2018-01-0669 Published 03 Apr 2018

Feasibility Study of Bi-directional Wireless Charging for Vehicle-to-Grid

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Citation: Tachikawa, K., Kesler, M., and Atasoy, O., “Feasibility Study of Bi-directional Wireless Charging for Vehicle-to-Grid,” SAE Technical Paper 2018-01-0669, 2018, doi:10.4271/2018-01-0669.

Abstract

Vehicle-to-Grid (V2G) technology is expected to play a role in addressing the imbalance between periods of peak demand and peak supply on the electricity grid. V2G technology enables two-way power flow between the grid and the high-power, high-capacity propulsion batteries in an electrified vehicle. That is, V2G allows the vehicle to store electricity during peak supply periods, and then discharge it back into the grid during peak demand periods. The authors have performed an architectural design and a modeling and simulation study for a bi-directional wireless charging system for V2G applications. This research activity aims to adapt an existing SAE J2954 compatible uni-directional system design to enable bi-directional wireless power transfer with minimum impact to system cost, while maintaining full compatibility with the requirements of SAE J2954.

Introduction

In an effort to address environmental concerns and enhance energy security, automakers have been developing electrified products such as plug-in hybrid vehicles (PHEVs) and battery electric vehicles (BEVs) for the past several years, and they are gaining momentum. Honda strives to electrify two-thirds of global automobile unit sales by 2030.

Simultaneously, renewable sources of energy have been playing an increasing role in the nation’s electricity grid. Due to the intermittent nature of many renewable sources, such as wind and solar power, it is becoming more difficult to maintain a balance between renewable energy availability and coincident peak demand. This challenge is commonly called the “duck curve,” due to the temporal imbalance between peak demand and peak renewable energy production. One way to prevent curtailment of the amount of electricity generated by renewable resources is to store the “excess” electricity, and then feed it back into the grid during the peak demand periods.

Vehicle-to-Grid (V2G) technology provides a means to accomplish this task. V2G technology enables two-way power flow between the grid and the high-power, high-capacity propulsion batteries in an electrified vehicle. This technology can therefore contribute to stabilizing the balance between supply and demand on the power grid [1, 2, 3].

Honda has been conducting an experimental demonstration of V2G at the University of Delaware [4] and at UC San Diego since November 2014, using a modified Honda Accord Plug-in Hybrid. This vehicle has been fitted with a bi-directional on-board AC/DC and DC/AC converter, which enables V2G functionality.

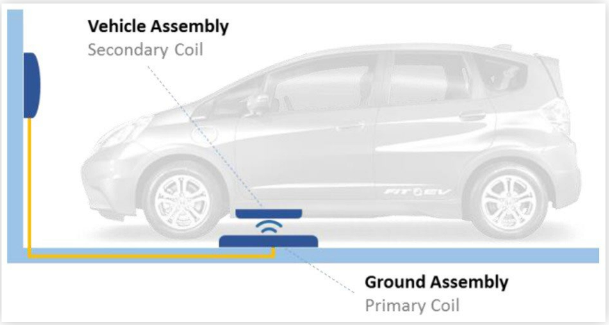
In addition, the authors have performed an architectural design and a modeling and simulation study for a bi-directional wireless charging system for V2G applications. This research activity aims to adapt an existing SAE J2954 compatible uni-directional system design to enable bi-directional wireless power transfer with minimum impact to system cost, while maintaining full compatibility with the requirements of SAE J2954. This paper discusses the predicted system performance, including output power and efficiency.

Bi-directional wireless charging technology can significantly improve usability because the physical connection between the vehicle and grid has been eliminated. In addition, such a system is expected to have a cost advantage, when compared to a conventional wireless charging system combined with a bi-directional on-board charger. These advantages can facilitate the large-scale introduction of V2G technology into the market.

Wireless Power for Electric Vehicles

Wireless charging for electrified vehicles, both battery electric and plug-in hybrid electric vehicles is rapidly developing as a viable alternative to traditional conductive charging methods. Car makers and consumers are attracted by the simplicity of fully automatic and hands free “park and charge”, and in the words of one carmaker: “Wireless Charging makes charging easier than refueling”. Figure 1 shows the basic components

FIGURE 1 Basic components of a wireless charging system.



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of a wireless charging system, including a grid connected wall box, a ground assembly unit (GA) and a vehicle assembly (VA) coil and electronics that can be connected directly to the vehicle battery.

In addition to a superior user charging experience, wireless charging offers several additional benefits to car makers and consumers. Connectors and cables are known to be a cause of potential field failure, given the mechanical stress of repeated insertion/removal cycles. Exposed charging cables can be a target for vandals and thieves. Exposure to severe weather can reduce the service life of charging cables and connectors and may be a hazard to drivers needing to connect or disconnect their vehicle in extreme heat, cold, wind, and precipitation. Level 1 & 2 conductive charging systems require that the vehicle be equipped with an on-board charger (OBC) to convert grid supplied AC power to suitable DC charging voltages. Because of regional differences in AC power frequency, voltage, and phasing, carmakers must customize the OBC for each region, leading to high costs of inventory, product validation, and stocking of spare parts. Wireless charging systems "abstract" the vehicle from the grid by interposing ground side power electronics that interface to the grid, while providing a globally standardized non-contact connection to the vehicle. In this way, a carmaker's global fleet of vehicles can be equipped with a common set of wireless charging components, which can operate in ANY geographic region as there is no direct connection made to AC grid power. Global standardization activities underway for wireless charging in North America, Europe and Asia will ensure the onboard components will operate regardless of region. This serves to reduce vehicle cost and simplify a global electric vehicle platform strategy for carmakers.

