

Development of Charging System for FIT EV

Tomoatsu MURAKAMI*

Hakaru SADANO*

ABSTRACT

A high-efficiency plug-in charging system has been developed for the FIT EV.

The goal of development of the system was to promote the more widespread use of EV. The development was conducted in order to increase the user-friendliness of EV with the aim of offering rapid, high-efficiency, and safe charging. The rapid charging was realized by setting the power of the on-board charger to maximize the capacity of the power distribution equipment employed in the Japanese and U.S. charging environments and expanding the range of the constant power charging control that maximizes the charger's performance. In addition, the minimization of the operating time of the charger has made it possible to realize high-efficiency charging. As a result, the developed system has realized the target of a minimum charging time of within three hours.

With regard to safe charging, the system employs protection against abnormal excess heat produced as a result of greater deterioration of the charge connector terminals under the conditions of use of the system than initially projected. The optimal positions for the charge lids were determined based on studies of the garages in users' homes and public charging stations.

1. Introduction

Today, increased environmental awareness on a global scale and concern over energy security originating in the instability of crude oil supply are stimulating technological development towards the achievement of increased energy efficiency in automobiles, which account for 20% of CO₂ emissions. As is well known, response to the Zero Emission Vehicle (ZEV) regulation in California necessitates the further electrification of automotive drive, and manufacturers are turning to active development of electric vehicles (EV) as the next stage beyond the hybrid electric vehicle (HEV).

The merits of EV are not limited to their environmental performance; the vehicles possess a variety of advantages over internal combustion engine (ICE) vehicles, including quietness and low running costs. Honda was the first major automaker to begin leasing an EV with the EV Plus in 1997. The EV Plus employed plug-in charging⁽¹⁾, utilizing a 4.2 kW on-board charger. Plug-in charging involves electrically connecting the vehicle and a commercial power source, and charging the traction battery with the necessary energy for vehicle operation. In the FIT EV, the aim was to achieve the world's highest figures for miles per gallon of gasoline-equivalent (MPGe) and increase user-friendliness. To determine MPGe, the amount of power consumed from the commencement of charging to the completion of mode driving is measured. This makes it important to increase the efficiency of the on-board charger. The efficiency and

power of the charger were therefore increased, its charging time was decreased, and the unit was further reduced in size.

This paper will discuss the aims for the development of the new charging system and the characteristics of the system.

2. Charging System: Issues and Targets

The plug-in charging necessary for EV corresponds to the supply of fuel to an ICE vehicle. Because the energy density of batteries is lower than that of fossil fuels, in order to achieve an equivalent supply of energy, the charging time for an EV is longer and the charging frequency is higher than the corresponding supply of fuel to an ICE vehicle. These are issues to be overcome in the quest to achieve more widespread use of EV.

Targets were established for the present development in an attempt to address these issues. These were:

(1) Charging in a short period

Minimum charging time target: Within three hours

(2) High level of charging efficiency

Charging efficiency target: 87% or more

(3) Safe charging

3. Overview of Charging System

This section will provide an overview of the charging system employed in the FIT EV.

* Automobile R&D Center

3.1. FIT EV Charging Environment

This section will discuss the charging environments in use in Japan and the U.S.

3.1.1. Specifications for Japanese charging environment

Figure 1 shows Japan's charging environment. Japan employs a quick-charging network based on the CHAdeMO standard, and, a quick-charging system that complies with this standard was employed in the Japanese FIT EV, given that it would therefore be sufficiently practical for charging when the vehicle was on the road. Making use of quick charging at 50 kW, the system can bring the battery to an 80% state of charge (SOC) within 20 minutes.

The main method of normal charging is overnight charging at home, and a specification with an output of 3.3 kW, able to charge the batteries at 200 V within six hours from the time the vehicle is returned home to the time it is driven out again, was therefore employed.

With regard to the on-board charging cable, in addition to a 200 V specification compatible with the recommended charging voltage, the vehicle is also fitted as standard with a 100 V specification for emergency charging.

