Aggregation and Bidirectional Charging Power Control of Plug-in Hybrid Electric Vehicles: Generation System Adequacy Analysis

Zhe Liu, Student Member, IEEE, Dan Wang, Member, IEEE, Hongjie Jia, Member, IEEE, Ned Djilali, and Weixin Zhang

Abstract—With increasing penetration of plug-in hybrid electric vehicles (PHEVs), it is necessary to introduce a two-way interactive mechanism between PHEVs and the power system to improve system reliability and satisfy the PHEV charging requirements. To address these requirements, a bidirectional charging power control method, based on the time series model of PHEV charging, is developed. The control strategy ensures that PHEVs achieve full-charge before the users’ desired disconnecting time, and allows the spare time during users desired charging horizons to be used to manage PHEV charging power and to respond to the generation capacity shortage signal. Grid-to-vehicle (G2V) and vehicle-to-grid (V2G) control strategies are defined to determine whether PHEVs draw power from the grid or inject power to the grid. Generation system adequacy and PHEV charging behavior are analyzed for various scenarios under this interactive mechanism, and the costs and benefits to vehicle users and utilities are analyzed based on several new generation system adequacy indices. The simulation results illustrate how charging power control can effectively improve generation system adequacy, particularly for higher PHEV penetration and when users are incentivized to extend charging horizons.

Index Terms—Charging power control, generation system adequacy, grid-to-vehicle (G2V), plug-in hybrid electric vehicles (PHEVs), vehicle-to-grid (V2G).

NOMENCLATURE

- $t_b$: Vehicle connecting time.
- $T_a$: Vehicle actual charging horizon (h).
- $t_a$: Vehicle actual disconnecting time.
- $T_c$: User desired charging horizon (h).
- $t_e$: User desired disconnecting time.
- $E_r$: Rated battery capacity (kWh).
- $E$: Battery capacity (kWh).
- $P_r$: Charging and discharging power (kW).
- $\mu$: Charging and discharging efficiencies.
- $\Omega$: Universal set of vehicles connected to grid.
- $\Omega_{G2V}$: G2V control set.
- $\Omega_{V2G}$: V2G control set.
- $\Omega_1$: Set of vehicles absorbing energy from grid.
- $\Omega_0$: Set of vehicles temporarily disconnected from grid.
- $\Omega_{-1}$: Set of vehicles injecting energy to grid.
- $\Delta T$: Simulation step (control step).
- $\Delta P_L$: Load curtailment caused by capacity shortage.
- $\alpha$: Factor that represents the remaining charging time of vehicles after G2V control.
- $\beta$: Factor that represents the remaining charging time of vehicles after V2G control.
- $q$: Factor to amplify the influence of parameter $\alpha$ and $\beta$.
- $n$: Charging state of vehicles.
- $n_g$: Operation state of generating units.
- $P_{G2V}$: G2V control power (MW).
- $P_{V2G}$: V2G control power (MW).
- $\bar{\Omega}$: Complementary set of $\Omega$.
- $P_G$: Aggregative generation capacity (MW).
- $\Omega_u$: Set of generating units.
- $P_{g,r}$: Rated power of units (MW).
- $P_{LB}$: Base load (MW).
- $P_{loss}$: Network loss (MW).
- $P_{L0}$: Initial total load without charging power control (MW).
- $P_L$: Total load after charging power control (MW).
- $P_{L,\text{curt}}$: Actual load curtailment considering charging power control (MW).
- $f$: Frequency of load curtailment.
- $N$: Total number of simulation steps where load curtailment happens.
- $N_{G2V}$: Total number of simulation steps where G2V control is implemented.
- $N_{V2G}$: Total number of simulation steps where V2G control is implemented.
- $R_{LOLE}$: Loss of load expectation (h/year).
- $R_{LOEE}$: Loss of energy expectation (MWh/year).
- $R_{LOLF}$: Loss of load frequency (occ/year).
The random nature of PHEV loads can severely limit power system reliability. In [14] and [15], PHEV load profiles were generated with two random variables: arrival time and required energy, and numerical results showed a sharp decrease in power system reliability with increasing PHEV penetration level. An alternative “battery exchange” EV charging mode was studied in [16] using a behavior extraction method to analyze its impact on system reliability. Meanwhile, the numerical results showed that power system reliability can be improved by the battery exchange mode, but to achieve the substantial reliability gains requires a large number of stored batteries; in addition, the gains come at the cost of some increase in unsatisfied user demand. Although large-scale PHEV integration has an ostensibly unfavorable influence on system reliability, many studies have shown that appropriate control of PHEV charging power may have significant benefits for system operators and customers. PHEV control can enhance system operation flexibility as well as energy storage to achieve fast and accurate response of frequency regulation [17], [18] and spinning reserves [19], [20], to minimize power losses and to improve load voltage profile [21], [22].

