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Opportunities and Challenges of Vehicle-to-Home, Vehicle-to-Vehicle, and Vehicle-to-Grid Technologies

This paper investigates and proposes methodologies, approaches, and foresights for the emerging technologies of V2H, V2V, and V2G.

By Chunhua Liu, Member IEEE, K. T. Chau, Fellow IEEE, Diyun Wu, Student Member IEEE, and Shuang Gao, Student Member IEEE

ABSTRACT | Electric vehicles (EVs) are regarded as one of the most effective tools to reduce the oil demands and gas emissions. And they are welcome in the near future for general road transportation. When EVs are connected to the power grid for charging and/or discharging, they become gridable EVs (GEVs). These GEVs will bring a great impact to our society and thus human life. This paper investigates and discusses the opportunities and challenges of GEVs connecting with the grid, namely, the vehicle-to-home (V2H), vehicle-to-vehicle (V2V), and vehicle-to-grid (V2G) technologies. The key is to provide the methodologies, approaches, and foresights for the emerging technologies of V2H, V2V, and V2G.

KEYWORDS | Electric vehicles (EVs); gridable electric vehicles (GEVs); power grid; renewable energy; smart grid; smart home; vehicle to grid (V2G); vehicle to home (V2H); vehicle to vehicle (V2V)

I. INTRODUCTION

With ever increasing concerns on environmental issues and clean energy, electric vehicles (EVs) have attracted more and more attention of governments, industries, and customers. EVs are popularly regarded as one of the most effective strategies to reduce the oil dependence and gas emission, and increase the efficiency of energy conversion [1]–[3]. Now, the car market is fermenting a revolution, and the trigger is all kinds of EVs.

In the past years, the EV technologies focused on individual components or systems in EVs, such as electric machines, drive systems, batteries, fuel cells, onboard renewable energy, and so on [3]–[7]. However, with the emerging concept of the smart grid, EVs will play a new role: energy exchange with the power grid. These EVs, called gridable EVs (GEVs), are capable of not only drawing the energy from the power grid with the plug-in function, but also delivering the energy back to the grid via the bidirectional charger. Furthermore, the bidirectional charger has the direct current (dc) link capacitor which is inherently able to provide the reactive power support to the power grid.

Traditional power plants with fossil fuel have a very low efficiency from sources to end users, approaching an overall efficiency of about 30%, whereas renewable energy sources have a high efficiency from generation to grid connection, approaching an overall value of about 70% [8]. However, the intermittent nature of renewable energy sources (such as wind power and solar power) adversely affects the grid voltage, frequency, reactive power, and so on. Hence, the power grid needs to be compensated or regulated [9]–[12]. In addition, this compensation becomes complicated in residential areas integrating with small-scale renewable energies. A single GEV is a good candidate to play a role of power compensation in the home grid [13]–[15].

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Furthermore, a group of GEVs is also a good candidate to support the community-grid operation [16]–[20].

Based on the charging/discharging capability of GEVs and the energy-efficient requirement of power grid, the vehicle-to-home (V2H), vehicle-to-vehicle (V2V), and vehicle-to-grid (V2G) concepts have become more and more attractive in recent years and probably will turn into reality in the near future. Actually, V2H, V2V, and V2G enable GEVs to not only serve as a transportation tool but also to act as controllable loads and distributed sources for the power grid. So, GEVs can play positive roles in the home grid, the community grid, and even the distribution grid during the charging and/or discharging period. Meanwhile, the corresponding bidirectional charger can inject the reactive power into the grid with its capacitor. In the grid system, the reactive power support is so essential that the system can retrieve additional reactive power from the capacitive devices to support those inductive devices demanding high reactive power. All these characteristics form new technologies of V2H, V2V, and V2G.

This paper investigates and discusses new technologies for GEVs connecting with the grid, namely, V2H, V2V, and V2G. The key is to present methodologies, approaches, and foresights of these emerging technologies, including frameworks, modeling, power electronics, battery technology, optimization strategies, reactive power support, and information and communication technology.

The rest of this paper is organized as follows. Section II will reveal the concepts of the V2H, V2V, and V2G technologies. Then, the frameworks for V2H, V2V, and V2G will be identified in Section III. In Section IV, modeling of the daily loads and GEVs as well as the V2H, V2V, and V2G systems will be explored. Then, Section V will discuss the power electronics technology for the V2H, V2V, and V2G systems, while Section VI will discuss the relevant battery technology. Section VII will present how to optimize and locate the GEVs. Consequently, Section VIII will illustrate the optimization of power quality using GEVs. In Section IX, the information and communication technology of V2H, V2V, and V2G will be discussed. Finally, conclusions will be drawn in Section X.

II. EMERGING CONCEPTS

EVs play a more and more important role in road transportation. According to the types of energy sources (gasoline or diesel, battery, and hydrogen fuel) and the propulsion devices (engine and motor), the whole spectrum of vehicles including the internal combustion engine vehicle (ICEV) and various EVs are depicted in Fig. 1 [3]. It can be seen that EVs can be generally classified as the hybrid EV (HEV), the battery EV (BEV), and the fuel-cell EV (FEV). Meanwhile, the HEV can be further classified as the conventional HEV (including the micro, mild, and full hybrids), the plug-in HEV (PHEV), and the range-extended EV (REV). All kinds of EVs enjoy the definite merit of energy diversification, as shown in Fig. 2. It can be found that the PHEV, the REV, and the BEV can be directly fed by electricity from the power grid. These EVs are called GEVs which can be directly plugged into the power grid to absorb energy as loads or to deliver energy as resources.