Several carmakers have announced their intention to introduce wireless charging to the market, with the first factory equipped vehicles expected to be available in early 2018. Every global carmaker now has an active program for investigation, pre-development or series production of vehicles equipped with wireless charging capability. Multiple Tier 1 s and infrastructure suppliers are engaged in the development of vehicle side and ground side hardware and software for wireless charging, and it is expected that between 2018 and 2022 many carmakers will introduce vehicles to the market with wireless charging capabilities.

Wireless charging use cases for private residential, multi-unit dwelling residential, commercial and public parking are now being developed. Wireless charging is especially appealing to power generation and power distribution companies because it enables and encourages charging of the vehicle during "off-peak" hours, when the owner is sleeping or when demand for fleet services is in a lull period. Given the average daily commuting range of 40 miles in the US, a vehicle will charge in 1-4 hours while the driver is sleeping, reducing the need for visiting fast charging or other public charging installations in all but the most extreme circumstances (long distance intercity travel). While the same overnight charging occurs with wired charging at home, wireless charging offers the same charge time and efficiency with an automatic charging experience not available when having to plug in.

Just as wireless charging will simplify connection of vehicles to the grid for charging purposes, it also simplifies connection to the grid for V2G purposes. While a driver with a fully charged battery would have little motivation to connect his or her car to the grid with a cumbersome charging cable while at work or shopping, a wireless connection will make that well charged battery available to the grid for V2G purposes, and could enable the battery to be recharged by the time the driver returns to the vehicle. V2G success will depend on having a large fleet of vehicles connected to the grid and available for discharge, and a transparent wireless connection of vehicle to grid can make the V2G application transparent to the car owner.

Wireless Power Transfer Technology

The technology behind wireless power transfer (WPT) of electric vehicles is based on the fundamental principle that a time varying magnetic field induces a voltage in a loop of conductor proportional to the rate of change of flux enclosed by the loop. This is the same principal on which transformers operate; however, in this case the two sides of the transformer (primary and secondary) are physically separated from each other with one side located on the ground and the other on the underside of the vehicle. While in a transformer the primary and secondary coils have a magnetic coupling coefficient, k, that is close to one, WPT systems must operate at much smaller coupling, $k \approx 0.1 - 0.3$, because of coil size constraints and the required distances and offsets between them. The use of resonance enables efficient power transfer (>90% end-to-end system efficiency) even at these low coupling levels. It can be shown that the maximum coil-to-coil efficiency, one component of the overall system efficiency, can be expressed in terms of the magnetic coupling coefficient and the coil quality factors, Q_1 and Q_2, as

$$\eta_{\max} = \frac{U^2}{\left(1+\sqrt{1+U^2}\right)^2} \tag{1}$$

where $U = k\sqrt{Q_1 Q_2}$ is a general figure-of-merit for any wireless power transfer system. Equation (1) shows how the coil-to-coil efficiency increases with U and that the high-quality factor resonators on both the ground and vehicle is critical for high efficiency power transfer. Coil-to-coil efficiency can be greater than 97% for well designed systems, and overall system efficiency as good or sometimes even better than existing wired chargers.

Of course, human safety is a prime concern for any product, and WPT systems utilizing magnetic fields are no different. Because magnetic fields interact weakly with the human body, it is possible to have an 11 kW WPT system operating underneath a vehicle while satisfying all regulatory guidelines for human exposures both around and inside the vehicle. The SAE J2954 standards activity will result in requirements that ensure human safety guidelines are met for all compliant WPT systems.

Standardization Activities

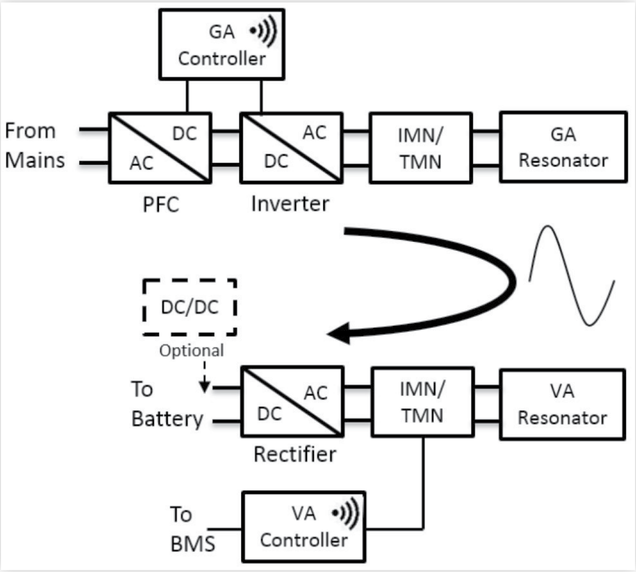
Activities to create a standard for WPT systems for charging EV and PHEV have been ongoing for several years. In 2010 SAE International formed the J2954 Committee to begin work on developing a standard for wireless charging of light-duty vehicles. IEC and ISO also have active group to create standards for the ground side and vehicle side, respectively, for wireless charging of vehicles. In 2016 SAE published the J2954 technical information report (TIR) followed in 2017 by the J2954 Recommended Practice (RP) [5], which describe requirements for WPT systems such as input power classes at 3.7 kW, 7.7 kW and 11 kW kW (WPT1, WPT2 and WPT3 respectively), ground clearance ranges (Z1, Z2 and Z3 covering 100 mm - 250 mm ground clearance), frequency of operation, efficiency targets, EMC limits, and safety requirements.

