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Development of Power Control Unit for Midclass Vehicle

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Abstract

Toyota Motor Corporation has developed the new midclass hybrid vehicle (HV). This vehicle incorporates Toyota Hybrid System II（THS-II）to improve fuel efficiency. For this system we have developed a new power control unit (PCU) that features size reduction, light weight, and high efficiency. We have also improved the ability to mass produce these units with the expectation of rapid popularization of hybrid vehicles (HV). The PCU, which plays an important role in THS-II, is our main focus in this paper. Its development is described.

Keywords: Inverter, Converter, hybrid vehicle

1 Introduction

Mobility is the base of the human society and economic activity, and widely contributes to society. Meanwhile, it has also brought the important issues of global warming and air pollution induced by CO2 emissions. Therefore, the development of environment-conscious vehicles that are fuel-efficient and have low-emissions is an urgent task today. To solve these issues, Toyota has been working to develop and popularize Hybrid Vehicles (HV). The debut of 1st generation HV-the world's first mass produced HV- was in 1997, doubled fuel efficiency compared with the gasoline vehicles. In 2003, a high voltage system using a boost converter was introduced as 2nd generation HV, achieving high-power and low-fuel consumption. The new midclass HV has been developed this time as a leader of 3rd generation HV, achieving the highest global standards, 50 mpg (US comb.) with high-power and low-fuel consumption. This HV system has the newly developed 3rd generation power control unit (PCU), and is optimized to make the most of the performance of a 1.8L engine and a high-speed, high-power motor. This PCU contributes to downsizing the motors by increasing the maximum system voltage from 500V to 650V, also improving the system efficiency. A direct cooling type has been employed into cooling system of Intelligent Power Module (IPM), achieving size reduction and lighter weight by greatly improving the cooling efficiency. This size reduction and lighter weight easily enables the PCU adoption into multiple models, enabling the rapid popularization of HV. This paper explains the specific technology of this 3rd generation PCU.

2 HV and PCU Specification

2.1 HV system specification

This HV system has increased the maximum voltage of the boost converter from 500V to 650V(Fig.1).

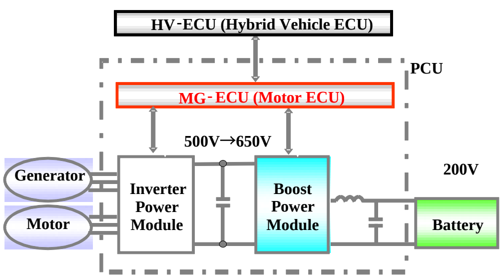


Fig.1 Composition of HV system

The higher voltage enabled the use of a high-speed, high power of motor with motor speed reduction device. The higher boost voltage leads to downsizing and system efficiency improvement. Table1 shows the specifications of HV system. Motor maximum output has been increase to 60kW, improving the power performance. Higher system efficiency improves fuel consumption by around 14% at 100km/h(Table 1).

	Current model	New model
Boost Voltage	500V	**650V**
System max output	82kW	**100kW**
Motor max output	50kW	**60kW**
Motor max rotation speed	6000rpm	**13000rpm**
Improvement ratio of fuel consumption	-	**14% @100km/h**

Table1 Specification of HV system

2.2 PCU specification

This figure below shows the PCU structure diagram. The table2 shows the PCU specifications. The PCU max output has been improved around 10%. The RMS, current of the motor inverter has been reduced from 230A(rms) to 170A(rms) by using higher boosted voltage and the motor speed reduction device. The reduced current enables loss reduction and power semiconductor downsizing.

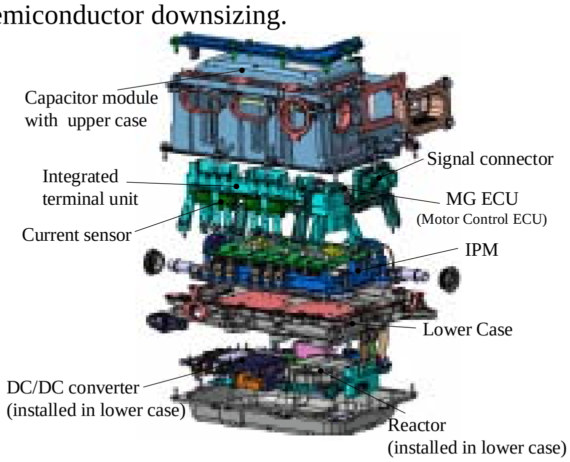


Fig.2 Structure of the 3rd generation PCU

		Current model	New model
Max Total Output	KVA	162	**178**
Max Boost Voltage	V	500	**650**
Generator max curren	Arms	75	**88**
Motor max current	Arms	230	**170**
Incoporated main components	-	Boost converter Generator inverter Motor inverter DC/DC converter A/C inverter	Boost converter Generator inverter Motor inverter DC/DC converter MG ECU
Weight	kg	21	**13.5**
Volume	Liters	17.7	**11.2**

Table2 Specification of PCU

In addition, volume is reduced by 37% and mass by 36% due to the newly developed IPM direct cooling, thinner capacitor film, improvement of DC/DC converter power density and the optimization of the layout of units. as shown.in Fig3.