The three emerging concepts of EV technologies are defined as follows.

- V2H shows that the GEV can be connected to a home grid for charging and/or discharging by the onboard or offboard bidirectional charger. Hence, the GEV is able to draw the energy from home or transfer its energy to home according to the control scheme.
- V2V shows that GEVs can transfer their energy by bidirectional chargers through a local grid, and then distribute the energy among GEVs by a controller (generally called the aggregator). The aggregator is responsible for collecting GEVs to make interaction
among themselves, and also interacting with the grid for the energy request over V2V.

- V2G shows that GEVs can be connected to the power grid to obtain energy, as well as feed energy back to the grid. Since each GEV's energy is quite limited, the aggregator turns to the group GEVs for charging and/or discharging as well as for grid regulation.

These emerging concepts make the energy usage of EVs more efficient and flexible. Over the developmental history of EVs, as depicted in Fig. 3, GEVs will be an important turning point and will play an active role in these V2H, V2V, and V2G technologies. The corresponding factors, features, and functions are summarized in Table 1. Thus, the proposed classification of V2H, V2V, and V2G, and, hence, the three-level framework, is the preferred framework for the smart grid, which possesses the merits of simplicity, effectiveness, controllability, practicality, and harmoniousness.

III. FRAMEWORKS

A. Framework for V2H

When the GEV needs charging and/or discharging, the convenient way for the user is to drive the vehicle home. In this way, the V2H is formed. Fig. 4 shows the proposed V2H framework, which consists of a GEV, a bidirectional charger, home loads, small-scale renewable generation [especially one wind turbine and some photovoltaic (PV) panels], a home-grid [including dc link and alternating current (ac) link], and the corresponding home controller. In Fig. 4, the solid lines represent the power flow while the dotted lines are the information flow; meanwhile, the red dotted line, the pink dotted line, and the blue dotted line correspond to the transmission line information, V2G line information, and V2V line information, respectively. The GEV can offer its battery for active power exchange with the home grid. Also, the onboard or offboard bidirectional charger can offer the bidirectional active power conversion, and provide the reactive power to the grid using its dc link capacitor.

The V2H framework achieves the following distinct features for the home grid operation.

- Generally, V2H involves a single GEV in a single house.
- V2H has a very simple configuration, hence it is easy to accomplish in reality.
- V2H is able to smooth the household daily load profile (DLP) with active power exchange.
- V2H is able to provide the reactive power to the home grid or even to the community grid.
- The reactive power support can be implemented without involving, or independent of, the GEV battery, because each charger can solely offer its capacitor for the grid operation.
- V2H can further interact with V2V and V2G operations.
- V2H has a very high efficiency during the operation.
- V2H is easy to be installed without largely changing the existing home grid.
- V2H can improve the effectiveness of home renewable energies by using GEV storage.
- Smart home becomes more attractive with the V2H operation.
- V2H can greatly improve the development of the smart grid.

B. Framework for V2V

When a number of GEVs are allotted to a community, this community will become a suitable power grid for the V2V operation [21]. By using the V2V operation, the power reserve can be kept within the community of GEVs, which can greatly reduce the power loss and the trading loss between the local community and the power grid. Also, the V2V framework can readily be performed in the existing grid. Fig. 5 shows the proposed V2V framework, which consists of
a number of V2H systems, a parking lot for GEVs, an aggregator, community loads, and other auxiliary equipment. In the proposed V2V framework, a portion of GEVs are connected to the grid by home grid interfaces. Meanwhile, another portion of GEVs are located at the parking lot and connected to the lower layer ac grid via the parking lot dc link. All these GEVs can interact with each other by the aggregator. Specifically, the aggregator is a control device which is able to collect all information about GEVs and the grid status, and execute the V2V operation. Namely, the aggregator is responsible for coordinated control of grouping GEVs for charging and/or discharging. Thus, the community GEVs can first distribute the energy among themselves and then interact with the grid for the overall energy request. In short, after GEVs serve the V2H operation and satisfy the basic requirement of GEV users, they are grouped by the aggregator for the V2V operation.

The V2V framework offers the following distinct features for the community grid operation.

- Generally, V2V involves multiple GEVs.
- V2V uses smart homes and parking lots for power exchange.
- V2H is incorporated into the V2V system. V2H mainly focuses on a domestic house with only one GEV interaction, whereas V2V aims to interact with a group of GEVs and coordinate them with the

