Deployment of Vehicle-to-Grid Technology and Related Issues

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Abstract

In order to reduce emissions and enhance energy security, renewable power sources are being introduced proactively. As the fraction of these sources on a power grid grows, it will become more difficult to maintain balance between renewable power supply and coincident demand, because renewable power generation changes frequently and significantly, depending on weather conditions.

As a means of resolving this imbalance between supply and demand, vehicle-to-grid (V2G) technology is being discussed, because it enables vehicles to contribute to stabilizing the power grid by utilizing on-board batteries as a distributed energy resource as well as an energy storage for propulsion.

The authors have built a plug-in vehicle with a capability of backfeeding to the power grid, by integrating a bi-directional on-board AC/DC and DC/AC converter (on-board charger) and a digital communication device into the vehicle. The vehicle is interconnected to a power regulation market in the United States. By participating in the regulation market, the authors verify that this V2G-capable car is able to create a value of more than $100/kW annually by charging and discharging power.

In order to widely adopt V2G technology in the real world, it is necessary to establish an overall system that enables adoption of the technology by interconnecting individual vehicles, users, grid operators, utilities, and governmental organizations. Standardization is also important for large-scale deployment of the technology, an area in which SAE has already been moving forward.

Introduction

Renewable power resources, such as solar and wind power, have been proactively introduced to the power grid to provide higher efficiency, better energy security, and lower greenhouse gas emissions. Because of the weather-dependent property of most renewable power resources and the essentially increasing demand, however, stability of supply-demand relationship could decrease.

Any instability in the power grid is now being resolved mostly by conventional generating capacities, such as thermal power plants that can be quickly adjusted to produce more or less power. In wholesale electricity markets, this form of adjusting the power level is traded at market price to encourage efficient markets. This balancing service may be called “regulation,” “frequency regulation,” or “primary reserves” in different regions.

Use of electric vehicles for the purpose of stabilizing the power grid has been discussed for more than a decade [1][2], and effects on the grid and eventual financial values have been calculated [3][4]. The system of using electric vehicles to backfeed power from the vehicle to the power grid is often called “vehicle-to-grid” or V2G.

However, those effects have been theoretical calculations in most cases, because electric vehicles usually have the capability only to charge, and cannot discharge. Therefore, financial values based on experiments were not available, and the effects of vehicle performance on the power grid, the effects of vehicle power flow on the vehicle performance, and the effects of grid signals on vehicle behavior have not been experimentally proven.

The authors have built a plug-in vehicle with the capability to both charge and discharge by integrating a bi-directional on-board converter (charger) and a digital communication device into the vehicle. The vehicle is interconnected to the power grid, and charges and discharges power in accordance with signals from a grid operator. The grid operator for this demonstration is PJM Interconnection.

This paper describes the configuration of the V2G system, the charge/discharge behavior of a vehicle with backfeeding capability, and the potential values expected from the vehicle.

Configuration of the V2G System

In many regions in North America, RTOs (regional transmission organizations) manage the electric power supply, in accordance with power demand. (These are sometimes referred to as ISOs, for Independent System Operators, and in Europe are referred to as TSOs, for Transmission System Operators.) Eleven RTOs cover the individual regions, as shown in Figure 1, and manage two-thirds of the electricity in the United States and more than half that in Canada by forecasting and monitoring supply and demand in the regions and sending commands to utility companies that directly control electricity supply, and sometimes to large energy consumers that control electricity demand.

