

Development of Vehicle System Supporting Vehicle-Grid Integration

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ABSTRACT

With the aim of achieving a balance between contribution to society and benefit to users, Honda has fabricated a plug-in electric vehicle that can help to stabilize electric power supply and demand by performing charge-discharge in collaboration with the power grid and obtaining a user benefit as compensation for that collaboration. The Accord Plug-In for the U.S. market was used as the base vehicle. It was equipped with an on-board bi-directional AC-DC converter unit that is capable of interconnection with the power grid and a digital communication unit that is capable of bi-directional communication between charge-discharge facilities and the vehicle. It was also equipped with a control application that has new power supply control functionality added to a base of charge control. This vehicle was used to participate in the frequency regulation market by means of the eV2G Project, a demonstration of Vehicle-Grid Integration technology conducted in the state of Delaware in the United States. The developed technology was demonstrated and the value to users was quantified. The results of the demonstration indicated that users able to participate in Vehicle-Grid Integration at home and at work for 18 hours per day can expect to receive an income of 3,000 dollars or more over a three-year period.

1. Background

The COP 3 conference held in 2007 with the participation of 187 or more countries adopted the Framework Convention on Climate Change (the Global Warming Convention) with the aim of reducing CO₂ as a way of addressing the increasing advance of global warming. This conference set targets and timetables for reduction of greenhouse gas (GHG) emissions, and each country is taking measures to reduce its GHG emissions.

The zero emissions vehicle (ZEV) regulations administered by the California Air Resources Board (CARB) in the state of California in the United States appear likely to bring increasing sales of plug-in electric vehicles (PEV) in that state. The California Public Utilities Commission (CPUC) estimates that 3.5 million PEV will be in use in 2022, and the installed battery capacity will rise to 30 GW⁽¹⁾.

Statistically speaking, private-use automobiles are considered to spend 96% of their lifetime parked. While the vehicle is parked, it is thought that the PEV battery can be connected to the power grid as a distributed power resource so that the electric power system can use it as a power buffer, thereby contributing to stabilization of the power supply. However, only the experimental use of PEV

batteries has been described, and envisioned actual-use scenarios have not been verified with vehicles. In the present usage environment, the distributed power resources are large batteries dedicated to that purpose or emergency power generation facilities at corporations, hospitals, and so on.

The function that connects a PEV and the electric power system is referred to as Vehicle-Grid Integration (VGI). This is a function that makes use of the battery installed in the PEV as a distributed power resource. Not only will VGI be capable of contributing to the reduction of GHG emissions by expanding the use of renewable energy resources, but it may also be able to provide PEV users with a financial reward for that use. The CPUC has made proposals for measures to build the social infrastructure for putting VGI into practical use⁽¹⁾.

In putting VGI into practical use, however, there are issues that must first be resolved. These include the reduction in battery durability due to VGI use, assurance of the electrical reliability and safety of charging and discharging electric power, and the balance achieved between functionality as a vehicle and as a participant in VGI^{(2), (3)}. It is important that these issues not be left just to automobile manufacturers, but that they be addressed in cooperation with a large number of stakeholders. In moving

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toward realization of the VGI concept, it is necessary for the public and private sectors, as well as for industry and academia, to work together on measures for establishing a system that can realize VGI⁽⁴⁾.

This paper will describe the development and verification of a vehicle system that supports VGI. The focus is on the state of California in the US, where active measures are being taken to introduce renewable energy resources and realize the VGI concept.

2. Electric Power Markets in the United States

The state of California passed the Global Warming Solutions Act of 2006, and has set a target for reduction of GHG emissions in California by 80% of the 1990 level by the year 2050. Another measure toward that target is the Renewable Portfolio Standard (RPS) of the California Energy Commission (CEC), the state's energy policy and planning agency. The CEC calls for the proportion of electric power generated in the state by renewable resources to be raised to 33% by the year 2020.