<table>
<thead>
<tr>
<th>Factors</th>
<th>V2H</th>
<th>V2V</th>
<th>V2G</th>
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<tbody>
<tr>
<td>Daily load profile of domestic electrical devices</td>
<td>Charging and discharging requirements from aggregator</td>
<td>Power flow of the power grid</td>
<td></td>
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<tr>
<td>Battery type (lead-acid, nickel-metal hydride or lithium-ion)</td>
<td>Number of available GEVs</td>
<td>Control and regulation requirements from grid operator</td>
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<tr>
<td>Battery capacity characteristics (rated capacity, available capacity, voltage, charging and discharging currents)</td>
<td>Battery type</td>
<td>Number of aggregators</td>
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<tr>
<td>State of charge</td>
<td>Battery capacity characteristics (rated capacity, available capacity, voltage, charging and discharging currents)</td>
<td>Number of available GEVs</td>
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<td>User driving habits</td>
<td>State of charge</td>
<td>Battery type</td>
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<tr>
<td>Arrival and departure time</td>
<td>User driving habits</td>
<td>Battery capacity characteristics (rated capacity, available capacity, voltage, charging and discharging currents)</td>
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<tr>
<td>Electricity price</td>
<td>Arrival and departure time</td>
<td>State of charge</td>
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<tr>
<td>Reactive power support with the bidirectional charger capacitor</td>
<td>Electricity prices</td>
<td>User driving habits</td>
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<th>Features</th>
<th>V2H</th>
<th>V2V</th>
<th>V2G</th>
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<tr>
<td>A single GEV to a single home</td>
<td>Multiple GEVs</td>
<td>Large number of GEVs</td>
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<tr>
<td>Most simple, least flexible</td>
<td>Power exchange within the local grid (lower layer)</td>
<td>Offering power services through the power grid (higher layer)</td>
<td></td>
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<tr>
<td>Simple infrastructure requirements and negligible transmission losses</td>
<td>less simple, less flexible</td>
<td>Least simple, most flexible</td>
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<tr>
<td>Easy installation</td>
<td>Uncomplicated infrastructure requirements and small transmission losses</td>
<td>Complex control</td>
<td></td>
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<tr>
<td>Operation in home-grid</td>
<td>Operation in community-grid</td>
<td>High infrastructure complexity and significant transmission losses</td>
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<th>Functions</th>
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<th>V2V</th>
<th>V2G</th>
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<tr>
<td>Act as a home backup generator and a controllable load</td>
<td>Act as energy sources to other local GEVs</td>
<td>Act as energy sources to provide grid ancillary services</td>
<td></td>
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<tr>
<td>Cooperate with domestic electrical devices for load shift</td>
<td>Reduce tariff by trading power within the local grid</td>
<td>Act as controllable loads</td>
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<td>Sell excess energy back to the grid at high priced peak time</td>
<td>Increase the charging and discharging efficiency of GEVs</td>
<td>Release excess energy back to the grid at high priced peak time</td>
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<tr>
<td>Charge energy at less expensive off-peak time</td>
<td>Establish an isolated V2V system</td>
<td>Act as distributed storages storing less-expensive off-peak energy</td>
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<tr>
<td>Contribute to home-grid or a micro-grid</td>
<td>Coordinate control of GEVs</td>
<td>Provide power for the premise</td>
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<td></td>
<td>Reactive power support</td>
<td>Coordinate with renewable energies</td>
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<td></td>
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<td>Reactive power support</td>
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<tr>
<td></td>
<td></td>
<td>Stabilize the grid for short periods</td>
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power grid. This kind of dividing the frameworks of V2H and V2V can improve the GEV coordination with the power grid based on the number of GEVs available.

- The GEV aggregator is employed for coordinated control of the V2V and grid operation.
- Power exchanges among GEVs, and then is requested if necessary from the power grid.
- The framework of V2V is comparatively less simple and less flexible.
- V2V has uncomplicated infrastructure requirements and small transmission losses.
- V2V can be further cooperated with small-scale renewable energies for the community grid operation.
- V2V can further improve the development of the smart grid.

C. Framework for V2G

Due to the small capacity of the battery storage in an individual GEV, a single GEV has nearly no impact on the power grid. Thus, the framework for V2G aims at a group of GEVs and their power distribution between the grid and GEVs [22]. Fig. 6 shows the proposed V2G framework which consists of a number of V2H systems, some parking lots or smart buildings, renewable energies, loads, GEVs and their aggregators, and other general grid elements. The smart building can achieve energy savings through various energy-efficient technologies, and is able to transmit the renewable energy harnessed from the building to the low-voltage (LV) network or other local devices. The GEV aggregators play a key role of allocating the power flow and the information flow between the grouped GEVs and the grid.

According to the grid voltage level, the GEVs can be classified as three kinds of clusters for energy distribution. The first kind of cluster is that GEVs are located at the LV network which facilitates V2H and V2V operations. In a practical situation, these GEVs are allotted to residential areas, parking lots, and smart buildings. The second kind of cluster is that GEVs are located at the medium-voltage (MV) network for the V2G operation. In a practical situation, these GEVs are allotted to GEV charging stations, particularly for fast charging and discharging. The third kind of cluster is that GEVs are also located at the MV network, but not advised for the use in the V2G operation. In a practical situation, these GEVs stop at the swapping stations for swapping their batteries so that all discharged batteries are collectively recharged or regenerated in the MV network. Moreover, in the first and second clusters, the GEV chargers also can offer the reactive power support via their internal capacitors.

The V2G framework has the following distinct features for the power grid operation.

- V2G involves a large number of GEVs.
- V2G can utilize smart homes, parking lots, and fast charging stations for power exchange.
- GEV aggregators are highly preferred for power allocation.
- GEVs take a very active role in the V2G operation for active power distribution.
- GEV chargers can provide reactive power to the grid using their internal capacitors.
- The active power support can be independent from the GEV battery.
- Optimization strategies for V2G system are highly feasible and flexible.
V2G can engage in V2H and V2V operations, or not.
V2G has the least simple but most flexible framework.
V2G is complicated to be controlled.
V2G is generally operated in large scale.
V2G can greatly improve the development of the smart grid.

IV. MODELING
Since the GEV is considered first for connecting with a home as V2H, and then considered for V2V and V2G, the domestic electrical devices have an important impact on the whole system. Hence, the domestic electrical devices, GEVs, and then the V2H, V2V, and V2G are modeled successively.


