging and conduct scientific and orderly charging, which brings relatively substantial benefits to grid operators and EV owners; (2) The orderly charging and discharging model of EVs that takes into account PV and V2G can more effectively reduce load peaks and reduce

peak-to-valley differences, and the total system revenue is also higher, while also effectively promoting the consumption of clean energy power generation.

Acknowledgments

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