

Development of Motor and PCU for a SPORT HYBRID i-MMD System

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ABSTRACT

A highly efficient SPORT HYBRID Intelligent Multi-Mode Drive system was developed in order to achieve a balance between the joy of driving and measures to address climate change and energy issues. The developed power train is composed of the engine, an electric coupled CVT with a built-in motor and generator, a Power Control Unit, and an Integrated Power Unit. The built-in motor was given higher torque, higher output, and higher efficiency by using reluctance torque and raising the voltage. The Power Control Unit was made more compact and power was increased by enhancing the unit's heat dissipation performance, and it was made more efficient by using a low-loss chip. As a result, the motor achieves maximum torque of 307 Nm and maximum output of 124 kW, while the Power Control Unit achieves a voltage increase of 700 V and total output of 400 kVA. The Power Control Unit including the motor achieved a maximum efficiency of 96%.

1. Introduction

In order to address climate change and energy issues, there is demand for motor vehicles with lower emissions and better fuel economy. Honda has responded to these expectations by developing the Integrated Motor Assist (IMA) system⁽¹⁾ installed in models such as the INSIGHT, CR-Z, FREED HYBRID, and FIT HYBRID, and by taking steps to reduce fuel consumption.

Honda has also been developing fuel cell electric vehicles⁽²⁾ and battery electric vehicles (EV) as highly advanced zero emission vehicles. A fuel cell EV uses hydrogen as fuel, causing it to react with oxygen in the air to generate electricity and provide driving power. A battery EV uses electricity stored in batteries for driving power. It has the advantage of not emitting exhaust gases when operating, but one issue faced by the battery EV is that it has a limited driving range compared to an Internal Combustion Engine Vehicle (ICEV). At present, there are also not many hydrogen stations or charging facilities, and more widespread use will be limited until the infrastructure is developed.

A 2014 model year Accord Plug-in Hybrid was developed in order to resolve these issues. The batteries can be charged from household power or other such sources, enabling EV operation for commuting, shopping, and

other such everyday short-range uses. When the remaining battery capacity diminishes, the vehicle can use the energy in gasoline to operate in hybrid mode, so the driving range is not limited by battery capacity.

The developed vehicle described here is equipped with the newly developed SPORT HYBRID Intelligent Multi-Mode Drive (SPORT HYBRID i-MMD) system⁽³⁾, which has a higher electric transmission ratio. The motor and Power Control Unit (PCU) were given enhanced performance and efficiency to achieve higher dynamic performance as well as fuel consumption of 115 MPGe (Charge Depleting mode: CD) and 46 mpg (Charge Sustaining mode: CS) and EV range of 13 miles. This Paper will describe the technology of the newly developed motor and PCU.

2. SPORT HYBRID i-MMD System

Figure 1 shows the SPORT HYBRID i-MMD system power train. The motor and generator are built into the case of the electric coupled CVT. The PCU is located above it. The engine is a 2.0 L Atkinson cycle engine developed for hybrid electric vehicle use.

Figure 2 shows the three operating modes of the SPORT HYBRID i-MMD system, namely (1) EV drive mode, in which the vehicle is driven by the motor

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using battery energy; (2) hybrid drive mode, in which the mechanical energy of the engine is converted into electrical energy to drive the vehicle using the motor; and (3) engine drive mode, in which the vehicle is driven using the engine.

Figure 3 shows a section view of the electric coupled CVT and the transfer paths under the various modes. The motor torque is transferred by means of gears to the driving shaft. In EV drive mode, the vehicle is driven using the motor, and the engine and generator are shut off. In hybrid drive mode, the engine torque is transferred to the generator and converted to electrical energy that is used by the motor to drive the vehicle. In engine drive mode, the overdrive clutch built into the electric coupled CVT is engaged and the engine torque is transferred to the driving shaft.

