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Development of Charging System for Plug-in Hybrid Vehicles

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Abstract

In recent years, many various energy sources have been investigated as replacements for traditional automotive fossil fuels to help reduce CO_2 emissions, respond to instabilities in the supply of fossil fuels, and reduce emissions of air pollutants in urban areas. Toyota Motor Corporation considers the plug-in hybrid vehicle (PHV), which can use electricity efficiently, to be the most practical current solution to these issues. For this reason, Toyota began sales of the Prius Plug-In Hybrid in January 2012 in both the U.S. and Japan. This is the first PHV to be mass-produced by Toyota Motor Corporation. Prior to this, in December 2009, Toyota sold 650 PHVs through lease programs for verification testing in the U.S., Europe, and Japan. The system of the recently launched mass-produced vehicle underwent major improvements in response to the results of this verification testing. As a result, EV range was increased with a smaller battery. This development also succeeded in drastically reducing the weight of the system. Reflecting the results of the verification testing, the charging system developed for this vehicle was developed to increase the efficiency, reduce the size, and enhance the convenience of the system and its components. This paper describes the development of this charging system.

Keywords: charging system, lithium battery, PHV (Plug-in Hybrid Vehicle)

1 Introduction

Various issues related to automobiles, such as reducing CO_2 emissions, resolving energy security problems (i.e., instability in the supply of fossil fuels), and reducing emissions of air pollutants in urban areas, must be solved in order for people to continue to enjoy the enjoyment of driving, the convenience of the ability to move freely, and the pleasure of having the comfortable moveable space that automobiles currently provide. Hybrid vehicles (HVs) are one of the most effective countermeasures to these issues. The fuel consumption reduction effects of HVs (i.e., those achieved through regenerative braking, idle stop when the vehicle is not moving, and EV driving at low and/or constant speeds) have achieved major improvements in fuel efficiency and reductions in exhaust emissions compared to a conventional internal combustion engine (ICE) vehicle.

Furthermore, the introduction of electric vehicles (EVs) is a possible means of reducing CO_2 and other emissions. By using electric power from the power grid, it is possible to reduce emissions of CO_2 and air pollutants to zero during driving. However, even when using the latest Li-ion battery technology, energy density is limited to about 1/50 of that of fossil fuels, and the cruising range on a single charge is short. While the cruising range can be increased in proportion to the size of the battery, this means sacrificing some of the cabin and luggage space to increase the battery to a size that will ensure cruising range equivalent to that of an ICE vehicle. Also, larger batteries lead to drastic increases in the weight and cost of the vehicle, and therefore are not practical. Additionally, charging a large capacity battery from an external source in a short period of time would require a DC external charger with the capacity for high electrical output, which requires the installation of dedicated infrastructure. Accordingly, when considering these limitations, it appears that EVs probably will not totally replace the conventional ICE vehicle, now or in the near future. It is assumed that, in the short term, the EV will function as a commuter vehicle that covers short distances.

The plug-in hybrid vehicle (PHV) is a potential solution for these issues. A PHV combines the merits of an EV, since it has zero emissions during driving with electric power, with the merits of an HV, since it does not sacrifice any of the practicality of a standard vehicle. For example, cruising range is equal to or better than that of a conventional ICE vehicle. Furthermore, the vehicle can be fully charged from a household socket in a relatively short period of time without requiring a DC external charger with the capacity for high electrical output. As a result, the system is convenient and easy to use. This paper describes the development of this charging system for the Prius Plug-In Hybrid, the first PHV to be mass-produced by Toyota Motor Corporation.

1.1 New PHV system for 2012 model

Figure 1 shows the PHV system for the 2012 model. The major changes from the base HV are as follows.

1) The battery pack system uses high-capacity Li-ion battery cells.
2) An external charging system compatible with AC 100 V/200 V is installed

This paper describes the charging system.

2 Objective of Charging System for 2012 Model PHV

The charging system was newly developed for the Prius Plug-In Hybrid, reflecting the results of the verification tests performed in the U.S., Europe, and Japan using the 2009 model PHV.

The aims of the charging system development were as follows.

- Achieve a highly efficient charging system
- Improve the convenience of the charging operation

3 Charging System

The charging system was developed in compliance with SAE J1772 Level 1 and 2 as well as IEC61851-1 and IEC61851-21 Mode 2 and 3. The system was designed to handle input voltages between AC100 V and AC240 V for compatibility with different charging environments around the world.

The time required to fully charge the battery is approximately 2.5 hours with an input voltage of 120 V and approximately 1.5 hours with 240 V. This was achieved by reducing charging unit losses, decreasing power consumption by auxiliary devices during charging, and reducing the losses of the power circuit by installing the charging inlet and charger close to the battery.