However, weather significantly impacts the amount of power generated and the times when power can be generated by solar power and wind power generation, which are typical of renewable energy resources that do not emit GHG. This means that the balance between demand and supply cannot readily be stabilized, making these unsuitable as baseload power sources. Another factor is that imbalances in electric power demand and supply can lead to deterioration of electric power quality, such as fluctuations in the frequency, distortion of AC voltage waveforms, and so on. Further deterioration of power quality increases the risk of large-scale power outages.

The power grid in the state of California is managed by an organization called an independent system operator (ISO) in order to stabilize the supply-demand balance of electric power. The California ISO constantly monitors the balance of demand and supply on the power grid and also forecasts demand. Based on the electric power demand forecast, the ISO works to stabilize the balance of electric power supply and demand by issuing power generation commands to electricity producers, establishing a wholesale power market for the procurement of electric power, and other such means.

2.1. Electric Power Market Transactions and Arrangements

The electric power market in California is operated by the ISO, and participated in by electric power companies, power transmission companies, power distribution companies, and other controlling entities.

The ISO uses the power demand forecasts as a basis for procuring electric power on the market a maximum of three years in advance. The power station operation plans are reformulated at set intervals with greater accuracy each time, and they are finalized on the day before operation. When an operation plan is finalized, further operational

Table 1 Examples of wholesale power markets

Ancillary service market	Frequency regulation market
	Primary reserve force market
	Secondary reserve force market
Energy market	Day-ahead electric power market
	Real time market
Transmission rights market	
Capacity market	

reserve capacity transactions, called the day-ahead electric power market, take place to prepare against unforeseen power station outages and so on. On, operational reserve capacity is procured by bidding based on operation plans.

Enterprises known as aggregators that combine and control distributed power resources bid on these electric power transactions. The system is arranged so that the aggregator placing the lowest price on the power wins the successful bid right. Aggregators receive revenue from their successful bid price and at the same time take on the responsibility for providing operational reserve capacity according to commands from the ISO. On the operation day, the ISO adjusts its commands according to the supply capacity secured in this way while maintaining the balance between supply and demand.

For this paper, the frequency regulation market shown in Table 1 has been selected as the market for VGI verification. The reason is that this market can make use of the PEV battery characteristics that enable output and input of high levels of power in a short period of time. Frequency regulation starts within 10 minutes after a command from the ISO, after which it has to be able to output and input electric power according to the command signals that are updated every four seconds. Meanwhile, there is a stable balance of output and input electric power within a specified time, and since fluctuations in the battery SOC are small, it is thought that the impact on battery deterioration will also be small.

Figure 1 shows the relationships among the stakeholders involved in the present research.

The structure of VGI is equivalent to that of the current frequency regulation market, with the exception of the distributed power resources being replaced by the VGI-capable vehicles. The roles of other stakeholders are equivalent both in the current market and in the VGI. The ISO issues commands to the aggregator to provide the electric power procured on the market according to the balance of supply and demand on the power grid. The aggregator transmits supply and demand control signals to vehicles participating in VGI. Depending on the supply and demand commands they receive, the vehicles either receive power or transmit power. In this way, the electric power on the power grid is adjusted, and in this arrangement, the vehicle users receive compensation for their participation.