3.1.2. Specifications for U.S. charging environment

Figure 2 shows the U.S. charging environment. Because there is basically no quick-charging network in the U.S. at present, a quick-charging system was not employed in the U.S. FIT EV. In its place, charging time was reduced by maximizing the output of normal charging as much as

	Type	Charge time	Electric Vehicle Supply Equipment (EVSE)	
Normal charge	100 V 12 A	23 hours	Portable type	
	200 V 15 A	6 hours	Installed type	
Quick charge	DC 50 kW MAX	20 min.		

Fig. 1 Overview of charging (Japan)

	Type	Charge time	Electric Vehicle Supply Equipment (EVSE)	
Normal charge	120 V 12 A	15 hours	Portable type	
	208 V 32 A	3 hours	Installed type	
	240 V 32 A			

Fig. 2 Overview of charging (USA)

possible.

The power distribution equipment fitted as standard in homes has a 32 A continuous rating. A 6.6 kW output that would maximize the capacity of the existing power distribution equipment was therefore set, making it possible to charge the batteries within three hours.

A 120 V specification, stipulated by Article 625 of the National Electrical Code (NEC) as suitable for fitting in a vehicle, was employed as the on-board charging cable.

3.2. Composition of Charging System

Figure 3 shows the basic composition of the plug-in charging system. The section outlined by the broken line in Fig. 3 shows the Japanese specifications of Quick charge system. Figure 4 shows a diagram of the vehicle layout of the system.

Main contactors are positioned at each of the poles of the traction battery. The traction system and the auxiliary equipment system, on the secondary side of the main contactors, are connected to the battery by the main contactors.

In the traction system, traction is obtained by transmitting electricity through the traction inverter to a traction motor.

A DC/DC converter and an on-board charger are connected to the auxiliary equipment system. The DC/DC converter converts power to be sent to the 12 V battery, and the on-board charger converts AC commercial electric power.

The traction battery, DC/DC converter and on-board

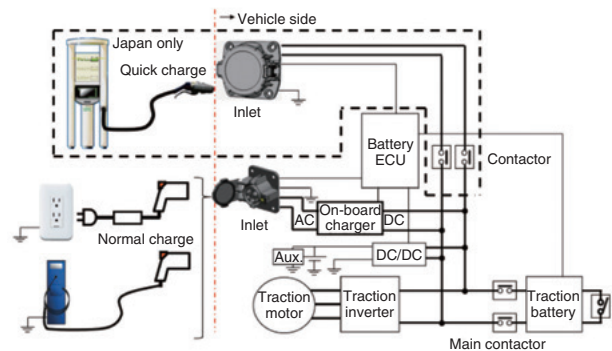


Fig. 3 Charging system

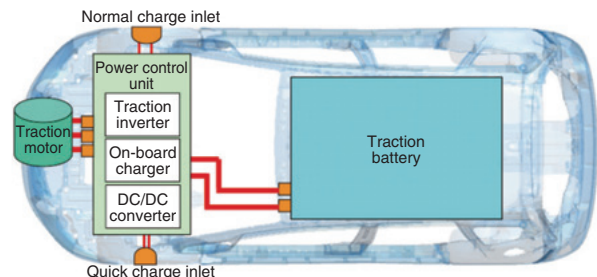


Fig. 4 Vehicle layout for FIT EV (Japan)

charger are all controlled by a battery Electric Control Unit (ECU). All of the communications wires necessary for charging are therefore connected to the battery ECU. Because the state of the traction battery and charge control are intimately related, it is necessary for a fail-safe function to go into effect rapidly in the event of a failure of the charging system. The charge control function was therefore incorporated in the battery ECU, which also has the twin functions of detecting the state of the battery and controlling the distribution of high-voltage power.

The control system for plug-in charging is made up of a communications function between electric vehicle supply equipment (EVSE) and the vehicle, charging output instructions and control, and charging system failure detection and fail-safe action.