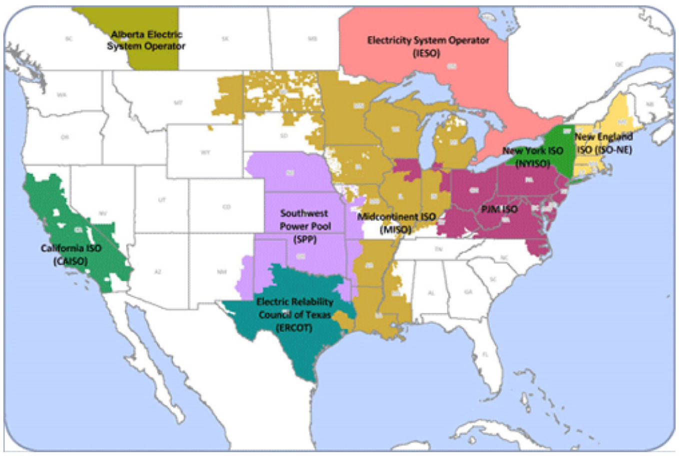

Figure 1. Areas covered by RTOs in North America [5]

There are about 3,300 electric utilities in the United States that generate, transmit, and distribute electric power to energy consumers [6]. Electric utilities include investor-owned companies, publicly owned companies, cooperatives, federal power agencies, and power marketers, and each controls the electric power supply and demand for electric power in its service area.

Under normal circumstances, the RTO sends commands to electric generators to adjust supply based on forecasts and the current status of supply and demand so that an adequate supply is matched to demand. On a slower cycle, the RTO sends commands or requests to large energy consumers, such as large-scale manufacturing facilities, when a sufficient supply is unlikely to be available for the power grid. In this case, the large energy consumers will reduce energy consumption by decreasing or sometimes stopping their operations, and will thereby contribute to balancing supply and demand in the power grid.

In the case of V2G systems, V2G-capable vehicles work both as a power supplier and as a power consumer. With the involvement of vehicles and an aggregator as well as the RTO, a V2G system can be realized, as shown in Figure 2. In this scheme, an aggregator works in a similar way to a large energy consumer as well as a power plant. An aggregator aggregates power from multiple vehicles so that the total power is sufficient to qualify for a contract to provide balancing power. When supply from the power grid is too low compared to demand, the vehicles discharge power from their propulsion batteries in accordance with a command from the RTO through the aggregator. When the power grid has excess supplies, the vehicles charge power from the grid to their batteries.

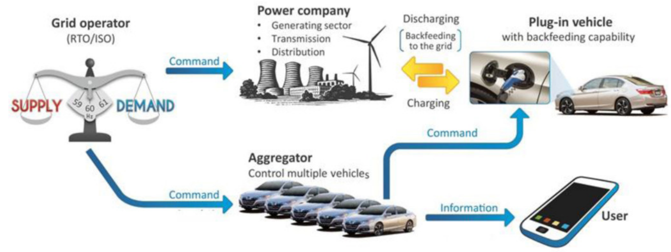

Figure 2. Overall configuration of V2G system

Power Market in Which Vehicles Can Participate

There are several different types of wholesale RTO electricity markets in addition to frequency regulation. These include capacity, peak power, and spinning reserves, among others. In addition, there are multiple potential services that can be provided to local utilities, such as VAR correction, voltage support, distribution feeder support, and transformer upgrade deferral.

Among the markets noted above, the frequency regulation market is thought to be a good market for V2G-capable vehicles to begin with, for the following reasons [3][4].

1. In the frequency regulation market, charging or discharging is only sustained for several minutes each at the longest. Therefore, a vehicle battery can maintain its state-of-charge (SOC).
2. Although individual charging or discharging is sustained for only several minutes, the cycles continue for an extended period of time and are needed throughout the day. A vehicle can therefore contribute to the power grid continuously, and it can receive financial benefits, whenever it is interconnected to the power grid.
3. The potential amount of payback to a vehicle is expected to be higher in the frequency regulation market than in other markets because of the market price.

Based on the above viewpoints, the authors prepared a V2G-capable vehicle and interconnected it into the power grid in the PJM Interconnection service area, and had the vehicle participate in the frequency regulation market. Using an aggregation service conducted by the University of Delaware, the V2G-capable vehicle worked as a distributed energy resource in the power market.

