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ASSESSMENT OF EV RESPONSE CAPABILITY CONSIDERING USER'S DEMAND

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ABSTRACT

Electric vehicle (EV) is an important demand response resource, which can optimize the operation of power grid by load shifting and vehicle to grid (V2G). Effective assessment of EV response capability is of great significance for optimizing grid operation and improving grid safety. Therefore, this paper proposes an EV response capability assessment method considering EV user's demand. Firstly, the state of EV when plugged in is calculated based on trip chain. Then, an EV charging strategy is used to minimize load variance, considering EV user's demand. Finally, the degree of EV charging demand relaxation and an EV response capability assessment method considering EV user's demand are proposed. Case studies on power-transportation coupling system containing RBTS Bus6 and Beijing transportation system show that the proposed EV response capability assessment method is effective.

Keywords: Electric Vehicle, Demand Response, Vehicle to Grid, Charging Strategy

NONMENCLATURE

Abbreviations

EV	electric vehicle
V2G	vehicle to grid
SOC	state of charge
EVCE	electric vehicle charging equipment

Symbols

NS	set of nodes in transportation system
S	set of roads in transportation system
t	index of time periods
w	EV power consumption for 1 km
m	driving distance of EV
t_i^{start}	daily travel start time
$t_{i,j}^{trip}$	time cost of a trip
$t_{i,j}^{stay}$	stay time in an area
$t_{i,j}^{wdep}$	time of leaving from Working Area
$t_{i,charge}$	time for fast charging
$P_{ch,i}$	charging power of EV
$\overline{P}$	the average of total power
P	total power of grid
$D_{Plug,i}$	state of plug in
N_s	number of EVs that satisfy users' demand
$t_{arr,i}$	time of arriving
$t_{leave,i}$	time of leaving
SOC_i^d	demand SOC of EV user
c	time Impedance of roads
l	length of roads
B	battery capacity of EV
P_{chf}	power of fast charging
P_{chr}	rated power of slow charging
P_{dis}	power of discharging
N	number of EVs
T	number of time periods

1. INTRODUCTION

For the advantage of clean and environmental protection, EV has been concerned and promoted worldwide. The charging of a large population of EVs will have a significant impact on the power grid, such as voltage-drops, excessive increase in power losses and overloading of distribution transformers [1]. On the other hand, an EV stays idle for 90% of a day [2], and EV can also provide energy to the power grid by V2G. Therefore, EV is an important demand response resource, which can be utilized to optimize the operation of power grid.

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The application of EV demand response has been widely studied in recent years. Reference [3] realizes peak shaving and valley filling by coordinating the charging of EVs. The coordinating charging and discharging EVs are utilized in [4] to lighten the fluctuation of wind power output and minimize the operation cost. A two-layer management structure of micro-grid is proposed in [5] to control EVs charging and discharging to minimize the cost of purchasing electricity. Additionally, EV demand response can also be utilized to provide ancillary service, improve safety and reliability of system, and reduce power loss, etc.

Due to the benefits of EV demand response to the power grid, it is of great significance to assess EV response capability effectively, and there have been many studies on the method of EV response capability assessment. In [6], it is considered that EV can discharge when the state of charge (SOC) exceeds a threshold. However, this method may make EV SOC cannot meet user's demand when user leaves, it is not realistic. Reference [7] believes that EV SOC after discharging should always meet EV user’s demand. However, EV can be charged again during the time after discharging, to meet user’s demand, the method in [7] may lead to decrease of EV response capability. Reference [8] considers user's demand as the constraint of EV charging and discharging, and assess EV response capability in the optimization period, but cannot accurately assess EV response capability at any time.

Therefore, an EV response capability assessment method considering EV user's demand is proposed in this paper. Firstly, the state of EV when plugged in is calculated based on trip chain. Then, An EV charging strategy is used to minimize load variance, considering EV user’s demand. Finally, the relaxation of EV charging demand and an EV response capability assessment method considering EV user’s demand are proposed. Results of case studies on power-transportation coupling system containing RBTS Bus6 and Beijing transportation system show that the proposed EV response capability assessment method is effective.

2. EV STATE CALCULATTION BASED ON TRIP CHAIN

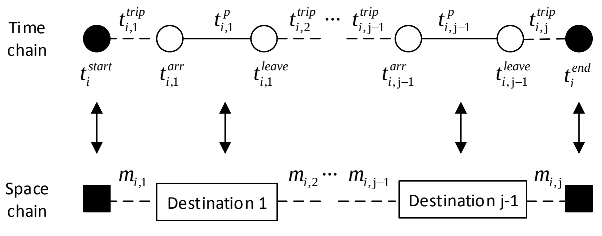

Fig 1 Trip Chain

Trip chain is used in this paper to simulate EV user’s daily travelling. As shown in Fig 1, a trip chain consists of a time chain and a space chain, the calculation method of variables in the trip chain will be introduced below.