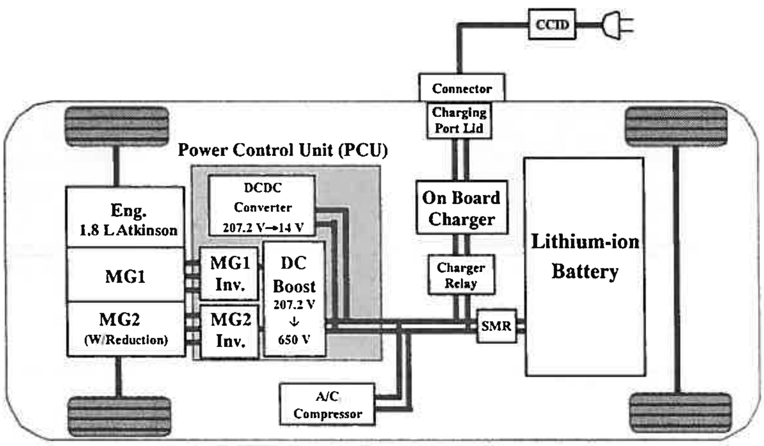

Figure 1: Configuration of newly developed PHV system

The charging control was designed to accurately charge the battery up to the target full state of charge (SOC). A full SOC that is too high may cause battery deterioration. In contrast, a full SOC that is too low may shorten the driving range in EV mode. For this reason, the control lowers the charging power during charging to achieve the appropriate SOC accurately. However, the charging power is only lowered in the region close to full charge to minimize the charging time.

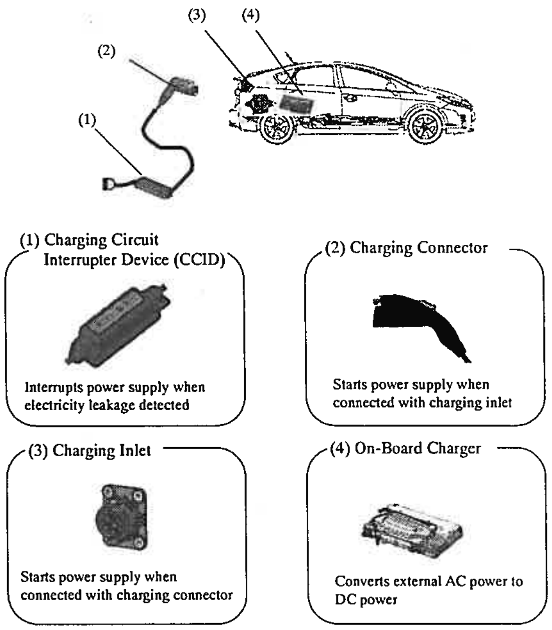

Figure 2: Charging system configuration

3.1 On-board charger

The on-board charger functions to convert the AC from a household power source to DC for charging the battery. The on-board charger was designed with an input voltage range from AC100 V and AC240 V for compatibility with different charging environments around the world. The maximum power is 2 kW.

An air-cooled on-board charger was adopted to enhance its installation freedom. As a result, the charger could be installed in a position below the battery pack that does not affect cabin space or engine compartment layout. This position also enables the adoption of compact charging power circuits, thereby increasing system efficiency and reducing system cost.

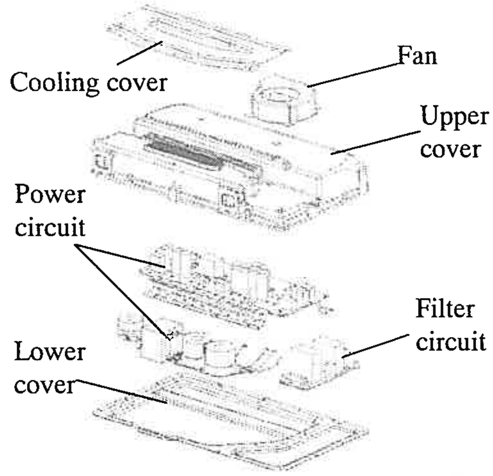

Figure 3: On-board charger structure

Table 1: On-board charger characteristics

Input Voltage	100 to 240 V AC
Input Current	12 A
Output Power	2 kW
Output Voltage	207.2 V
Input Frequency	50/60 Hz
Efficiency	87% (120 V AC)

3.1.1 Internal circuits

The main components of the internal charge circuits are an input noise filter and power factor control (PFC) circuit, a DC-DC converter circuit, an output noise filter, and a controller for the PFC circuit and the DC-DC converter circuit.

