

Development of a New Two-Motor Plug-In Hybrid System

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ABSTRACT

A highly efficient two-motor plug-in hybrid system is developed to satisfy the global demands of CO₂ reduction. This system switches three operation modes, what is called "EV Drive", "Hybrid Drive" and "Engine Drive", to maximize fuel efficiency according to the driving condition of the vehicle. Practical plug-in EV (Electric Vehicle) capability is also realized by adding a high-power on-board charger and a high capacity Li-ion battery to the original system.

The outlines of the system components including a newly developed Atkinson cycle engine, a highly efficient electric coupled CVT (Continuously Variable Transmission) with built-in motor and generator, an integrated PCU (Power Control Unit) and an exclusive battery for plug-in HEV (Hybrid Electric Vehicle) are described in this paper.

In addition to the switching of three driving modes and the efficiency improvement of each device, cooperative control of the hybrid system is introduced.

By installing this system in 2014 Accord plug-in hybrid, superior fuel economy is achieved with values of 46 MPG in CS (Charge Sustaining) mode and 115 MPGe (Miles Per Gallon equivalent) in CD (Charge Depleting) mode. 13 miles of AER (All Electric Range) is also achieved while maintaining sufficient driving performance as a mid-size sedan.

MPGe is a unit of fuel economy for the alternate fuel vehicles such as plug-in hybrid or electric vehicles. The ratings are calculated by converting used electric energy into equivalent amount of gasoline.

CITATION: Higuchi, N., Sunaga, Y., Tanaka, M. and Shimada, H., "Development of a New Two-Motor Plug-In Hybrid System," *SAE Int. J. Alt. Power.* 2(1):2013, doi:10.4271/2013-01-1476.

INTRODUCTION

Compliance with global strengthening of emission regulations is an urgent issue for the automobile industry. The final solution for this requirement should be to putting zero-emission vehicles, such as BEV (Battery Electric Vehicle) or FCEV (Fuel Cell Electric Vehicle) into practical use. However, they could not be a suitable replacement of conventional cars because of their limited driving range and higher cost due to current technical limitations. Therefore, HEV (Hybrid Electric Vehicle) application has been expanding globally as one of practical solutions.

A new two-motor plug-in hybrid system which realizes both environmental friendliness of zero-emission vehicles and practicalities of HEVs is developed to satisfy this situation and main features are discussed in this paper.

OVERALL CONFIGURATION

The major components of the new two-motor plug-in hybrid system are placed in the vehicle as shown in [Figure 1](#). An electric coupled CVT (e-CVT) is installed in the position of a conventional transmission and utilized in combination with an Atkinson cycle engine optimized for HEV application. The PCU (Power Control Unit) is positioned above the e-CVT and cooled by an independent water cooling circuit separated from the engine. Various functions including high-voltage inverters, VCU (Voltage Control Unit) and motor/generator ECU (Electric Control Unit) are integrated in the PCU. IPU (Intelligent Power Unit) is installed behind the rear seats and cooled by cooling fans located in the trunk room. A Li-ion battery specially designed for plug-in hybrid, a DC/DC converter, a high-power on-board charger and a battery ECU constitute the IPU as one package. [Figure 2](#) shows a structure of the IPU.

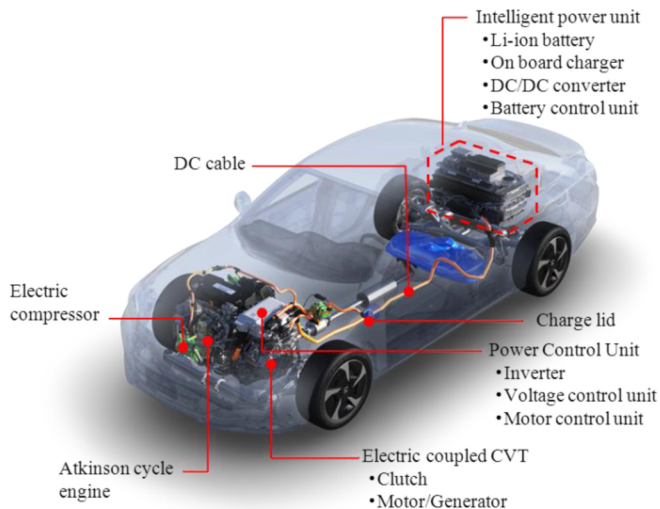


Figure 1. Overall system configuration

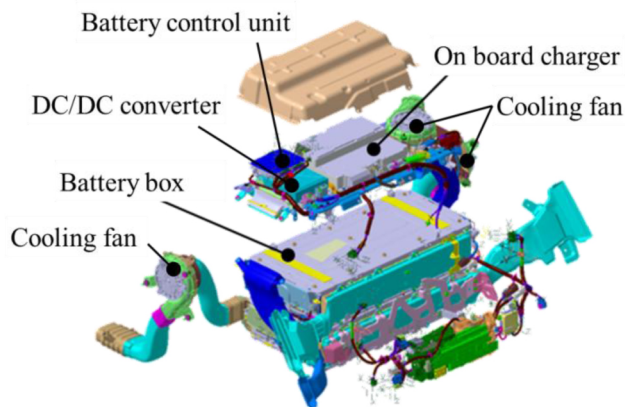


Figure 2. IPU (Intelligent Power Unit)