A. Modeling of Domestic Electrical Devices

Table 2 shows the typical case of domestic electrical devices which are classified as three main types of devices based on their features and behaviors, namely, the even-smooth type, the stochastic-behavior type, and the fixed-program type. These three types of electrical devices can be modeled as daily load profiles (DLPs) to express their functions to the grid [13]. Since different households have different electrical devices and operating features, their DLPs are different. Nevertheless, by measuring the electric power of households, the statistics and data of electrical devices can be obtained. Fig. 7 shows the typical DLPs of a household with three types of loads. It can be seen that the fixed-program type and the stochastic-behavior type dominate the power consumption.

Since the statistics of households are based on the measuring data, we need a huge data collection to build an accurate DLP model. Thus, based on the existing data, a household DLP generator is proposed in [14]. Fig. 8 shows the flowchart according to the usage probability of domestic electrical devices. The allocation and usage frequency of domestic electrical devices change with the size of housing. The profile of $x$ units of housing can be generated by combining the profile of each housing unit. The housing unit is a house, an apartment, or a room that is occupied as separate living quarters. Also, a random $\tan \varphi$ between 0 and 0.5 is selected to represent the reactive power injected by the housing.

It is worthy to mention that each GEV is able to offer $3 \sim 4$ kW power for the household. So, a GEV’s battery power is enough for a household’s usage of several hours. This is also true for V2H, V2V, and V2G with the use of GEV battery power.

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Fig. 7. Household DLP curves.

Fig. 8. Household DLP generator.
B. Modeling of GEVs

When GEVs connect to the grid via household or other interfaces, they have an obvious impact on the household or a grid. Building an accurate GEV model can effectively improve the control strategy for the household or the grid operation. The following equations describe the power flow of GEVs when they connect to the home grid, and then link with the power grid via aggregators:

\[ V2H: \quad P_{H,n}^G + \sum_{n=1}^{k} P_{n,t,n}^G \leq P_{t,max}^H, \quad t = 1 \sim T \]  

\[ V2V: \quad \sum_{n=1}^{k} P_{n,t,n}^G = 0, \quad t = 1 \sim T \]  

\[ V2G: \quad P_{t}^G + \sum_{n=1}^{k} P_{n,t,n}^G = P_{t}^S, \quad t = 1 \sim T. \]  

The basic constraints for the above GEV models can be summarized as

\[ |P_{t,n}^G| \leq P_{n,max}^G, \quad t = T_n^c \sim T_n^d, \quad n = 1 \sim N + K \]  

\[ SOC_{n,min} \leq SOC_{t,n} \leq SOC_{n,max}, \quad t = T_n^c \sim T_n^d, \quad n = 1 \sim N + K \]  

\[ \eta_{n,H} = \begin{cases} 1, & P_{t,n}^G \geq 0 \\ -1, & P_{t,n}^G < 0 \end{cases} \]  

\[ t = T_n^c - T_n^d, n = 1 \sim N + K \]  

\[ \frac{W_n^c + P_{t,n}^G \eta_{n,H} AT}{C_n}, \quad t = T_n^c, \quad n = 1 \sim N + K \]  

where \( \Delta T \) is the length of the time period, \( T \) is the number of the time period, \( N \) is the number of GEVs at home, \( K \) is the number of GEVs in the aggregation, \( T_n^c \) is the number of the time period when the \( n \)th GEV is connected to the home grid, \( T_n^d \) is the number of the time period when the \( n \)th GEV is disconnected from the home grid, \( P_{t,n}^G \) is the power of the GEV charger, \( P_{t,n}^H \) is the output power of the \( n \)th GEV at the \( t \)th time period, \( P_{t,n}^S \) is the power of the power system at the \( t \)th time period, \( \mu_{t,n} \) is the sign of the charging–discharging operation, \( P_{t,n}^{H, max} \) is the maximum power of the \( n \)th GEV, \( P_{t,n}^{H, min} \) is the minimum power of the \( n \)th GEV, \( SOC_{n,min} \) is the initial capacity when the \( n \)th GEV is connected to the home grid, \( SOC_{n,max} \) is the maximum capacity when the \( n \)th GEV is disconnected from the home grid, \( SOC_{n,min} \) is the minimum value of the SOC of the \( n \)th GEV, \( SOC_{n,max} \) is the maximum value of the SOC of the \( n \)th GEV, and \( C_n \) is the rated capacity of the \( n \)th GEV.

C. Modeling of V2H, V2V, and V2G Systems

The modeling of V2H, V2V, and V2G systems should be based on the objectives and their constraints. The general objectives for V2H, V2V, and V2G are the load variance minimization, cost minimization, cost-efficiency optimization, cost-emission minimization, power loss minimization, load shift and peak load reduction, reactive power compensation, and so on. Based on the aggregated sizes of GEV battery and capacitor, V2H, V2V, and V2G have their individual objectives and constraints. A general modeling diagram for the V2H, V2V, and V2G systems is proposed as depicted in Fig. 9. Based on this modeling diagram, the objective functions and constraints can be grouped and bounded to perform the desired optimization target.

V. POWER ELECTRONICS

In the V2H, V2V, and V2G systems, the power electronics are their fundamental hardware components for performing electric energy conversion. Typically, the power converters or bidirectional chargers play the role of power exchange between the GEVs and the home grid or the community grid. According to the power level and function of power electronics, three types of converter networks are proposed for the V2H, V2V, and V2G systems.

Fig. 10 shows the proposed converter network for the V2H system. This system consists of the ac link, the dc link, the bidirectional converter for GEV, unidirectional converters for renewable energies, the bidirectional converter for the ac link and the dc link, the control circuit, and other relevant power electronics. It is worthy mentioning that the GEV charger can be designed as the dc/dc type or the dc/ac type. With the proposed converter network, the ac link and the dc link can readily take actions for the sources and loads. Thus, this converter network can not only provide the platform for active power exchange between the GEV and the home, but also offer the interfaces for power delivery in household and power grids. Moreover, the proposed network can offer the reactive power support for the grid using the capacitor of the GEV converter.
Fig. 9. Proposed general modeling diagram for V2H, V2V, and V2G systems.

