Development of SPORT HYBRID i-MMD Control System for 2014 Model Year Accord

Hirohito IDE* Yoshihiro SUNAGA* Naritomo HIGUCHI*

ABSTRACT

A highly efficient two-motor hybrid system named SPORT HYBRID Intelligent Multi-Mode Drive was developed and mounted in the 2014 model year Accord to meet global demands for CO_2 reduction. The control system switches the three drive modes of “EV drive,” “Hybrid drive” and “Engine drive” according to the driving conditions. Together with hybridization, this helped to enhance fuel economy by 39%. In addition, cooperative control between components was developed that supports the large system configuration, and helped to achieve both reliability and driving performance. Installation of this system and control technology in an Accord plug-in hybrid achieved an EV driving range of 13 miles and fuel economy of 115 MPGe (Charge Depleting mode) and 46 mpg (Charge Sustaining mode). Furthermore, sufficient driving performance was also maintained while observing the constraints required to secure reliability.

1. Introduction

Demands are increasing further on the automotive industry to reduce the environmental load, such as by reducing CO_2 emissions. The Integrated Motor Assist (IMA) system, which is lighter in weight and more compact, has been proposed as one method for addressing this issue. In addition, zero emission systems such as fuel cell EV systems and battery EV systems have also been proposed. Enhancements such as even higher hybrid system efficiency and longer zero emission cruising ranges are urgently needed to further reduce the environmental load in the future. A new two-motor hybrid system called SPORT HYBRID Intelligent Multi-Mode Drive (SPORT HYBRID i-MMD) was developed to meet these demands[(1)]. This hybrid system features higher efficiency than previous hybrid systems, and also provides power performance enabling use in mid-size sedans. In addition, this system also increased the zero emission cruising range of the SPORT HYBRID i-MMD Plug-in that is equipped with a large-capacity battery and a plug-in charging function.

This paper describes the goals and features of the newly developed two-motor hybrid system using the SPORT HYBRID i-MMD Plug-in as an example. In addition, this paper also discusses the control system that contributed to increasing efficiency and securing vehicle reliability, and the performance achieved by an actual vehicle.

* Automobile R&D Center

2. Development Goals

The previous IMA system made use of the characteristics of a lightweight and compact hybrid system to achieve enhanced fuel economy mainly in compact cars. However, similar enhancements in fuel economy are also needed for mid-size sedans and larger classes to reduce the environmental load in the future. Therefore, the two-motor hybrid system SPORT HYBRID i-MMD was newly developed with the aim of high efficiency. This system switches the three modes of EV drive, Hybrid drive and Engine drive according to the driving conditions, and has the following features compared to the IMA system.

(1) Expanded EV driving range and higher efficiency
(2) Expanded area enabling highly efficient engine operation
(3) More efficient recovery of deceleration energy

As a result, it is thought that this system can achieve good fuel economy. However, the system configuration is larger than that of the IMA system, and coordinated operation is needed to maintain sufficient driving performance while observing the various constraints for securing reliability. Therefore, a control system was developed that simultaneously realizes both fuel economy and driving performance by performing the appropriate control for the system in accordance with various environmental and driving conditions.

3. Overview of System

3.1. Overall Configuration

Figure 1 shows the major components of the SPORT HYBRID i-MMD system. An electric coupled CVT comprising two motors (motor and generator) and a clutch is built into the transmission case and located inside the engine room together with a newly developed Atkinson cycle engine optimized for HEV[2]. A Power Control Unit (PCU) incorporating a voltage control unit that boosts the Li-ion battery voltage, a motor control unit used to control the motor[3] and generator, and an inverter is located above the electric coupled CVT. An Intelligent Power Unit (IPU) consisting of a Li-ion battery, a DC/DC converter, and a battery control unit that controls the Li-ion battery and DC/DC converter is located behind the rear seat. The plug-in hybrid vehicle is also equipped with a dedicated high-capacity Li-ion battery and high-output onboard charger, enabling city driving in EV drive mode with a range of 10 miles or more.

3.2. Overview of Powertrain

Figure 2 shows an overview of the powertrain, which consists of an inline 4-cylinder 2.0 L engine and an electric coupled CVT unit. This Atkinson cycle engine employs VTEC, electric VTC and cooled EGR, and friction has been reduced, enabling achievement of both high output of 105 kW and 10% higher efficiency in terms of Brake Specific Fuel Consumption (BSFC) compared to the previous 2.0 L engine. The motor achieves high output of 124 kW and high efficiency of 96% (max.) by increasing the voltage with a booster and making use of reluctance torque. Table 1 lists the major specifications of the powertrain.