2.1 Space chain

1) EV daily travelling schedule

The activity based travelling schedule model proposed in [9] is used in this paper to generate the space chain. Residential Area is the starting and ending area of daily travelling, and destinations include Working Area, Shopping Mall, Hospital, Residential Area (mid-tour returns home) and Scene Spot, then EV daily travelling schedule can be sampled based on statistical probabilities. Working Area is usually the first destination after leaving home, therefore, if the destinations contain Working Area, it should be fixed in the first place. And if the destinations contain Residential Area (mid-tour returns home), it should be placed in a random position except for the beginning and the end of all destinations, other sampled destinations are randomly permutated.

2) Driving distance

The travel route shortest travel time of EV is selected according to the.

$$\min \sum_{r,s\in NS} c_{rs}(t) \tag{1}$$

Then the driving distance and power consumption of EV can be calculated as follows.

$$m_{i,j} = \sum_{(r,s)\in S} l_{rs} \tag{2}$$

$$\Delta SOC_{i,j} = \sum_{(r,s)\in S} w_{rs}(t)\cdot l_{rs} / B \tag{3}$$

Where $w_{rs}(t)$ is the power consumption of EV for 1 km, can be calculated by the method in [10].

2.2 Time chain

1) Daily travel start time

Daily travel start time is the departure time from the Residential Area, which follows a normal distribution [11].

$$f_{t_i^{start}}(t) = \frac{1}{\sigma_1\sqrt{2\pi}} e^{-(t-\mu_1)^2/2\sigma_1^2} \tag{4}$$

Where $\mu_1 = 7.8$, $\sigma_1 = 1.5$.

2) Driving time

EV driving time can be calculated as follows.

$$t_{i,j}^{trip} = \sum_{(r,s)\in S} c_{rs}(t) \tag{5}$$

3) Middle trip start time

If the middle trip starts in Working Area, the middle trip start time is the departure time from the Working Area, which follows a normal distribution [11].

$$f_{t_i^{wdep}}(t)=\frac{1}{\sigma_2\sqrt{2\pi}}e^{-(t-\mu_2)^2/2\sigma_2^2} \tag{6}$$

Where $\mu_2=17.5$, $\sigma_2=0.5$.

If the middle trip starts in other areas, the middle trip start time can be calculated as follows.

$$t_{i,j}^{leave}=t_{i,j}^{arr}+t_{i,j}^{stay} \tag{7}$$

$$f_{t_{i,j}^{stay}}(t)=\frac{1}{\sigma_3\sqrt{2\pi}}e^{-(t-\mu_3)^2/2\sigma_3^2} \tag{8}$$

Where $\mu_3=1.5$, $\sigma_3=0.5$.

2.3 Fast charging analysis

To reduce damage to EV battery and keep SOC at a safe level, if the user is on the route and finds that the SOC will be less than 20% when arriving at next destination, the user will change current route and select the nearest EV charging station for fast charging.

Existing fast charge chargers of EV charging stations generally charge EV SOC to about 80% with a big power, and then the battery is slow charged with a small power. Therefore, in this paper, the user is considered to leave the charging station after SOC reaches 80%. Time for fast charging can be calculated as follows.

$$t_{i,\text{charge}}=(0.8-(SOC_i(t_{i,j}^{leave})-\Delta SOC_{i,\text{station}}))B_i/P_{chf} \tag{9}$$

3. EV CHARGING STRATEGY

3.1 EV management architecture and process

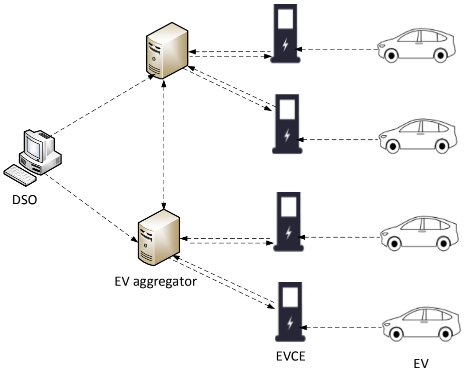

Fig 2 EV hierarchical management architecture

Since EV parks in Residential Area and Working Area most of the day, this paper considers that EV can only be slow charged in above areas. As shown in Fig 2, a hierarchical management architecture is adopted to coordinated EVs.

When an EV is plugged in the distribution system, a smart charging strategy will be carried out to minimize the load variance, and the problem can be formulated as:

$$\min\sum_{t=1}^{T}\left(\sum P_{ch,i}(t)+P(t)-\bar{P}\right)^2 \tag{10}$$

And the following constraints should be satisfied.

$$SOC_i^{t_{leave}}\geq SOC_i^{d} \tag{11}$$

$$0.2\leq SOC_i(t)\leq 1 \tag{12}$$

$$(1-\mathrm{D}_{Plug,i}(t))\cdot P_{ch,i}(t)=0 \tag{13}$$

$$P_{ch,i}(t)=\{0,P_{chr}\} \tag{14}$$

Where $\mathrm{D}_{Plug,i}(t)=1$ when EV is plugged in and 0 for otherwise.