In the present study, we investigate the impact of bidirectional charging power control on generation system adequacy and PHEV charging behavior. First, an interactive mechanism between power system and PHEVs is introduced. In this aggregative architecture, an aggregator that may be a utility or a third party is considered as a new market player who collects and transmits PHEV charging data to a power system control center, as well as receives service requests from system operators and issues control commands to available vehicles. Secondly, we propose a time-series model for PHEV charging that does not violate full-charge constraints at the end of the users desired disconnecting time. Based on this model, a bidirectional control strategy of PHEV charging power is developed to make full use of spare time during users desired charging horizon to reduce generation capacity shortage. Disconnecting charging load with grid-to-vehicle (G2V) control and discharging stored battery with vehicle-to-grid (V2G) control are used to manage the energy transfer between power systems and PHEVs. Finally, the impact of charging power control on generation system adequacy is demonstrated. In order to quantify the extra cost to utilities or benefit of customers from auxiliary services, some new indices are formulated, i.e., the “expected energy compensated” by charging power control (EEC) and the “expected load compensated” by charging power control (ELC). In summary, the proposed method originating from the conventional reliability analysis in [23] provides a new method for system planning and long-term analysis. The adequacy of systems integrating PHEVs can be assessed to ensure system security. Also, reasonable penetration of PHEVs without reliability violation can be roughly determined. The main contribution of the proposed method is that the interaction between system adequacy and charging behavior can be synchronously analyzed in a unified framework.

II. INTERACTIVE MECHANISM OF PHEV AGGREGATIVE ARCHITECTURE

Integrating PHEV into power systems can be categorized into two modes, namely, the centralized charging mode, which is utilized in commercial charging stations or large-scale parking lots, and the distributed charging mode, which is utilized, for instance, by users who own charging panels in their residential garages or apartment complexes [24]. Regardless of which mode is chosen by users, each individual vehicle represents...
only “noise” to the power system; hence the need to aggregate vehicles into large fleets, whose combined impacts are tangible for the grid [25]. An aggregative architecture is conceptually illustrated in Fig. 1.

The aggregator plays an important role in this architecture. As an interactive agent between power systems and vehicles, the aggregator provides regulation services by organizing a large number of PHEVs. From a business viewpoint, the aggregator is responsible for establishing a contract with each vehicle owner and another contract with the grid operator [26]. The stakeholders pursue their maximum benefit from these transactions. According to [27], the aggregator can be easily treated as a conventional ancillary service provider and the additional communication workload is less than that under the direct architecture.

We focus on physical properties of aggregators in this mechanism. The aggregator assesses and updates vehicles status when they are connected to the grid. This includes state of charge (SOC), rated charging power, battery capacity, and user preset parameters that depend on the driving behavior of customers, such as desired charging horizon and disconnecting time. Raw data are processed by aggregating each individual vehicle within the same community into a single controllable power resource. At this step, the integrated control capability is evaluated by analyzing which vehicles can be controlled. An aggregative signal reflecting vehicle charging state is transmitted to grid operator through the communication network. Depending on system analysis results, a raw control signal is issued by the grid operator. The aggregator then decomposes the control signal into detailed commands for each individual vehicle based on the SOC of batteries.

III. BIDIRECTIONAL CHARGING POWER CONTROL MODEL

To mitigate the risk caused by generation capacity shortages, a bidirectional charging power control model, G2V and V2G, is introduced in this section. The G2V control determines which vehicles can be disconnected from grid and is first used to reduce charging load. If capacity shortage arises, the V2G control is activated to determine which vehicles can inject power to the grid, and is then applied to expand generation capacity. A detailed description of these models is given below.

A. Time Series Charging Model

Prior to quantifying the availability of PHEV control, a time series charging model is first required. We start by defining several concepts of battery and user preset parameters.