The modes are selected so as to minimize fuel consumption under various operating conditions. EV drive mode is used when starting the vehicle under low load. Hybrid drive mode is used when under high load or when accelerating. Engine drive mode is used when cruising at high speeds. In this system, the motor is used both for driving the vehicle and for regeneration, while the PCU performs both electric power conversion and voltage control.

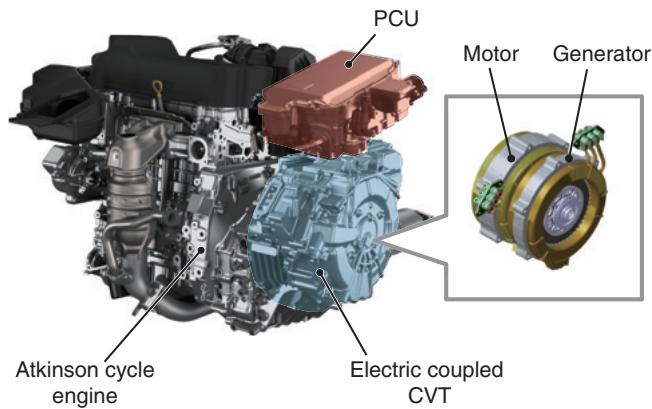


Fig. 1 Hybrid power train

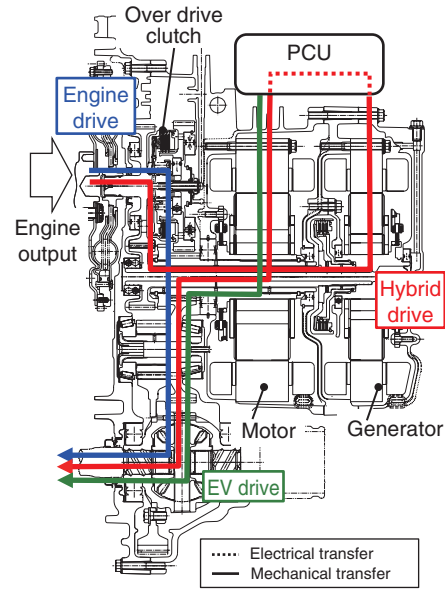


Fig. 3 Section of electric coupled CVT

3. Motor

Under the SPORT HYBRID i-MMD system, the motor is required to drive the vehicle throughout its driving force range. The vehicle's acceleration performance and maximum speed depend on the motor torque, output characteristics, and maximum rotor speed, while motor efficiency has a large influence on fuel consumption. Therefore a high-torque, high-output, high-efficiency motor is called for. At higher maximum motor speeds, rotor strength becomes an issue, so that measures to reduce stress are needed. Furthermore, higher motor output is accompanied by increased motor heat generation, so that a cooling system is needed in order to assure stable driving force. In order to achieve the 115 MPGe (CD) fuel consumption and higher dynamic performance that are performance targets for the vehicle, the motor was developed with the target performance values shown in Table 1.

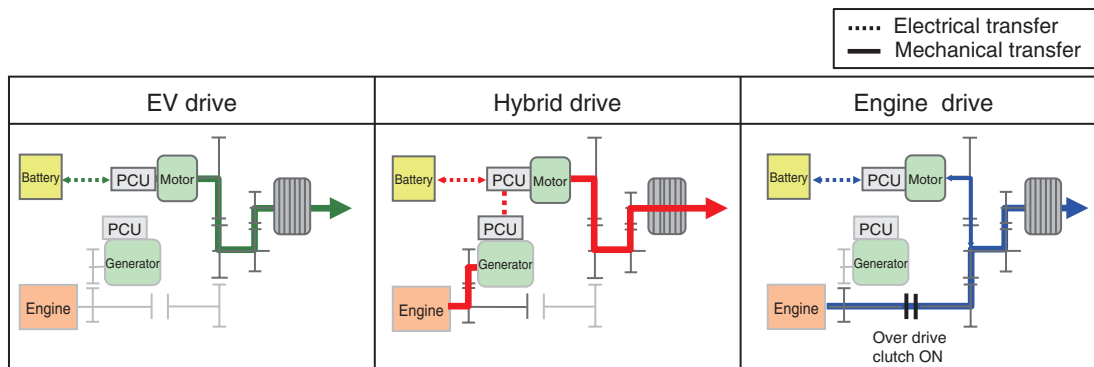


Fig. 2 Operation modes

Table 1 Target performance of motor

Max. torque	307 Nm
Max. power	124 kW
Max. speed	12584 rpm
Max. motor and PCU efficiency	96%

