Categorized analysis of the response characteristics of EVs in Shanghai

Kaiyu Zhang¹, Shanshan Shi¹, Zeyu Liu², Kele Li², Yun Zhou², Donghan Feng²

¹Electric Power Research Institute, State Grid Shanghai Municipal, Shanghai, China
²Key Laboratory of Control of Power Transmission and Conversion (Ministry of Education), Shanghai Jiao Tong University, Shanghai, China

*liuzeyu@sjtu.edu.cn

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Abstract

With the increase in the scale of electric vehicles (EVs), the charging demands bring more challenges to the power grid. Ordered charging alleviates the impact of disordered charging and vehicle-to-grid (V2G) technology provides a measure to convert EVs from loads to dispatchable resources. In this paper, based on a statistic of newly licensed EVs in Shanghai, a categorized analysis of the response characteristics of EVs is conducted, and the dispatchable resource of the EVs is further modeled for the resource assessment in Shanghai.

1 Introduction

EVs are a clean, efficient, and renewable means of transportation, which is of great significance for alleviating the energy crisis, reducing greenhouse gas emissions, and improving air quality. In recent years, with the advancement of battery technology, the improvement of charging facilities, the support of policies and the demand of the market, EVs have developed rapidly worldwide. According to statistics from the International Energy Agency (IEA), global EV sales exceed 10 million in 2022, accounting for 14% of new car sales. Among them, China is the largest EVs market, and its sales account for 60% of the total global EVs sales [1].

The large-scale development of EVs also brings more challenges to the power grid. On the one hand, the charging demand of EVs will increase the load and peak-valley difference of the power grid, which may cause problems such as grid overload, voltage fluctuation, frequency deviation, etc. [2]; On the other hand, EVs as mobile energy storage devices have flexibility and dispatchability, if they can achieve orderly charging or V2G technology, they can provide services such as peak shaving, frequency regulation, backup, etc. for the power grid, improving the stability and reliability of the power grid [3].

Therefore, how to effectively utilize EVs as schedulable resources is an important research topic. At present, many scholars in China and abroad have carried out theoretical analysis and empirical research on this, mainly from the following aspects: (1) Establishing a response model and scheduling strategy for EVs, considering the charging demand of EVs, user behavior, and V2G potential [4]. (2) Assessing the impact and contribution of EVs to the grid, analyze the impact of EVs on grid load, voltage, frequency and other parameters under different charging modes, and calculate the quantity and cost required for EVs to provide regulation services [5]; (3) Designing a system combining EVs and renewable energy sources (RES) explores how to use EVs as energy storage devices to smooth the intermittency and uncertainty of RES, and optimize system operation and economic benefits [6]. However, in the existing research, there are still some deficiencies. First, when building EV response models, it is often assumed that EVs have full or partial V2G functions, and users are willing to participate in V2G services. But in fact, there is no case of large-scale commercial operation of V2G technology in China so far, so this assumption may not match the actual situation. Second, when assessing the scheduling potential of EVs, deterministic or probabilistic methods are often used, and the analysis is based on data from specific regions or types of EVs. But this approach ignores possible differences and correlations between different regions or different types of EVs, and thus may not accurately reflect the value of EVs as dispatchable resources at the overall market or system level. Finally, when designing a system combining EVs with RES, often only a single microgrid or distributed system is considered, and optimization is performed based on simplified or idealized models. However, this method ignores the possible interaction and coordination problems between the microgrid and the main grid, as well as the technical obstacles and policy restrictions that may be encountered in actual operation.

In response to the above questions, this paper conducts a categorized analysis of the response characteristics of EVs in Shanghai, and further assesses the dispatch potential of EVs in Shanghai. Firstly, this paper introduces the main classification and characteristics of EVs, including flexibility, time, and amplitude characteristics. Then, a unified response model is proposed in this paper, taking into account uncertainties such as charge initiation time, initial SOC, and discharge depth. Furthermore, this paper evaluates the dispatch potential of all EVs in Shanghai using the Monte Carlo method, and analyzes the impact of V2G technology and vehicle electrification on the dispatch potential. Finally, the paper summarizes the main conclusions and suggests directions for future research.
2. Categorized response characteristics of EVs

2.1 Flexibility characteristics

In general, the charging pattern of EVs can be summarized into 3 types:

A. Inflexible charging:

The EV user wants to charge as quickly as possible, so the EVs will not offer any flexibility.