*Definition 1*: Vehicle connecting time $t_b$

The connecting time represents when users arrive at their destination and connect their vehicles to the grid. Obviously, the charging power can be, in principle, controlled from this time if necessary.

*Definition 2*: Vehicle actual charging horizon $T_a$

The actual charging horizon represents how long it takes for vehicle to achieve a fully charged state without control

$$T_a = \frac{E_r}{P_r \mu}$$  \hspace{1cm} (1)

where $E_r$ is the rated capacity, $P_r$ is the rated charging and discharging power, and $\mu$ is the charging and discharging efficiencies.

*Definition 3*: Vehicle actual disconnecting time $t_a$

The actual disconnecting time corresponds to the time when a vehicle completes charging and is disconnected from the grid

$$t_a = t_b + T_a.$$  \hspace{1cm} (2)

*Definition 4*: User desired charging horizon $T_e$

The desired charging horizon represents the user’s intention to supply auxiliary services through charging power control, which can be either according to the contract between users and aggregators, or preset on charging piles by users in a manner similar to paying for parking fees. In this paper, this is taken as the longest charging horizon accepted by users and conceptually defined as a function of actual charging horizon, i.e.,

$$T_e = \rho T_a \hspace{1cm} (\rho \geq 1).$$  \hspace{1cm} (3)

The difference between the desired and actual charging horizon, i.e., $(\rho - 1)T_a$ from (3), provides spare time in the charging horizon that can be used to manage charging power. Since each user has different driving habits, $\rho$ is taken to meet a uniform distribution in the interval $[\rho_0, \rho_1]$. 

Fig. 1. PHEV aggregative architecture. (a) Vehicle-to-grid network. (b) Information flow.
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that a generation capacity shortage happens at time state till the capacity reaches the desired level. Let us suppose power control is not implemented, the battery remains charged acceptable to the users to disconnect the vehicle from the grid.

Δa control step Ω set of vehicles, criterion in (5) is defined as G2V control set be implemented immediately. A fleet of vehicles meeting the reduce the load curtailment, the charging power control should be implemented.

Definition 5: User desired disconnecting time $t_e$

The desired disconnecting time represents the latest time acceptable to the users to disconnect the vehicle from the grid

$$t_e = t_b + T_e.$$ (4)

A group of five parameters is allocated to each individual vehicle. An useful hypothesis is that vehicles always absorb energy from the grid if generation capacity is adequate, which ensures that battery charging has the highest priority, since users are assumed to prefer complete charging as soon as possible to respond to uncertain driving demand in the future.

B. G2V Control Model

G2V control determines which vehicles would be temporarily disconnected from the grid, i.e., into inactive states which neither absorb nor release energy. The control trajectory of an individual vehicle is illustrated in Fig. 2.

The charging process starts at time $t_b$, which is the time when the users connect their vehicles to the grid. If the charging power control is not implemented, the battery remains charged state till the capacity reaches the desired level. Let us suppose that a generation capacity shortage happens at time $t_i$ and $t_j$. To reduce the load curtailment, the charging power control should be implemented immediately. A fleet of vehicles meeting the criterion in (5) is defined as G2V control set $\Omega_{G2V}$. For an individual vehicle $k$ at time $t_i$, if the vehicle remains inactive for a control step $\Delta T$, and then the battery still can be charged up to the user’s desired capacity level at the disconnecting time $t_e$, the vehicle $k$ belongs to the set $\Omega_{G2V}$. However, at time $t_j$, there is insufficient time to charge the battery up to the user’s desired capacity level at the disconnecting time $t_e$ after the vehicle remains inactive for a control step $\Delta T$, so the vehicle cannot be included as an element of $\Omega_{G2V}$. If $\Omega$ represents the universal set of vehicles, $\Omega_{G2V} \subset \Omega$

$$\Omega_{G2V} = \left\{ k \left\lbrack \int_{t_i + \Delta T}^{t_e} \mu_k P_{r,k} dt + E_{i,k} \right\} > E_{r,k}, k \in \Omega \right\}. \quad (5)$$