3.2.1. Composition of normal charging system

AC commercial electric power input from the EVSE is transmitted via power wires from the vehicle inlet to the on-board charger. The on-board charger converts the AC power to DC, and charges the traction battery. The EVSE is connected to the battery ECU by means of communications wires in the inlet.

3.2.2. Composition of quick-charging system

The quick-charging system is compatible with CHAdeMO V0.9.

DC power input from the charger is transmitted from the vehicle inlet to the traction battery via the contactors. The charger is connected to the battery ECU by means of communications wires in the inlet.

3.2.3. Position of charge lids

Table 1 shows the position of the charge lids for each sales area.

(1) Normal charging

In both Japan and the U.S., home charging is the standard method of normal charging. The user plugs the vehicle in after parking it in the garage, and the charge lids for normal charging were therefore positioned on the driver's seat side in order to help ensure sufficient space.

(2) Quick charging

Because numerous quick-charging stations are located at the side of the road (for example in rest areas on expressways), the quick-charging lid was positioned on the passenger seat side.

4. Technologies Employed to Realize Charging in a Short Period

In order to realize charging in a short period, it was necessary to increase the output of the on-board charger. Figure 5 shows an external view of the on-board charger.

Table 2 shows a comparison of the specifications of the on-board chargers used in the FIT EV and the EV

Table 1 Location of charge lid

Sales area	Normal charge	Quick charge
Japan	Right side	Left side
USA	Left side	

Table 2 Comparison of on-board charger specifications

	EV Plus	FIT EV
Volume	8.6 L	8.1 L
Weight	11 kg	10 kg
Power	4.2 kw	6.6 kW
Cooling	Water	Water
Efficiency	84.4%	91.9%

PLUS. The FIT EV charger is more compact than the unit employed in the EV PLUS while realizing increased power. The charger produces 6.6 kW from a smaller unit than a competitor's 3.3 kW on-board charger. Figure 6 shows the relative positioning of the FIT EV charger against other models.

The rest of this section will discuss the technologies employed to reduce the size of the charger despite its increased output.

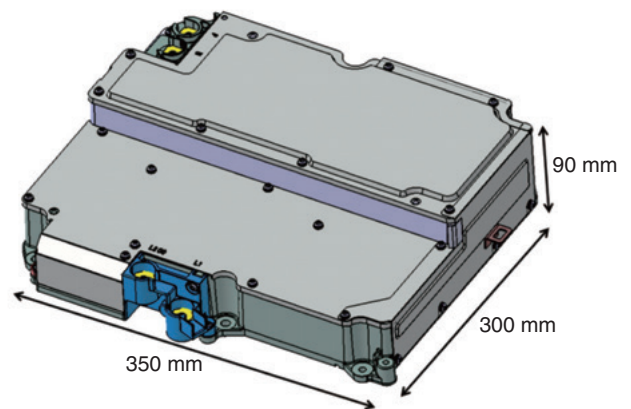


Fig. 5 External view of 6.6 kW on-board charger

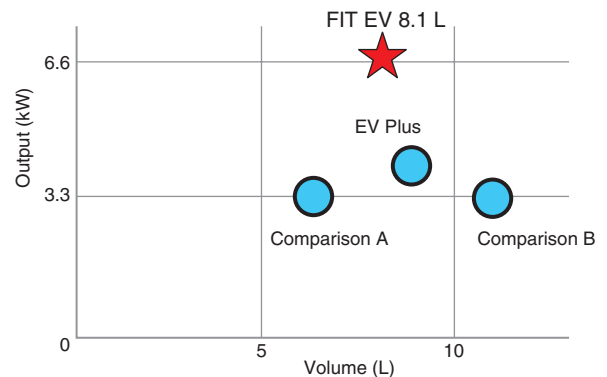


Fig. 6 Volume-power ratio

4.1. Cooling Configuration

The on-board charger is positioned inside the Power Control Unit (PCU). The PCU is fitted with a water jacket for cooling, and the on-board charger is attached to the water jacket to cool it. Figures 7 and 8 show the configuration.