POWER TRAIN

Overview

An overview of the power train is shown in Figure 3 and operation modes of this system are explained in Table 1.

This system can be operated in three operation modes explained below.

In “EV Drive” mode, the electric motor physically connected to the driveshaft propels the vehicle by using electric energy stored in the high voltage battery. In “Hybrid Drive” mode, the electric motor is driven by electric energy generated by the generator using output from the engine. In “Engine Drive” mode, the engine-drive clutch located between the engine and wheels is engaged, and the vehicle is directly propelled by the engine output.

Fuel efficiency of all driving conditions is maximized by switching these three driving modes properly.

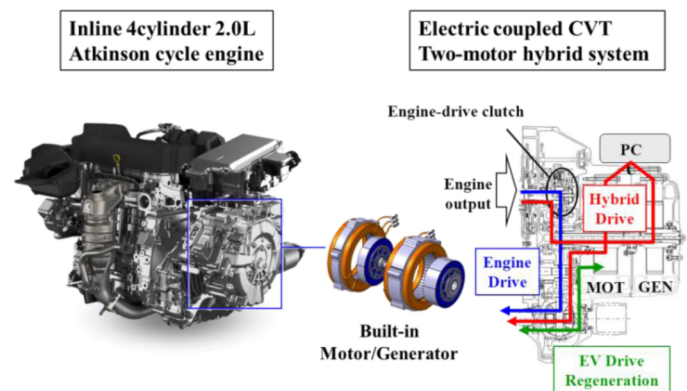


Figure 3. Hybrid power train

Table 1. Operation modes

EV Drive	Hybrid Drive	Engine Drive
Use electric energy from battery to drive motor	Use electric energy from engine generator to drive motor, with assistance from battery	Use engine to directly drive wheels

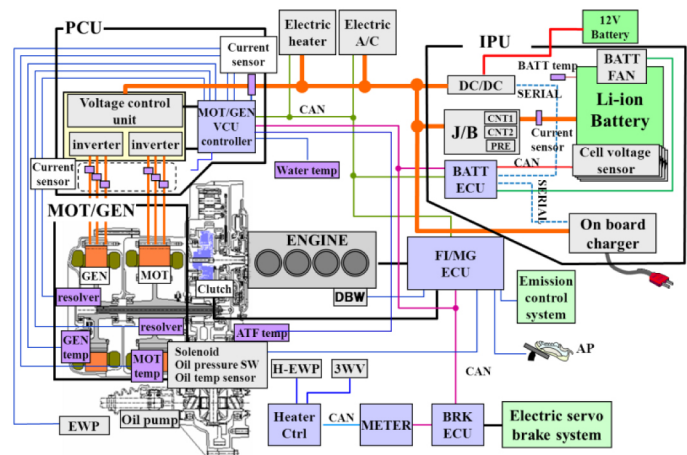


Figure 4. Block diagram of hybrid system

Figure 4 is a block diagram of this system. The powertrain system of this vehicle consists of an Atkinson cycle engine, an e-CVT with built-in motor and generator, a PCU and a high-voltage battery. ECUs, which control these power train components, realize cooperative control each other through the on-board communication network.

Moreover, an overall system configuration is designed for cooperative control with related systems such as an electric servo brake, an electric air conditioner and an electric heater

to optimize system efficiency according to the situation of the vehicle.

The outlines of the powertrain components and related systems are described in the following sections.

Atkinson cycle engine

A 2.0 L DOHC (Double Over Head Camshaft) engine for this two-motor hybrid system is developed newly. Atkinson cycle and cooled EGR (Exhaust Gas Recirculation system) are adopted and these technologies combine with the VTEC (Variable valve Timing and Electric Control) system. This engine has two cam profiles, output cam and fuel economy (FE) cam, so maximum output 105 kW and 10% improvement of BSFC are attained.

VTEC system and operation area are shown in Figure 5 and 6. Engine power performance and enhancement of fuel consumption are shown in Figure 7 and 8.