Depending on the generation capacity shortage, an integer programming problem formulated in (6)–(8) below is solved to determine how many vehicles in $\Omega_{G2V}$ would be controlled

$$\min \sum_{k \in \Omega_{G2V}} \left\lbrack \frac{n_{e,k}}{\alpha_{i,k}} \right\rbrack^q \quad (6)$$

s.t. $\sum_{k \in \Omega_{G2V}} n_{i,k} P_{r,k} \geq \Delta P_L$ \quad (7)

$$\alpha_{i,k} = t_e - t_i - \Delta T - \frac{E_{r,k} - E_{i,k}}{\mu_k P_{r,k}} \quad , \quad k \in \Omega_{G2V} \quad (8)$$

where $n_{i,k}$ is the state of vehicle $k$ at time $t_i$, value 0 represents active states to absorb energy from grid, otherwise value 1 represents inactive states to be disconnected from grid; $\Delta P_L$ is load curtailment caused by capacity shortage without control; $\alpha_{i,k}$ is a factor that represents the remaining charging time of vehicle $k$ at time $t_i$ after G2V control; $q$ is a factor that is used to amplify the influence of parameter $\alpha_{i,k}$, especially when the parameter $\alpha_{i,k}$ for each vehicle in $\Omega_{G2V}$ is similar, a relatively larger value can be assigned to parameter $q$, normally we set $q$ to value 1; $\Delta T$ is the control step, this electric vehicle model is used in adequacy analysis, which is a long-term assessment, thus the control step is set to 1 h, and it is also named as the simulation step in adequacy analysis; $t_e$ is the desired disconnecting time of vehicle $k$; $P_{r,k}$ is the rated charging and discharging power of vehicle $k$; $E_{r,k}$ is the rated capacity of vehicle $k$; and $E_{i,k}$ is the battery capacity of vehicle $k$ at time $t_i$. In this optimal model, scheduling vehicles depend on the remaining charging time of their batteries, which indicates the time segment from the end of charging to disconnection of vehicles from grid. The longer this charging time, the higher the priority of the vehicle. In other words, this model ensures that the vehicles, which do not immediately need full-charge, have a high priority to be controlled.

C. V2G Control Model

Similar to the G2V control, the V2G control determines which vehicles would feed their stored energy back to the grid as controllable generation resources. Fig. 3 defines the variables involved in the V2G model. Labels of the various lines in Fig. 3 are the same as that in Fig. 2.

The decision criterion is different from V2G control set $\Omega_{V2G}$ and is formulated as

$$\Omega_{V2G} = \left\{ k \left\lbrack \frac{E_{i,k} \geq \int_{t_i}^{t_i + \Delta T} \mu_k P_{r,k} dt}{E_{i,k} < \int_{t_i}^{t_i + \Delta T} \mu_k P_{r,k} dt + E_{r,k} \quad ; \quad k \in \Omega \right\} \right\}. \quad (9)$$

The first criterion ensures that there is sufficient stored energy available for discharge at the next control step. The second criterion ensures that there is sufficient time to achieve full-charge after vehicles are kept in G2V state for a control...
step. The full-charged vehicles will be disconnected from grid and not controlled again, thus the sets of vehicles are related by $\Omega_{\text{V2G}} \subset \Omega_{\text{G2V}} \subset \Omega$. The optimal model to schedule vehicles in the V2G control set is given by

$$\begin{align*}
\min \sum_{k \in \Omega_{\text{V2G}}} n_{i,k}^q \\
\text{s.t.} \quad \sum_{k \in \Omega_{\text{V2G}}} n_{i,k} p_{r,k} \geq \Delta P_L
\end{align*}$$

(10)

$$\beta_{i,k} = t_{e,k} - t_i - \Delta T - \frac{E_{r,k} - E_{i,k} + P_{r,k} \Delta T}{\mu_k}, \quad k \in \Omega_{\text{V2G}}$$

(12)

where $n_{i,k}$ is the state of vehicle $k$, and has value 0 for absorbing energy from the grid and value 1 represents injecting energy to the grid.

### D. Coordination Between G2V and V2G Control

When a raw control signal reflecting the generation capacity shortage is delivered from the control center to an aggregator, it should be decomposed and allocated to each individual vehicle. Thus, it is important to coordinate the control between G2V and V2G mode to compensate for the capacity shortage. The control power, $P_{\text{G2V}}$ for G2V and $P_{\text{V2G}}$ for V2G, can be, respectively, calculated by summing the rated charging power of vehicles belonging to set $\Omega_{\text{G2V}}$ and $\Omega_{\text{V2G}}$. According to $\Omega_{\text{V2G}} \subset \Omega_{\text{G2V}} \subset \Omega$, the relationship $P_{\text{G2V}} > P_{\text{V2G}}$ exists.