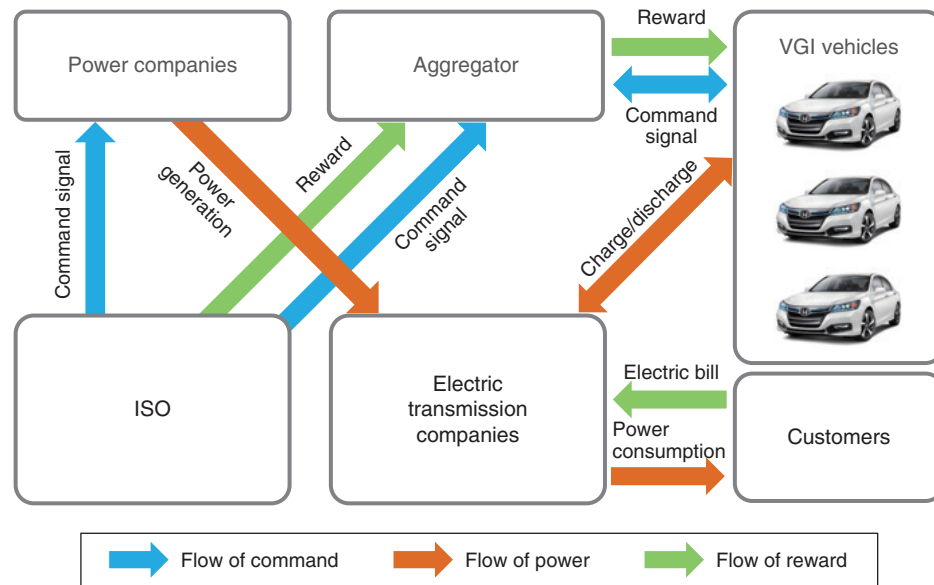


Fig. 1 Structure of VGI

3. Development Goals

Users who purchase a PEV that supports VGI can earn income by participating in the wholesale power market through an aggregator. Meanwhile, VGI uses the vehicle's battery, which means that, for constructing the system, it will be necessary to understand characteristics of battery deterioration caused by use of VGI, to establish charge-discharge control for the purpose of achieving a balance between vehicle usability and VGI, to assure the robustness of vehicle control functions with respect to the quality of electric power on the grid, and to assure responsiveness and controllability with respect to charge-discharge commands.

Controls and hardware to address these issues were created. The validity of their specifications was verified using demonstration vehicles.

4. Configuration of Vehicle Systems

4.1. System Concept

The conventional PEV has only the functionality to recharge from the power grid. A PEV that supports VGI, on the other hand, has a bi-directional power transfer function for sending and receiving electric power between the power grid and the vehicle battery, bi-directional communication function for exchanging control information with the aggregator that is needed for the output and input of electric power, and functions for controlling the vehicle components, including discharging power.

The concept for this research was defined as adding VGI functionality while maintaining the functionality, performance, or quality of the base PEV. In order to achieve such a system with minimum changes to existing systems in the vehicle, the authors aimed at integrating only

the bi-directional power conversion capability and the bi-directional communication functionality, and building a control system that can maximize the value obtainable by VGI without diminishing the intrinsic value of the vehicle.

4.2. System Configuration

Figure 2 shows an example of electrical and communication links established with the grid for implementing VGI. When an ordinary residence is taken as the example, a distribution board for receiving and distributing electric power and a unit known as an electric vehicle power system (EVPS) that controls charging and discharging are integrated between the vehicle and the power grid. The EVPS not only handles the transmission of electric power and circuit switching, it also has the functionality for converting charge-discharge control signals sent and received by the aggregator over Internet connection using TCP/IP into a power line communication (PLC) signal in the HomePlug Green PHY (HPGP) physical layer for communication between the EVPS and the vehicle as defined in SAE J2931⁽⁵⁾. An SAE J1772⁽⁶⁾ connector is used to connect the VGI-capable vehicle with the EVPS, allowing the vehicle to transfer electric power and communicate with the aggregator.

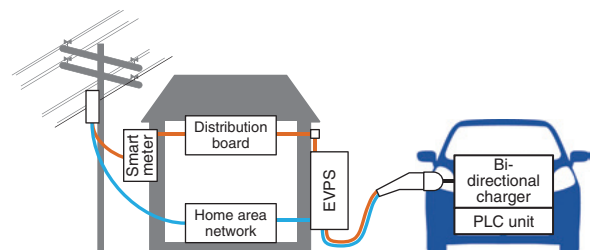


Fig. 2 VGI connection system

The hardware that is built into the vehicle is based on the conventional PEV system with the system connecting to the outside of the vehicle, as described above (Fig. 3). The connector that transfers power is also used for communicating with outside the vehicle. In place of the on-board uni-directional converter unit (the on-board charger: OBC) that converts AC power from the grid into DC power to charge the on-board battery, the vehicle is equipped with an on-board bi-directional converter that also functions to convert DC power to AC power; this enables VGI connections not just at home, but also at destinations away from home. PLC communication by the HPGP system, which is capable of high-speed, bi-directional communication of high-volume data defined by SAE J2931, was adopted for communication between the vehicle and the EVPS, and a dedicated PLC unit was put in place. PLC communication is superposed on the control pilot line (CPL), which is a signal for charge control, so a dedicated connection is not needed.