As a part of the J2954 activity, a testing program was completed in 2016 in which WPT1 and WPT2 systems from three suppliers were tested in both matched and interoperable configurations. WiTricity participated in this testing and has an interoperable WPT2 system with performance that exceeds the requirements laid out in the J2954 TIR and RP. It is this system which is used as the basis for the bi-directional study described herein.

WiTricity System for G2V

A basic block diagram for the WiTricity WPT system for G2V power flow in shown in Figure 2. On the ground side, AC energy from the grid is converted to a variable DC voltage in the power factor correction stage, then back to the power transfer frequency (nominally 85 kHz) in the inverter stage. An impedance matching network (IMN), consisting of capacitors and inductors and containing a variable reactance element to form a tunable matching network (TMN), converts the largely inductive impedance of GA resonator coil to enable the inverter to efficiently drive the system over the range of impedances reflected back from the vehicle side resonator. The magnetic field created by the GA resonator coil couples to the VA resonator coil, inducing a voltage that drives the VA electronics, comprising a tunable impedance matching network and a rectifier. The output of the rectifier is connected directly to the vehicle battery for charging. Some systems may optionally utilize a DC/DC converter for impedance conversion, but the TMN enables exclusion of this component. Information exchange between the ground and vehicle sides for system control occurs via a standard wifi connection.

FIGURE 2 Block diagram for a WPT system (G2V).



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The WPT system must operate over a range of relative coil positions (X, Y, Z) and output battery voltages as specified in the SAE J2954 TIR. These are summarized in Table 1 for the Z2 ground clearance class.

The magnetic coupling varies with relative GA/VA coil position (i.e. parking position), and the vehicle battery voltage and output power determine the effective loading condition on the system. This range of expected operating conditions determine the range of impedances that must be driven by the ground side inverter. To reduce the burden on the inverter (which reduces cost and improves efficiency), a TMN is used on both the GA and VA to keep the impedance seen by the inverter in a smaller and more desirable range.

TABLE 1 Summary of the operating conditions expected for the WPT system.

X range (direction of vehicle travel)	+/– 75 mm
Y range (lateral direction)	+/– 100 mm mm
Z range	140-210 mm
Battery Voltage range	280-420 V DC

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FIGURE 3 TMN operating region for GA/VA position of highest coupling (top plot) and for the weakest coupling position (bottom plot). The shaded region is the set of possible TMN states in which full power delivery is possible over the full range of battery voltages.

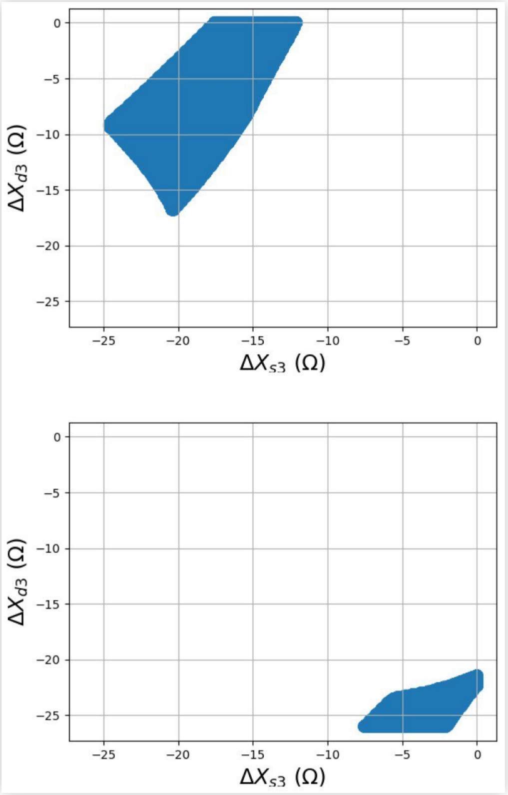

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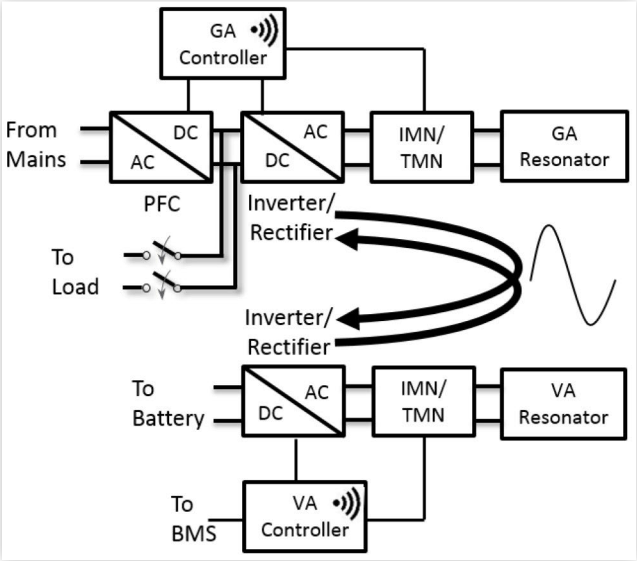
Figure 3 illustrates the benefit of having a tunable matching network on both the GA and VA. In these plots, the X-axis is reactance of the ground side TMN and the Y-axis is the reactance of the vehicle side TMN. The controller can adjust the reactance of either TMN over the full range shown. The shaded region is the set of GA/VA TMN reactance values in which it is possible for the inverter to efficiently deliver full power (7 kW in this case) over the full range of battery voltages. The top plot corresponds to a high coupling position, i.e., the VA is centered above the GA at the minimum Z-height (X = 0, Y = 0, Z = 140 mm), while the bottom is the weakest coupling position (X = 75 mm, Y = 100 mm, Z = 210 mm). It is seen in the upper figure that the IMN values are clustered near the upper left corner, whereas in the lower one they are clustered in the lower right corner with no common operating points. Without the TMN it would not be possible to deliver full power at all offset positions.