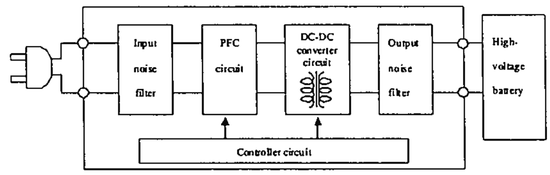

Figure 4: Block diagram of on-board charger circuits

The input and output noise filters consist of an inductor and capacitor. The size of the noise filters was reduced by using inductors with excellent impedance characteristics.

The power factor of the PFC circuits was improved to enable the suppression of high frequencies. A power factor of at least 0.99 was achieved for the developed charger by improving the control of the PFC circuits.

The DC-DC converter circuit consists of an isolating transformer and a switching circuit to drive the transformer. It functions to isolate the AC power source from the vehicle power source. The size and weight of the isolating transformer was reduced by adopting low-loss core materials, as well as by optimizing the core shape and winding structure. These measures enabled the development of a highly efficient on-board charger.

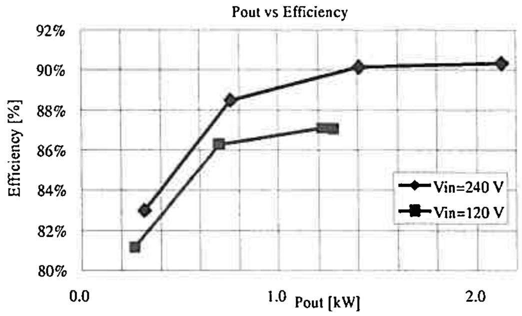

Figure 5: On-board charger efficiency

3.1.2 Cooling

The charger case includes cooling fins to help cool the heat generated by the switching devices, transformer, coil, and the like during charging. The shape of the cooling fin and cooling paths were optimized in the design process using simulations.

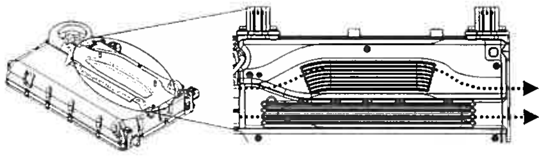
Figure 6: Cooling fins

3.2 Charging cable

The charging cable is the part of the charging system that is directly operated by the user. To improve its usability when charging the vehicle, various improvements were incorporated based on the verification test results and user opinions with the 2009 model.

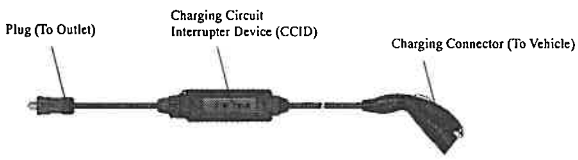

Figure 7: Charging cable

3.2.1 Charging circuit interrupter device (CCID)

The purpose of the CCID is to prevent electrical shocks by detecting AC power leakages and shutting off the power by interrupting the charging circuit with a relay. The CCID also controls the current in the charging cable within the range of the rated current by communicating the rated current of the charging cable to the vehicle using a communication protocol that complies with both SAE J1772 and IEC61851-1.

To make the 2012 model easier to charge, a bus bar was adopted for the charging current supply circuit. As a result, the size of the CCID was reduced by approximately 40% compared to the 2009 model by increasing the number of parts that can be installed in the same space.

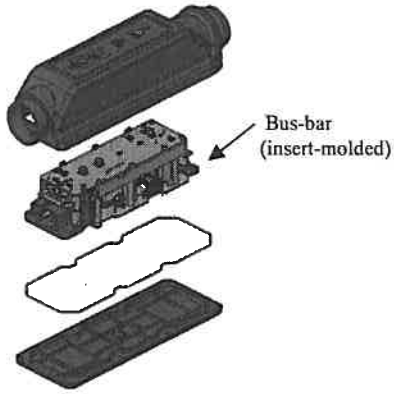

Figure 8: CCID structure

3.2.2 Charging connector

The charging connector was made easier to use by incorporating various improvements identified through the verification test results and user opinions with the 2009 model.

The shape of the charging connector was made ergonomically easier to operate and a padlock slot was provided on the latch release button to reduce the risk of charging cable theft when charging the vehicle at night or other times when the driver is away from the vehicle.

The charging connector also has a charging connector cap to improve durability by reducing the risk of foreign matter intrusion into the connector end.