4.3. VGI Control

4.3.1. Battery control

In order to create more value in the frequency regulation market described above, a VGI-capable vehicle is required to be connected with the power grid over a longer period of time and implementing VGI with higher output. However, at the same time, this can cause insufficient charge time, chronic low SOC, and accelerated battery deterioration. VGI constitutes a technology that uses PEV batteries while the vehicles are parked. Maximizing the benefit obtained through VGI and responding to user demand for driving are requirements of battery control systems.

In this research, the following three points were taken into consideration in setting the target SOC during VGI operation.

(1) Maximize the benefits that can be obtained through VGI

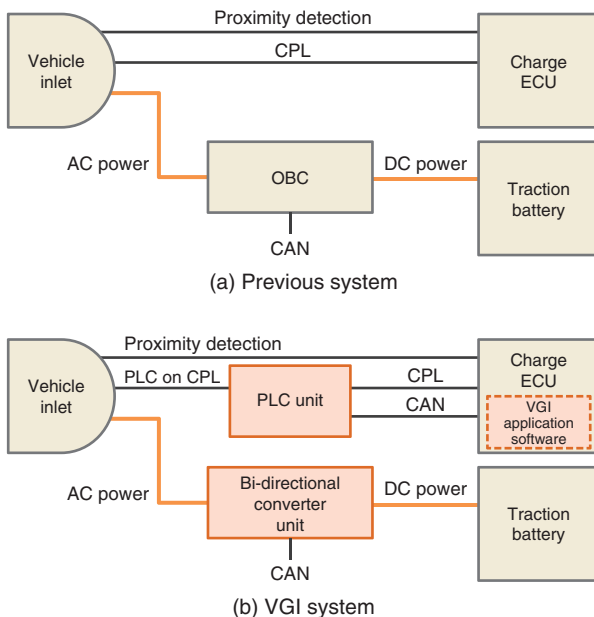


Fig. 3 Comparison of charging system

Table 2 Battery deterioration simulation with VGI operation

VGI use case	Simulation condition
Area	LA, California
SOC	90%
Peak power	± 4 kW
Effective power	2.4 kW
Operating time	8:00 p.m. - 6:00 a.m. 10 hr/day (36500 hr)
Simulation period	10 yrs, 100,000 miles

Table 3 Result of battery deterioration ratio with VGI working

Battery pack capacity	Capacity retention		Deterioration ratio
	Without V2G	With V2G (Used for 10 yrs)	
20 kWh	78%	75.9%	-2.1%

(2) Assure the EV driving range required by the user

(3) Limit the impact of VGI on battery deterioration

In general, the deterioration of lithium-ion batteries tends to be advanced by high temperatures and a high SOC. While VGI is active, batteries tend toward a lower SOC than when they are fully charged, and so it is thought that no increase in the rate of deterioration would occur. However, in a scenario of a continuing power transfer by VGI operation when the SOC remains at 80% or greater, which is in the vicinity of a full charge, the battery temperature may be held higher than the ambient temperature due to the heat generated by the charge-discharge power, which could lead to additional deterioration. In order to identify the increase of the rate of battery deterioration, a simulation of battery deterioration that integrated a battery-equivalent circuit with a thermal simulation of cooling was carried out to predict how battery deterioration would be affected during VGI use (Tables 2 and 3). The simulation envisioned VGI use in the possible usage environment of the vehicle, so in addition to temperature and other such environmental factors and the input and output of electric power for driving, the simulation also incorporated data on VGI power input and output obtained from the frequency regulation market. The result showed about 1.5°C higher battery temperature rise, averaged over the vehicle life, given the assumption that VGI would be implemented for 10 hours per day while the vehicle is parked. For a PEV with a 20-kWh battery installed, this was estimated to cause 2% deterioration over a 10-year period.