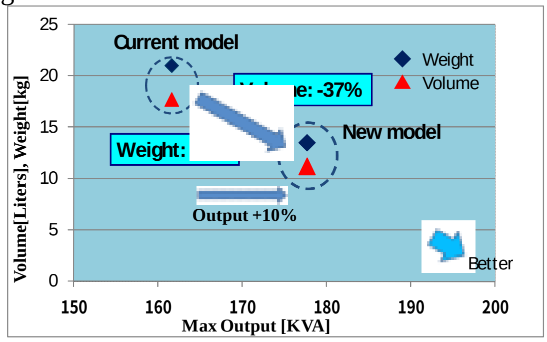


Fig.3 Size reduction, light weight of New PCU

Fig4 shows the electrical loss comparison of the PCU for current model and that for new model. The loss has been decreased by 25% by utilizing trench-gate type, thinner IGBTs, switching speed improvement and current reduction by breakdown voltage improvement, and optimization of switching frequency.

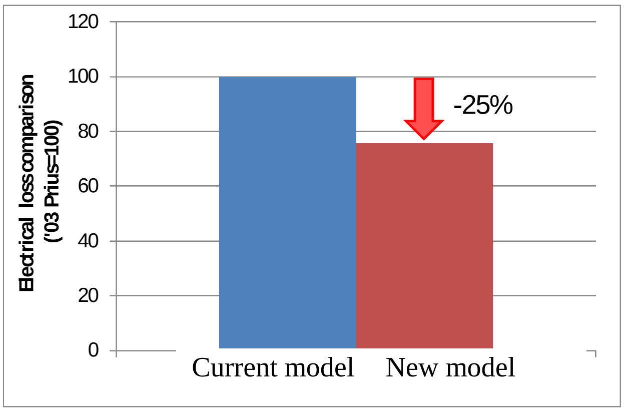


Fig.4 Electrical loss Comparison (vs. Current model)

3 New Technology of each component

3.1 Intelligent Power Module(IPM)

3.1.1 Basic structure of IPM

The IPM consists of the high voltage power module and the control circuit. The power module contains the heat sink for improving the cooling performance, the insulating substrate for assuring insulation, and the powersemiconductor, Insulated Gate Bipolar Transistor (IGBT) and Free Wheel Diode (FWD) for switching large current by an external control signal. Since the 1st generation, the IPM had been mounted with grease onto the heat sink (Fig.5). However in the 3rd generation the cooling efficiency has been improved by developing the direct cooling type (Fig.6). Also a new technology has been established, which assures a thermal shock resistance without using copper alloy with low coefficient of linear expansion.

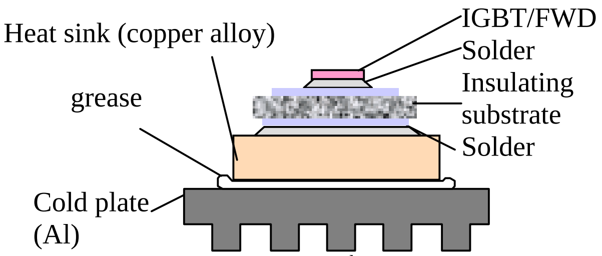


Fig.5 A cross section of the 2nd generation module

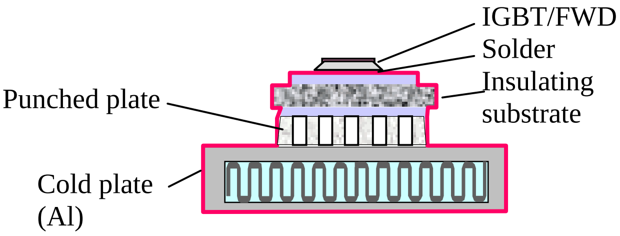


Fig.6 A cross section of the 3rd generation module

3.1.2 Power module

The 2nd generation IPM used a boost converter to make it possible to increase the input voltage into the IPM. Consequently, the current output of the IPM decreased. Therefore the number of IGBTs decreased which downsized the IPM.

To achieve a further downsizing of IPM, it was necessary to reduce the size of power semiconductors by improving the cooling efficiency as well as reducing power loss of the power semiconductors.

