An Evaluation Framework for the Adjustable Capacity of Electric Vehicles' Charge and Discharge Load Based on Capacity Reliability

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Abstract. With the development of new power systems with new energy as the main body, the number of electric vehicles is proliferating, and the demand for charging and discharging of electric vehicles is also increasing. However, the disordered charging and discharging load of electric vehicles also bring significant challenges to the power system's safe and stable operation. To this end, a framework for evaluating the adjustable capacity of electric vehicle charging and discharging load based on capacity credibility is proposed. First, we simulate the charging and discharging load of electric vehicles based on the Sequential Monte Carlo Algorithm; then, we calculate the corresponding system's reliability based on the expectation of insufficient power supply; finally, we use the dichotomy to calculate the related credible capacity and capacity credibility. The simulation results show that the framework can effectively evaluate electric vehicles' adjustable capacity under different charging and discharging modes and scales and provide a theoretical basis for the safety assessment and effective dispatch of large-scale electric vehicle grid-connected distribution networks.

1. Introduction

In recent days, at the ninth meeting of the Central Finance and Economics Committee, President Xi Jinping proposed peaking carbon by 2030 and carbon neutral by 2060 and proposed building a new power system with a new energy mainstay [1]. Although the total number of new energy Electric Vehicles (EVs) has increased year by year, which has promoted the clean and low-carbon development of energy consumption, the disorderly charging of large-scale electric vehicles is bound to cause voltage control problems harmonics, and balance of supply and demand [2][3]. These issues pose a severe threat to the structure and operation of the distribution network.

Compared with traditional loads, electric vehicle batteries' energy storage characteristics enable EVs to be used as a mobile distributed energy storage device for two-way transmission of electric energy to the grid. Effective charging and discharging control of electric vehicles can realize the functions of peak regulation, frequency regulation, and increase of reserve capacity of the system [4][5] and smooth load fluctuations and reduce grid operation risks, and improve grid operation efficiency and reliability. Historical research mainly establishes an optimization model to minimize the load peak-valley difference or the best economic benefit and solve the optimal charge and discharge load curve of each electric vehicle [6]. However, few literatures evaluate the impact of different types of...
electric vehicle charge and discharge loads on the balance of power system supply and demand from power system reliability.

Capacity credibility is an index that quantifies the ability to generate units to provide capacity for the power system [7], and it has been used in the field of wind power in the early days [8][9]. In the context of a new power system with new energy as the main body, flexible loads with flexible adjustment capabilities can play a similar role to generator sets. Therefore, Nolan and Zhou et al. extended the definition of capacity credibility to flexible load fields [10]. Literature [11] studies the capacity credibility of energy storage and demand-side response resources. Literature [12] uses capacity credibility to measure the emergency power supply capability of demand-side response resources under disaster recovery scenarios. However, there is no literature to study electric vehicle charging and discharging loads to provide equivalent generating capacity for the power system from the perspective of capacity credibility.

Therefore, this paper proposes a framework for evaluating the capacity reliability of electric vehicles’ charge and discharge load adjustability. First, a final charging behavior decision module for electric vehicle owners that integrates electric vehicle battery State Of Charge (SOC), electric vehicle user charging habits, and discharging willingness is proposed. Based on this module, the 8760 electric vehicles charging and discharging load is simulated based on the Sequential Monte Carlo Algorithm. Then, we calculate the corresponding system’s reliability based on the expectation of insufficient power supply. Finally, we use the dichotomy to calculate the related credible capacity and capacity credibility.

2. Capacity credibility index of electric vehicle charging and discharging load
This article uses Equivalent Load-Carrying Capability (ELCC), Equivalent Firm Capacity (EFC), Equivalent Conventional Capacity (ECC), and Equivalent Generation Capacity Substituted (EGCS) as four capacity credibility indicators to construct an assessment framework for the adjustable capacity of electric vehicle charging and discharging loads. The specific definitions of the four indicators are as follows:

2.1. Equivalent Load-Carrying Capability
Reliable capacity index of electric vehicle based on equivalent load capacity can be defined: At the same level of reliability, the load capacity that electric vehicles can supply. See equation (1)-(2) for details:

\[
 \begin{align*}
 E_{1}^{\text{dec}} & = \sum_{i=t}^{T} R_{i} \{ P_{i,j} + \sum_{g \in G} C_{g,j} \cdot d_{i} \} \\
 E_{2}^{\text{dec}} & = \sum_{i=t}^{T} R_{i} \{ \sum_{g \in G} C_{g,j} \cdot d_{i} + C_{\text{dec}} \} \\
 E_{\text{dec}} & = E_{2}^{\text{dec}}
 \end{align*}
\]