Fig. 11 shows the proposed converter network for the V2V system. The proposed network includes the V2H converter interfaces, an aggregator, and other auxiliary components. The key of this network is to add an aggregator for household GEV power aggregation. Also, the converters take into account the V2V effect. Hence, this converter network can be used for the community grid, in which the community GEVs can first distribute the energy among themselves and then interact with the grid for the overall energy request. In addition, the V2V converter network fully utilizes the V2H hardware, and the reactive power support becomes attractive in this network.

Fig. 12 shows the proposed converter network for the V2G system. This network integrates different converters
and interfaces for the high-voltage (HV), MV, and LV networks. The LV converter network is for the V2H and V2G operations, whereas the MV converter network is for the V2G operation (usually for fast-charging station). The HV converter network is not used directly for the V2H, V2V, and V2G operations. The converters for renewable energies are unidirectional, which have the intermittent nature. The converters for GEVs are supposed to be bidirectional, which are able to exchange power as expected. In addition, the reactive power support from the GEV chargers can be involved in the grid operation [23]–[25].

![Fig. 11. V2V converter network for the community.](image1)

![Fig. 12. V2G converter network for the power grid.](image2)
Table 3 shows the Society for Automotive Engineers (SAE) standards for charging GEVs [26]. Nevertheless, it is highly suggested that the household should adopt the power level over 3 kW for the GEV converter design because it can offer more room for reactive power support and shorter time for battery charging. In addition, Table 4 summarizes the power level, characteristics, functions, and applications for the design of GEV power electronics.

VI. BATTERY TECHNOLOGY

Battery is the key component of the GEV, which has a significant impact on the V2H, V2V, and V2G systems. First, the battery offers the energy for the GEV. Also, the battery plays the role of energy exchange between the GEV and the power grid. Furthermore, the battery energy can be further exchanged among GEVs.

<table>
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<tr>
<th>Charging way</th>
<th>Nominal voltage</th>
<th>Maximum current</th>
<th>Continuous Power</th>
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<tbody>
<tr>
<td>AC level 1 with 1-phase</td>
<td>120V</td>
<td>12A or 20A</td>
<td>1.44kW or 1.92kW</td>
</tr>
<tr>
<td>AC level 2 with 1-phase</td>
<td>240V</td>
<td>40A or 80A</td>
<td>7.7kW or 19.2kW</td>
</tr>
<tr>
<td>AC level 3 with 3-phase</td>
<td>208V, 480V &amp; 600V</td>
<td>400A</td>
<td>Up to 100kW</td>
</tr>
<tr>
<td>DC level 1</td>
<td>200–450V</td>
<td>80A</td>
<td>&lt;36kW</td>
</tr>
<tr>
<td>DC level 2</td>
<td>200–450V</td>
<td>200A</td>
<td>&lt;90kW</td>
</tr>
<tr>
<td>DC level 3</td>
<td>200–600V</td>
<td>400A</td>
<td>&lt;240kW</td>
</tr>
</tbody>
</table>

Table 4 Comparison of Power Electronics for GEVs
Table 5 lists three main types of batteries, namely, the lead–acid (Pb–acid), the nickel–metal hydride (Ni–MH), and the lithium-ion (Li–ion), for GEVs [27], [28]. The Pb–acid type has the lowest energy density and lowest cycle life. Furthermore, it has the memory effect for charging, which needs to fully charge each time. Thus, the Pb–acid type is not preferred for modern GEVs. On the contrary, the Ni–MH and Li–ion batteries have much better performances, hence favoring modern GEVs.

Fig. 13 shows the cost effectiveness of these three batteries. It can be found that Li–ion has the highest capital cost per unit power and unit energy, leading to the high initial cost of those high-performance GEVs. Thus, Ni–MH can still play a role for those economical GEVs. Nevertheless, both Ni–MH and Li–ion need to have a significant reduction of cost in order to improve their cost effectiveness for the V2H, V2V, and V2G operations.

Based on the specific energy, specific power, life cycle, and cost effectiveness of these three main batteries [29], it can be identified that all of them are suitable for BEVs, Ni–MH is preferred for the light-duty economical PHEV and REV, and Li–ion is favorable for the heavy-duty high-performance PHEV and REV.

Since there are many cells stacked in series to achieve the required voltage for the GEV, the battery reliability depends on the reliabilities of several hundred cells. Table 6 compares the cell and battery reliabilities of a typical GEV, adopting various batteries to achieve the voltage level of about 312 V [30]. It can be seen that the cell reliabilities of these batteries are all over 97%; however, when the cells are connected in series, only Li–ion can offer the battery reliability over 90%.

VII. OPTIMAL SIZING OF GEV AGGREGATION

In the V2H system, GEVs are connected to the home grid. Then, they can be further connected to the power grid in V2V and V2G systems. Since an individual GEV’s energy capacity is limited, it is not suitable to control a single GEV in the grid system. However, when they are grouped, their energy content becomes sizable enough for the grid operation. In this case, all GEVs are grouped by the GEV aggregators. Hence, the grouped GEVs can be considered as distributed energy resources or flexible loads for discharging or charging.