The bidirectional WPT system will also take advantage of the flexibility that the TMN provides. It will be used to overcome the variable loading conditions and range of vehicle positions encountered in practice.

FIGURE 4 Block diagram for a bi-directional WPT system.



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Bi-directional WPT Considerations

Most earlier work on bi-directional wireless power transfer assumed that the coils and impedance matching were symmetric. See [6, 7, 8] as examples of this. In that case the symmetry ensures the system should perform equally well transferring power in either direction. However, for wireless charging of vehicles, the application requirements generally limit the space available on vehicle for a VA resonator, and the desired (X, Y, Z) offset range requires a larger GA coil, so the WPT system is generally asymmetric. For example, the size of the GA coil used in this work is 650 x 500 mm while the VA size is 334 x 334 mm. In addition, the IMN component values are not the same on the GA and VA.

The focus of this work is to determine if the uni-directional system described in the previous section can be adapted to provide power flow in the reverse direction (V2G) while maintaining J2954 compliance for G2V operation. Of course, a few modifications are required to enable bi-directional operation, but one goal is to keep the number of changes to a minimum. In particular, we would like to use the same GA and VA resonators and fixed IMN networks if possible.

A block diagram of a bi-directional WPT system is shown in Figure 4. It is a slightly modified version of the G2V system, as can be easily seen by comparing it to the diagram in Figure 2. To support bi-directional operation, the rectifier on the VA side is modified to act as an inverter during V2G operation during which power is supplied by the vehicle battery. Likewise, control of the inverter in the GA side is modified, such that it can be also used as a rectifier. Additionally, the ground side must be modified to allow power to be delivered back to the grid during V2G operation. We show this as a separate load being switched in, but it could be accomplished in other ways. Overall, these modifications require only minor hardware changes; semiconductor switches replace the rectifier diodes so that it becomes equivalent to the inverter on the ground side, and switches added to the ground side for connecting a load. In addition, the controllers must now support both operating modes and be responsible for mode changes in the inverter/rectifier blocks.

With these modifications, power can be transferred either from G2V or from V2G. The G2V mode is the same as explained above. In V2G mode, the battery directly drives the VA side inverter. This means there is no bus voltage control as in G2V operation. However, a DC to DC converter could be added (shown as optional in Figure 2), it could be used to provide bus voltage adjustment. In V2G mode, the VA Resonator becomes the transmitter coil and the GA Resonator becomes the receiver coil. Due to reciprocity, the coupling between the two coils is the same in both directions, hence the theoretical power transfer efficiency remains the same. However since different matching networks are used in the VA and GA, the overall system performance is different for the two different operation modes. In the next section, the system performance for both G2V and V2G operation is explored.

Bi-directional performance

We tested different possible scenarios using a WiTricity system simulation tool. Scenarios include different vehicle battery voltages (Vbatt) and GA bus voltages (Vbus) cases and different coil positions. In the forward power transfer (G2V) mode, thanks to the PFC, Vbus can be adjusted in the designed range (typically 360-500 V DC) while the vehicle battery state-of-charge determines the load voltage seen by the system (280-420 V DC). It is possible that more than one bus voltage can be used to drive the same load voltage, so we evaluate the full set of input/output voltage pairs. The results for G2V operation for different Vbus and Vbatt conditions are shown in the upper plot in Figure 5. For a given vehicle Vbatt, if there is a single Vbus that enables the target power to be delivered, the WPT system is considered fully functional for that value of Vbatt. The black color represents the points where the target power can be delivered (7.0 kW for this case). Different tones of gray indicate less than maximum power can be delivered. The tones change for every 10% change in maximum delivered power. As an example, if Vbatt is 360 V, Vbus can be any value between 320 V to 500 V to deliver the target power. Whereas if Vbus is set to 300 V, then 90% of the target power can be transferred.

On the other hand, for vehicle to grid (V2G) mode, system operation must be considered differently since the vehicle battery voltage determines the driving voltage for the system and is not adjustable. In this case, Vbatt becomes the bus voltage for the V2G operation and it is called V_{VAbatt}. It is assumed that load is a constant voltage load and it is called V_{GAload}. Since it is not possible to change V_{VAbatt}, in principle the system needs to operate at each combination of bus and load voltages. The results for V2G operation are shown in the lower plot in Figure 5 where the same color scheme is used to indicate the level of power transfer that is possible. For example, if the GA load voltage is 360 V, and the battery voltage on the VA is 300 V, then the maximum delivered power is 90% of the target power. In the V2G mode it is not possible to adjust the bus voltage to increase the delivered power. Although this is the case, full power is still possible over a wide range of input/output voltage conditions, especially for the higher battery states of charge. The TMN functionality on the GA and VA plays a major role in enabling significant power transfer across all the operating points.