Configuration of the V2G-Capable Vehicle

A V2G-capable vehicle can be realized by installing a bi-directional power converter and allowing additional communication specifically for V2G operations. In order for a vehicle to adjust only the charging power, a bi-directional converter is not required, because reducing charging power or interrupting a charging session will reduce demand on the power grid, and thereby the vehicle will be able to contribute to the power grid to some extent.

However, a bi-directional converter has the ability to contribute to stabilizing the power grid much more than a uni-directional converter for the following reasons.

1. A bi-directional converter has twice the ability to adjust power flow between a vehicle and the power grid, that is, for a given

power, *p*, uni-directional can be from 0 to +*p*, whereas bi-directional can be from -*p* to +*p*.

2. A bi-directional converter allows V2G operation for practically unlimited durations by repeating charging and discharging cycles, while a vehicle with a uni-directional converter stops charging once its battery is full.

Therefore, the authors prepared a V2G-capable vehicle with an AC/DC and DC/AC bi-directional converter and an extra digital communication device, based on a production plug-in hybrid car with a 6.7 kWh battery pack and a 6.6 kW on-board AC/DC converter. The bi-directional converter for the V2G-capable vehicle is a prototype unit, and has reduced power compared to the production 6.6 kW uni-directional converter. The bi-directional converter was designed and built to conform to the basic requirements of IEEE Standard 1547 [7] in order to ensure safety and grid power quality. The requirements are discussed later in this paper.

Digital communication devices are installed both on the vehicle and on the electric vehicle supply equipment (EVSE) so that the EVSE can receive commands from PJM Interconnection, the commands can be transferred from the EVSE to the vehicle, and the relevant signals can be sent from the vehicle to the EVSE.

The communication devices installed on the EVSE and the vehicle are also prototype units. The units allow communication necessary for V2G operation by using digital communication over pilot. SAE J1772 [8] specifies not only the requirements for a vehicle charging coupler but also for signaling. The authors take advantage of the 5% duty cycle as specified in SAE J1772 to enable communication between the EVSE and the vehicle. Digital communications over the pilot meets the specification of IEC 61851-1 Annex D [9].

Figure 3 shows the V2G-capable vehicle that the authors prepared as noted above. The vehicle charging inlet coupler conforms to SAE J1772 just as the production vehicle does, and no extra connection is added. Data from the vehicle is wirelessly transmitted to the authors' site, and is used for detailed analysis.

Figure 3. V2G-capable vehicle

Figure 4 shows the configuration of the vehicle. The right-hand side from the dotted line is the system on board the vehicle. The bi-directional converter allows both charging to and discharging from the vehicle by way of the SAE J1772 charge coupler within the allowable current of the EVSE.

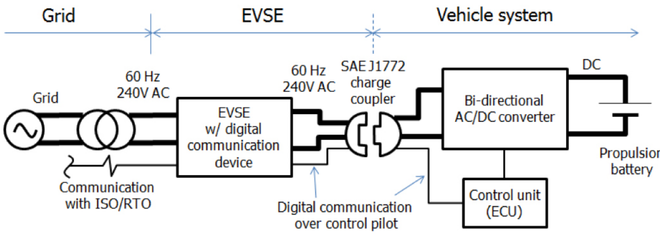

Figure 4. Configuration of the V2G-capable vehicle

The EVSE is required to be capable of communicating with the vehicle in order to allow the vehicle to control its charging/discharging power in accordance with commands from RTO. Therefore, as shown in Figure 4, digital signals are superimposed on the control pilot line.

Currently, a J1772 coupler transmits a proximity signal, an EVSE state signal, and an allowable current value signal. But for wide adoption of V2G technology in the future, the EVSE with the communication capability to the aggregator will have to be standardized. Although there are multiple RTOs in the United States, as shown in Figure 1, the EVSE must be able to properly handle commands from the power grid and communicate with a vehicle. The signal from RTO to aggregator can be customized to multiple RTOs, indeed the aggregator must be customized to the RTO as the rules of power provision, not only the signals, vary. Therefore, the aggregator, like the utility and RTO, are localized. However, there is a need for coordination between EVSE manufacturers, and standardization of relevant communication is desired.