4.3.2. Charge-discharge control

The charge-discharge is controlled according to the battery condition in order to achieve battery control described above.

In the case of VGI intended for participation in the frequency regulation market, the aggregator controls electric power by issuing charge-discharge commands to multiple

vehicles that are connected to the power grid.

As explained above, the frequency regulation market as it is administered at present utilizes fixed power generation facilities and stationary batteries. Consequently, they are always connected to the power grid and the available electric power is ensured. VGI, on the other hand, utilizes batteries that are installed in vehicles and that are therefore not always connected to the power grid. Furthermore, even when they are connected to the power grid, the battery temperature may rise high in the extreme heat of summer or fall low in the bitter cold of winter, and the amount of available power can also be expected to vary from vehicle to vehicle.

Under these circumstances, the aggregator will be unable to calculate the regulating power, and frequency regulation will fail to be implemented. The system was therefore set up to have the vehicle transmit its own power limit value to the aggregator, so that it could receive a charge-discharge command value in accordance with its battery state. This enables the aggregator to monitor the capabilities of individual vehicles' charging and discharging so that the power can be distributed appropriately. This also made it possible to create a control system that would not adversely impact battery deterioration.

When the various conditions of temperature, SOC, and so on do not allow the vehicle to charge or discharge, so that it cannot respond to aggregator demands, the system stops the vehicle's charge-discharge activity and goes into a standby state.

Figure 4 shows the typical content of communication that is required between the vehicle and aggregator in order to implement these various forms of control.

In order to implement VGI without losing any of the performance of the base vehicle, the control is designed to set a lower limit for battery SOC so that the minimum guaranteed driving range is ensured. Steps are also taken so that the vehicle will be at full charge at the time set on the charging timer by the user. The estimated time to a full charge is calculated and the time to finish VGI discharge is determined. The control is set up so that it subsequently only performs charging (Fig. 5).

4.4. Bi-directional Converter Unit for Installation in VGI-Capable Vehicle

4.4.1. Circuit configuration

In addition to the OBC function of converting AC power from the power grid into DC power to charge the on-board battery, the bi-directional converter unit for VGI-capable vehicles needs to have the capability to convert DC power from the on-board battery into AC power and discharge it onto the power grid. One method for providing these two functionalities on-board would be to install a DC-AC inverter unit exclusively for discharging power in addition to the OBC. Another method would be to install a bi-directional converter unit that has circuits capable of converting AC and DC power in both directions. For this research, a bi-directional converter system was selected in order to minimize increases in the size and weight of the unit as well as the increase in cost, for the purpose of limiting both the curtailment of vehicle interior space and the impact on fuel economy on the road. The bi-directional converter unit was fabricated by changing the rectifier circuit component and the power factor correction (PFC) circuit component that are parts of the OBC into an AC-DC conversion circuit⁽⁷⁾.