FIGURE 5 System performance with no additional system modifications at the strongest coupling position (upper G2V, lower V2G). Darkest color indicates full power transfer is possible for that input/output voltage combination, and delivered power is scaled down by 10% for lighter tones.

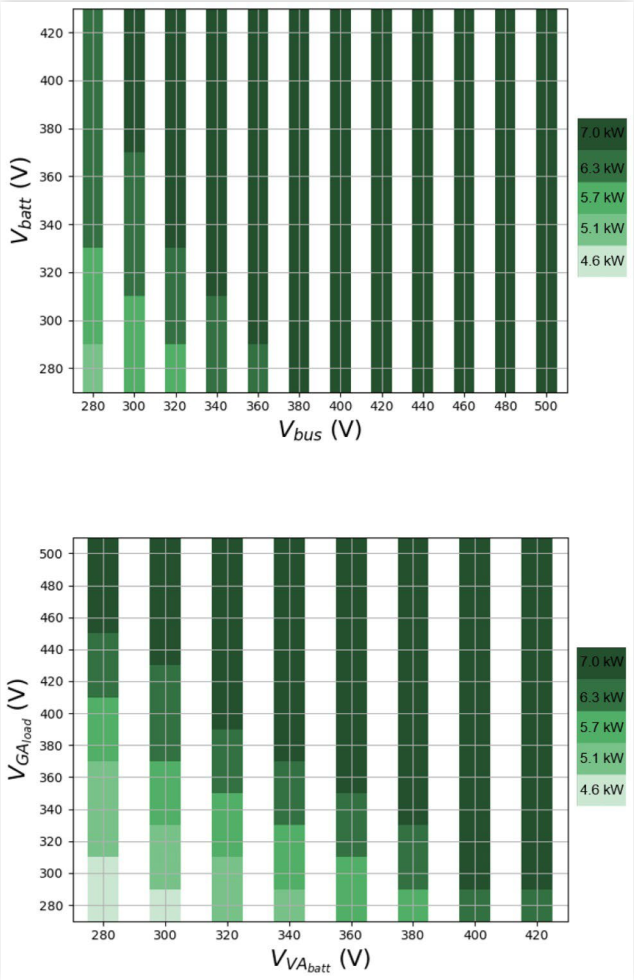

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Figure 6 shows the predicted DC-DC efficiency under the power delivery conditions from Figure 4. This efficiency accounts for the estimated losses in the coils, the IMN/TMN components, inverter and rectifier, but do not include losses in the PFC. In both G2V and V2G cases the predicted efficiency is high (>95%) under all conditions.

WPT system performance can vary with the location of the VA with respect to GA, largely because of changes in the

FIGURE 6 Efficiency map for the strongest coupling position for G2V operation (upper) and V2G operation (lower).