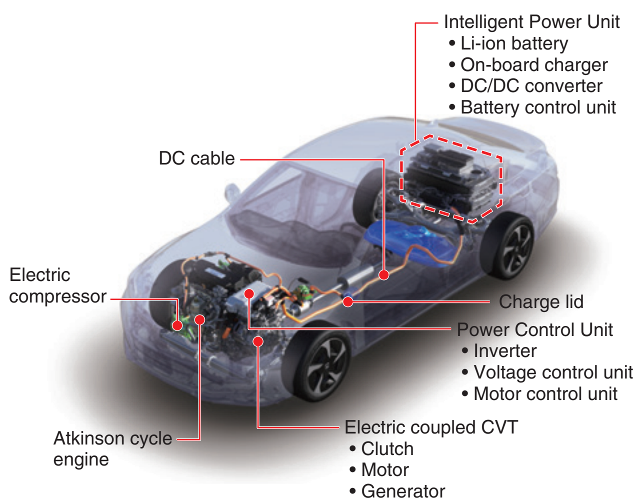

Fig. 1 Overall system configuration

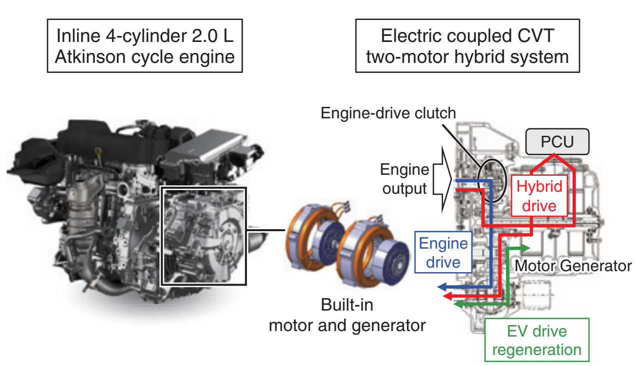

Fig. 2 SPORT HYBRID i-MMD powertrain

Table 1 Specifications of hybrid powertrain

Engine	Type	L4 DOHC Atkinson
	Max. power [kW]	105
	Max. torque [Nm]	165
Motor	Type	Interior permanent magnet synchronous motor
	Max. power [kW]	124
	Max. torque [Nm]	307
	Max. speed [rpm]	12584
	Max. voltage [V]	700

3.3. Overview of Plug-in Hybrid Operation

Figure 3 shows an overview of plug-in hybrid operation.

Plug-in hybrid operation is classified into the following two modes.

The first mode is called Charge Depleting mode (CD mode). This mode mainly performs EV drive using the electric energy stored in the Li-ion battery by plug-in charging. CD mode expands the EV drive operation range and secures a 13-mile EV range by setting a high threshold for engine start as shown in Fig. 3.

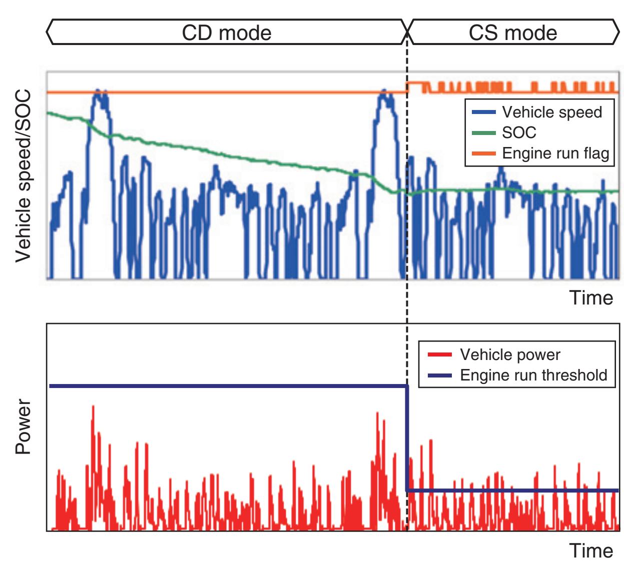

Fig. 3 Plug-in hybrid operation

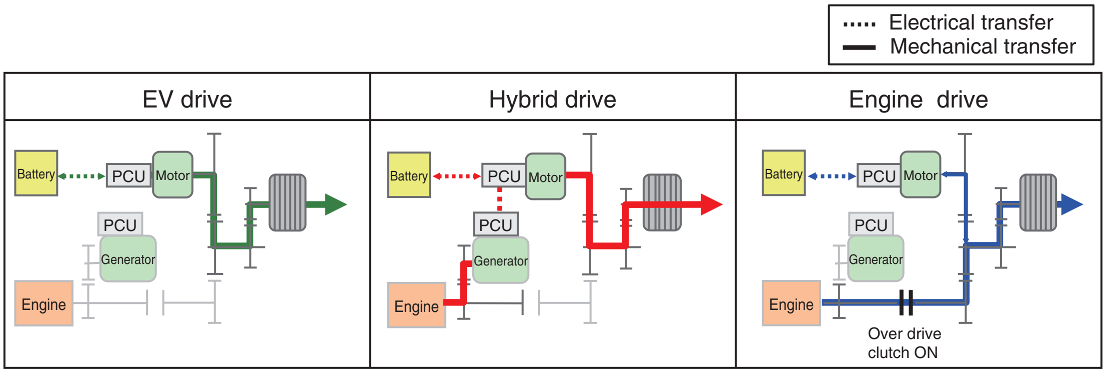

Fig. 4 SPORT HYBRID i-MMD operation modes

The second mode is called Charge Sustaining mode (CS mode). In this mode, when the State of Charge (SOC) of the Li-ion battery falls below the specified value, the vehicle is propelled using gasoline as the energy source so that the SOC stays within the specified range. In other words, the vehicle functions as a hybrid vehicle.

3.4. Overview of Drive Modes

Figure 4 shows the types of drive modes of the SPORT HYBRID i-MMD system. This system has three drive modes, and the system efficiency is enhanced by selecting the appropriate drive mode according to the driving conditions.

The first mode is called EV drive mode. In this mode, the vehicle is propelled by the motor using the electric power stored in the Li-ion battery.