4.2. Reduction of Capacity of Power Factor Correction (PFC) Circuit Output Electrolytic Capacitors

Figure 9 shows a block diagram of the on-board charger circuits.

The electrolytic capacitors used in power factor correction (PFC) circuits have the function of helping to ensure the ripple voltage and minimum voltage that are essential to the normal functioning of the DC/DC converter

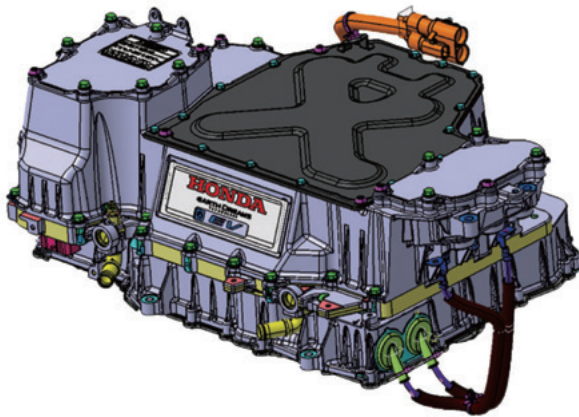


Fig. 7 External view of power control unit

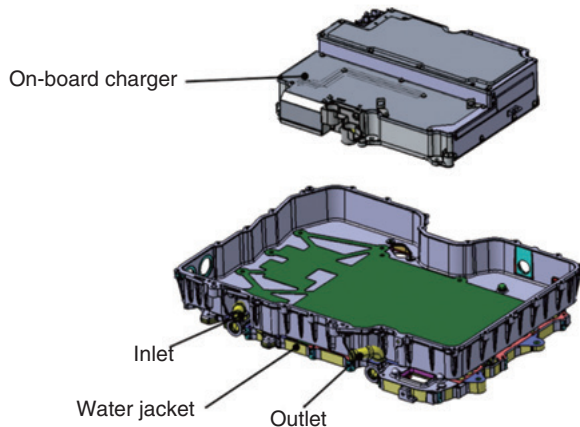


Fig. 8 Cooling structure of on-board charger

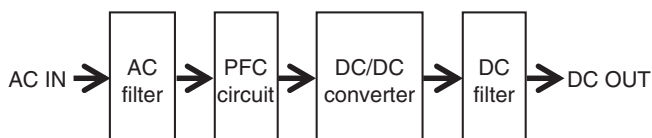


Fig. 9 Block diagram of on-board charger circuits

circuits in the on-board charger. The following methods were employed to address the issue of reducing size by reducing their capacity to the minimum.

4.2.1. Measures in response to increased ripple voltage

When the capacity of the electrolytic capacitors was reduced, ripple voltage superimposed on the commercial power supply sine waves increased. A measurement method in which the value was averaged for every commercial half-cycle was adopted in order to cancel the amount of increase by averaging during measurement.

4.2.2. Measures in response to increase in voltage fluctuation with sudden changes in input voltage

When the capacity of the electrolytic capacitors was decreased, the ability of the system to absorb fluctuations due to sudden changes in the voltage of the commercial power supply declined. To help ensure that this did not result in the termination of charging by the on-board charger due to the operation of over-voltage protection, the system was configured to suspend operation at a lower voltage than the level for operation of the over-voltage protection in order to help prevent voltage increase.

4.3. Increased Switching Frequency

The use of a switching frequency of 90 kHz reduced the magnetic flux density of the windings of the transformer and other parts, making it possible to reduce the size of the cores.

In addition, because the ripple current in the windings was reduced, it was also possible to reduce the size of the smoothing capacitors.

5. Technologies to Realize Increased Charging Efficiency

The energy efficiency (MPGe rating) of EV is evaluated as plug-to-wheel efficiency, based on the tank-to-wheel efficiency (fuel efficiency) used as a benchmark for ICE vehicles. Charging efficiency, an aspect of the MPGe rating, is the power ratio between the output end (the outlet) and the input end (the traction battery). Charging time is the time necessary to proceed from a state in which the low charge indicator is lit to a state of full charge.