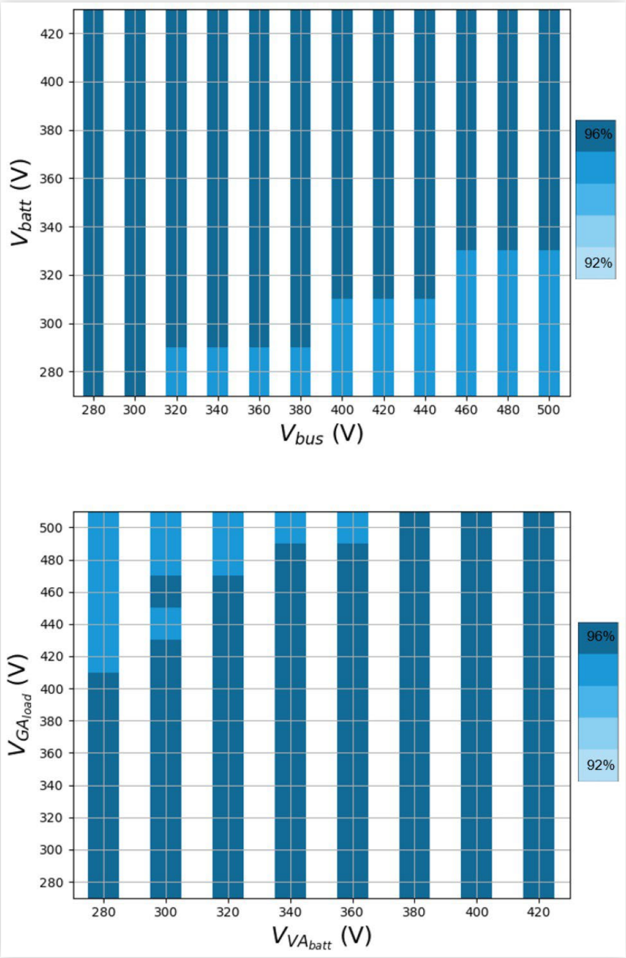

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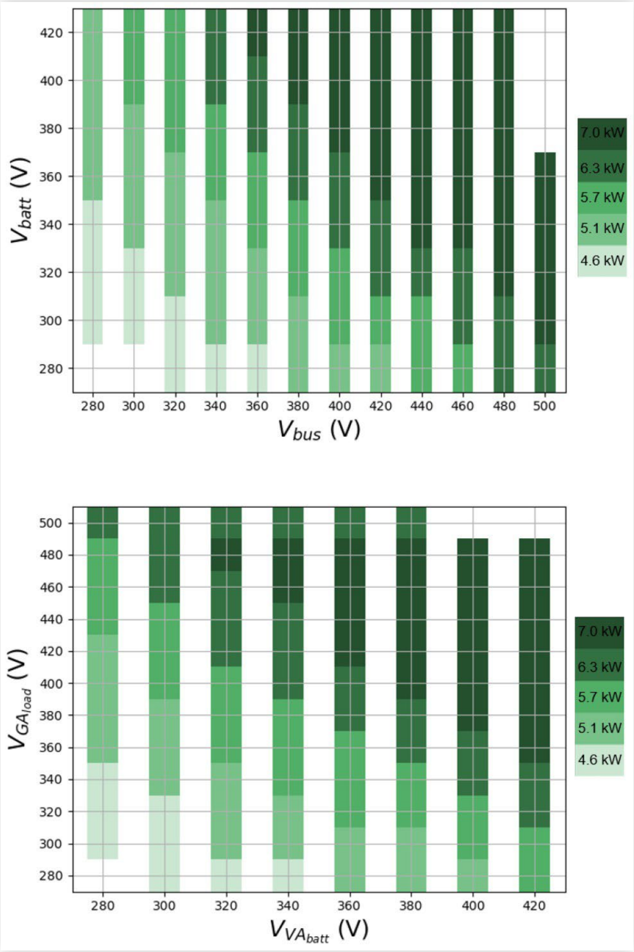
FIGURE 7 System performance with no additional system modifications at the weakest coupling position (upper G2V, lower V2G). Darkest color indicates full power transfer is possible for that input/output voltage combination, and delivered power is scaled down by 10% for lighter tones.



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magnetic coupling between the coils. Magnetic coupling directly influences the possible coil-to-coil efficiency (see Equation (1)), but also impacts the reflected impedance and coil currents required for power delivery. This means the maximum power delivery may change with coil position. To illustrate, the power transfer performance at the weakest coupling position is shown in Figure 7. As before, the top plot is for G2V operation and the bottom plot is for V2G operation. When compared to Figure 5, we see that power transfer at full target power is possible at fewer input/output voltage combinations for both operating modes. While for G2V operation full power is achievable at all but the lowest battery voltages, there is a reduced level of power transfer possible for V2G operation. The TMN plays a critical role to improve the level of power that can be delivered even at the lowest coupling point.

Figure 8 shows the predicted DC-DC efficiency map when the coils are in the minimum coupling position. At lower coupling values, the system must operate at higher coil currents to deliver the same level of power, resulting in higher losses in the coils and somewhat reduced coil-to-coil efficiency (evident from Equation (1)). However, the predicted efficiency is still greater than 93% across this set of operating conditions.

FIGURE 8 Efficiency map for the weakest coupling position for G2V operation (upper) and V2G operation (lower).