3.1. Enhancement of Motor Efficiency

Figure 4 shows the torque characteristics of the motor together with the high-efficiency area of the conventional motor and the operating areas when operating normally. As to ways in which the motor is used, there is high frequency of operation in the low-load area when city driving. When cruising at high speed, the vehicle will be in engine drive mode and the motor will be running in the vicinity of zero torque. Meanwhile, the conventional motor has the high-efficiency area in the high-output range and the motor is not making effective use of the high-efficiency area.

An enhancement of efficiency in the low-load area was aimed at in order to enhance efficiency during normal operation. Losses in the motor can be divided into copper loss, which occurs in the coil, and iron loss, which occurs in electrical steel. In the low-load area, a higher proportion of loss consists of iron loss, and in order to enhance efficiency in the low-load area, iron loss has to be reduced. In order to reduce iron loss in the low-load area, it is effective to reduce the mass of electrical steel and to reduce magnetic flux. These aims were achieved by using reluctance torque and raising the voltage.

3.2. Making Use of Reluctance Torque

Reluctance torque is torque that uses the magnetic salience of the rotor⁽⁴⁾. In general, flux passes readily through iron but does not pass readily through air and magnets. A greater difference in how readily a material passes flux results in a greater magnetic force of attraction. If this force could be used, then motor torque could be increased without increasing magnet torque; greater compactness would enable reduction in the mass of electrical steel; and reduction in magnetic flux would achieve a reduction in iron loss.

The developed motor is of the interior permanent

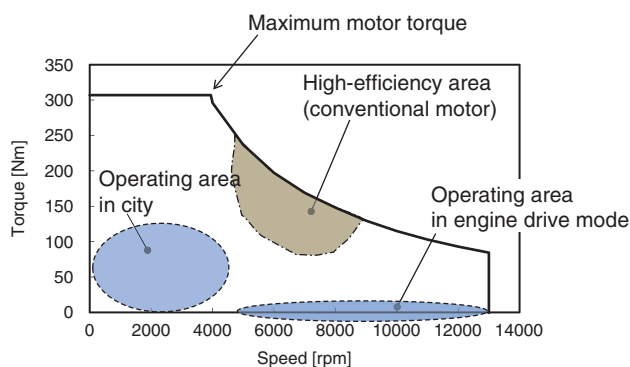


Fig. 4 Motor torque characteristics and operating area

magnet synchronous type, and a distributed winding was selected as the winding type for the stator. Figure 5 shows a section view of the motor. In order to maximize the reluctance torque effect, the magnets are placed in V-shaped arrangements. When the angle α in the V-shape is smaller, the torque increases. However, this also results in an increased torque ripple that may cause louder motor sound. Angle α was determined in consideration of motor torque and torque ripple. Figure 6 shows the torque at different current phase angles. The current phase angle indicates the timing of the alternating current with respect to the rotor position. When the current phase is 0 degrees, the magnet torque is at its maximum. The developed motor reaches maximum torque when the current phase is 55 degrees. A magnet circuit was achieved in which the maximum torque is 82% greater than the magnet torque and the ratio of reluctance torque is high.