The design target figures for the bi-directional converter

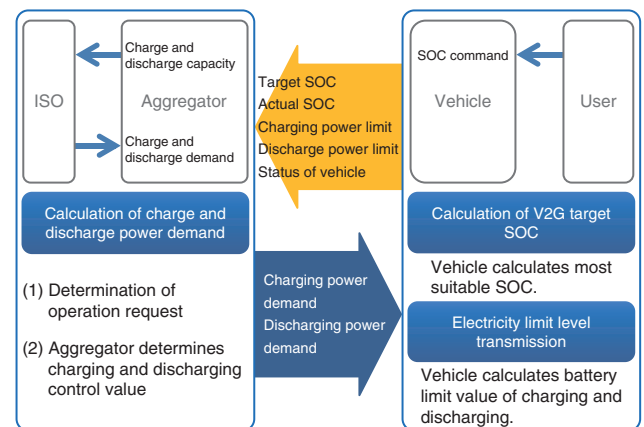


Fig. 4 Communication between aggregator and vehicle

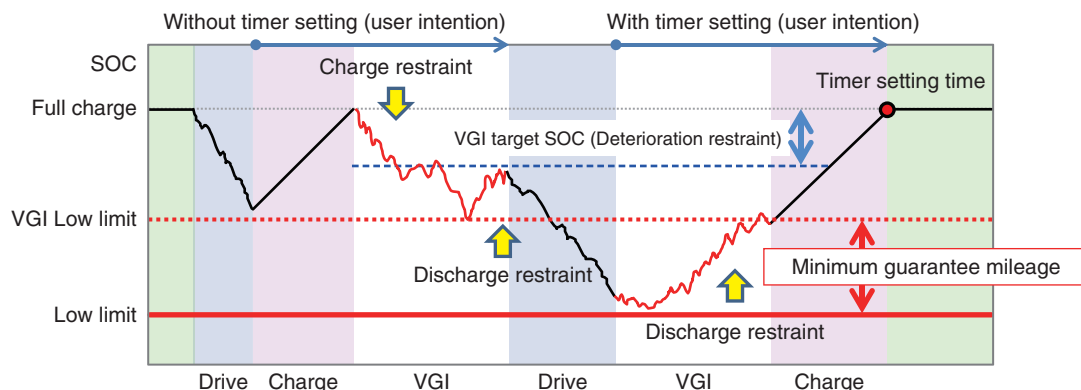


Fig. 5 VGI control for customer

Table 4 Design target of bi-directional converter

Item	Design target	Note
Volume	≤ 10 L	Equal to or less than 2013 model
Efficiency	Charge $\leq 90.6\%$ (240 VAC)	Equal to or more than 2013 model
	Discharge $\geq 87\%$	More than power conditioner for facilities

unit are shown in Table 4. The conversion efficiency during charging was made equal to or better than that of the base model, thus ensuring charging performance. For minimizing impact on space utility in a vehicle, the target volume for the unit's circuit component was defined as a volume of 10 liters.

Figure 6 shows the circuit configurations of a uni-directional converter and the bi-directional converter fabricated in this research. The AC-DC converter component has a rectifier circuit function (AC-DC conversion) and a power factor correction function, in addition to which there is a function for converting the DC power of the vehicle's traction battery to AC for the power grid. In conjunction with making the transferred power bi-directional, the secondary side (battery side) of the DC-DC converter was also changed from a diode rectifier circuit to a semiconductor switching element, enabling the circuit to convert power in both directions.

4.4.2. Applicable standards

The only function of the OBC was to receive electric power from the grid. Therefore, in the case of North American specifications, for example, communications between inside and outside the vehicle as well as the compatibility and safety of connectors and other such items,

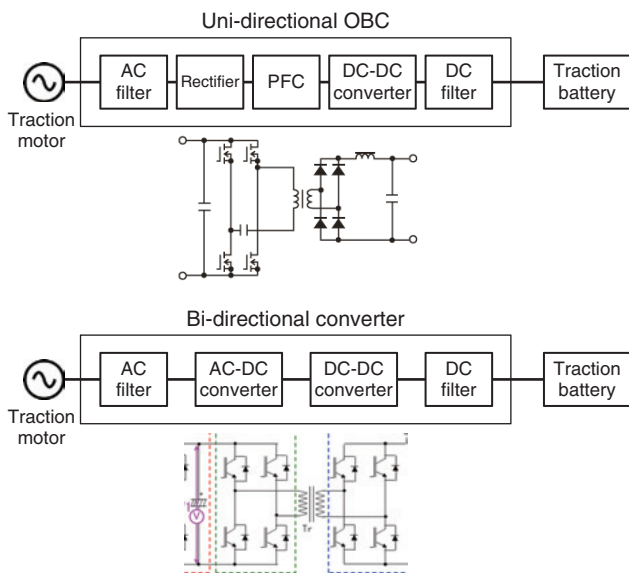


Fig. 6 Comparison between uni-directional and bi-directional converters

Table 5 Standards related to VGI

	charge	VGI
OBC	AC charging compatibility for grid	SAE J1772 SAE J2894 IEC 61851
		discharge power quality leak intercept NEC 702 NEC 705
Grid connection	—	grid parallel off grid follow grid protection anti islanding operation automatic recovery IEEE 1547