B. Flexible charging:

The user wants the EV to be charged at least to the target SOC before a deadline but is indifferent about the details during the charging procedure. EVs of this type can be dispatched in a feasible area shown in Fig 1. Type A and B have no requirements for the charging pile.

C. V2G-possible charging:

The charging is flexible (same as B), and V2G is optional with the EV user if the incentive is considerable. EVs of this type can be dispatched in a feasible area shown in Fig 2. V2G function is a requirement for the charging pile.

Currently, V2G charging piles have not been widely operated commercially, therefore, in the following analysis, we use the expression “type B/C” to describe the charging pattern that the EV has enough time for flexible charging, but the willingness and ability to V2G are not sure.

![Feasible area of flexible charging (grey area)](image)

Fig. 1 Feasible area of flexible charging (grey area)

Within type B, the power levels are different.

C. V2G-possible charging:

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Currently, V2G charging piles have not been widely operated commercially, therefore, in the following analysis, we use the expression “type B/C” to describe the charging pattern that

The driving and charging times of different EVs are differentiated, which will affect the time characteristics.

(1) Private passenger EVs

Private passenger EVs are usually charged by the private charging piles after being used during the day. The household nature makes it type B/C.

As for the charging starting time, although there are no official statistics on the resident travel survey in Shanghai, considering the similarity of residential activities, NHTS (national household travel survey), an authoritative source on public travel behavior conducted by the Federal Highway Administration of America, is applied for passenger EV analysis. According to NHTS 2017 [7], the ending time of the travel (also seen as the start of charging) is shown in Fig.3. The kernel density estimation method is used to obtain the probability distribution of the starting time of charging, the probability density curve of which is drawn in brown. The result shows that the probability reaches the peak at 17:00-18:00, which is the evening rush time.

![Probability density curve](image)

Fig. 2 Feasible area of V2G-possible charging (grey area)

2.2 Time characteristics

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(a) Private passenger EVs

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(b) Business EVs

Business EVs are charged by the public charging piles during the business hours. The charging starting time is usually before 18:00, which is the end of the business day.

(c) Utility EVs

Utility EVs are charged by the dedicated charging piles, which are located near the utility stations. The charging starting time is usually after 18:00, which is after the business hours.

Table 1 Summary of charging scenarios of EVs in Shanghai

<table>
<thead>
<tr>
<th>EV</th>
<th>Charging pile</th>
<th>Public station type</th>
<th>Power</th>
<th>Starting time</th>
<th>Charging duration</th>
<th>Charging pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passenger</td>
<td>Private</td>
<td>-</td>
<td>Low</td>
<td>As Fig 4</td>
<td>Long</td>
<td>B/C</td>
</tr>
<tr>
<td>Private</td>
<td>Private</td>
<td>Institution</td>
<td>Low</td>
<td>As Fig 4 (institution line)</td>
<td>Long</td>
<td>B/C</td>
</tr>
<tr>
<td>Private</td>
<td>Public</td>
<td>Public</td>
<td>Low</td>
<td>As Fig 4 (public line)</td>
<td>Short</td>
<td>A</td>
</tr>
<tr>
<td>Business</td>
<td>Public</td>
<td>Housing estate &amp; public</td>
<td>High</td>
<td>As Fig 4 (housing estate line &amp; public line)</td>
<td>Short</td>
<td>A</td>
</tr>
<tr>
<td>Bus</td>
<td>Public</td>
<td>Bus station</td>
<td>High</td>
<td>As Fig 4 (bus station line, before 18:00)</td>
<td>Short</td>
<td>A</td>
</tr>
<tr>
<td>Bus</td>
<td>Public</td>
<td>Bus station</td>
<td>High</td>
<td>As Fig 4 (bus station line, after 18:00)</td>
<td>Long</td>
<td>B/C</td>
</tr>
<tr>
<td>Utility</td>
<td>Truck</td>
<td>Dedicated</td>
<td>High</td>
<td>No available data (assumedly similar to the bus station line, before 18:00)</td>
<td>Short</td>
<td>A</td>
</tr>
<tr>
<td>Truck</td>
<td>Public</td>
<td>Dedicated</td>
<td>High</td>
<td>No available data (assumedly similar to the bus station line, after 18:00)</td>
<td>Long</td>
<td>B/C</td>
</tr>
</tbody>
</table>
In fewer cases, they may also be charged during work times, which usually happens in institution charging stations. A statistic from Lianlian Charge, the official platform of charging facilities in Shanghai, shows the time distribution of charging in different categories of public charging stations in 2020, as shown in Fig.4 [8]. The broken lines show the unified percentage of the starting time of charging orders, and a comparison in the total charging order numbers is shown in the color bar above.