3.3. Raising the Voltage

When the motor operates at high speed, a flux weakening current⁽⁴⁾ is generated. Also, below a certain voltage, the generated output is limited by an inductance component in the coil. In order to reduce iron loss, the coil windings were increased to the area where the magnetic flux density of the electrical steel becomes saturated when the maximum current passes through it, the torque was increased the weight of the electrical steel was reduced. There are issues, however, of an increase in inductance

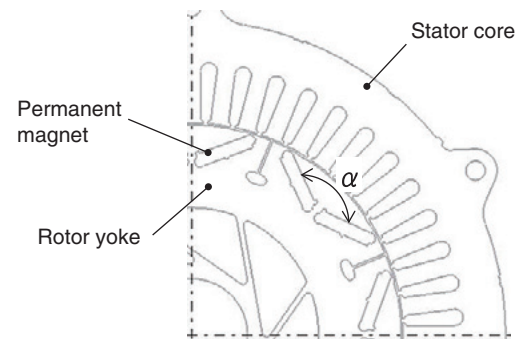


Fig. 5 Profile of motor core

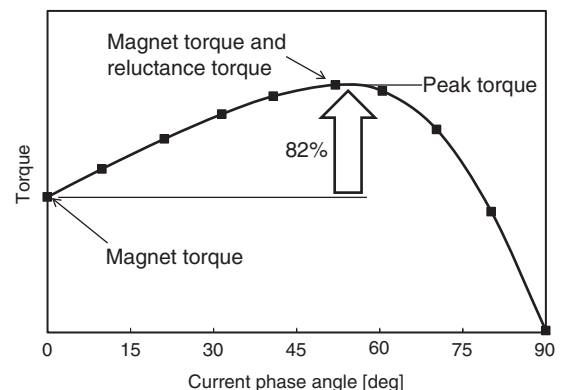


Fig. 6 Torque at different current phase angles

and decrease in output. The voltage was raised in order to resolve these issues. Figure 7 shows the motor voltage and torque characteristics. The voltage increase is carried out by the voltage control unit (VCU) that is built into the PCU. With an applied voltage of 700 V, compared to 300 V, the output increases by 50% or more, achieving a maximum output of 124 kW without enlarging the motor body.

3.4. Increasing Rotor Speed

When the motor's rotor reaches a high rotation speed, the rotor needs to be stronger, and that strength becomes an issue. At high speeds, there is an increase in the centrifugal force of the magnets in a radial direction. This causes high stress to occur in the center ribs at the centers of the V-shaped magnets and in the side ribs at either side of them. One effective way of reducing the stress is to increase the width of each rib, but this results in increased flux leakage from the magnets that become ineffective for torque, and the motor torque is reduced.

In order to resolve these issues, slits were made in the rotor yoke structure. Figure 8 shows the results of stress