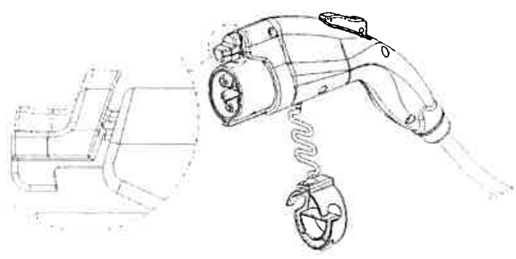
Figure 9: Charging connector structure

To improve usability in cold temperatures, the cable sheath was re-designed to increase flexibility. As a result, the cable of the 2012 model is approximately 50% more flexible than the 2009 model. Since the operating force of the latch release button may increase due to a build up of ice, the shape of the charging connector and latch were re-designed to reduce the operating force in freezing conditions.

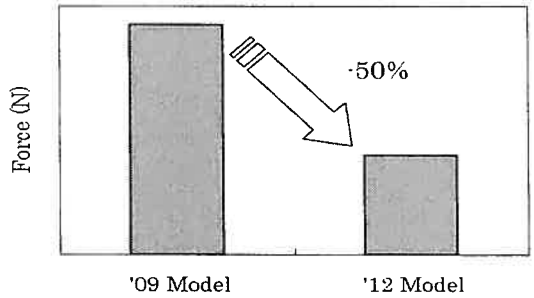

Figure 10: Cable flexibility

3.2.3 Charging inlet

A LED lamp was added to the charging port lid. This lamp lights up the connecting portion of the charging inlet to make it easier to use the charging cable at night. The charging indicator is located close to the charging inlet to notify the user that charging is taking place. The visibility of the charging indicator during charging was also improved. Although the 2009 model was equipped with inner and outer lids, the inner lid was removed for the 2012 model to make the charging operation as easy as possible by reducing the number of required steps. In addition, if the vehicle is driven away with the charging port open, a warning lamp on the meter display alerts the driver to close the lid.

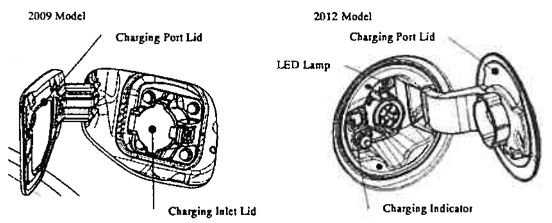

Figure 11: Charging inlet structure

3.2.4 Battery

A new lithium ion (Li-ion) battery cell with high specific energy was developed with characteristics suited for use in PHVs. These battery cells greatly reduce the weight and cost of the system compared with the 2009 model.

The same frame construction as the 2009 model was adopted for the battery pack to ensure high strength and rigidity. The 2012 model also adopted an aluminum extruded material to reduce weight. The combined effects of this frame construction and the high-capacity high specific energy cell reduced both the weight and volume of the battery pack by approximately 50%. As a result, the specific energy of the new battery pack is substantially greater than the 2009 model. Consequently, despite increasing the total battery energy to more than three times the base Prius HV, the Prius Plug-in Hybrid has virtually the same cabin and luggage space.

4 Future Outlook

It will not be possible to avoid the need to effectively use electricity as a source of drive power, to help respond to the various issues facing automobiles, such as energy security problems, CO_2 emissions, and reducing emissions of air pollutants. When considering current technological and social issues (i.e., battery issues such as the high unit cost of energy, low energy density, and short cruising range, and social issues such as the need to build new charging infrastructure), it is likely that EVs will take more time to become a truly effective solution to these issues.

However, a PHV uses electricity as an energy source in the same way as an EV, yet ensures the same level of utility and convenience as a conventional HV. Additionally, it is possible to create a system configuration with a relatively low cost increase over that of a conventional HV simply by adding a charging system. Consequently, the popularity of the PHV may grow since it is the most practical environmentally friendly vehicle for the near future. In developing a highly practical charging system, Toyota is aiming to further popularize the PHV.

The effective use of electricity in the future depends on further improvements in systems and components (such as increasing efficiency, reducing size and weight, and improving usability). In combination with the development of vehicle-to-vehicle (V2V), vehicle-to-house (V2H), and vehicle-to-grid (V2G) applications, charging systems with even greater functionality and performance will be required. Manufacturers must continue to work toward improving the function, performance, and practicality of charging systems to increase the popularity of PHVs.

5 Conclusions

- The Prius Plug-in Hybrid is the first PHV to be mass-produced by Toyota and sales began in early 2012.
- The charging system was developed by improving the charging system based on the system and components of the 2009 model.
- A highly convenient charging system was developed by reflecting the results of verification tests performed in 2009.

References

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