Test Results

With the V2G-capable vehicle shown in Figure 3 and described above, the authors obtained test results by interconnecting the vehicle to the power grid in the service area of PJM Interconnection.

Figure 5 shows the actual charge/discharge behavior of the vehicle in response to commands from the power grid (Charge request and Discharge request). This result shows that the vehicle's response to the request is so fast that the actual output curve almost overlaps with the request curves.

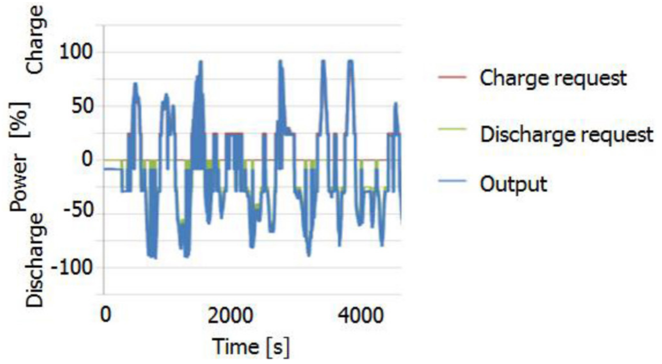

Figure 5. Characteristics of command following

In the case of a conventional thermal power plant, for example, natural gas or coal is combusted, and heat is generated. The heat generates steam from boiled water or high temperature gas, which spins a turbine. The turbine spins a shaft connected to a generator. Thereby, the generator produces electric power.

This generating system depends on heat for spinning the turbine and the generator, but obviously, generating heat requires some time, and thus response time is not short.

V2G power output, on the other hand, depends on a vehicle battery system and power electronics. The response of a vehicle battery system to the request is very fast. This fast response characteristic is also a good property of a V2G system because the supply-demand relationship easily and rapidly changes as users turn on/off switches and when generators or power lines fail and are restored.

Figure 6 shows the transition of state-of-charge. The control algorithm in this case is that the vehicle follows commands in the frequency regulation market and the battery is controlled so that the state-of-charge does not fall below 40% of the battery capacity. The important points on this graph are as follows.

A). State-of-charge does not significantly rise or fall.

B). Each charge or discharge is sustained only for a short duration.

Point A) is similar to battery control in the charge-sustaining mode of a plug-in hybrid vehicle, and the actual charge/discharge power is expected to be far less than the driving power. Therefore, the effect of a V2G on battery durability is estimated to be limited. Some people have expressed concern about the degradation of batteries due to additional V2G operation, but when data from the operated vehicle was analyzed, it showed no signs that additional operation accelerates further degradation of the battery.

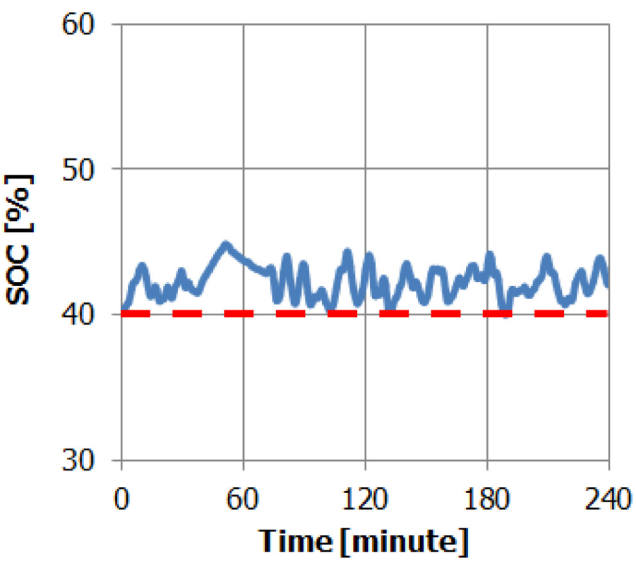

Figure 6. Transition of state-of-charge

With the bi-directional converter, which has been designed and built to conform to the basic requirements of IEEE Standard 1547, test operation has been conducted properly and safely without disturbing the power grid to which the vehicle is interconnected.