Variables in (10)-(14) can be calculated as follows.

$$SOC_i^{t_{leave}}=SOC_i^{t_{arrive}}+\sum_{t=t_{arrive}}^{t_{leave}}P_{ch,i}(t)/B_i \tag{15}$$

$$\mathrm{D}_{Plug,i}(t)=\begin{cases}1, & t_{arr,i}<t<t_{leave,i}\\ 0, & others\end{cases} \tag{16}$$

$$\bar{P}=\frac{1}{T}\sum_{t=1}^{T}(P_{ch,i}(t)+P(t)) \tag{17}$$

$$P(t)=P_0(t)+\sum_{j=1}^{i-1}P_{ch,j}(t) \tag{18}$$

$$SOC_i^{t_{arrive}}=1-\sum_{(r,s)\in S_a}w_{rs}\cdot l_{rs}/B_i+\sum SOC_i^{ch} \tag{19}$$

4. EV RESPONSE CAPABILITY ASSESSMENT METHOD CONSIDERING USER'S DEMAND

4.1 Degree of EV charging demand Relaxation

To assess the response capability of EV, the degree of EV charging demand relaxation is proposed.

$$L_i(t)=t_{leave,i}-t-(\mathrm{SOC}_i^{d}-\mathrm{SOC}_i(t))\mathrm{B}_i/P_{chr,i} \tag{20}$$

$L_i(t)$ reflects the relation between remaining chargeable time and required charging time of EV. The smaller $L_i(t)$ is, the stronger EV charging demand is, and the weaker the response capability is, vice versa.

4.2 EV response capability assessment method

According to the definition of $L_i(t)$, EVs can be classified as follows.

1) $L_i(t)<0$

User's demand cannot be satisfied, even EV is continuous charged from current to departure time.

2) $0\leq L_i(t)<\Delta t$

If EV is charged continuously from now to the departure time, user's demand can be satisfied, but the charging process is uninterrupted.

3) $\Delta t\leq L_i(t)<\Delta t(1+P_{dis,i}/P_{chr,i})$

The EV charging process can be interrupted, but if EV discharges, user's demand cannot be satisfied.

4) $L_i(t)\geq\Delta t(1+P_{dis,i}/P_{chr,i})$

The charging process can be interrupted and EV can also discharge.

To reduce damage to EV battery, EV SOC should not be less than 20%, the EV which can discharge at time t should satisfy (21).

$$\begin{cases} L(t) \geq \Delta t(1+P_{dis,i}/P_{chr,i}) \\ D_{Plug,i}(t)=1 \\ SOC_i(t)-P_{dis,i}/B_i \geq 0.2 \end{cases} \qquad (21)$$

So the response capability of EV at time *t*, considering user's demand, can be determined by (22).

$$P_i^r(t)=\begin{cases} P_{dis,i} & ,(21)\ is\ satisfied \\ 0 & ,others \end{cases} \qquad (22)$$

To describe the relationship between the EV SOC when user leaves and the user’s demand, user’s satisfaction is defined as follows.

$$r=N_s/N \qquad (23)$$

5. CASE STUDY

As shown in Fig 3, the power-transportation coupling network containing RBTS BUS6 and Beijing transportation system is used in this paper. The parameters of RUTS BUS6 is from [12], and the areas where load points locate in are shown in Table I. Since the ratio of private vehicles to residential users is 1.86 [11], so 2370 EVs are considered in the system, under the EV penetration rate of 50%.

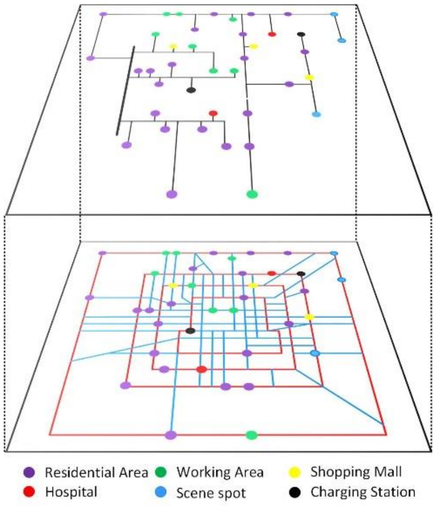

Fig 3 power-transportation coupling network

To verify the effectiveness of the proposed response capability assessment method, following cases are simulated.

Case1: EV can discharge if (21) is satisfied.

Case2: EV can discharge if the SOC is higher than a threshold, the threshold is set as 80%, 70%, 60% and50% respectively [6].