The second mode is called Hybrid drive mode. In this mode, the engine power is converted to electric power by the generator, and the vehicle is propelled by the motor using this electric power (the system operates as a series hybrid). When the generator produces less electric power than is consumed by the motor, the shortage is compensated by discharge from the Li-ion battery. When excess electric power is generated by the generator, it is charged to the Li-ion battery.

The third mode is called Engine drive mode. In this mode, the engine and axles are coupled at fixed gear ratios using a clutch, and the wheels are driven directly by the engine (the system operates as a parallel hybrid). In this case the motor performs assist and charging functions, and power is discharged from the Li-ion battery (assist) or charged to the Li-ion battery.

4. Control System

4.1. Control System Configuration

Figure 5 shows the block diagram of the SPORT HYBRID i-MMD system. The control units for the power train components comprising the engine, electric coupled CVT with built-in motor and generator, PCU, and IPU communicate through a Controller Area Network (CAN) with a redundant design. In addition, related components such as an electric servo brake[4] and a full-electric compressor for air conditioning communicate through the CAN, and cooperative control is performed according to the environmental and driving conditions. Power management control, and in particular control related to fuel economy performance and driving performance under various constraints, is described below.

4.2. Major Goals of Power Management Control

The major goals of power management are to:

(1) Enhance fuel economy in each drive mode;

(2) Enhance fuel economy by switching the drive modes; and

(3) Secure driving performance under various constraints.

Regarding (1) and (2), fuel economy performance can be enhanced by taking into account the acceleration and deceleration intent of the driver and the constraints and efficiency characteristics of each component. Regarding (3), for example when the constraint of a battery power limit arises, driving performance is secured by performing cooperative control between the components so that any excess or shortage of electric power relative to the motor output is compensated by the generator output. The control methods used to achieve the above targets are described below.

4.3. Enhancement of Fuel Economy Performance in Each Drive Mode

The SPORT HYBRID i-MMD system modes that operate the engine are Hybrid drive mode and Engine drive mode. Fuel economy performance in each mode is mainly governed by the thermal efficiency of the engine. This means that the keys to enhancing fuel economy are how to more efficiently operate the engine, and how to increase the efficiency of the overall system. An overview of engine operation in these two modes is described below.

4.3.1. High-efficiency operation in Hybrid drive mode

In Hybrid drive mode, there is no mechanical transmission path from the engine to the wheels. That is to say, there is no constraint on rotational speed between the vehicle velocity (which is proportional to the motor speed) and the engine and generator. This means that the engine speed can be set arbitrarily relative to the vehicle speed. Therefore, control is basically performed so that the engine operating point traces the minimum BSFC line determined uniquely relative to the engine output. Furthermore, the engine output is adjusted toward operation points with higher efficiency on the blue minimum BSFC line as shown in Fig. 6. At this time, any excess or shortage of generated electric power relative to the motor output is compensated by the battery energy.

4.3.2. High-efficiency operation in Engine drive mode

In Engine drive mode, the engine and wheels are coupled via a fixed reduction gear, so the engine speed is determined uniquely with respect to the vehicle speed. The relationship between the engine speed and the torque when cruising on a flat road is shown by the dashed line in Fig. 6. Engine drive mode is used in the high-speed cruising area, but when driving on a flat road the engine operating point deviates to the low torque side of the minimum BSFC line. In this case, the engine torque is increased so that the engine operates at a more efficient operating point, and this increase in torque is absorbed by the regeneration operation of the motor. Conversely, under conditions where the engine operating point deviates to the high-torque side of the minimum BSFC line, the engine torque is reduced and the difference is compensated by motor drive. In this manner, control is performed to converge the engine operating point to the higher-efficiency area by motor regeneration and motor drive.