In the meantime, the vehicle system, especially the bi-directional converter, needs to accept commonly observed disturbances on the power grid, such as surges, voltage swells, voltage dips, or voltage waveform distortion. Although there are already many plug-in vehicles on the road and on the grid, most of those vehicles have only uni-directional converters, and experiences with interconnecting vehicles that allow bi-directional power flow are limited. Further investigation on the grid power quality that may affect the circuit of the bi-directional converter will be important for large-scale deployment of the system.

The propulsion battery of the V2G-capable vehicle needs to undergo more charging and discharging during V2G operations than that of a normal plug-in electric vehicle without V2G. However, power for charging and discharging the battery is much smaller than the maximum power of the battery, which is required for vehicle acceleration. Therefore, the extra degradation caused by V2G operations is negligible small. As a further test, we conducted durability tests at high temperature, which reveal that battery degradation with V2G operations is almost identical with that without V2G operations as shown in Figure 7. The charge/discharge profile for the tests was regenerated from actual V2G operations as shown in Figure 5.

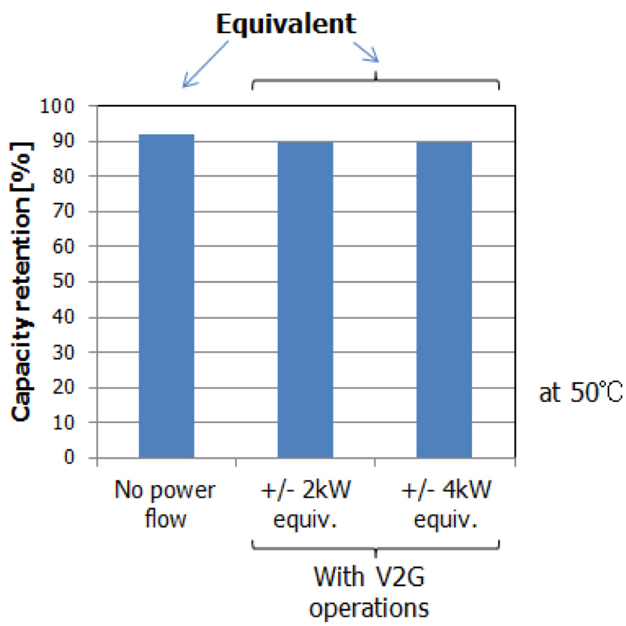

Figure 7. Capacity retention rate after high temperature durability tests, showing near equivalence in capacity whether or not V2G is added.

Values created by V2G operations can be calculated from wholesale regulation market prices. In the case of wholesale regulation market of PJM Interconnection, Regulation Market Capability Clearing Price (RMCCP) and PJM Regulation Market Performance Clearing Price (RMPCP) in $/MWh are determined by the regulation market. For simplicity, the values are obtained from multiplication of those prices, power of charging and discharging, and duration when the vehicle is interconnected to the power grid.

Hourly values of RMCCP and RMPCP in October 2014 are shown in Figure 8 as an example [10]. The spikes in the figure show that, at each of those moments, the power grid needed, and paid a premium for, the regulation capability to power suppliers, including V2G-capable vehicles. In other words, V2G-capable vehicles can produce higher values in those moments. This graph also shows that there is some value at all times, not only at peak periods, and not only during the day.

The values that the vehicle could produce annually are calculated as $623 when connected at home only, and $1,014 at both home and work, under the following assumptions.