Case3: EV can discharge only when the SOC after discharging is higher than user’s demand [7].

Table I Area of load points in RBTS BUS6

Area	Load point
Residential Area	1 2 3 4 7 8 9 10 11 13 18 19 22 23 25 27 28 29 31 33 36 39
Working Area	6 14 16 17 20 21 24 30
Shopping Mall	15 26 38
Hospital	12 32
Scene Spot	34 35 37
Charging Station	5 40

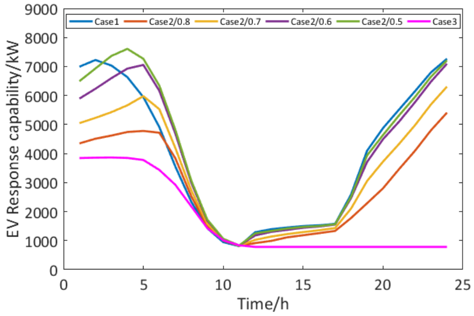

Fig 4 EV response capability in Residential Areas

As shown in Fig 4, EV response capability of different cases in Residential Area are different, and that of Case3 is significantly lower, it is because that the SOC of most EVs cannot meet users’ demand when returning to Residential Area. Case1 has higher response capability from 11:00 to 2:00 of the next day. After 2:00, due to the approaching departure time, V2G may cause users’ demand cannot be met, the response capability of Case1 decreases and is lower than that of Case2.

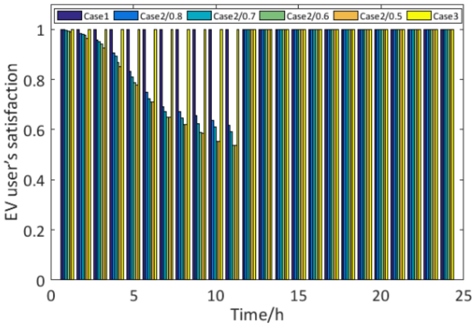

Fig 5 EV user’s satisfaction in Residential Areas

EV user’s satisfaction in Residential Area is shown in Fig 5, which means if EV discharges at time *t*, the probability that EV SOC can meet user’s demand when the user leaves. The satisfaction of Case1 and Case3 are always 1. In Case2, the satisfaction remains close to 1 from 12:00 to 24:00, however, it decreases significantly from 1:00 to 11:00, and the lower the SOC threshold is, the lower the satisfaction is.

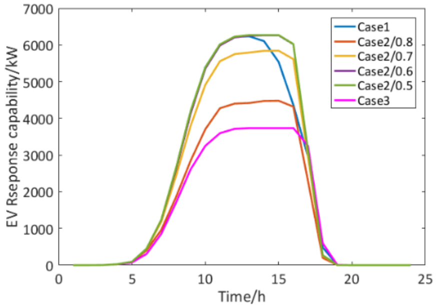

Fig 6 EV response capability in Working Area

EV response capability in Working Area is similar to that in Residential Area. It's worth noting that the response capability of Case2 with threshold of 50% and 60% are almost the same. The reason for the same response capability of Case2 with threshold of 50% and 60% is that the number of EVs with SOC of 50%-60% in Working Area is almost 0, as shown in Fig 7.

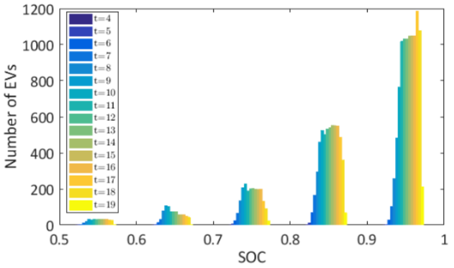

Fig 7 EV SOC distribution in Working Area

EV user's satisfaction in Working Area is similar to that in Residential Area, as shown in Fig 8.

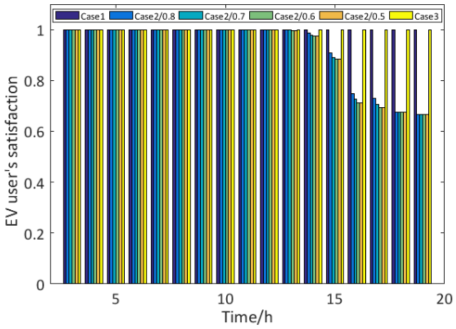

Fig 8 EV user's satisfaction in Working Area

6. CONCLUSION

This paper proposes an EV response capability assessment method considering user's demand. Trip chain is used to calculate the state of EV when plugged in, and an EV charging strategy is used to minimize load variance. The degree of EV charging demand relaxation is proposed and is used to assess EV response capability. Results of case studies on power-transportation coupling system containing RBTS Bus6 and Beijing transportation system show that the proposed method can maximize EV response capability while satisfying user's demand.

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