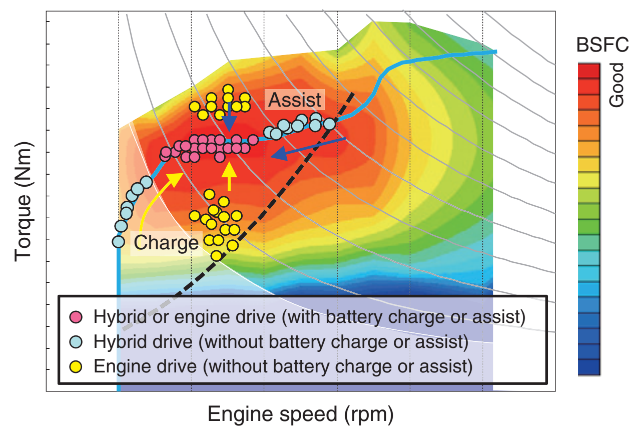

Fig. 6 Engine operating point

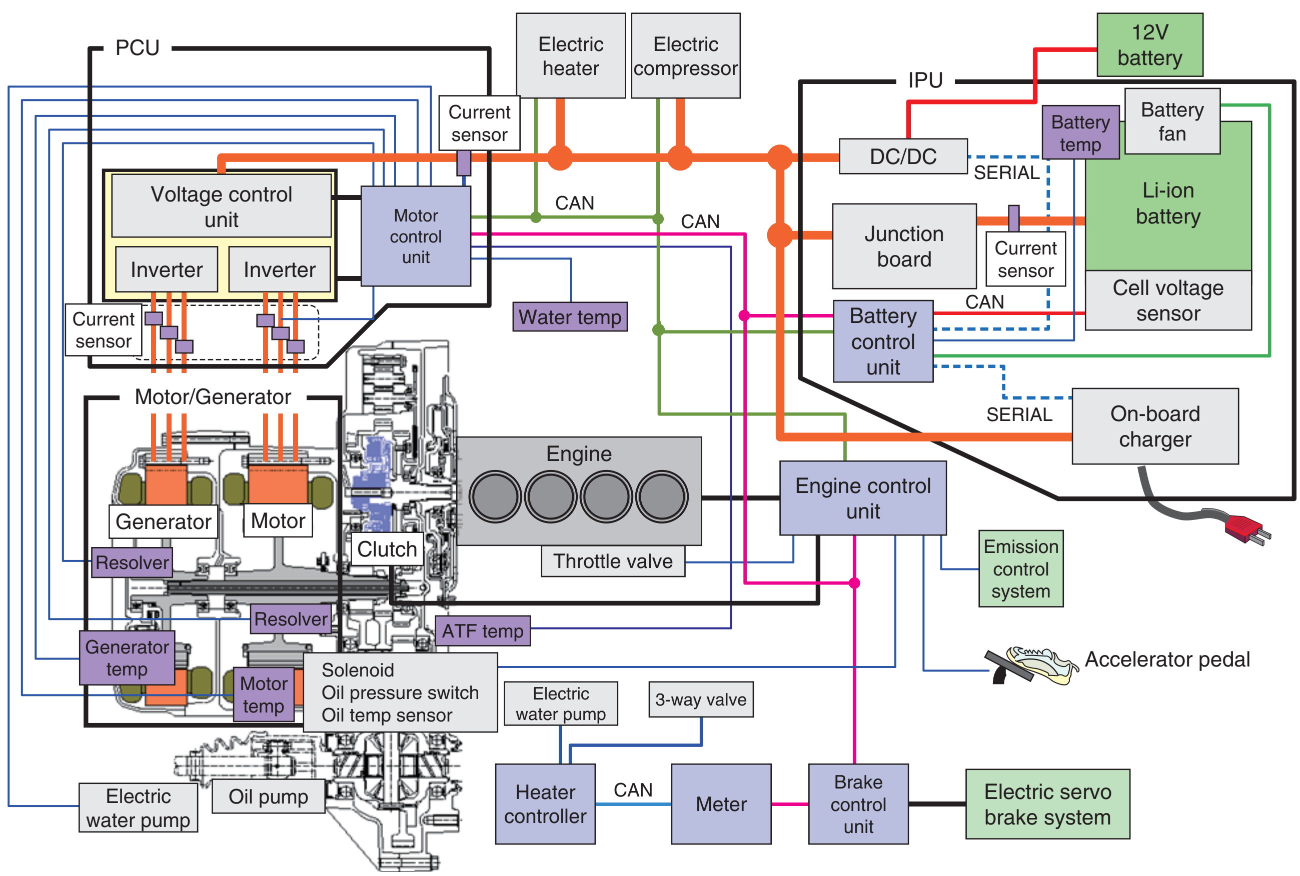

Fig. 5 Block diagram of SPORT HYBRID i-MMD system

4.4. Enhancement of Fuel Economy Performance by Switching the Drive Mode

In order to enhance vehicle fuel economy, it is necessary to enhance the thermal efficiency of the engine as described in 4.3. above, and at the same time increase the efficiency of the overall system by increasing the energy transfer efficiency from the engine output to the axle output. The SPORT HYBRID i-MMD system achieves higher efficiency by switching the drive mode.

Figure 7 shows an overview of switching the drive mode according to the vehicle speed in CS mode, and Fig. 8 shows the driving force diagram and the drive mode operating areas. EV drive mode is mainly selected in the range from launch to city and other low-speed driving in order to avoid a drop in fuel economy due to low-load engine operation. When driving at medium speeds, fuel economy is enhanced by performing intermittent operation that switches between EV drive and Hybrid drive or between EV drive and Engine drive as appropriate in consideration of the balance between the thermal efficiency of the engine and the Li-ion battery charge/discharge loss. When driving at high speeds, Hybrid drive mode or Engine drive mode is selected as appropriate to achieve the highest energy transfer efficiency.

4.4.1. Switching between EV drive and Hybrid drive (Engine drive)

Mode switching called intermittent operation is performed as appropriate in the driving power area where EV drive can be selected. In this case, the Li-ion battery is charged during Hybrid drive (or Engine drive), and then operation switches to EV drive using the accumulated electric energy. Figure 9 shows the fuel economy enhancement effect due to switching between EV drive and Hybrid drive.

This shows that in consideration of the balance between the thermal efficiency of the engine and the Li-ion battery charge/discharge loss, fuel economy enhancement effects of up to approximately 50% can be obtained in the low driving power range by performing intermittent operation, compared to the case when the engine always operates (Battery charge 0 kW line in Fig. 9). Conversely, the fuel economy enhancement effect of intermittent operation decreases and fuel efficiency instead tends to drop in the high driving power range. Therefore, the EV drive area was determined in consideration of the fuel economy enhancement effect.