V2G control makes the charging duration longer than G2V control. Facing the uncertain driving behavior of customers in future, the long charging duration has negative influence on the trip of customers. Additionally, the G2V control only requires temporarily disconnecting vehicles and there is no energy exchange between grid and vehicles; however V2G control feedbacks the power to grid and the existed energy in batteries is used to compensate the shortage of generation capacity. From the macroscopic point, the impact of V2G control on charging process is more serious than that of G2V control. Consequently, G2V control is considered to have higher priority than the V2G control in this study.

### IV. Generation System Adequacy Analysis

Based on the charging power control model introduced in the previous section, a generation system adequacy analysis method is proposed in this section.

#### A. Summary

The purpose of generation system adequacy analysis, which is illustrated conceptually in Fig. 6, is to assess generation risk due to capacity shortage by considering the impact of generator outage and load fluctuation. The mismatch between generation and load causes energy loss. G2V control reduces aggregative charging power, while V2G control expands generation capacity. As a result, a new energy supply and demand balance is achieved along with a reduction or elimination of energy loss. Such reshaped load and generation profiles can improve generation system reliability.
The state of unit $i$ at time $j+1$ can be determined as

$$n_{g,i,j+1} = \begin{cases} n_{g,i,j} & j < j+1 \in \left[t_0t_0 + D_i\right] \\ n_{g,i,j} \in \left[t_0t_0 + D_i\right], j + 1 \not\in \left[t_0t_0 + D_i\right] \\ \bar{n}_{g,i,j} & j + 1 \in \left[t_0t_0 + D_i\right], j \not\in \left[t_0t_0 + D_i\right] \end{cases}$$ (14)

where $n_{g,i,j}$ is the state of unit $i$ at time $j$, with a value of 0 representing outage state, a value of 1 normal state; $\bar{n}_{g,i,j}$ is the adverse state of unit $i$ at time $j$; $t_0$ is the start time of unit state $i$ at time $j$.

The aggregative generation capacity at time $j+1$ can be calculated as

$$P_{G,j+1} = \sum_{i \in \Omega_a} P_{g,r,i} n_{g,i,j+1}$$ (15)

where $\Omega_a$ is the set of generating units; $P_{g,r,i}$ is the rated power of unit $i$. The generating unit ratings and reliability data reported in [29] are adopted in this paper. If PHEV load is not involved, generation system adequacy can be assessed with the comparison between generation and load curve sampled by previous method. The analysis method considering PHEV load is presented in the next section.

### C. Adequacy Analysis Algorithm with PHEV Control

A generation adequacy analysis algorithm is proposed here. The main procedure is as follows:

1. Initialize parameters of the power grid, i.e., reliability data, initial state of generating units, base load profile, and simulation step $\Delta T$.

2. Set simulation time $j = j + 1$. Allocate the state duration to each generating unit using (13). Then, determine the state of units using (14). Finally, calculate the aggregative generation capacity using (15).

3. Check whether the current simulation time represents the beginning of a day. If so, go to step 4), otherwise, skip to step 5).

4. Initialize parameters of vehicles, such as rated capacity $E_r$, rated charging power $P_r$, vehicle connecting time $t_b$, and user desired disconnecting time $t_e$.

5. Calculate the total load as follows:

$$P_{L,i,j} = P_{L,B,j} + \sum_{k \in \Omega_j} n_{0,k,j} P_{r,k}$$ (16)

where $P_{L,B,j}$ is the base load at time $j$ and $n_{0,k,j}$ is the initial state of vehicle $k$ at time $j$.

6. Compare the total load with generation capacity. The generation capacity shortage can be formulated as

$$\Delta P_{L,j} = \begin{cases} 0, & P_{G,j} \geq P_{L,j} + P_{loss} \\ |P_{G,j} - P_{L,j} - P_{loss}|, & \text{otherwise} \end{cases}$$ (17)

where $P_{loss}$ is the network loss.