As mentioned before, in the previous cooling structure, the grease between a heat sink and a cold plate had high thermal resistance (Fig 7).

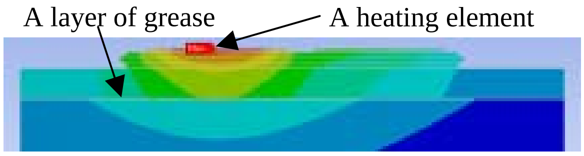


Fig.7 Heat distribution of the conventional cooling structure (2nd generation)

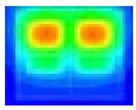
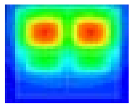
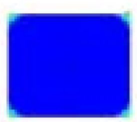
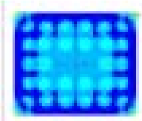
In the newly developed direct cooling structure, the elimination of grease between insulating substrate and water leads to an improvement of the cooling efficiency. In this structure, however, thermal stress from the cold plate, which has a high coefficient of linear expansion, acts on the insulating substrate, which has a low coefficient of linear expansion, directly, leading to a decrease in thermal shock resistance.

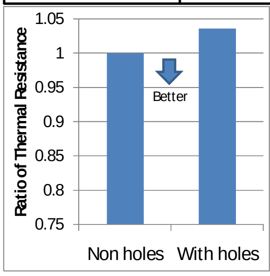
To solve this problem, a punched plate of the same

material as the cold plate has been added between the insulating substrate and the cold plate and decreases the thermal stress.

Due to holes in this punched plate, it is possible to decrease the stress concentrated at the edge of the insulating substrate in thermal shock test and keep the same thermal shock resistance as the conventional structure.

Moreover, optimizing the shape of the punched plate, considering the trade off characteristic between the stress relaxation and the cooling efficiency(Fig8), improved the cooling efficiency by 30% compared with that of the 2nd generation (Fig.9).

Shape of the punched plate	Non holes	With holes
Heat distribution		
Distribution of the Amplitude deformation		



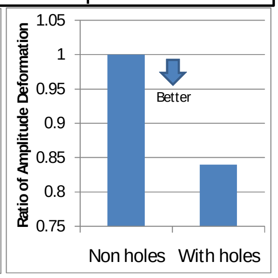


Fig.8 Trade off characteristic between the stress relaxation and the cooling efficiency depending on the shape of punched plate

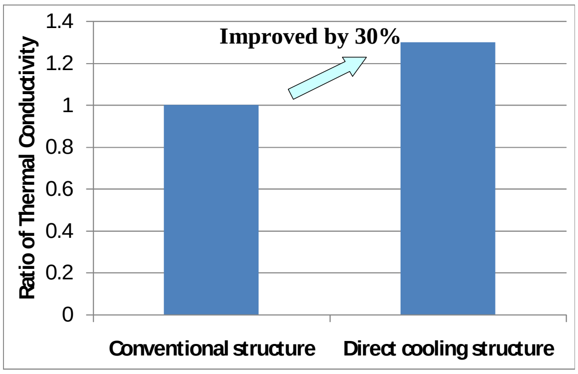
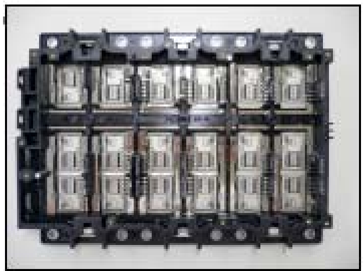


Fig.9 Improvement of the cooling efficiency by direct cooling structure

The 3rd generation IPM has been downsized by using this direct cooling structure, and the newly developed power semiconductors.
Now the IPM for generator/motor and boost converter is the same size as the IPM for the generator/motor for the 2nd generation but the maximum output is increased. (Fig10).



The 2nd generation Power module for generator/motor

The 2nd generation IPM for boost converter

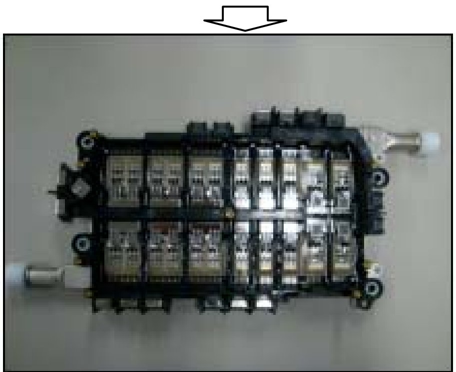


Fig.10 The 3rd generation power module

3.1.3 Power Semiconductor

We have adopted the trench-gate structure and thin wafer technology to newly developed IGBTs to achieve downsizing, higher output and efficiency of PCU. Compared to IGBTs of the current model with the planar-gate structure, the new IGBTs, with the trench-gate structure have five times the current capacity of the same area and make it possible to reduce the size of active area by 35%.