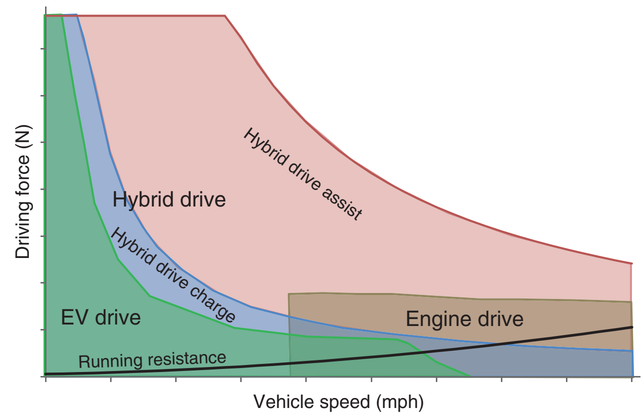

Fig. 8 Operating area of three driving modes (CS mode)

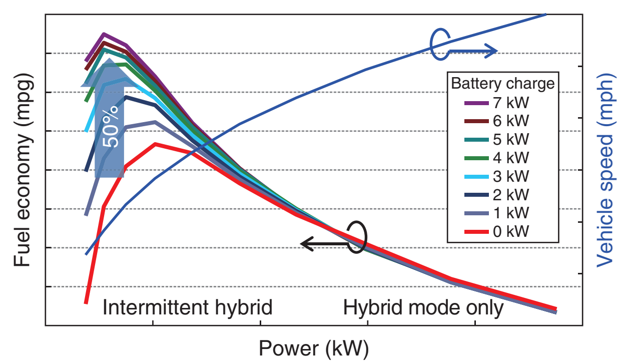

Fig. 9 Fuel economy enhancement of intermittent operation

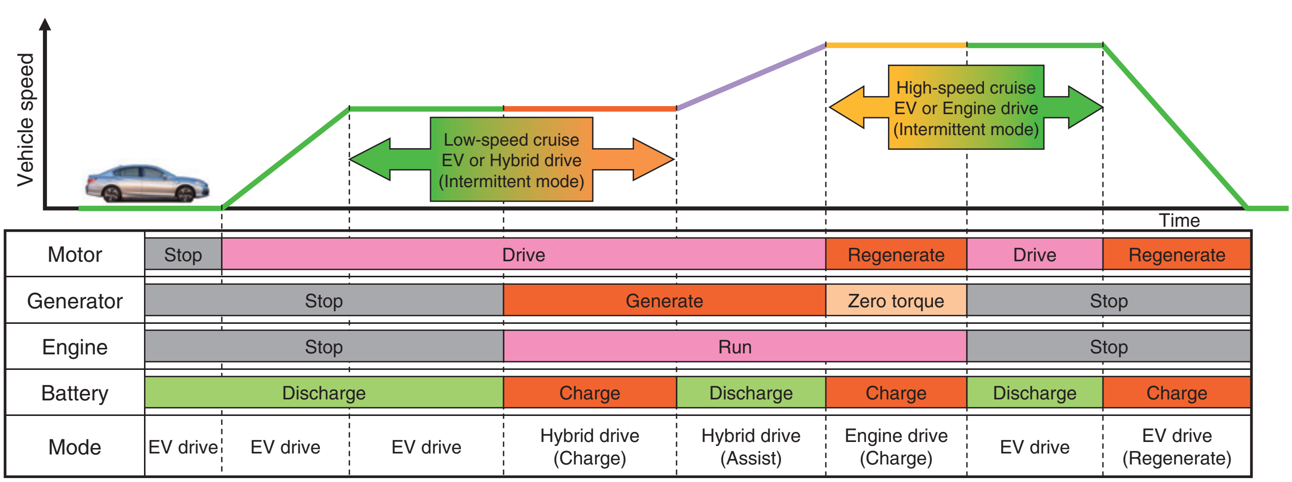

Fig. 7 CS mode operation

4.4.2. Switching between Hybrid drive and Engine drive

Figure 10 compares the Hybrid drive and Engine drive fuel economy.

The colored area in Fig. 10 indicates the area in which Engine drive provides better fuel economy, and the white area indicates the area in which Hybrid drive provides better fuel economy. The black line indicates the driving resistance when driving on a flat road. This shows that when accelerating gently from cruising, Engine drive mode has a higher energy transfer efficiency than Hybrid drive mode, so fuel economy performance is up to 12% better. Conversely, Hybrid drive mode provides better fuel economy performance in areas with a higher driving load. Therefore, Hybrid drive mode and Engine drive mode are switched based on these relationships.

4.5. Securing Driving Performance under Constraints

The SPORT HYBRID i-MMD system consists of various components, and each component is subject to constraints in order to secure reliability. For example, these

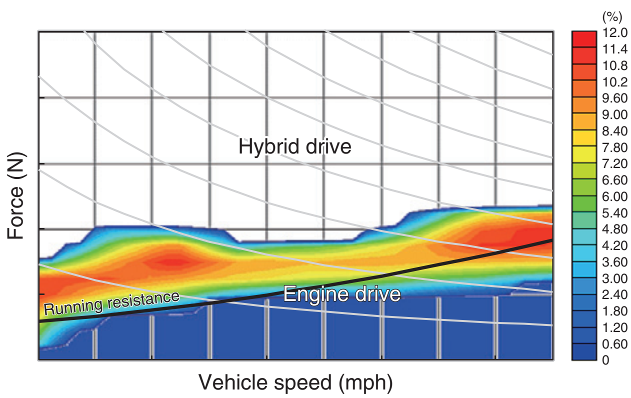

Fig. 10 Comparison of fuel consumption of hybrid drive and engine drive

constraints include a motor torque limit, generator torque limit, and battery power limit. In particular regarding the battery power limit, accurate control is demanded from the viewpoint of securing Li-ion battery durability, and this limit is known to greatly influence the driving performance of a system using a series hybrid. Therefore, cooperative control between each component to support various environmental and operating conditions is described below using the battery power limit as an example.