(2) Business passenger EVs

Business passenger EVs are type A since the unit time cost is high.

(3) Utility EVs

Utility EVs are usually charged at high power for their large battery capacity, regardless of the time of the day.

EV buses run in cycles and can be charged whenever they arrive at the terminal station, so the charging time is randomly distributed during the running hours. But the charging processes during the running hours are quick charging for urgent energy supplements, so they belong to type A and offer no flexibility. Some of them are attached to the charging piles during break hours. In this case, they belong to type B/C. EV trucks have similar time characteristics. The time characteristics are as shown in the bus station line in Fig. 4.

To sum up, the charging scenarios of EVs with different usages and charging conditions are listed in Table 1.

### 2.3 Magnitude characteristics

#### (1) Categorized numbers

The annual increment of passenger EVs and utility EVs from 2016 to 2022 is summarized in Table 2, and visualized respectively in Fig 5 (a) and (b).

#### Table 2 Annual EV increment in Shanghai

<table>
<thead>
<tr>
<th>Year</th>
<th>Passenger vehicle</th>
<th></th>
<th>Utility vehicle</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HEV</td>
<td>BEV</td>
<td>HEV</td>
<td>BEV</td>
</tr>
<tr>
<td>2016</td>
<td>30229</td>
<td>8978</td>
<td>508</td>
<td>4779</td>
</tr>
<tr>
<td>2017</td>
<td>43282</td>
<td>20714</td>
<td>429</td>
<td>5181</td>
</tr>
<tr>
<td>2018</td>
<td>56325</td>
<td>24333</td>
<td>136</td>
<td>3440</td>
</tr>
<tr>
<td>2019</td>
<td>43030</td>
<td>24581</td>
<td>604</td>
<td>1947</td>
</tr>
<tr>
<td>2020</td>
<td>59550</td>
<td>77110</td>
<td>12</td>
<td>2994</td>
</tr>
<tr>
<td>2021</td>
<td>86223</td>
<td>145783</td>
<td>116</td>
<td>5963</td>
</tr>
<tr>
<td>2022</td>
<td>140921</td>
<td>208476</td>
<td>631</td>
<td>16102</td>
</tr>
</tbody>
</table>

As shown in Fig. 5, the majority of EVs in Shanghai are passenger EVs, and BEVs are more than HEVs, especially among utility EVs. The annual EV increment in Shanghai experienced an obvious increase in recent 3 years. A study points out that this mainly attributes to technological competition and other influence factors including scrappage, market, space, and total quantity regulation [9].
In passenger EVs, HEV was in the lead before 2019 but surpassed by BEVs since 2020. On the one hand, the subsidy policy revised in 2019 and 2020 has more tendentiousness toward BEVs. On the other hand, with the development of public charging facilities and the matured private charging pile installment process, electricity supplement becomes more convenient, improving the attractiveness of BEVs in driving cost and licence acquisition. In utility EVs, BEVs have been occupying a preponderant percentage since 2016, because commercial EVs have bigger space for large capacity batteries, and have stable periodical accessibility to charging piles, which means BEVs can fully utilize the advantages of electric drive.

(2) Categorized capacities

As described in 2.1, battery capacity is important when analysing the dispatch potential. According to the statistics from CITIC Securities, the average battery capacity of different kinds of EVs in China from 2019 to 2021 is shown in Fig. 6.

![Fig. 6 Average battery capacity of EVs in 2019-2021](image)

The obvious difference in the battery capacity of passenger EVs, EV buses, and EV trucks indicates the differentiated dispatchable capacity.

(3) Categorized powers

According to the White Paper on Charging Behaviour of Chinese EV Users 2022, published by EVCIPA (Electric Vehicle Charging Infrastructure Promotion Alliance), the use percentage of public charging piles with different power is illustrated in Fig. 7 [10].

![Fig. 7 Usage percentage of public piles with different power levels](image)

3 Dispatch potential assessment of Shanghai

3.1 Overall charging demand

According to the statistics from Shanghai Electric Vehicle Public Data Collecting Monitoring and Research Centre, by December 2022, out of the total 5,370,000 vehicles, 946,000 EVs have been registered in Shanghai (910000 are passenger EVs). The average daily driving vehicle number is 465000, and the average daily driving distance is 31,770,000 km. Thus, assuming the average energy consumption per km is 0.16 kWh, the estimated average daily energy consumption is 5,083,200 kWh. This is approximately 1% of the total electricity consumption of Shanghai.