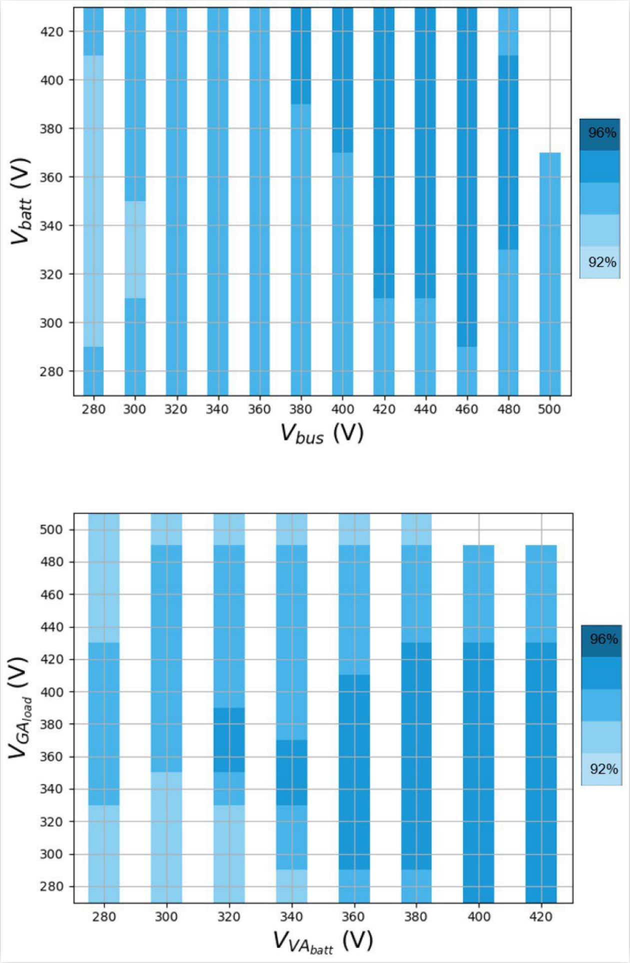

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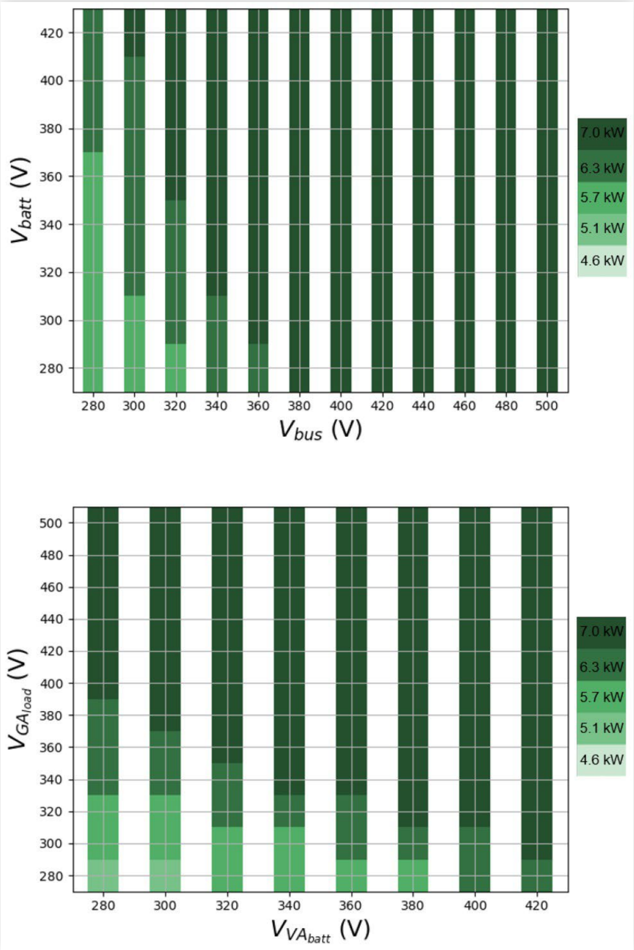
FIGURE 9 System performance with increased TMN range at the strongest coupling position (upper G2V, lower V2G). Darkest color indicates full power transfer is possible for that input/output voltage combination, and delivered power is scaled down by 10% for lighter tones.



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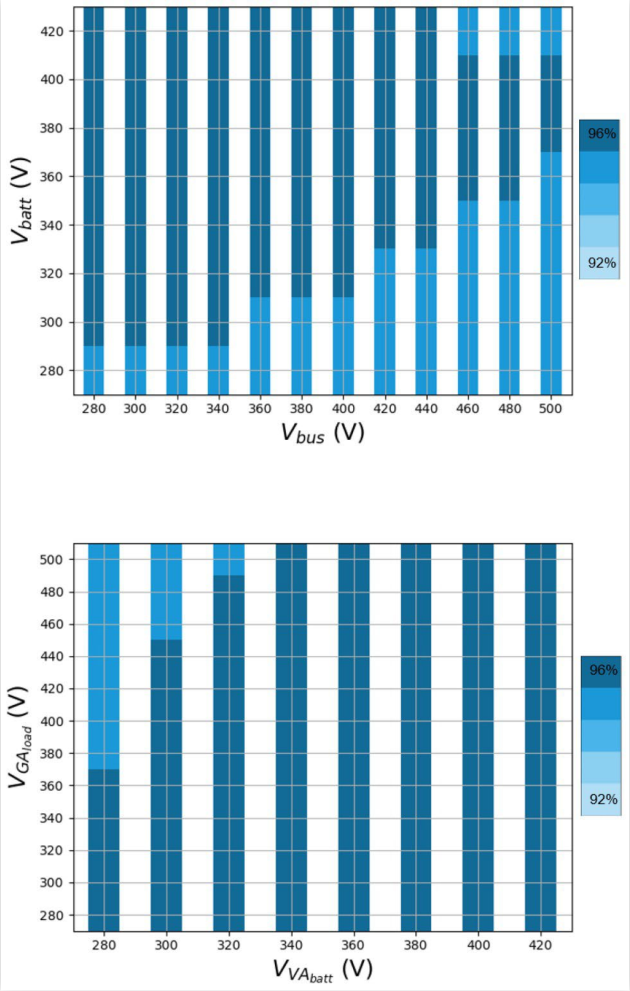
We also explored the impact on WPT performance of increasing the reactance adjustment range on both the GA and VA TMN to 36 Ohms from the original range of 27 Ohms. This is a relatively minor hardware modification that can improve overall performance. The power delivery results with this modification are shown in Figure 9, for the strongest coupling position and Figure 11 for the weakest coupling position. Comparison with Figure 5 and Figure 7 shows the larger range of input/output voltage combinations at which full target power is achieved as well as the increased level of power delivery at other points when the TMN range is increased.

Predicted efficiency maps with the expanded TMN range are shown in Figure 10 for the highest coupling position and in Figure 12 for the weakest coupling position. The efficiency varies with coupling as before but remains high across all of the operating points.