The power management control obtains the acceleration and deceleration intent of the driver (accelerator and brake pedal operations) and the power and torque limit information from each component, and performs the appropriate cooperative power control within the limit range. Under conditions where the battery power is limited, such as in low-temperature environments, and the acceleration and deceleration intent cannot be satisfied by battery power alone, power management control selects Hybrid drive mode and accurately balances the motor, generator and engine outputs to both satisfy the battery power limit and achieve sufficient driving performance. Figure 11 shows the block diagram of this control.

Power management control first calculates the target vehicle driving force from the acceleration and deceleration intent of the driver and the motor torque limit requirement. Next, it calculates the target engine power that matches the sum of the target motor power calculated from the target vehicle driving force and the target battery power calculated from the energy management control. The target engine power is corrected as necessary by the battery power regulator. After that, the target engine speed and target engine torque are calculated from the corrected target engine power. Here, the target engine speed and torque values select the point at which the engine efficiency is maximized. Finally, the engine power, generator power and motor power are corrected in consideration of various constraints including the battery power limit. This control system

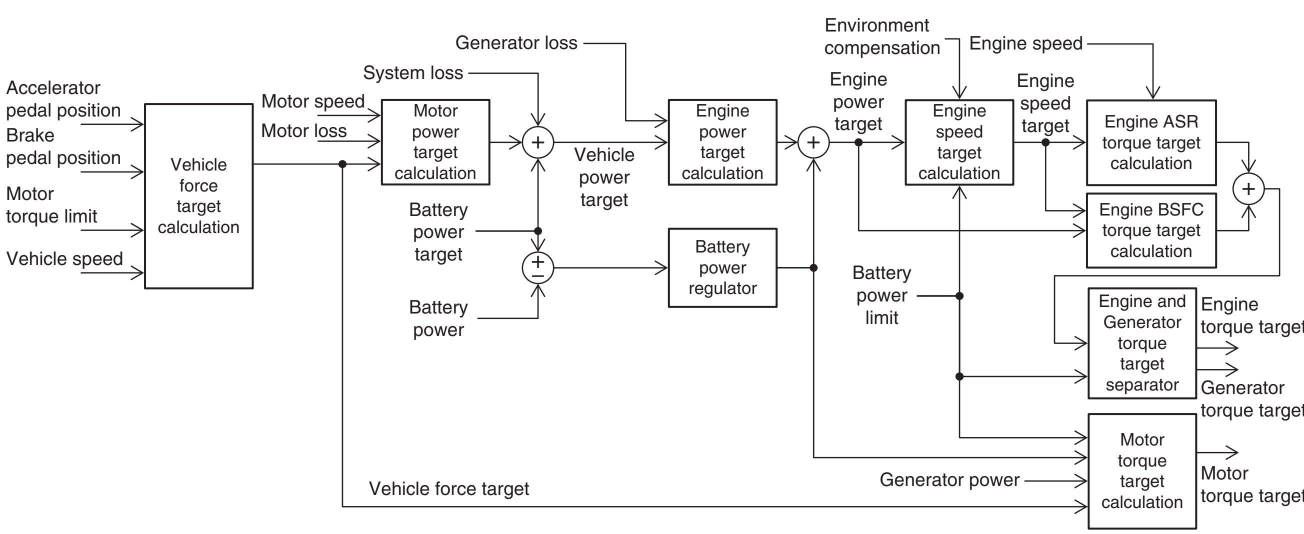

Fig. 11 Power management control

configuration balances the acceleration and deceleration intent of the driver, the battery SOC convergence properties, the battery power limit performance, and the constraints of other components.

In addition, the motor and generator power calculated as noted above are accurately corrected with rapid response so that the battery power limit can be satisfied even when the battery power is greatly limited, such as at extremely low temperatures or when the power fluctuates sharply due to sudden acceleration or deceleration.

At extremely low temperatures, the battery power is strictly limited to help secure battery durability. To maintain sufficient driving performance with this limit, the motor and generator need to output power in excess of 100 kW, and accurate control that can maintain this power balance within a battery power limit of several kW or less is also needed. In addition, when accelerating or decelerating rapidly on low-μ road surfaces such as snow-covered roads, wheel-spin and tire-lock occur, and the resulting fluctuation in motor speed produces rapid changes in the motor power. This means that rapid response control is also required that can maintain the power balance within the limit even in these types of situations. The power correction method used to achieve both high accuracy and rapid response is described below.

4.5.1. Estimation of battery power

Rapid response battery power control requires battery power information with little delay or dead time, so the battery power is estimated swiftly. The battery power can be measured from the Li-ion battery voltage sensor and current sensor. However, there are also the sensor delay factors, battery capacitor characteristics, the characteristics of the capacitors and reactors inside the PCU, the communication delay between each control unit, and other factors. This means that there are delay and dead time characteristics between the motor and generator power fluctuation recognized by the control units and the battery power fluctuation. Those delay and dead time characteristics cannot be ignored for the rapid control response requirement, so the battery power is estimated indirectly from the motor and generator power and other loss information. Figure 12 shows the high-voltage components of this system.