1. The calculated prices are based on the average wholesale market prices of PJM Interconnection between January 2013 and December 2014.
2. The vehicle is assumed to have the capability to charge and discharge at 6 kW each, thus it does not fill the battery and stop operating.
3. The vehicle is connected at home from 8pm to 8am.
4. The vehicle is connected at work from 11am to 5pm. For simplicity, the calculation does not consider weekdays or the weekend; each day is considered the same.

Wholesale market revenue varies based on a number of factors, such as the time of a day, the day of a week, the season, the market situation, and obviously the driver's behavior. A V2G business model will have to encourage drivers to keep their vehicles plugged in as often as possible, for example, by paying for the number of hours they are connected.

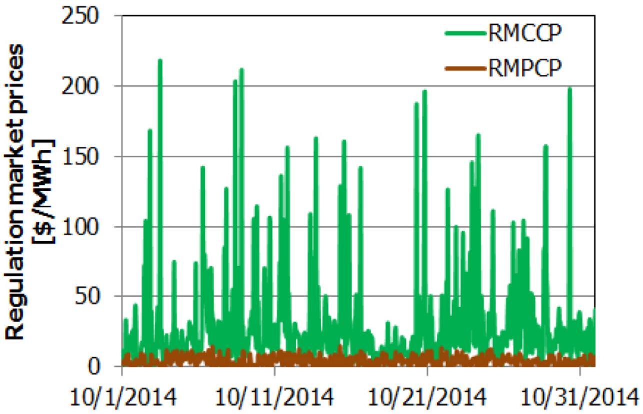

Figure 8. Hourly data of PJM Interconnection RMCCP and RMPCP in the wholesale regulation market in October 2014

Unresolved Social Issues

For large-scale deployment and commercialization of V2G technology, laws, regulations, standards, and stakeholders' understanding will be important.

Among others, it is important to receive the understanding of the utility companies. Because the V2G vehicle system is quite similar to a solar generation system in the way that the system can supply power to the power grid, a similar approval procedure for interconnecting backfeedable units can be used. However, for the approval procedure of interconnecting vehicles, characteristics of a vehicle system need to be fully taken into account.

One of the intrinsic features of a vehicle system is that a vehicle travels. A vehicle can be interconnected at multiple locations that have different interconnection conditions from each other, as shown in Figure 9. Giving interconnection approvals to individual vehicles at individual locations is, therefore, not a realistic idea. For this reason, the University of Delaware model is to register the EVSE with the utility and RTO, as the EVSE always resides in one location, and have the vehicle pass its certification to the EVSE.

Another important characteristic of a vehicle system is that on-board devices receive vibrations and temperature cycles harsher than a stationary device. Sometimes, a device is exposed to a corrosive condition, such as salt water. The level of harshness depends on which position a vehicle device is installed at, how a vehicle is used, where a vehicle is located and driven, and so on. Setting one single level of requirements would cause extra weight, volume, and cost for vehicle devices installed under milder conditions or at a protected position. Therefore, rather than standardizing comprehensive requirements, the vehicle manufacturer shall be required to ensure the durability against such harsh conditions of on-board devices for V2G, as is the case with other vehicle components.

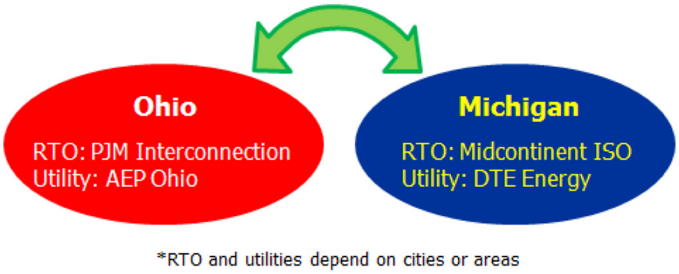

Figure 9. One possible case is that a vehicle is interconnected at multiple locations

In addition to the above characteristics, a vehicle system has a characteristic that a function is enabled by multiple components, and that a component can work in multiple ways. For V2G control, for example, not only the bi-directional converter and the control unit but also the battery pack and various kinds of sensors interact with each other and enable appropriate charge/discharge control. At the same time, the control unit may work not only for V2G control but also propulsion control. Therefore, it is not simple to define what composes the V2G control feature.