7. If generation capacity shortage occurs, use the coordinate control method in Fig. 4 to balance the load and
generation. Then calculate the compensated power through G2V and V2G control as follows:

\[ P_{G,j} = \sum_{k \in \Omega_j} n_{k,j} P_{r,k} \]  

(18)

\[ P_{V,j} = 2 \cdot \sum_{k \in \Omega_{j-1}} P_{r,k} \]  

(19)

Step 8) Update the charging state of vehicles and recalculate the total load using

\[ P_{L,j} = P_{L,B,j} + \sum_{k \in \Omega_j} n_{k,j} P_{r,k} \]  

(20)

where \( n_{k,j} \) is the charging state of vehicle \( k \) after control at time \( j \), with a value 1 representing a vehicle that belongs to \( \Omega_j \), and similarly, values 0 and \( -1 \) represent vehicles belonging to \( \Omega_0 \) and \( \Omega_{j-1} \), respectively.

Step 9) Calculate load curtailment as follows:

\[ P_{L,\text{curt},j} = \begin{cases} 0, & P_{G,j} - P_{L,j} - P_{\text{loss}} \geq 0 \\ \left| P_{G,j} - P_{L,j} - P_{\text{loss}} \right|, & \text{otherwise} \end{cases} \]  

(21)

Step 10) Update the generation system adequacy [23] and load control indices in Tables I and II.

Step 11) Check whether the convergence criterion or preset simulation time is attained. If not, loop back to step 2), otherwise, save and analyze simulation results.

V. CASE STUDY

The impact of bidirectional charging power control on generation adequacy is illustrated and analyzed in this section. The case study is divided into three parts: 1) a base case used to analyze the interaction between charging power control and generation adequacy; 2) impact of PHEV penetration on generation adequacy; and 3) impact of user desired charging horizon on generation adequacy.

A. Base Case

The Roy Billinton Test System (RBTS) is used in this study. The ratings and reliability data can be found in [29]. The system has 2 generator buses, 4 load buses, 9 transmission lines, and 11 generating units. The minimum and maximum ratings of the generating units are 5 and 40 MW, respectively. The system peak load is 185 MW and the total installed generating capacity is 240 MW. The parameters for PHEV simulation are listed in Table III [11]. In the base case, a fleet of 7500 PHEVs is considered, with 2500 and 5000 vehicles integrated into the system for daytime and nighttime charging.

Fig. 7 shows the generation adequacy simulation curves for the base case. The annual load curve is repeatedly used in the simulation, thus 1 year is considered as a sampling cycle, and also named as a sample year. In addition, a sample year is the time scale to observe the variation tendency of adequacy indices. The generation capacity curve and some parameters are created by the sampling method, since the sampling size is small, the curves oscillate at the start. With the sample number increasing, the curves balance out and the solution tends to be stable.

Four curves are shown in each figure. The black one is calculated with conventional adequacy analysis method in [28]; the red one is generated with conventional method considering the integration of PHEVs; the blue one is formed with proposed method only considering G2V control; the green one is created with proposed method both considering G2V and V2G control. In base case, the influences of PHEV integration and charging power control on generation adequacy are weak except for the LOLF index. Only the frequency of generation capacity shortage is reduced whether using G2V or V2G control.

The load control indices presented in Fig. 8 reveals how much energy the electric utilities or aggregators need to reduce system

<table>
<thead>
<tr>
<th>TABLE I</th>
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<tr>
<td><strong>GENERATION SYSTEM ADEQUACY INDICES</strong></td>
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<tr>
<td><strong>Generation adequacy indices</strong></td>
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<tr>
<td>Loss of load expectation (LOLE) (h/year)</td>
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<tr>
<td>Loss of energy expectation (LOEE) (MWh/year)</td>
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<tr>
<td>Loss of load frequency (LOLF) (occ/year)</td>
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<tr>
<td>Loss of load duration (LOLD) (h/occ)</td>
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</tbody>
</table>

The generation system adequacy indices reflect the average inadequacy of system in 1 year. \( N_j \) indicates the total number of simulation steps where the load curtailment happens until time \( j \). In these equations, the symbols \( \Delta T \) in the numerator and denominator are retained and not omitted to insure the meaning of equations clear and complete; \( f_j \) indicates the frequency of load curtailment during the period from the simulation start to time \( j \). It is noted that the frequency of load curtailment is different from the number of load curtailment. For example, at time \( j \), load curtailment happens, and at time \( j + 1 \), load curtailment still exists, thus the number of load curtailment is 2, but the frequency of load curtailment is 1. Expression \( jAT / 8736 \) converts the simulation time to year, in this paper, it is a transform from hour to year.