were ensured by complying with the relevant SAE and IEC standards. In the case of a bi-directional converter, however, it has functions for both charging and discharging power to the grid. It was necessary, therefore, for the design to comply with standards relating to safety functions, such as the function of suspending electric power discharging when the system detects a power outage on the grid, and standards relating to maintaining the electric power quality, such as shaping the power supply waveform and applying harmonics. The standards required for compliance are shown in Table 5.

Since this research applies to North America, the design was made to comply with IEEE 1547⁽⁸⁾.

4.4.3. Robust control against the electric power quality on the grid

The electric power quality on the grid is known to vary with the method of generation, environmental conditions, load conditions, and other such factors. Through monitoring the power quality on the grid over a long period of time, the results revealed that substandard voltage waveform was observed (Fig. 7). When this kind of voltage waveform from the grid is used to control the unit, the control specifications have to allow for sufficient robustness. The impact of the substandard voltage waveform on the unit was therefore verified in both hardware and control aspects, and the impact was addressed by enhancing the abnormal waveform detection performance of the unit and increasing the reliability of its protective operation.

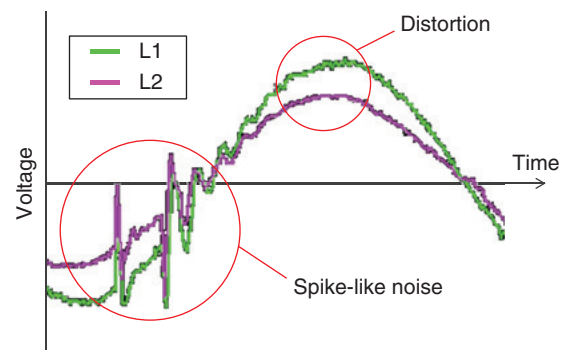


Fig. 7 Example of grid power quality

5. Demonstration Results

Honda participated in the eV2G Project, a demonstration of the VGI concept held at the University of Delaware in the United States, for the purpose of verifying the robustness and quantifying the value of the basic technology created in this research. (See Fig. 8.) This demonstration is being administered by a consortium that includes America's largest ISO (PJM Interconnection), an electricity generating company (NRG Energy), and a VGI aggregator (the University of Delaware). This project is engaged in demonstrating the compatibility of VGI on the frequency regulation market operated by PJM Interconnection.

An Accord Plug-In for the U.S. market was used as the base vehicle in the demonstration. The demonstration vehicle was equipped with an on-board bi-directional AC-DC converter unit (output of ± 2 kW) capable of interconnection with the power grid in compliance with IEEE 1547, and a vehicle smart link (VSL) unit for digital communication between the vehicle and the equipment provided by the University of Delaware. The VSL unit replaces the PLC with a control area network (CAN), which is similarly superposed on the CPL. The control application is based on charge control with production specifications to which a discharge control function, a function for fault detection during discharge, and a fail-safe function were newly added.

Verification was conducted over the 12-month period from November 2013 to November 2014. It involved confirmation of VGI controllability, SOC adequacy, and other aspects of system compatibility, verification of the validity of converter unit settings for interconnection with the power grid, and quantification of user benefits.

Data on grid connection times, grid power quality, and vehicle electric power input and output was acquired in the demonstration. The operations of the various vehicle components and failure detection data were analyzed, and the market compatibility of basic VGI technology as well as the quantification of user benefits were also evaluated.

5.1. Ensuring Robust Control with Respect to Grid Power Quality

As a result of long-term monitoring of the grid power quality, it was found that voltage waveforms occasionally fall significantly short of the values specified in the



Fig. 8 VGI capable Accord participating in eV2G project

Table 6 SOC control responsiveness

Item	Expectation	Experimental data
SOC band	$\pm 10\%$	+4.1% -3.5%
Average output	± 0.5 kW	+0.55 kW -0.46 kW
Peak output	± 2.0 kW	+1.9 kW -1.5 kW

standard. The on-board bi-directional AC-DC converter was robustly operated until the end of the demonstration.