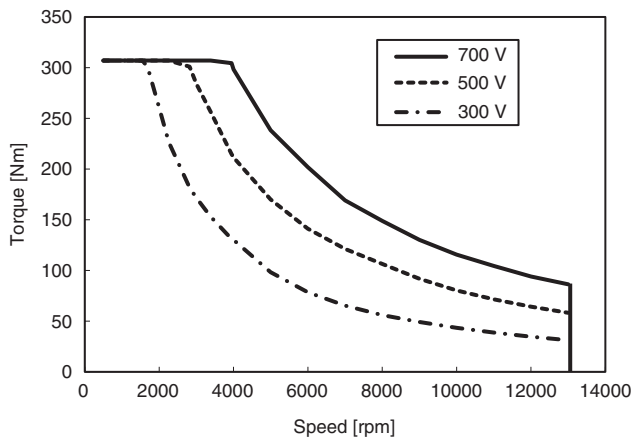


Fig. 7 Motor voltage and torque characteristics

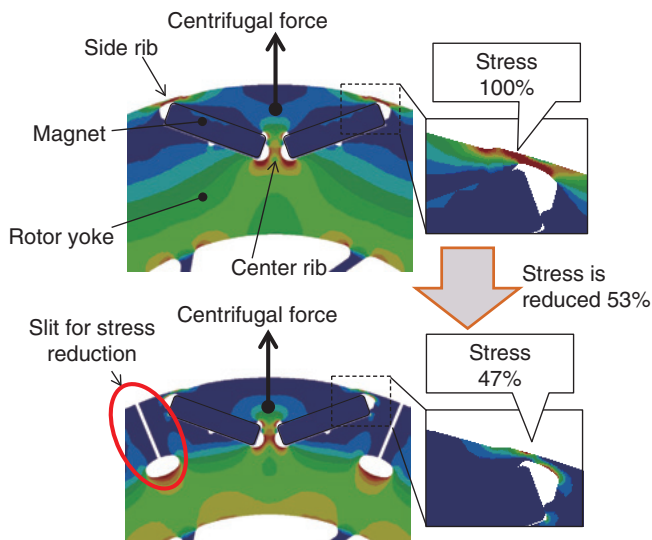


Fig. 8 Comparison of simulated stress distribution

analysis during rotor rotation.

A slit structure was adopted, and the use of low-rigidity steel in the vicinity of the slits resulted in a 53% reduction of the stress that concentrates in the side rib on the outside of the magnets, and this achieved an increase in speed without increasing the thickness of the side ribs.

3.5. Motor Cooling System

An oil cooling system was constructed for stable motor operation. Figure 9 shows the cooling system and Fig. 10 shows the structure of the motor cooling system. The heat originating in mechanical loss inside the electric coupled CVT as well as in copper loss and iron loss occurring in the motor is taken into the cooling medium of automatic transmission fluid (ATF) and transported to the ATF cooler to be released. The motor is cooled by ATF that is dripped from a pipe located above the coil. Construction of this cooling system enabled stable actuation of the motor.

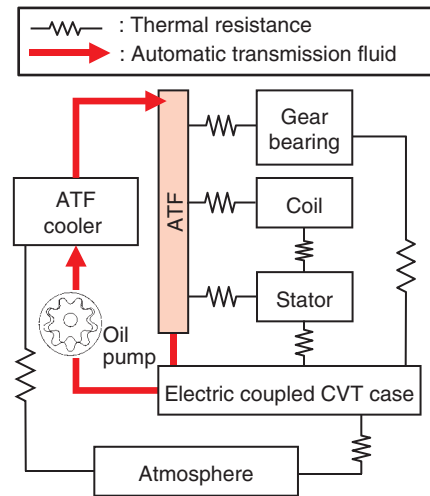


Fig. 9 Cooling system

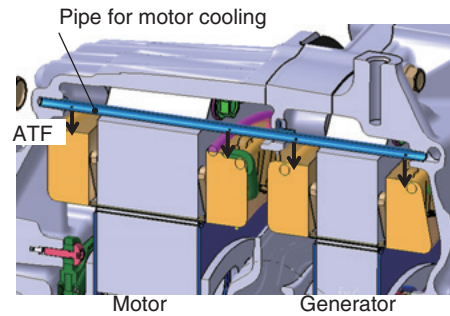


Fig. 10 Structure of motor cooling system

4. PCU

The PCU performs the function of electric power conversion for the batteries, motor, and generator, and it affects motor output and fuel consumption. The size and

Table 2 Target performance of PCU

PCU total max. output	400 kVA
System voltage	700 V
Max. motor and PCU efficiency	96%
PCU volume	11.5 L

installed location of the PCU also affect cabin space. In order to provide cabin space equal to that in conventional gasoline-powered vehicles, the PCU has to be installed in the engine compartment together with the 12-V battery for the vehicle's electrical system. In order to achieve the target output and fuel consumption for the vehicle as well as to assure cabin space, a PCU that provides higher output, greater efficiency, and greater compactness is needed. The PCU was developed with the performance target values shown in Table 2.

4.1. Enhancement of PCU Output and Compactness

Figure 11 shows a block diagram of the PCU. Figure

12 shows the internal configuration of the PCU. The PCU components include an intelligent power module (IPM), ECUs to control the motor and generator, capacitors, a reactor, and current sensors. The IPM is composed of a power module (P/M) that converts electrical current by switching, a gate driver (G/D) for switching control, and an ECU for VCU control. Placing P/M, G/D, VCU ECU for the motor, generator, and VCU in an integrated package achieves common use of parts and greater compactness. For the capacitors, functional integration of secondary smoothing capacitors for the motor, generator, and VCU, together with integrated packaging of primary smoothing capacitors and noise filters for the VCU, achieved greater compactness. Higher output capability was also implemented by enhancing the heat dissipation of the IPM and using high-voltage connectors with high-current capability for the DC and three-phase sections.