In the following derivation, \( n \) is the number of buses, \( P_i \) is the real power flow from bus \( i \) to bus \( i+1 \), \( Q_i \) is the reactive power flow from bus \( i \) to bus \( i+1 \), \( P_{Li+1} \) is the real power of load at bus \( i+1 \), \( Q_{Li+1} \) is the reactive power of load at bus \( i+1 \), \( V_i \) is the system voltage at bus \( i \), \( r_{i+1} \) is the resistance of line connecting bus \( i \) and \( i+1 \), \( x_{i+1} \) is the reactance of line connecting bus \( i \) and \( i+1 \), \( P_{Loss,i+1} \) is the power loss between bus \( i \) and \( i+1 \), \( P_{Agg,i+1} \) is the active power magnitude injected by GEV aggregation at bus \( i+1 \), \( Q_{Agg,i+1} \) is the reactive power magnitude injected by GEV aggregation at bus \( i+1 \), \( S_{Agg,i+1} \) is the size of GEV aggregation at bus \( i+1 \), \( w_p \) is the real power multiplier set to 0 when there is no active power source or set to 1 when there is an active power source, \( w_q \) is the reactive power multiplier set to 0 when there is no reactive power source or set to 1 when there is a reactive power source, \( V_{max} \) is the maximum permissible bus voltage, \( V_{min} \) is the minimum permissible bus voltage, \( m \) is the total number of GEVs, \( SOC_x \) is the state of charge of vehicle \( x \), \( SOC_{max} \) is the maximum value of SOC, \( SOC_{min} \) is the minimum value of SOC, \( SOC_{x,max} \) is the upper limit of SOC set by the user of vehicle \( x \), \( SOC_{x,min} \) is the lower limit of SOC set by the user of vehicle \( x \), \( \mu_x \) is the user factor of vehicle \( x \), \( f_{sq} \) is the charging–discharging factor, \( \varphi_x \) is the converter efficiency of vehicle \( x \), \( C_{d,x} \) is the available charging capacity of vehicle \( x \), \( C_{d,x} \) is the available discharging capacity of vehicle \( x \), \( C_x \) is the rated capacity of vehicle \( x \), \( TC_x \) is the total charging capacity, \( TC_{d,x} \) is the total discharging capacity, and \( C_{out} \) is the available system output capacity.
The objective function of the optimal power loss from a bus to a bus can be obtained by summing the power loss of each bus. Hence, the total power loss in this grid system, hence minimizing the total power loss. The unit circuit between two buses is defined in Fig. 15, in which the power loss can readily be calculated [31].

The proposed GEV aggregator is able to integrate into any bus of the grid system. Hence, the total power loss from a bus to a bus can be obtained by summing the power loss of each bus. The objective function of the optimal sizing and location of the aggregator can be expressed as

$$\text{Fitness} = \min \sum_{i=0}^{n} \left( \frac{P_i^2 + Q_i^2}{V_i^2} \right) \times r_{i+1}. \quad (10)$$

This fitness function indicates that global fitness value can be obtained only if the total power loss of the system is minimized.

A practical system can be regarded as a combination of a number of unit circuits. Also, the power loss on the line results in a voltage drop between the neighbor buses. In this situation, the GEV battery power and the converter capacitor can be utilized to regulate the bus voltages via providing the active and reactive power. Moreover, the GEV aggregator can play the role of coordinated control to support the power grid operation.

The constraints and practical concerns in terms of the GEV aggregation are summarized as follows:

$$P_{\text{Loss},i,i+1} = P_i - P_{i+1} = \left( \frac{P_i^2 + Q_i^2}{V_i^2} \right) r_{i+1} \quad (11)$$

$$P_i - \frac{r_{i+1}(P_i^2 + Q_i^2)}{V_i^2} - P_{L,i+1}$$

$$+ \omega_p P_{\text{agg},i+1} - P_{i+1} = 0 \quad (12)$$

$$Q_i - \frac{x_{i+1}(P_i^2 + Q_i^2)}{V_i^2} - Q_{L,i+1}$$

$$+ \omega_q Q_{\text{agg},i+1} - Q_{i+1} = 0 \quad (13)$$

$$V_{i+1}^2 = V_i^2 - 2(r_{i+1} P_i + x_{i+1} Q_i)$$

$$+ \left( r_{i+1}^2 + x_{i+1}^2 \right) \left( \frac{P_i^2 + Q_i^2}{V_i^2} \right) \quad (14)$$

$$|V_{\min}| \leq |V_i| \leq |V_{\max}| \quad (15)$$

$$\text{SOC}_{x,\max} \leq \text{SOC}_{x}\leq \text{SOC}_{x,\min} \quad (16)$$

$$0 \leq C_{x} \leq \left( \text{SOC}_{x,\max} - \text{SOC}_{x,\min} \right) \quad (17)$$

$$C_{\text{out}} = TC_{d} + TC_{c} \quad (18)$$

$$f_{\text{cd}} = \frac{C_{\text{out}}}{|TC_{d}| + |TC_{c}|} = \frac{TC_{d} + TC_{c}}{|TC_{d}| + |TC_{c}|} \quad (19)$$

where (11) calculates the power loss between bus $i$ and bus $i+1$, (12)–(14) represent the power flow at bus $i$, and (15) and (16) express the limitations of the bus voltage, the SOC, and the available charging and discharging capacities.

The signal of the GEV aggregation for charging and discharging is listed as follows:

$$f_{\text{cd}} > 0, \text{discharging} \quad \{ f_{\text{cd}} = 0, \text{isolated} \} \quad f_{\text{cd}} < 0, \text{charging}$$
where (17) defines the total output capacity of the V2G system, (18) defines factor $f_{cd}$ to express the charging or discharging attribute of the system, and (19) expresses the characteristics of the system when $f_{cd}$ is equal to different values.