5.2. Response and Control with Respect to Input-Output Command

The aggregator receives figures for the lower SOC limit usable in VGI from each vehicle. It uses those figures to forecast and manage the electric power input and output for the group of VGI vehicles as a whole, as well as to determine values for charge-discharge command for each vehicle. As shown in Table 6 and Fig. 9, these functions combined with the SOC management control in the vehicle were confirmed to provide control that was capable of complying with the lower limit SOC values. It was also confirmed that electric power input and output by the vehicle successfully followed the charge-discharge commands received (Fig. 10).

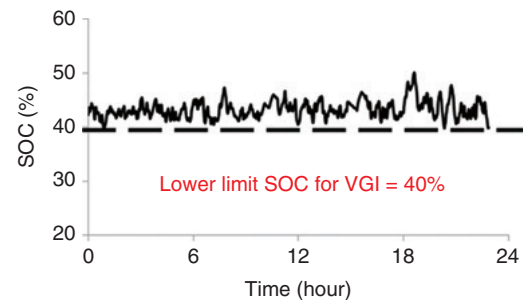


Fig. 9 SOC control performance

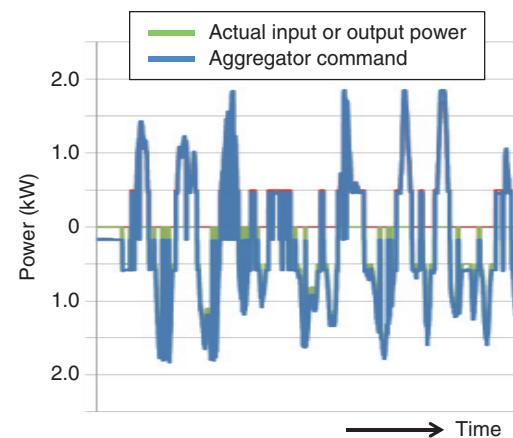


Fig. 10 Transient response performance of VGI system

Table 7 Incentive obtained through VGI

Connected time (hr/day)	Estimated value based on (Q1, 2013 – Q2, 2014) (\$)	Average (\$/month)	Estimated value in 3 years (\$)
18	1,733	91	3,276
12	1,065	56	2,016

5.3. Quantification of Income to Users

Data on connected times acquired from participation in the frequency regulation market during the demonstration together with unit prices for electric power from actual transactions on the market were used to calculate the income to users. The results are shown in Table 7. In the case of users that participate in VGI for 12 hours at home and six hours at work, for a total of 18 hours per day, it was found that they would receive an income averaging US\$91 per month, or \$3,000 over a three-year period. Even users whose VGI participation amounted to 12 hours per day would receive \$2,000. This confirmed that sufficient benefit would be gained.

6. Conclusion

- (1) The basic technology was created, with VGI vehicle hardware and control specifications, for establishing electrical connections between vehicles and the power grid, and for accurately performing charge and discharge operations according to aggregator commands. The hardware and control specifications for an on-board bi-directional AC-DC converter with the robustness and ability to operate in concert with an unstable electric power grid were confirmed. The ability to follow demand for input and output of electric power and the potential for compatibility with battery SOC control were also confirmed.
- (2) Deterioration of the vehicle battery due to utilization of VGI was verified by a simulation based on input-output demand waveforms from the aggregator that were acquired during the demonstration. With the scenario of a PEV with a 20-kWh battery installed and charge-discharge output of ± 4 kW, it was estimated that deterioration would be advanced by about 2% over a 10-year period.
- (3) As a result of participation in the demonstration and actual operation of a frequency regulation market, it was found that users participating in VGI at home and at work for 18 hours per day could be expected to earn an income of \$3,000 or more from operation over a three-year period.

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