4.2. Enhancing the IPM for Higher Output and Greater Compactness

Figure 13 shows a configuration diagram of the IPM.

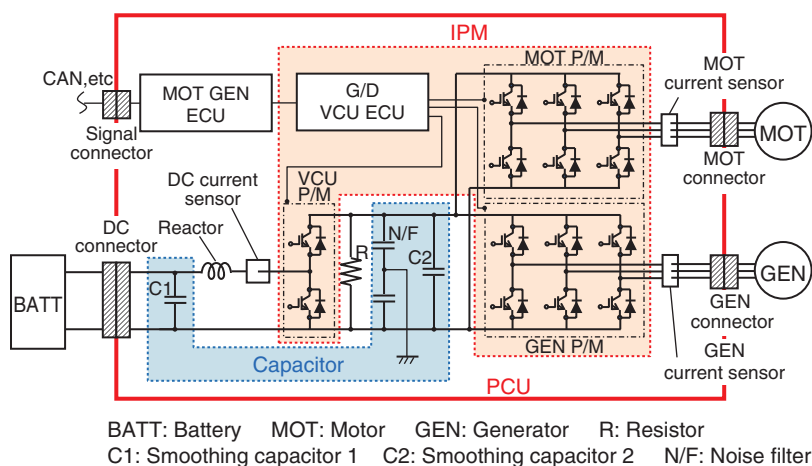


Fig. 11 Block diagram of PCU

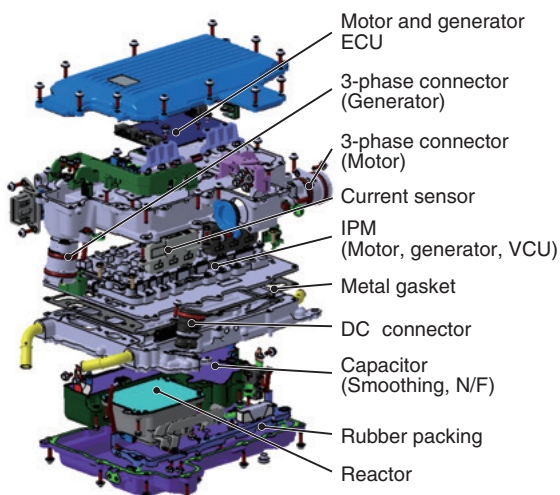


Fig. 12 Configuration of PCU

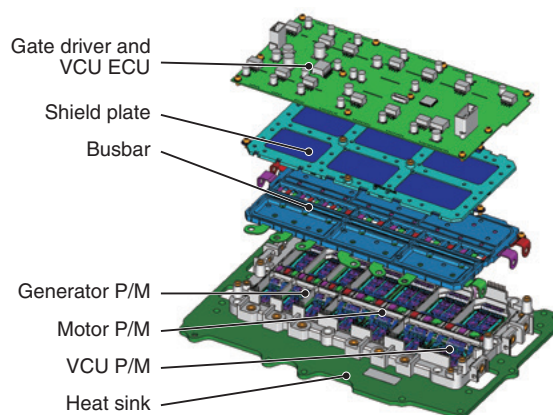


Fig. 13 Configuration of IPM

The IPM consists of P/M, G/D, and VCU ECU for the motor, generator, and VCU, heat sinks, and so on. When the voltage or current applied to the P/M is increased, the chips inside the P/M generate more heat. Even though more chips are needed, increasing their number also increases the volume of the PCU. In order to achieve the targets for increased output and decreased PCU volume, the heat dissipation of the P/M was increased and the temperature and number of the chips were reduced.