<table>
<thead>
<tr>
<th>TABLE II</th>
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<tbody>
<tr>
<td><strong>LOAD CONTROL INDICES</strong></td>
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<tr>
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<tr>
<td>Expected load compensated by G2V control (ELC-G2V)</td>
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<td>Expected energy compensated by G2V control (ECC-G2V)</td>
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<tr>
<td>Expected load compensated by V2G control (ELC-V2G)</td>
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<tr>
<td>Expected energy compensated by V2G control (ECC-V2G)</td>
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</table>

The load control indices reflect the average energy compensated by G2V and V2G control in 1 year. \( N_{G2V,j} \) and \( N_{V2G,j} \) respectively, indicate the total number of simulation steps where the G2V and V2G control are implemented until time \( j \).
TABLE III
PARAMETERS FOR PHEV SIMULATION

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Quantity</th>
<th>Value</th>
<th>Unit</th>
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</thead>
<tbody>
<tr>
<td>$P_r$</td>
<td>Rated charging and discharging power</td>
<td>$U(3.5)$</td>
<td>KW</td>
</tr>
<tr>
<td>$E_r$</td>
<td>Rated capacity</td>
<td>$U(5,20)$</td>
<td>KWh</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Factor reflecting user desired charging horizon</td>
<td>$N(1,75,0.01)$</td>
<td>-</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Charging and discharging efficiency</td>
<td>0.95</td>
<td>-</td>
</tr>
<tr>
<td>$L_d$</td>
<td>User disconneting time</td>
<td>$U(10,20)$ or a.m. or p.m.</td>
<td></td>
</tr>
<tr>
<td>$\Delta T$</td>
<td>Simulation step</td>
<td>1</td>
<td>h</td>
</tr>
</tbody>
</table>

$U(a, b)$ represents a random integer number that obeys the uniform distribution on the interval $[a, b]$; $U(a, b)$ represents a random number that obeys the uniform distribution on the interval $[a, b]$; $N(a, b)$ represents a random number that obeys the normal distribution with parameter $a$ and $b$.

*The vehicles are divided into two groups, one charging during daytime, the second charging during nighttime.

Fig. 7. Generation adequacy simulation curves in base case. (a) LOLE. (b) LOEE. (c) LOLF. (d) LOLD.

Fig. 8. Load control indices in base case. (a) G2V control. (b) V2G control.

Fig. 9. Aggregative charging power. (a) Without control. (b) With control.

(a) with (b), it is clear that the variation range of charging power in the controlled case (b) is wider than that in (a). This is because load control delays the charging time and shifts charging power to other spare times.

The probability distribution of aggregative charging power is illustrated in Figs. 10 and 11. The charging power without control in Fig. 10 basically follows the normal distribution, whereas the distribution for the controlled case shown in Fig. 11 is irregular. Comparing Fig. 10(b) with Fig. 11(b) reveals two distinct areas, located to the left and right of the normal distribution. The charging power in the left area is smaller than that without load control, and is caused by generation capacity shortage whereby some vehicles are temporarily disconnected or forced to feed power back to the grid. The right area is in stark contrast to the left one. Because the prior load control utilizes stored energy or hinders charging, vehicles have to continue their uncompleted charging. The results at times in higher charging power than in the case without control further illustrate the shifting of charging power to the other spare time by load control.

Obviously, charging power control has little impact on generation system adequacy for the base case, but this does not necessarily imply that charging power control cannot effectively improve system reliability. The underlying reason here is that the extra PHEV load does not bring about higher risk than that caused by base load, and the control capability is also constrained by PHEV penetration and user desired charging horizons. Other scenarios are therefore investigated below.