Where: \( C_{g,j} \) represents the generating power of the conventional unit \( g \) at time \( t \); \( G \) represents the set of traditional units; \( d_{i} \) represents the load value of the system at time \( t \); \( T \) represents the cycle length, in this study \( T = 8760 \text{h} \); \( P_{i,j} \) represents the equivalent power generation corresponding to the orderly discharge load of electric vehicles; the power units of the first three are all MW. \( C_{\text{dec}} \) represents the credible capacity value of electric vehicles under this definition, and the unit is MW. \( R_{i} \) is the system reliability index and is calculated using Expected Energy Not Supplied (EENS). The specific equation (2) is as follows:

\[
 E_{\text{dec}} = \text{EENS}_{t} = \sum_{i=t}^{T} R_{i} \{ A_{i}, B_{i} \} = \sum_{i=t, B_{i} > A_{i}} (B_{i} - A_{i})
\]

Where: \( A_{i} \) represents the total power generation value of the system at time \( t \); and \( B_{i} \) represents the system’s total load value at time \( t \).
The corresponding capacity reliability index can be defined as the ratio of the load capacity that the system can supply to the ideal charge and discharge load capacity of an electric vehicle under the same reliability level, namely \( \eta_{evc} \), as shown in equation (3)-(4):

\[
\eta_{evc} = \frac{C_{evc}}{C_{ev}}
\]

(3)

Where: \( C_{ev} \) represents the ideal adjustable capacity of electric vehicles, which is defined in this article as the sum of all electric vehicles' charge and discharge powers that can be called at a particular time. The specific equation (4) is as follows:

\[
C_{ev} = N_{ev} \times P_d
\]

(4)

Where: \( N_{ev} \) represents the total number of electric vehicles planned to be connected to the grid; \( P_d \) represents the charging and discharging power of electric vehicles, and the unit is still MW.

2.2. Equivalent Firm Capacity, Equivalent Conventional Capacity, and Equivalent Generation Capacity Substituted

From the perspective of the power generation side, the size of the generator assembly capacity of different reliability (100%, <100%, a certain actual value) that the electric vehicle load can replace is defined as the corresponding EFC, ECC, and EGCS, and the general equation is as follows:

\[
\begin{align*}
E_{1e}^{cc} &= \sum_{i=T}^{1} R_{i} \{P_{ev,i} + \sum_{g=0}^{C_{ce}} C_{g,i} \cdot d_{i}\} \\
E_{2e}^{cc} &= \sum_{i=T}^{2} R_{i} \{C_{ce} + \sum_{g=0}^{C_{ce}} C_{g,i} \cdot d_{i}\} \\
E_{3e}^{cc} &= E_{2e}^{cc}
\end{align*}
\]

(5)

Where: \( C_{ce} \) represents the installed capacity of the corresponding generator set, and \( E_{1e}^{cc} \) and \( E_{2e}^{cc} \) represent the system's reliability. The specific calculation equation is the same as equation (2), and the other symbols are defined in equation (1).

The corresponding capacity credibility index can be defined: Under the same system reliability level, the ratio of the capacity of the generator assembly that can be equivalently replaced by the electric vehicle to the ideal charge and discharge load capacity of the electric vehicles, that is \( \eta_{cc} \), which is calculated as follows:

\[
\eta_{cc} = \frac{C_{ce}}{C_{ev}}
\]

(6)

Where: \( cc = efc / ecc / egcs \).

3. Simulation of Charge and Discharge Load of Electric Vehicle Based on Sequential Monte Carlo Algorithm

This article takes private electric cars as the research object and chooses office locations and residential areas as parking locations. Set the charge and discharge scheduling period to 8:00 to 17:00 and 19:00 to 7:00 the next day. Private electric cars' time to reach the two places obeys the normal distribution \( N(9.3,1.9^2) \) and \( N(19.2,2.8^2) \) [13]. According to the National Household Travel Survey (NHTS), the daily mileage of electric vehicles follows a lognormal distribution, and the probability density function is:

\[
f(x) = \frac{1}{x\sigma\sqrt{2\pi}} \exp \left[ -\frac{(\ln x - \mu)^2}{2\sigma^2} \right]
\]

(7)