Summary

With V2G power transfer technology, the total battery capacity of all electrified vehicles provides a potentially large energy reservoir that could be used for grid stabilization and to satisfy

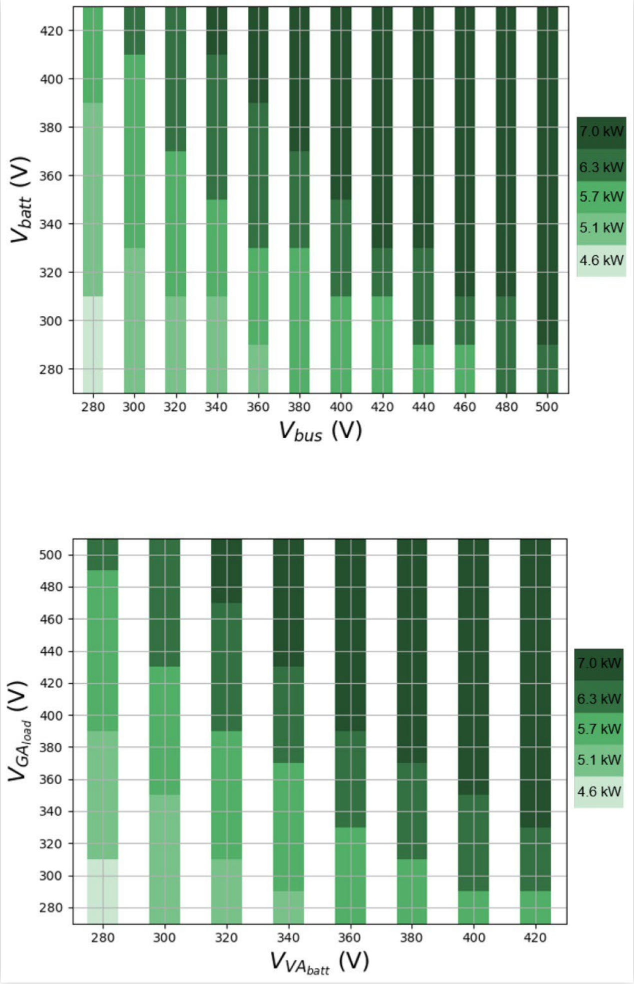
FIGURE 10 Efficiency map with increased TMN range at the strongest coupling position (upper G2V, lower V2G).



peak energy demand. In addition, wireless charging technology for electric vehicles is being developed to enable an automatic and "hands-free" charging experience. The combination of these technologies, V2G functionality in WPT systems, will be necessary to take full advantage of the vehicle battery energy for grid purposes, especially as autonomous vehicles become prevalent.

In this paper, we have shown through system simulations that bi-directional wireless power transfer is possible with a system that meets the emerging standard being developed by SAE J2954. This means vehicles can charge G2V at any standard compliant wireless charging station, while also being

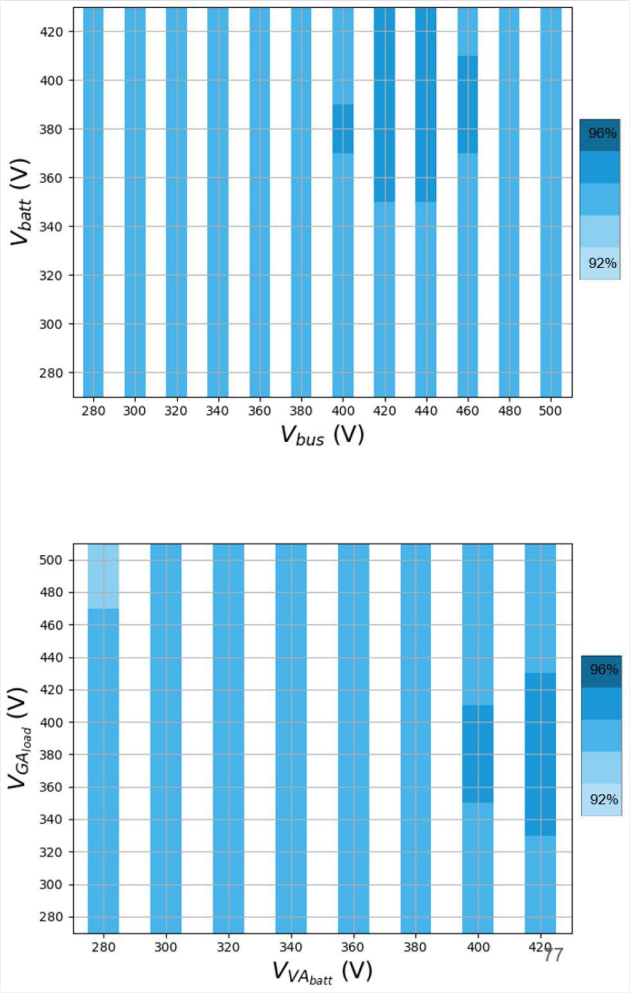
FIGURE 11 System performance with increased TMN range at the weakest coupling position (upper G2V, lower V2G). Darkest color indicates full power transfer is possible for that input/output voltage combination, and delivered power is scaled down by 10% for lighter tones.



able to transfer power back to the grid at bi-directional charging stations. Only small modifications to on-vehicle hardware are necessary to enable this functionality.

Similar power transfer levels (7 kW) and efficiency (>90%) are possible in both G2V and V2G directions. The use of a tunable matching network facilitated operation over a wide range of operating conditions (coil positions and battery voltages) and enabled performance improvements for operation in both G2V and V2G modes.

FIGURE 12 Efficiency map with increased TMN range at the weakest coupling position (upper G2V, lower V2G).



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Definitions/Abbreviations

WPT - Wireless Power Transfer
G2V - Grid-to-vehicle
V2G - Vehicle-to-grid
PFC - Power factor corrector
IMN - Impedance matching network
TMN - Tunable matching network
GA - Ground assembly
VA - Vehicle assembly

ISSN 0148-7191