Regarding these high-voltage components, the battery power P_{bat} is the sum total of the motor and generator input power P_{mot} and P_{gen}, the motor and generator inverter loss P_{invmot} and P_{invgen}, the boost loss P_{vcu}, the DC/DC converter loss P_{dcdc}, and the air conditioner and heater loss P_{ac}. Therefore, the power equation shown in Eq. (1) below is constantly satisfied.

$$P_{bat} = P_{mot} + P_{gen} + P_{invmot} + P_{invgen} + P_{vcu} + P_{dcdc} + P_{ac} \quad (1)$$

Equation (1) shows that the battery power can be estimated by compensating the various losses based on the motor and generator power. The input power to the motor and generator can be measured by a phase-current sensor and a boosted-voltage sensor. The motor and generator inverter loss and the boost loss can be estimated using the nominal values determined from the prescribed parameters. The DC/DC converter loss information and the air conditioner and heater loss information are obtained from the respective control units via the CAN. The controller estimates the battery power from this information. Figure 13 shows the configuration of this controller.

4.5.2. Power compensation for battery power control

Accurate battery power control with a rapid response is performed using the estimated battery power calculated as described above. It was noticed that battery power fluctuation mainly occurs due to motor and generator power fluctuation, and that the power is correlated with the torque. Therefore, a configuration was selected that controls the battery power by compensating the motor and generator torque command values calculated by power management control. In addition, the estimated battery power contains some error due to factors such as temperature characteristics and manufacturing error, so this error needs to be compensated. Therefore, the effects of this error are removed by calculating the deviation between the actual battery power and the estimated battery power, and compensating the battery power limit value based on the calculated deviation. Figure 14 shows this controller configuration using the generator torque compensation side as an example.

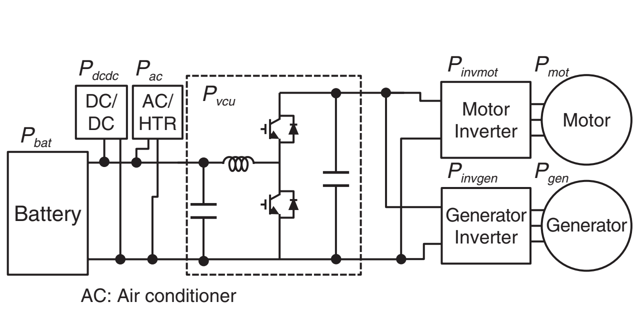

Fig. 12 High-voltage component

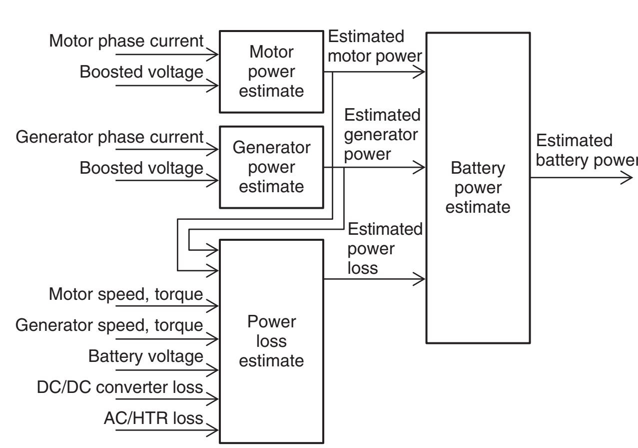

Fig. 13 Battery power estimator

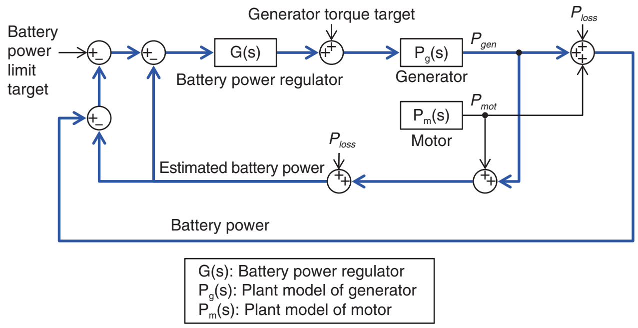

Fig. 14 Closed loop of battery power limit to battery power

A closed loop is formed between the battery power and the battery power limit value as indicated by the blue arrows in Fig. 14. Therefore, the battery power can be converged to within the power limit value range by adding the regulator G(s) between the battery power and the battery power limit value, and compensating the motor torque and generator torque calculated by power management control.

5. Performance Achieved by an Actual Vehicle

Figure 15 shows the fuel economy enhancement effect of the SPORT HYBRID i-MMD Plug-in system compared to a current gasoline engine vehicle. Compared to the current gasoline engine vehicle, the SPORT HYBRID i-MMD Plug-in system enhanced fuel economy in the EPA fuel economy measurement modes by 104% in City mode, 35% in Highway mode, and 70% in Combined mode, and achieved fuel economy of 46 mpg. Figure 16 shows the breakdown of this 70% fuel economy enhancement effect. This control contributed to the 39% enhancement in fuel economy due to hybridization. In addition, a 13-mile EV range and fuel economy of 115 MPGe were achieved in CD mode.