The current EV penetration rate in Shanghai is 946,000/5,370,000 = 17.62%, therefore, if all vehicles are replaced by EVs, EV charging can take up to approximately 5% of the total electricity consumption. This is a huge component of the power system, and if the dispatch potential is fully utilized, it will play an important role in power grid regulation and control.

Based on the categorized analysis of response characteristics of EVs in Shanghai, we can assess the dispatch potential to provide a reference for the power grid dispatching and for further planning of construction. As analysed above, further development of V2G technology and vehicle electrification have vital effects on the dispatch potential, which will also be discussed in this section.

3.2 Unified response model

As discussed in Table 1, EVs only have flexibility in certain scenarios of type B/C. This indicates that type B and type C can be unified in the same response model with different discharging coefficients.

At time point $t_{\text{start}}$, the charging/discharging curve of EV $i$ in the following time is limited by the upper bound and lower bound of the feasible area, and the power is limited by the maximal charging/discharging power of the pile.

\[
\varepsilon_i^{\text{ub}}(t) \leq \varepsilon_i(t) \leq \varepsilon_i^{\text{lb}}(t)
\]

\[
-p_{\text{discharge}}^{\text{max}} \leq p_i(t) \leq p_{\text{charge}}^{\text{max}}
\]

where $p_{\text{discharge}}^{\text{max}} = 0$ if the charging pile does not have V2G function.

At time point $t_{\text{start}}$, the lower bound of the feasible area of EV $i$ is a piecewise function:

\[
\varepsilon_i^{\text{lb}}(t) = \begin{cases} 
\text{Soc}_{i_{\text{start}}} - C_i = p_{\text{discharge}}^{\text{max}}(t - t_{\text{start}}), & t_{\text{start}} \leq t \leq t_{\text{disstop}}^{\text{start}} \\
\text{Soc}_{i_{\text{depth}}} - C_i, & t_{\text{disstop}}^{\text{start}} < t \leq t_{\text{fen}}^{\text{start}} \\
\text{Soc}_{i_{\text{depth}}} + C_i + p_{\text{charge}}^{\text{max}}(t - t_{\text{fen}}^{\text{start}}), & t_{\text{fen}}^{\text{start}} < t \leq t_{\text{limit}}^{\text{start}} 
\end{cases}
\]
Since the discharging willingness and ability of EV \(i\) is unknown to the PSO (power system operator), the discharging depth is a stochastic variable, described by the mathematical expectation \(\text{Soc}_{i}^{\text{exp,depth}}\):
\[
\text{Soc}_{i}^{\text{exp,depth}} = \text{Soc}_{i}^{\text{start}} (1 - \mu_{\text{dis}})
\] (4)
where \(\mu_{\text{dis}} \in [0, 1]\) is the discharging coefficient, equalling to the probability that EV \(i\) is willing and able to discharge. \(\mu_{\text{dis}}\) is a dependent variable of discharging incentive and dischargeable pile proportion. Let \(m\) denote the discharging incentive, and \(\theta_{\text{dis}}\) denote the dischargeable pile proportion, then \(\mu_{\text{dis}}\) can be expressed as
\[
\mu_{\text{dis}} = f(m)\theta_{\text{dis}}
\] (5)

\(t_{\text{alert}}^i\) and \(t_{\text{distop}}^i\) are calculated by
\[
t_{\text{alert}}^i = t_{\text{limit}}^i - \frac{(\text{Soc}_{i}^{\text{target}} - \text{Soc}_{i}^{\text{target}})C_i}{P_{\text{max}}^{\text{charge}}}
\] (6)

\[
t_{\text{distop}}^i = t_{\text{start}}^i + \frac{\text{Soc}_{i}^{\text{start}} - \text{Soc}_{i}^{\text{exp,depth}}}{P_{\text{max}}^{\text{discharge}}}
\] (7)

At time point \(t_{\text{start}}\), the upper bound of the feasible area of EV \(i\) is a piecewise function:
\[
e_{\text{ful}}^i(t) = \begin{cases} \text{Soc}_{i}^{\text{start}}C_i + P_{\text{max}}^{\text{charge}}(t - t_{\text{start}}^i) & t_{\text{start}}^i \leq t \leq t_{\text{distop}}^i \\ C_i & t_{\text{distop}}^i < t \leq t_{\text{limit}}^i \end{cases}
\] (8)
\(t_{\text{distop}}^i\) is calculated by
\[
t_{\text{distop}}^i = t_{\text{start}}^i + \frac{1 - \text{Soc}_{i}^{\text{start}}}{P_{\text{max}}^{\text{charge}}}
\] (9)

From the analysis above, it is clear that the only controllable parameter by the PSO is the discharging incentive \(m\), which means that the PSO can affect the dispatch potential of the EV fleet by adjusting \(m\).