Given this, the ideal measure to increase the MPGe rating via the range covered by plug-in charging would be to reduce power loss from the outlet to the traction battery to zero.

As will be discussed below, comprehensive reduction of charging-related loss during the development of the FIT EV charging system resulted in the achievement of a charging efficiency of 87.9%.

5.1. Reduction of Loss via Reduction of Charging Time

The reduction of charging time not only has considerable benefits from the perspective of users, but also significantly

affects charging efficiency.

During plug-in charging, devices including the on-board charger and battery cooling system are in operation. If the charging time is lengthy, the energy loss associated with the operation of these devices reduces charging efficiency per charge.

In order to reduce charging time in the FIT EV charging system, both hardware-based measures, in particular the realization of increased output from the on-board charger, and software-based measures to realize charging control able to maximize charger performance, were employed.

On the hardware side, the output of the charger was determined based on consideration of compliance with legally stipulated regulations and standards and potential increase in the size of the charger.

On the software side, a control specification that would maximally increase the range of constant power charging, making it possible to maximize the performance of the hardware, was realized by means of accurate prediction of the relationship between the voltage characteristic during charging and the SOC by the battery ECU. Switching to constant voltage charging during the final stage of the charging process controls overshoot, which reduces the durability of the battery, in addition to increasing the accuracy of full charge. Figure 10 shows the relationship between SOC and charging power.

5.2. Design of On-board Charger for High Efficiency

In a plug-in charging system, loss from the on-board charger represents the major factor in loss. Reduction of loss from the on-board charger contributed to increased efficiency, reduction of size and weight, and reduction of power consumption for cooling.

Figure 11 shows efficiency for different output levels of the on-board charger.

5.2.1. Use of soft switching

Soft switching has been employed to reduce switching

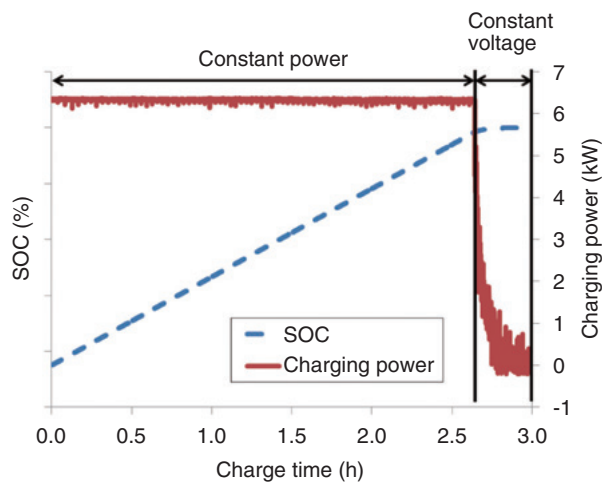


Fig. 10 Charging power control

loss. Figure 12 shows the soft-switching circuit employed in the FIT EV. As the circuit diagram shows, soft switching has been realized through the use of a resonance choke in the circuit.

5.2.2. Reduction of loss from rectifying diodes

The reduction of surge voltage due to the application of soft switching made it possible to reduce the withstand voltage of the diodes from 1200 V to 600 V. This reduced the diode recovery current, increasing the efficiency of the DC/DC converter in the on-board charger by approximately 1%. Figure 13 shows the switching waveform and loss.

5.2.3. Reduction of loss in transformer and chokes

(1) Reduction of loss in coils

Due to the skin effect, high-frequency alternating current does not flow for a depth equivalent to the skin depth. The surface area of the electrical wires can be increased in order to reduce the resistance of the alternating current as a result of this phenomenon. Litz wire was therefore employed. Figure 14 shows a structure of a Litz wire.