Where: \( \mu \) is the expected value of the daily travel distance \( \mu = 3.68 \); \( \sigma \) is the standard deviation, \( \sigma = 0.88 \).
3.1. Charge and discharge behavior decision

Considering the loss of car batteries caused by frequent charging and discharging, car owners' possible charging and discharging behaviors are simplified: single continuous charging, single continuous discharging, and no charging and discharging. Factors that affect the final charging and discharging behavior of car owners include: the user's charging habits $X$, discharging scheduling willingness $Y$, and the battery power at the charging location $SOC(t_a)$. Assuming that the user has $a\%$ probability of choosing to charge during the day, and $b\%$ possibility to be willing to participate in the discharge scheduling, set the expected charging SOC during the day and night to $max_1 SOC$ and $max_2 SOC$, respectively, and set the minimum allowed travel SOC as $SOC_{min}$.

The specific corresponding relationship is shown in Table 1 below:

Table 1. Relationship between various influencing factors and users' final charging and discharging behavior.

| Parking place         | $SOC(t_a)$ | $X$ | $Y$ | Final behavior          |
|-----------------------|------------|-----|-----|-------------------------|
| Office location       |            |     |     |                         |
| $SOC_{min} < SOC(t_a) < SOC_{max1}$ | $X > a\%$ | $Y > b\%$ | Discharge               |
| $SOC(t_a) > SOC_{max1}$ | /          | $Y > b\%$ | /                      |
| $SOC_{min} < SOC(t_a) < SOC_{max1}$ | /          | $Y < b\%$ | /                      |
| $SOC(t_a) < SOC_{min}$ | /          | /    | /   | Stay only               |
| Residential area      |            |     |     |                         |
| $SOC_{min} < SOC(t_a) < SOC_{max2}$ | $X > a\%$ | $Y > b\%$ | Discharge               |
| $SOC(t_a) > SOC_{max2}$ | /          | $Y > b\%$ | /                      |
| $SOC_{min} < SOC(t_a) < SOC_{max2}$ | /          | $Y < b\%$ | /                      |
| $SOC(t_a) < SOC_{min}$ | /          | /    | /   | Stay only               |

3.2. Calculation of SOC and charging and discharging time for electric vehicles

Suppose the SOC value of the electric vehicle when it leaves the parking place is, then:

$$SOC(t_a) = (SOC(t_a') - \frac{D}{L}) \times 100\%$$  \hspace{1cm} (8)

$$SOC(t) = \begin{cases} 
(SOC(t_a) + T_c \times \frac{P \times \eta_c}{S_{ev}}) \times 100\% & \text{charge} \\
SOC(t_a) & \text{stay only} \\
(SOC(t_a) - T_d \times \frac{P \times \eta_d}{S_{ev}}) \times 100\% & \text{discharge}
\end{cases}$$  \hspace{1cm} (9)

In equation (8): $t_a$ represents the arrival time; $SOC(t_a)$ represents the SOC when arriving at the current parking place; $t_a'$ represents the departure time at the previous parking place; $SOC(t_a')$ represents the SOC when leaving the previous parking place; $D$ represents the driving distance between the last parking location and the current parking location; $L$ represents the maximum driving distance of the electric vehicle.

In equation (9): $t_a$ represents the time of leaving, $SOC(t_a)$ represents the SOC when leaving the current parking place; $T_c$ represents the single charging time, $\eta_c$ represents the charging power, the unit is MW, $\eta_d$ represents the charging efficiency; $T_d$ represents the single charging time, and $P_d$ represents discharging power, the unit is MW, $\eta_d$ represents the discharge efficiency; $S_{ev}$ represents the battery capacity of the electric vehicle, the unit is MWh.
Let $T_c$ be the duration of a single charge and $T_d$ be the duration of a single discharge. According to the charge and discharge scheduling time and the battery SOC allowable charge and discharge time, the charge and discharge time can be calculated as follows:

$$T_c = \min \left[ \frac{(SOC_{\text{max}} - SOC(t_i)) \times S_{\text{ae}}}{P_c \times \eta_c}, t_i - t_a \right]$$  \hspace{1cm} (10)

$$T_d = \min \left[ \frac{(SOC(t_i) - SOC_{\text{min}}) \times S_{\text{ae}}}{P_d \times \eta_d}, t_i - t_a \right]$$  \hspace{1cm} (11)

Where: $SOC_{\text{max}}$ represents the expected SOC during charging.