These are some examples of the characteristics of the vehicle system that stationary equipment does not have.

Some traditionally recognized standards, such as UL standards, are primarily intended for stationary units, and do not take into account the requirements for vehicle systems, such as volume and weight restrictions, vibration and other environmental conditions. It means that the requirements in the traditionally recognized standards are not necessarily appropriate for an on-board system or an on-board device.

Most utility companies have routine standards to interconnect a power-producing device onto the power grid. However, traditionally recognized standards may not be appropriate for mobile systems like automobiles. Therefore, the auto industry and the electric power industry will have to build appropriate standards for V2G technology, which may in turn be required by local authorities. In fact, SAE has already been in the process of building new standards, which will be important to establish the social system for realizing V2G.

As a basis for such new standards for V2G, IEEE Standard 1547 can be considered to have basic requirements to ensure power quality and safety. IEEE 1547 establishes criteria and requirements for interconnection of distributed energy resources, and applies to distributed resources, such as solar inverters and small wind turbines, in order to ensure safety and grid power quality. This allows the power grid to maintain its power quality and ensures the safety of electric power workers when working on de-energized power lines. The authors believe new standards for V2G system should be established based on those basic requirements in the IEEE standard while taking vehicle systems into account. The new standards should be properly established and recognized by utility companies, state governments and municipal governments so that they can be incorporated into the utilities' approval process as well as laws relevant to ensuring the safety of V2G systems. Such standards are already being developed by SAE committees working, for example, on SAE draft standards J3068 and J3072, including connectors, communication, and on-board, utility-interactive inverter systems. The authors expect that development of those standards will progress in parallel with development of the technology. We still need time to finalize practically usable standards.

Establishing a business model will be also required to commercialize the technology. However, as the value and the benefits become clearer, relevant businesses are expected to be established spontaneously. Some power companies have already begun this process in the U.S. and in Europe, for example. Therefore, establishing a business model is not a big concern.

Conclusions

The authors have prepared a V2G-capable vehicle for actually interconnecting with the power grid and providing grid services. The vehicle has been proven to be able to charge and discharge power in accordance with commands from an RTO, PJM Interconnection. In addition, it commercially participated in the frequency regulation service of the wholesale power market. The operation of the vehicle has been conducted properly and safely as designed, while contributing to stabilizing the power grid.

Degradation of the propulsion battery caused by the additional power transfer is proven to be very small, and thus not a major issue because the charge/discharge power level is much lower than the maximum power of the battery system required for vehicle acceleration. Revenue per car is shown to be attractive.

For large-scale deployment and commercialization of V2G technology, relevant laws, regulations, and standards will have to be appropriately established. Such legislation and standardization will encourage development of the technology. Understanding of stakeholders, such as lawmakers, governments, standardization organizations, and utility companies will be essential to enabling those legislation and standardization.

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Definitions/Abbreviations

DER - Distributed energy resource

EVSE - Electric vehicle supply equipment

IEEE - Institute of Electrical and Electronics Engineers

ISO - Independent service operator

RMCCP - Regulation Market Capability Clearing Price

RMPCP - Regulation Market Performance Clearing Price

RTO - Regional transmission organization

SOC - State-of-charge (of battery)

TSO - Transmission system operator

UL - Underwriters Laboratory

V2G - Vehicle-to-grid

The Engineering Meetings Board has approved this paper for publication. It has successfully completed SAE's peer review process under the supervision of the session organizer. The process requires a minimum of three (3) reviews by industry experts.

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