For the cores, a dispersed arrangement that reduced individual gap widths without changing the total gap length

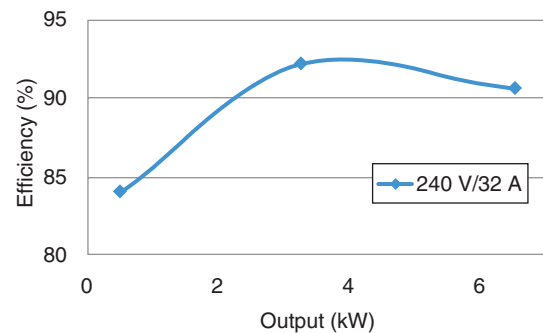


Fig. 11 On-board charger efficiency

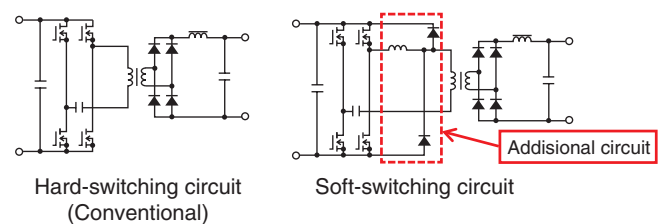


Fig. 12 Comparison of switching circuits

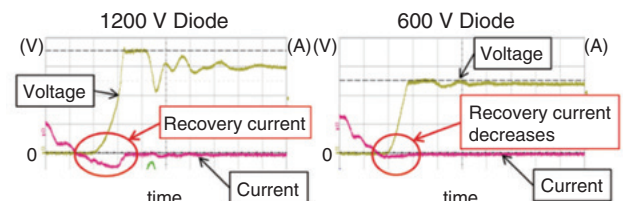


Fig. 13 Comparison of diode recovery current

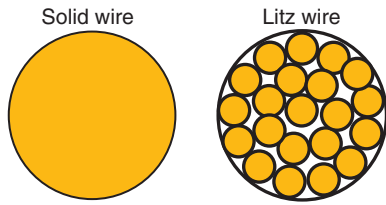


Fig. 14 Structure of solid wire and litz wire

was adopted. This reduced the degree of linkage of the leakage flux with the coils, reducing loss.

(2) Reduction of loss in the cores

Dust cores were employed in order to reduce loss. When dust cores are employed, heat is dissipated from the surface into the air due to the toroidal shape of the cores, thermal resistance becomes the issue. Resin molding of the choke was considered as a means of addressing the issue, but half-molding was finally adopted due to the increase in weight associated with the former method.

6. Technologies for Increased Safety

When charge connectors installed in vehicles deteriorate, connection resistance increases and excessive heat may be generated. A thermistor that detects excessive heat has therefore been fitted in the terminal employed in the vehicle inlet; when a preset temperature threshold is reached, charging current is reduced to help prevent excessive heat in the charge connector. Figure 15 shows the mounting configuration for a thermistor in an inlet for normal charging.

This measure is employed for both quick charging and normal charging. With consideration of the heat resistance of the structural parts of the charge connectors, a value that would not result in mistaken detection was employed as the threshold value for heat protection.

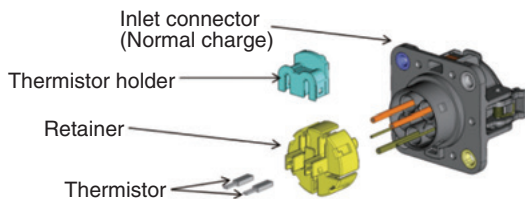


Fig. 15 Structure of inlet thermistor

7. Conclusion

A compact and lightweight on-board charger has been developed that increases the efficiency of the FIT EV plug-in charging system as a whole and introduces the latest technologies to the system. As a result, a charging efficiency of 87.9% has been achieved, and targets for the realization of a short charging time, high efficiency, and a

high level of safety have been met. According to a Honda survey conducted at the end of August 2012, the system achieved the world's highest MPGe rating. The system is also sufficiently competitive as a product, able to charge a battery within three hours.

References

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■ Author ■



Tomoatsu MURAKAMI



Hakaru SADANO