### 3.3. The charge-discharge electric vehicle mode

To effectively study the impact of the initial charging and discharging time of electric vehicles on the power system’s reliability, this paper selects eight typical charging and discharging modes of electric vehicles and simulates the charging and discharging loads of electric vehicles separately for each charging and discharging method. As shown in Table 2 below:

| Mode | Charge mode | Discharge mode |
|------|-------------|----------------|
| 1    | Charge upon arrival | / |
| 2    | Delayed charge | / |
| 3    | Charge during low static load | / |
| 4    | Charge during low dynamic load | / |
| 5    | Charge upon arrival | Discharge upon arrival |
| 6    | Delayed charge | Discharge upon arrival |
| 7    | Charge during low static load | Discharge during peak static load |
| 8    | Charge during low dynamic load | Discharge during peak dynamic load |

The delayed discharge in the charging mode 2 is set to the last discharge in the charge-discharge scheduling period, that is $t_d = t_i - T_d$, the charging start time. The static load refers to the initial system load, and the dynamic electric vehicle load refers to the initial system load and the grid-connected electric vehicle load. After the electric vehicle arrives, it first searches for the lowest value of the load during the dispatch period, uses it as the midpoint of the charging period, and discharges vice versa. Details as follows:

$$load(t_{\text{mc}}) = \min \{load(t_i)\} \quad t \in \left[ t_a + \frac{T_c}{2}, t_i - \frac{T_c}{2} \right]$$  \hspace{1cm} (12)

$$t_c = t_{\text{mc}} - \frac{T_c}{2}$$  \hspace{1cm} (13)

$$load(t_{\text{md}}) = \max \{load(t_i)\} \quad t \in \left[ t_a + \frac{T_d}{2}, t_i - \frac{T_d}{2} \right]$$  \hspace{1cm} (14)

$$t_d = t_{\text{md}} - \frac{T_d}{2}$$  \hspace{1cm} (15)

In equation (12)-(15): $t_{md}$ represents the time corresponding to the load's highest point. $t_{mc}$ represents the time corresponding to the lowest point of load. $load(t_i)$ represents the load sequence.

### 3.4. Basic process of electric vehicle charging and discharging load simulation

This paper takes private electric cars as the research object. Based on the research mentioned above in this section, the 8760-hour charging and discharging load data of electric vehicles is simulated based on the Sequential Monte Carlo Algorithm. The simulation process is as follows:

Step 1: Initialize the serial number of the electric vehicle, $n = 1$.

Step 2: Initialize the simulation time, $i = 1$. 

5
Step 3: Generate a random number for the daily mileage $D$, a random number for the time of arrival at the charging location $t_s$, a random number for the charging habit $X$, and a random number for the user's willingness to discharge $Y$, and select the electric vehicle charging and discharging mode in Table 2.

Step 4: According to equation (8), calculate the battery power at the parking place $SOC(t_s)$.

Step 5: According to Table 1, judge the final charging and discharging behavior when the car arrives at the location.

Step 6: Calculate the required $T_c$ and $T_d$ according to equation (10) and (11).

Step 7: Arrange the charging start time $t_c$ and discharge start time $t_d$ according to equation (12)-(15) and the electric vehicle charging and discharging mode selected in step 3.

Step 8: Calculate the battery power at the moment of leaving according to $ct$, $cT$, $dt$, $dT$, and equation (9), and produce the charging power curve and discharge power curve of the car for another day.

Step 9: Judge whether the simulation time is over, if $i < 365$, then $i = i + 1$ repeat step 3-9; otherwise, go to the next step.

Step 10: Judge whether all electric vehicles have been simulated, if $n < N$, then $n = n + 1$, repeat step 3-10, otherwise, go to the next step.

Step 11: Accumulate and output the charge and discharge load curves of all electric vehicles.

4. Capacity credit assessment process

According to Section 2, we can realize the credible capacity (CC) evaluation of the orderly charging and discharging loads of electric vehicles by evaluating and comparing the system reliability before and after the electric vehicle load is connected to the grid. To this end, this study uses a CC evaluation algorithm based on Sequential Monte Carlo Simulation (SMCS). The specific process is as follows:

Step 1: Enter the basic parameters of the Roy Billinton Test System (RBTS).

Step 2: Use the SMCS algorithm to simulate the 8760 sequence that generates a conventional generator set's power output.

Step 3: According to the data provided by the RBTS reliability test system, such as the proportion of daily peak load hourly value, weekly peak load hourly value proportion, and other data, derive the 8760-hour load sequence of the system throughout the year. See the literature for specific data and generation methods [14].