The genetic algorithm (GA) is applied to solve this optimal sizing problem. Fig. 16 shows the flowchart of the optimal sizing of GEV aggregator using the GA. First, the value of $f_{cd}$ is initialized. When $f_{cd} > 0$, the GEV aggregation is considered as a discharging entity to the power system, and the active and reactive power it provides will be positive in the power flow calculation. When $f_{cd} < 0$, the GEV aggregation is considered as a charging entity to the system, and its active and reactive power will be negative in the power flow calculation. If $f_{cd} = 0$, the GEV aggregation will be an isolated system outside the power system. Next, the GA is started to find the optimal size and location of the GEV aggregation in the given power system. The initial population of individual solutions is randomly generated, which contains the entire range of possible solutions. These individual solutions are checked and repaired with the constraints before reproduction. Then, the fitness value of each individual is evaluated in the population. The best fit individuals are selected to be parent generations to reproduce new generations by crossover, mutation, and elitism. The new generations will be evaluated by the fitness function as well. This process will iterate until the set number of generations is reached. The least fit populations will be replaced constantly by newly generated populations with iteration. Once the end criteria are satisfied, the best solution is found.

**VIII. OPTIMIZATION OF POWER QUALITY**

**A. Impact of Charging GEVs**

When there is a large number of GEVs connected to the grid (probably the smart grid in the future), they definitely bring the power quality issue to the grid system. Also, the future grid probably integrates with renewable energy sources as distributed generators (such as wind power plants and solar power plants), and energy storages for power reserve such as batteries and power fast response such as the superconducting magnetic energy storage (SMES) [32]–[34].

In order to illustrate the impact of GEVs on the power system, a typical power system integrated with GEVs, SMES, and wind turbines is established for exemplification. Fig. 17
shows the proposed 33-bus four-lateral distribution system which can illustrate the power quality and performance in the V2G system [16], [22]. This system includes two SMES units, two wind generation units, and six PHEV units. The six PHEV units can be regarded as GEV aggregators in the system. The V2G impact due to the charging issue of GEVs is analyzed. The basic parameters of GEVs are summarized in Table 7.

Based on the aforementioned system and the GEV parameters, the charging scenario and the specific impact of GEV charging are discussed. First, the charging scenario is defined as home charging with the V2H system. It is expected that the GEV owners return home and their GEVs should be fully charged by the next morning. Fig. 18 shows two charging styles, namely, the uncontrolled charging and the simple off-peak charging. It can be found that even a simple controlled charging strategy can greatly improve the grid performance. In addition, the investigation of the power quality in terms of line loading and voltage deviation is performed, as shown in Figs. 19 and 20.

### B. Mathematical Model

In order to improve the power quality of the V2G system, a specific mathematical model is proposed. This model consists of the objective function and the corresponding constraints. The power loss optimization is given by [22]

\[
\min P_{\text{loss}} = \min \sum_{i=1}^{N_r} \sum_{l=1}^{l_{\text{max}}} R_l I_i^2 \quad (20)
\]

The constraints include the power balance, generation limits, transmission line limits, the charging rate limit, the battery capacity limit, total charging energy, and the initial state of charge. They are governed by

\[
\sum_{i=1}^{N_r} P_{Gi}(t) = P_{\text{load}}(t) + \sum_{i=1}^{N_r} P_{Vi}(t) + P_{\text{loss}}(t) \quad (21)
\]
\[
P_{\text{min}}^{i \text{min}} \leq P_{Gi}(t) \leq P_{\text{max}}^{i \text{max}} \quad (22)
\]
\[
|I_i| \leq I_{i \text{max}}^{\text{max}} \quad (23)
\]
\[
P_{\text{EV, min}} \leq P_{\text{EV, i}}(t) \leq P_{\text{EV, max}} \quad (24)
\]
\[
0 \leq E_{\text{EV, int}} + \int P_{\text{EV, i}}(t) dt \leq E_{\text{EV, max}} \quad (25)
\]
\[
\int P_{\text{EV, i}}(t) dt = E_{\text{EV, max}} - E_{\text{EV, int}} \quad (26)
\]
\[
E_{\text{Vi, int}} = \sum_{k=1}^{n_{\text{Vi}}} \text{SOC}_{Vi,k} E_{Vi,k} = n_{Vi} E_{Vi,\text{avg}} \quad (27)
\]

where \(t_{\text{max}}\) is the whole planning period, \(l_{\text{max}}\) is the number of the transmission lines in the 33-bus power network, \(R_l\) is the resistance of the \(l\)th transmission line, \(I_i\) is the line current, \(N_r\) is the number of PHEVs connected to the grid at time \(t\), \(sN_r\) is the total number of the generation units, \(P_{Gi}(t)\) is the small-size distributed generation at the time step \(t\), \(P_{Vi}(t)\) is the charging rate of PHEV aggregation at time step \(t\), \(P_{\text{loss}}(t)\) is the power losses at the time step \(t\), \(P_{\text{min}}^{i \text{min}}\) and \(P_{\text{max}}^{i \text{max}}\) are the lower and upper bounds of the output power of the generation unit \(i\), \(E_{\text{Vi, int}}\) is the initial battery energy of PHEV aggregation, \(n_{Vi}\)...