B. Case 1: Impact of PHEV Penetration

To investigate the impact of PHEV penetration, the number of vehicles is set as twice that of the base case. The generation adequacy simulation curves in Fig. 12 show that, with the exception of LOLD, the indices are significantly reduced by charging power control. According to Table I, LOLD can be considered as an extension of LOLE and LOLF. The degree of variation of LOLD represents the relative variation of LOLE and LOLF compared to their original value; hence LOLD may be higher than in the case without load control. LOEE decreases from 695.77 to 650.70 MWh/year, and LOLE can almost be controlled to attain the original system value. Comparing Fig. 12 with Fig. 7, the reduction of adequacy indices is larger than the one in the base case, indicating that higher PHEV penetration yields not only higher risk, but also stronger control capacity.

In Fig. 13, the index EEC-G2V is higher than the one in the base case. But ELC-G2V is similar for both scenarios, which
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Fig. 10. Distribution of charging power without load control. (a) Probability of charging power. (b) Cumulative probability of charging power at time 21:00 and 11:00.

Fig. 11. Distribution of charging power with load control. (a) Probability of charging power. (b) Cumulative probability of charging power at time 21:00 and 11:00.

Fig. 12. Generation adequacy simulation curves in Case 1. (a) LOLE. (b) LOEE. (c) LOLF. (d) LOLD.

Fig. 13. Load control indices in Case 1. (a) G2V control. (b) V2G control.

illustrates that G2V control in Case 1 prevents more load curtailment than in the base case for similar charging horizons. The indices for V2G control are low for both cases, because G2V control is given the highest priority in this study, based on the price of auxiliary services.

C. Case 2: Impact of User Desired Charging Horizon

The impact of parameter $\rho$ (see Table III) is examined next by adjusting its value adjusted to follow the normal distribution $N(2.5, 0.01)$; in effect this represents an extension of users...
desired charging horizon. Other parameters remain in the base case.

The simulated generation adequacy curves are presented in Fig. 14 and show that the indices are significantly reduced to the level without PHEV integration by charging power control. The important LOEE index is reduced from 727.67 to 548.06 MWh/year. Similar to Case 1, comparison between Figs. 7 and 14 reveals that the distribution of charging power in 1 day changes with the adjustment of parameter $\rho$; this may increase mismatch between load and generation and bring higher risk. However, control capability can be improved to ensure system risk remain sufficiently low.

The load control indices for Case 2 are shown in Fig. 15. The average energy used by G2V and V2G control per year is 199.92 and 17.92 MWh, respectively. Comparing them with Fig. 8, the energy needed to compensate generation capacity shortage is higher than that in the base case, which indicates that with longer charging horizons vehicles take on a more onerous task to manage the balance between load and generation, and obtain more benefits from auxiliary services.

This analysis shows that the control capability can be improved by prolonging the user desired charging horizon or/and increasing PHEV penetration. The charging power control reduces only the risk brought by PHEV integration and has little impact on the inherent risk of power system. In fact, PHEV penetration remains typically constant during fixed time segments of the day/night, and hence incentive policies to encourage users to extend their charging horizon will be the most effective way of eliminating the risk brought by vehicle charging.

**VI. Conclusion**

This study focused on the interaction between generation system adequacy and PHEV behavior under charging power control. An aggregative architecture that integrates PHEVs into the power system was presented in conjunction with a time series model developed to simulate the charging trajectory of vehicles. A bidirectional charging power control model was proposed to manage the power balance between generation and load allowing reduction of charging load (G2V) and expansion of generation capacity (V2G). The coordinated control of each individual vehicle depends on the remaining charging time. New indices indirectly reflecting the costs and benefits of supplying PHEV auxiliary services were also presented to quantify the impact of PHEV integration under different scenarios.

The numerical results show that although integration of PHEVs brings extra risk to a power system, this risk can be significantly reduced by charging power control within the control capability of vehicles which is limited by the battery parameters and customer driving habits. Further, PHEV penetration and user desired charging horizon are found to have a strong impact on control capability. The proposed method reduces the conservativeness of previous work considering the electric vehicles as conventional load, and supply a new method for system planning or long-term analysis.

The new load control indices are useful to indirectly measure the impact of charging power control and benefit to electric utilities. Additional applications of the new indices to cost-benefit analysis should be developed in the future. Based on the electricity price, the new indices can be extended to calculate the costs of charging power control or the benefits to electric vehicle owners. Charging power control does bring new uncertainties to power systems; how to predict the artificial and controllable “uncertainties,” and eliminate the “bad” response to improve system reliability is hence another important and interesting topic for future work.

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