Figure 14 shows the structure of the P/M substrate. The conventional substrate structure has an insulating substrate and heat-dissipating plate connected by solder, and the substrate connected to the heat sink by thermal compound placed between them. The heat-dissipating structure adopted here eliminates the heat-dissipating plate and thermal compound, instead connecting the insulating substrate directly to the heat sink by means of solder for a direct cooling-type P/M. In the case of a direct cooling structure, the linear expansion differential between the insulating substrate and the heat sink causes greater stress on the solder than in the conventional structure, but the structure here uses high-strength lead-free solder to assure durability equal to that of the conventional structure. The adoption of a direct cooling structure achieves a 24% enhancement of heat-dissipation performance and, as shown in Fig. 15, fewer chips and greater compactness.

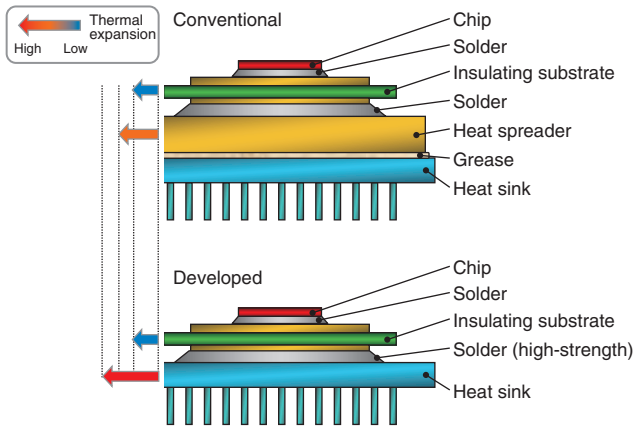


Fig. 14 Structure of P/M substrate

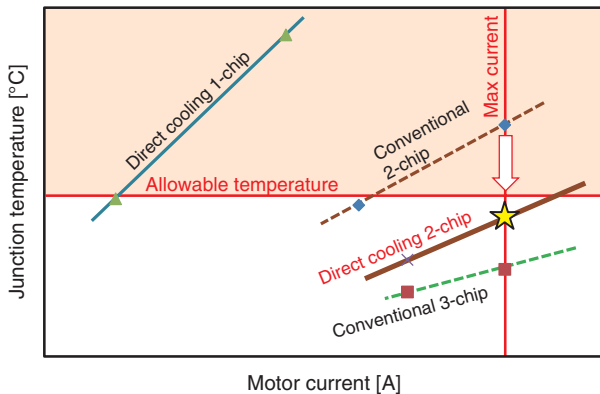


Fig. 15 Comparison of P/M substrate characteristics

4.3. High-Voltage Connectors with High-Current Capability

Figure 16 shows the internal terminal structure of the DC and three-phase connectors that attach to the PCU. A conventional terminal structure has a male terminal that fits against a contact area on the female terminal side and was clamped in one direction to provide the contact area. Here, however, the male terminal was made into a cylinder that fits into a contact area on the female terminal side with a cross-section that has a circular arc and is clamped toward the center so that the number of contacts (the contact area) is increased. These measures were able to halve the contact resistance, support the higher output resulting from the increase in current, and make the PCU compact enough to install in the engine compartment. Compared to conventional connectors, the weight and volume per ampere were reduced 30% while doubling the allowable current.

4.4. Enhancing the IPM for Higher Efficiency

An Insulated Gate Bipolar Transistor (IGBT) capable of high-power, high-speed switching was adopted as the switching device for the IPM. IGBT performance is one of the factors with a large influence on PCU efficiency. The IPM in this system implements loss reduction on the IGBT. The IGBT adopted here has the P-base localized in the surface structure and the gate placed differently (Fig. 17). This