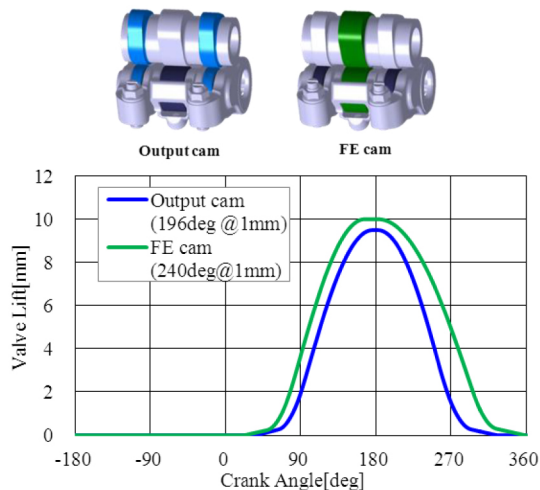


Figure 5. VTEC system

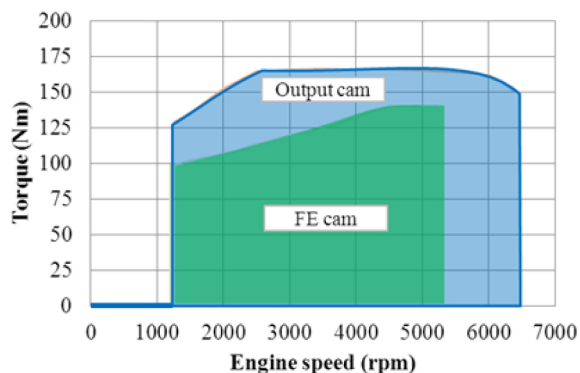


Figure 6. VTEC operation

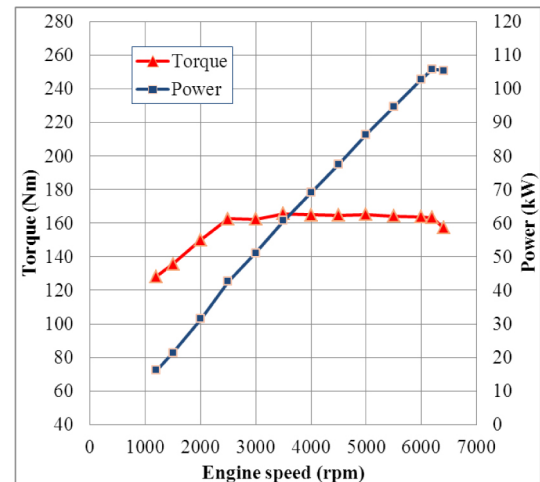


Figure 7. Output performance

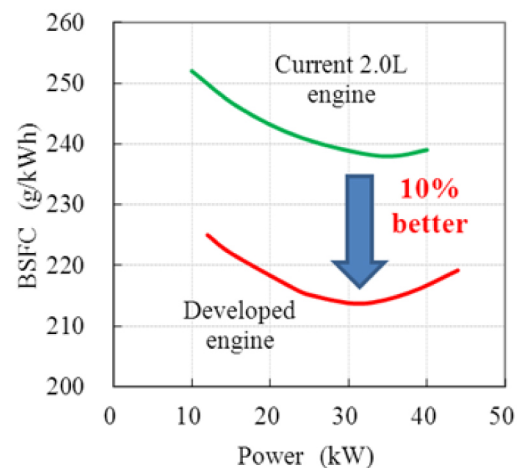


Figure 8. Enhancement of fuel consumption

e-CVT (electric coupled CVT)

A cross-sectional view of the e-CVT is shown in Figure 9. The e-CVT has a three-shaft configuration which consists of input, counter and output shaft. Transfer efficiency maximization and the miniaturization of the transmission structure are realized simultaneously by reducing the number of engagements of the gear teeth. By accelerating rotating speed of the generator compared to the engine, the generator can be operated in efficient area and its width can be reduced. As a result, the e-CVT is suitable for engine room installation since its overall width is equal or thinner than conventional transmissions.

The e-CVT has two mechanical oil pumps to deal with three driving modes of the system. One is mounted on the input shaft of the e-CVT to control the engine-drive clutch and cool the motor and generator. Another one for lubrication is mounted on the output shaft.