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average battery capacity</td>
<td>9.4 kWh</td>
</tr>
<tr>
<td>Maximum charging rate</td>
<td>3 kW</td>
</tr>
<tr>
<td>All-electric range</td>
<td>60 km</td>
</tr>
<tr>
<td>Average energy use per driving cycle</td>
<td>59 Wh/km or 23 km/l</td>
</tr>
<tr>
<td>Expected number of PHEVs</td>
<td>1000</td>
</tr>
</tbody>
</table>

Table 7 GEV Parameters

![Fig. 18. Charging load performances.](image1)

![Fig. 19. Charging line loss.](image2)

![Fig. 20. Charging voltage drop.](image3)
is the number of PHEVs aggregated at each node, $\text{SOC}_{Vi,k}$ is the initial SOC of each PHEV battery pack, $E_{Vi,k}$ is the battery storage capacity of each PHEV, $E_{Vi,\text{avg}}$ is the mean value of the PHEV initial SOC, $T$ is the time interval, $E_{Vi,\text{max}}$ is the maximal amount of energy to recharge the vehicles at the end of the charging period, $P_{\text{min}}^{Vi}$ is the minimal recharging rate, $P_{\text{max}}^{Vi}$ is the continuous power rating of an electricity outlet, and $t_k$ is the time step within the charging period.

C. Case Study for Power Quality Improvement

The load shift is an obvious V2G function for the grid operation. In this case, the V2G power is the additional portion of load demand and added to the base load in the distribution grid. Fig. 21 shows the daily load profiles in summer and winter with and without optimization. It can be seen that with V2G control strategy the peak load can be cut down and the valley can be filled. In addition, the GEV charging can be conducted at the night when the wind power plants generate the excessive power.

Moreover, the V2G operation can function to improve the grid power quality of line losses and voltage deviation, which are shown in Fig. 22. It can be found that the total power losses are reduced and also the violence of the load limit at each transmission line is avoided. It can be seen that with the optimal control, the voltage drop can be relieved particularly in the heavy-loaded buses.

IX. INFORMATION AND COMMUNICATION

A. Characteristics of Information and Communication

Apart from physical connections with the power grid, the GEV has other interaction with the grid for V2H, V2V, and V2G operations, namely, the information and communication.

The V2G operation requires a reliable and secure two-way communication network which enables the message exchanges between GEVs and the power grid. In order to implement the V2G control method, the grid operator has to collect the data from GEVs to employ the V2G power for providing ancillary services while the GEVs has to submit and receive the signals from the grid operation, control, and monitoring centers to actively participate in the V2G control strategy.

The functionality of the communication network needed for V2G, V2V, and V2H depends mainly on the ancillary services provided and the general optimal control strategy to be implemented. After the requirements for implementing the ancillary services are figured out, the communication architecture and technologies are then selected to fit in with the needs. For instance, in the home charging scenario, GEVs are connected to the charging infrastructure for the whole night, which is much longer than the required period for fully charging. So, the energy stored in GEVs can be employed to provide peak load shaving, frequency control, and spinning reserve. Also, the feasibility of the selected communication network is evaluated based on the needs of the V2G, V2V, and V2H applications.

Various V2G communication networks were suggested [8], [35], [36]. The diversity and flexibility of V2G communication networks pose a bigger challenge to the architecture building. A direct V2G control system is the...
simplest architecture, where the GEVs are directly supervised by the grid operator. But the large number of GEVs penetrated in the grid tremendously increases the computation load of the grid operator and, therefore, makes this option unlikely to be adopted for wide application of V2G. Most of the recent V2G communication networks adopt indirect V2G architectures, where the third entity, namely, the aggregator, is involved in reducing the workload of the grid operator. An aggregator is used to supervise a number of GEVs and communicate with the grid operator. Thus, to build a practical V2G communication network, the characteristics of the multilayer multiagent V2G system should be taken into account.

A key function of the communication network is to facilitate GEV participation in offering various ancillary services. The typical services that the V2G operation (also applicable for V2V and V2H) can offer are summarized as follows:

- load shifting—peak shaving and valley filling;
- renewable energy integration;

<table>
<thead>
<tr>
<th>Table 8 Development of Information and Communication for V2G</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Evolution of GEV integration</strong></td>
</tr>
<tr>
<td>Preparation</td>
</tr>
<tr>
<td>Milestone 1</td>
</tr>
<tr>
<td>Milestone 2</td>
</tr>
<tr>
<td>Milestone 3</td>
</tr>
</tbody>
</table>

![Fig. 23. ICN architecture.](image)
• reserve power supply;
• regulations—frequency and voltage;
• reactive power support.

According to the above V2G ancillary services, the development of information and communication for V2G is summarized in Table 8. The development is supposed to have a preparation period and three milestones. After that, it is expected that the GEV is able to interact with the power grid without any impediment.

B. Technology of Information and Communication

Since the physical frameworks of V2H, V2V, and V2G correspond to the small, middle, and large areas, their information and communication networks (ICNs) are defined to cover different-region regions. Fig. 23 shows the ICN architecture which integrates the home area network (HAN), the local area network (LAN), and the wide area network (WAN) for V2H, V2V, and V2G communications.

X. CONCLUSION

The GEVs are one of the best ways to improve the environmental quality from fossil-fuel pollution. They also bring great challenges and opportunities to the power grid, which leads to the birth of V2H, V2V, and V2G. This paper has thoroughly discussed the following important issues: new concepts relevant to GEVs; frameworks for V2H, V2V, and V2G operations; modeling of domestic electrical devices; GEVs; as well as the V2H, V2V, and V2G systems, and relevant power electronics and battery technologies for GEVs. Furthermore, a case study on the optimization of V2G operation has also been carried out. Finally, the information and communication for V2H, V2V, and V2G have been presented.

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