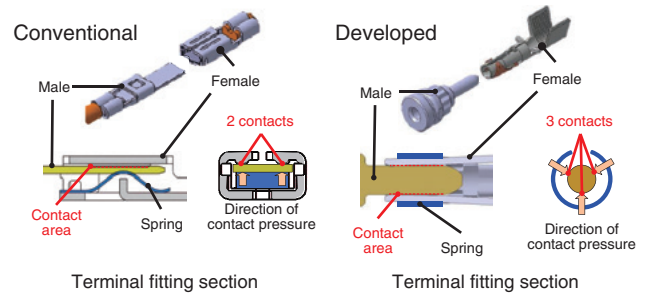


Fig. 16 Structure of high-voltage connector

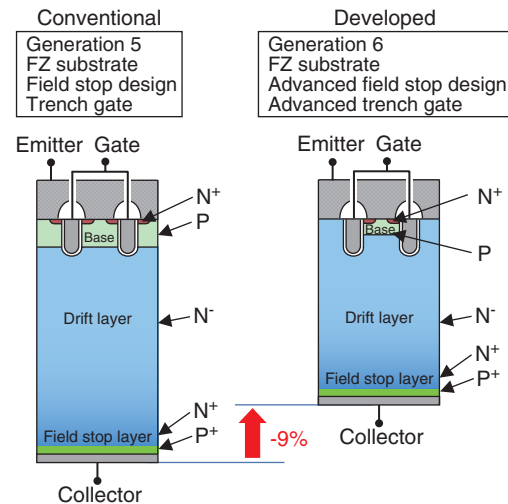


Fig. 17 Structure of IGBT

structure does not lose the carrier collection effect while enhancing the turn-on di/dt controllability and enabling application of the low-resistance N-drift layer. This limits oscillation during turn-off while achieving a 9% reduction in the thickness of the device and a 20% enhancement in loss characteristics⁽⁵⁾.

5. Performance

Figure 18 shows the achieved motor performance and motor efficiency with the PCU. Using a PCU that achieves maximum output of 400 kVA and a voltage increase to 700 V, the motor achieves maximum torque of 307 Nm, maximum output of 124 kW, and maximum speed of 12584 rpm. The motor and PCU together achieve a maximum efficiency of 96%. In addition, controlling the voltage to maximize the high-efficiency area expands the high-efficiency area into the large low-load area, achieving enhanced efficiency in the normal operating area.

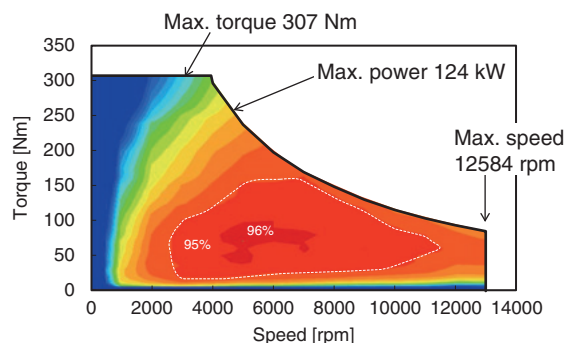


Fig. 18 Motor performance and efficiency with PCU

6. Conclusion

The motor and PCU were developed in order to achieve a balance between the joy of driving and measures to address climate change and energy issues. This achieved the following:

- (1) Motor given higher torque, higher output, and higher efficiency by using reluctance torque and raising the voltage
- (2) Higher rotor speed achieved by rotor slit construction that reduces stress
- (3) Stable actuation of the motor achieved by oil cooling system
- (4) Increased system voltage to 700 V by installation of VCU, and higher PCU output by enhancing IPM heat dissipation and adopting high-voltage connectors with high-current capability
- (5) Enhanced PCU compactness by increasing IPM heat-dissipation performance and unifying parts with identical functions
- (6) Enhanced IPM efficiency and compactness by adopting low-loss IGBT

Adoption of the above technologies achieved maximum torque of 307 Nm, maximum output of 124 kW, and maximum motor speed of 12584 rpm in the motor, and output of 400 kVA and volume of 11.5 L for the PCU, together with efficiency of 96% for the motor and PCU combined.

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