### 3.3 Dispatch potential assessment

The dispatch potential can be described by the upward and downward adjustable power within the time slot after the dispatch instruction is issued.

From the unified response model described by (1)-(9), we can see that most of the variables are accompanied by uncertainties, making it extremely difficult to find the analytical form of the dispatch potential. To deal with the uncertainties, the Monte-Carlo method is an effective measure to reveal the profile of the dependent variables. Assume the EV are charged at the maximal power once attached to the charging pile until the dispatch instruction is received. The dispatch potential is calculated assuming that the dispatch instruction is issued one hour in advance so that the charging process can be adjusted timely. The EV is regarded to be able to provide upward/downward adjustable power if it can increase/decrease the power from that of the former 15 minutes and keep it for the next 15 minutes. In this case, the upward and downward adjustable power are the same because of the duality of the former and the next 15 minutes.

The Monte-Carlo simulation procedure can be summarized as the following 4 steps:

Step 1. Create \(n\) EVs of different categories according to Table 2 and Fig. 5.

Step 2. For each EV, set the charging scenario according to Fig. 4 and Table 1, set the battery capacity according to Fig. 6, sample the charging starting time according to Fig. 4, and the starting SOC as Table 3. Then, calculate the upward and downward adjustable power, and the transferable load within the next 15 minutes according to (1)-(9).

Step 3. Sum up the results in Step 2, scale them by the estimated daily average energy consumption of all EVs in Shanghai, and output them as an experiment point.

Step 4. Repeat Steps 1-3 until there are enough experiment points to give the profile of dispatch potential.

The assumed parameters for assessment are listed in Table 3.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment points</td>
<td>100</td>
<td>V2G has not been widely practiced in Shanghai</td>
</tr>
<tr>
<td>Discharging coefficient</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Starting SOC distribution</td>
<td>(N(30, 10^2))</td>
<td></td>
</tr>
<tr>
<td>EV number every point</td>
<td>9460</td>
<td>1% of EVs in Shanghai</td>
</tr>
<tr>
<td>Plug-out time limit of private EVs</td>
<td>U(6:00am, 8:00am)</td>
<td>Plug-out time of private EVs depends on morning activities like work</td>
</tr>
<tr>
<td>Plug-out time limit of utility EVs</td>
<td>6:00 am</td>
<td>Plug-out time of utility EVs is earlier</td>
</tr>
</tbody>
</table>

The Monte-Carlo simulation gives the dispatch potential of all EVs in Shanghai in a day, as shown in Fig. 8.
In Fig. 8, the brown line is the average adjustable power, surrounded by the grey stripe showing the ±3SD range. As shown in Fig. 8, the dispatch potential reaches the peak at around 18:00-19:00, which is the peak hour that EVs are attached to charging piles. The maximal dispatch potential of EVs takes about 2% of the approximately 18000 MW yearly average load during evening hours in Shanghai. This result indicates the promising potential of dispatching EVs as mobile energy storage for peak shaving and other grid controlling.

A less optimistic finding is that during the load valley of Shanghai, at 02:00-08:00, the dispatch potential of EVs also drops to a low level. One of the causes is that in this paper, the spontaneous load transferring of EV users is not considered, while in practice, some users with smart charging piles will set the start of charging at 22:00, which is the start time of the valley-electricity price. This is an interesting topic for future research.

4 Conclusion

Since the charging habit and driving characteristics of different kinds of EVs have huge difference, the dispatch abilities are also different, which requires a categorized analysis for meticulous research. Based on the statistics on the numbers, behaviour features, and charging scenarios of EVs in Shanghai from multiple information resources, a categorized analysis of the response characteristics of EVs in Shanghai is conducted in this paper.

Furthermore, an assessment of the dispatch potential of the EVs is given based on the response characteristics. The result reveals the profile of the value of EVs as mobile energy storage systems and can serve as a reference for the PSO of Shanghai. The methods applied in this paper have reference significance for similar research.

Future studies can be focused on the effect of the promotion of V2G technology and the user willingness for participating in V2G programs.

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6 References

[8] ‘Big data summary of Shanghai charging and swapping facilities’, https://mp.weixin.qq.com/s/Futpk8exAgNC0W15tDhMbg, accessed 23 May 2023