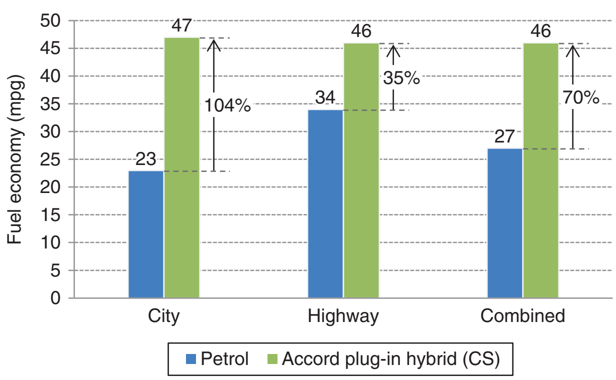

Fig. 15 Comparison of fuel economy

Figure 17 shows the results for highway driving that includes acceleration and deceleration (US06 mode) under a constraint (battery power limit). These results confirmed that the power shortage relative to the motor output under the battery power limit can be compensated by adjusting the generation level of the generator, maintaining sufficient driving performance while converging the battery power

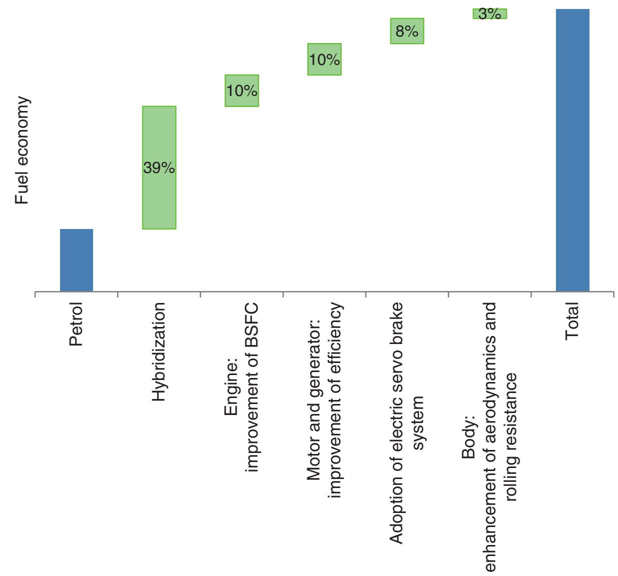

Fig. 16 Contributions to fuel economy enhancement of proposed SPORT HYBRID i-MMD Plug-in system

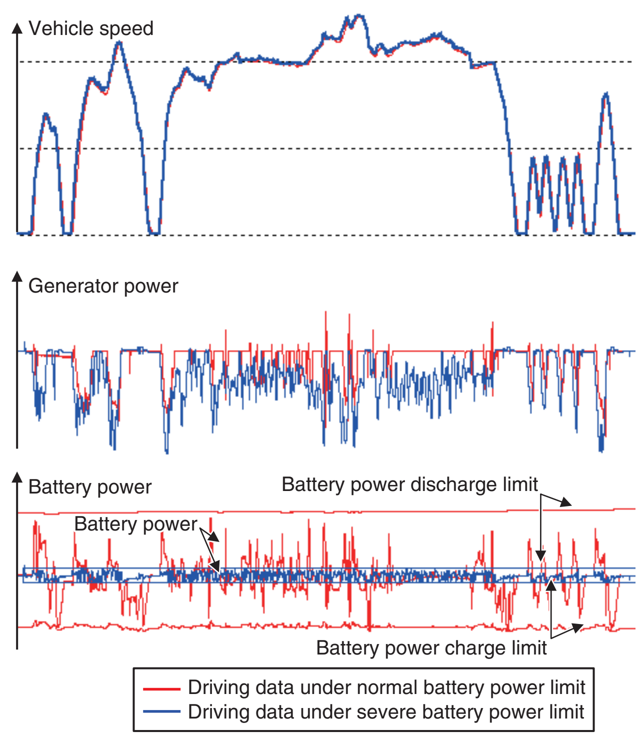

Fig. 17 Power management in US06 mode

to within the limit range. In addition, Fig. 18 shows the battery power behavior when the motor power changes suddenly during wheel spin and sudden braking. This confirmed that the battery power is similarly converged to within the limit range even in these types of situations. The motor and generator power exceeds 100 kW under the above conditions, but the battery input/output power is converged to a range of several kW or less.

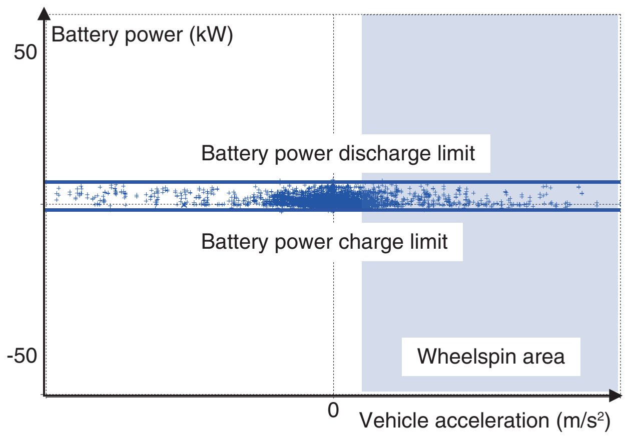

Fig. 18 Vehicle acceleration and battery power

6. Conclusion

A control system was developed for the two-motor hybrid system SPORT HYBRID i-MMD, and achieved the following performance when mounted in the 2014 model year Accord.

(1) The new control system contributed to a 39% increase in fuel economy by switching three drive modes as appropriate according to the driving conditions, and by enhancing the thermal efficiency of the engine and the energy transfer efficiency. In addition, the following fuel economy performance was achieved.
EV range: 13 miles
CD fuel economy: 115 MPGe
CS fuel economy: 46 mpg

(2) When driving with a battery power limit, cooperative control between each component enabled maintaining of sufficient driving performance while converging the battery power to within the limit range.

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■ Author ■



Hirohito IDE | Yoshihiro SUNAGA | Naritomo HIGUCHI