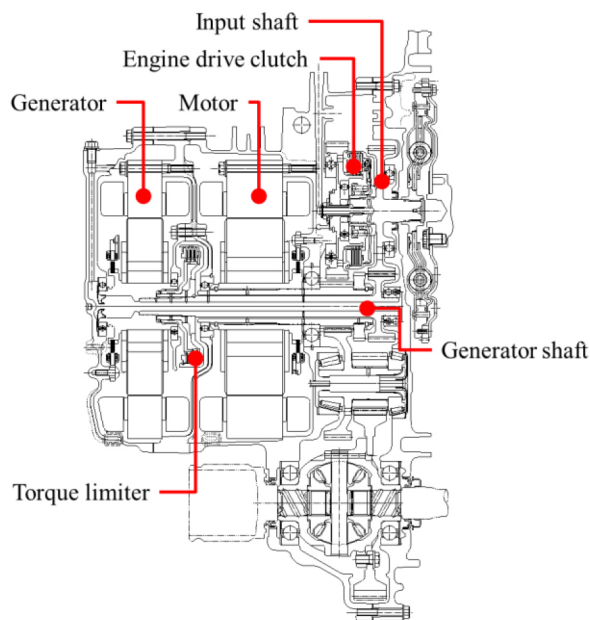


Figure 9. Cross-sectional view of e-CVT

System efficiency of “EV Drive” and regeneration is maximized since the motor output is transferred to the final gear through only two engagements of the gear teeth. Friction loss of the engine-drive clutch that switches “Hybrid Drive” and “Engine Drive” is reduced 46 to 80% compared with conventional automatic transmissions due to optimization of its clearance and the facing area.

To improve drivability of the vehicle, the engine-drive clutch is controlled in cooperation with the engine, the generator and the electric motor. If driving mode is changed from “Hybrid Drive” to “Engine drive”, the speed difference between input and output is eliminated by controlling engine speed using the generator prior to the engagement of the clutch. In this way, the clutch can be engaged without noise and vibration.

Motor

A high torque and power motor with smaller size is developed by utilizing reluctance torque, high-speed rotation and voltage amplification up to 700 V to meet system feature that requires the largest driving power during “Hybrid Drive” mode. Table 2 shows achieved specifications of the motor.

Table 2. Specification of motor

Type	Synchronous motor
Max. torque [Nm]	307
Max. power [kW]	124
Max. speed [rpm]	12584

The frequency of low-load operation is high during city driving and high speed cruising. In these areas, magnet torque should be reduced and reluctance torque needs to be

increased since an iron loss caused by magnetic flux fluctuation has sizable proportion.

The profile of motor core is shown in Figure 10. To maximize reluctance torque, a distributed winding motor with an IPM rotor utilizing “V” configuration magnets is developed. Figure 11 shows relationship between motor torque and current angle. Developed motor torque is enhanced 82% compared with the torque of 0 degree by utilizing reluctance torque.

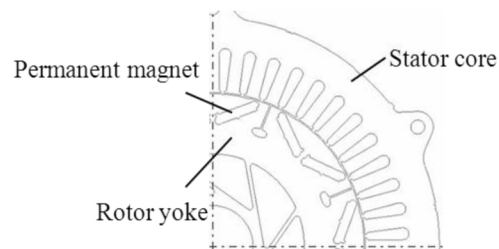


Figure 10. Profile of motor core

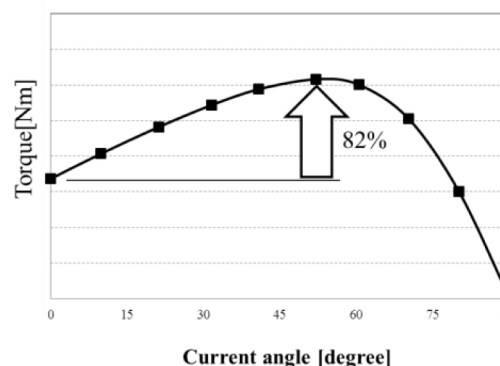


Figure 11. Torque characteristic vs. current angle

To realize high speed rotation of the motor, slit structures are made on the rotor yoke. Simulated stress distribution on the rotor with rotation is shown in Figure 12. Large stress is concentrated on the ribs outside of the magnets at the time of high speed rotation because of centrifugal forces of the permanent magnets. In order to reduce the stress on the ribs, structural rigidity around the slit is made low. As a result, stress concentration is reduced 53%.

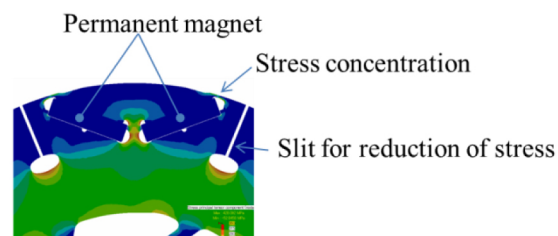


Figure 12. Simulated stress distribution

Battery voltage is amplified to realize both miniaturization and higher power of the motor. If the voltage