Step 4: Enter the basic parameters of the electric vehicle model.

Step 5: Based on the input data in step 4, use the SMCS algorithm to simulate and generate an 8760h sequence of electric vehicle charging and discharging load in eight charging and discharging modes. The above steps 1-3 and 4-5 are independent of each other and can be performed simultaneously.

Step 6: Calculate the size of the system reliability parameters $EENS_0$ that are not incorporated into the electric vehicle load according to the 8760h sequence of the conventional generator set and the 8760h sequence of the system load.

Step 7: According to the 8760h sequence of the conventional generator set, the 8760h sequence of the system load, and the 8760h sequence of the orderly charging and discharging loads of electric vehicles, calculate the size of the system reliability parameters $EENS_{EV}$ under the charging and discharging load of electric vehicles.

Step 8: Compare the relationship between $EENS_0$ and $EENS_{EV}$. When $EENS_0 < EENS_{EV}$, the electric vehicle load appears as an equivalent load, and $C < 0$. When $EENS_0 > EENS_{EV}$, the electric vehicle load appears as an equivalent generating unit, and $C > 0$. Use dichotomy to calculate the corresponding credible capacity and capacity credibility. The detailed content of the conventional
power generation unit’s output power simulation algorithm in step 2 and the dichotomy of step 8 is in document [15].

5. Case study applications
In this study, the RBTS system is used for example analysis. The system parameters are shown in the literature [16]. It mainly studies the four credible capacities $C_{elc}$, $C_{efc}$, $C_{ecc}$, and $C_{egcs}$ of electric vehicles under the different numbers of electric vehicles and different charging and discharging modes and the corresponding Capacity credibility $\eta_{elc}$, $\eta_{efc}$, $\eta_{ecc}$, and $\eta_{egcs}$. The electric vehicle battery model adopts Nissan Leaf. For details, see page 16 of literature [13], where $S_{\text{max}} = 24\text{KWh}$, $P_e = P_d = 4.8\text{kW}$. The user’s charging habit $a\% = 30\%$ and the user’s willingness to discharge $b\% = 50\%$.

![Figure 1. Credible capacities.](image1)

![Figure 2. Capacity credibility.](image2)
It can be seen from Figure 1 that most of the values of the credible capacity of electric vehicle loads under the four indicators are negative, and their absolute values increase linearly with the increase in the total number of vehicles. The most noticeable growth is Mode 1 and Mode 5. Through different charging and discharging start time adjustment strategies, the growth rate of the absolute value of the credible capacity can be slowed down. The adjustment effect of Mode 8 is the most obvious. The picture shows that under the premise of considering the initial load of the system and the current grid-connected load of electric vehicles, guiding users to discharge during peak periods and charge during low valley periods is conducive to fully tapping the adjustable capacity of electric vehicles and can even provide sufficient power to the system. The unfavorable load is transformed into an equivalent power generation unit.

It can be seen from Figure 2 that the capacity credibility of the electric vehicle load under the four indicators is a specific negative value and will not fluctuate sharply as the number of electric vehicles increases. When a proper charging and discharging start time adjustment strategy is adopted, the corresponding credibility value will gradually approach 0, or even greater than 0, and then act as an equivalent power generation unit in the power supply balance of the power system.

6. Conclusion
This paper proposes a framework for evaluating the adjustable capacity of electric vehicles' charge and discharge load based on capacity credibility. A decision-making method for charging and discharging electric vehicles' behavior at the parking place is proposed, which integrates the charging habits and discharging scheduling willingness of electric vehicle owners. Based on this module, we simulated the charging and discharging behavior of electric private car owners over a long period based on the Sequential Monte Carlo Algorithm. Finally, this paper proposes an electric vehicle charging and discharging strategy based on static load trough charging and dynamic load peak discharge and presents eight electric vehicle charging and discharging scenarios. Through the comparison of credible capacity and capacity credibility in different methods, it is proved that the framework presented in this paper can effectively quantify the adjustable potential of electric vehicle load under different charging and discharging strategies. Simultaneously, the electric vehicle charging and discharging strategy proposed in this paper can adapt to electric vehicle power curve adjustment in a large-scale and long-term range and is beneficial to electric vehicles as equivalent power generation units to improve the sufficiency of the power system. We hope that this paper's research results can provide theoretical suggestions for the safe and stable operation of the new power system with new energy as the main body.

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