Furthermore, the breakdown voltage of the new IGBTs has been improved by 50% compared with that of conventional IGBTs.

Generally, there is a trade-off between breakdown voltage and steady-state loss, however, reducing the Si substrate area, which acts only as the resistance and doesn't influence the other characteristics, has decreased the thickness of the new IGBTs by 60% (Fig11). Its steady-state loss has been reduced by 25%, while improving the breakdown voltage greatly compared with the conventional IGBTs.

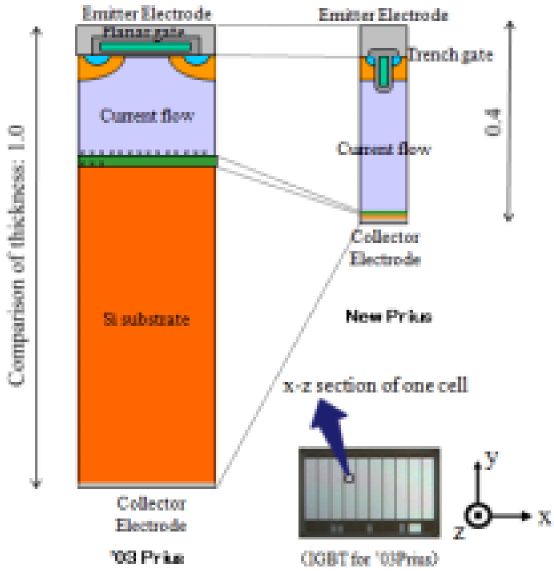


Fig.11 IGBT cross section (x-z)

3.2 Reactor

A reactor is required to boost voltage in the normal operating area stably, minimize loss, and minimize vibration for cooling and noise performance. The characteristics of reactor are decided by the magnetic characteristics of steel cores, the number of turns and size of coil and the gap length. Previously electrical steel sheets (t0.1mm) had been adopted to the cores especially to prevent overheating. However as their manufacturing processes were extremely complicated, it was not suitable for mass production. Therefore, we have developed new substitutive cores for electrical steel sheets and made mass production of the reactor easier.

3.2.1 High Density Magnetic Composite

We have newly developed a High Density Magnetic Composite (HDMC) core, molded out of iron particles and surrounded by an insulating layer. We simplified mass production by simplifying processes, while keeping the same magnetic characteristics as a core with electrical steel sheets. Fig12 and Fig13 each shows the magnetic characteristics and the manufacturing processes of HDMC core compared with that of conventional one.

Additionally, it is possible to control the magnetic characteristics of HDMC by controlling the shape and size of iron particle, insulating layer, relative density of cores etc. Therefore HDMC will be applied to other HV components widely in the future.

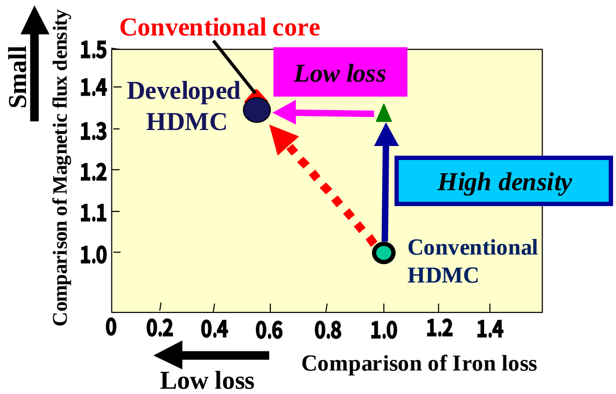


Fig.12 Magnetic characteristics of HDMC core

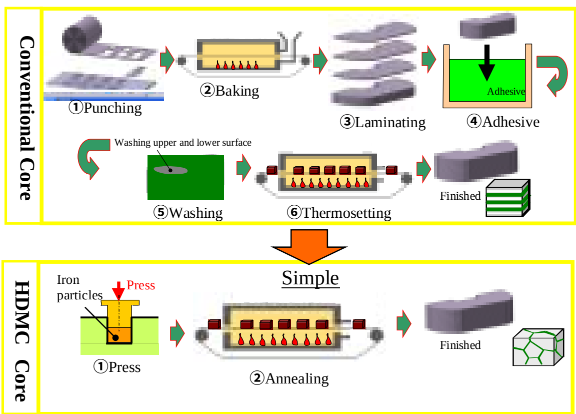


Fig.13 Comparison of the manufacturing process

3.2.2 Noise Performance Improvement

The reactor is required to have a low vibration performance and good electromagnetic characteristics. This is because the reactor vibration is transmitted through the body to the passenger cabin, which produces noise. The vibration of HDMC core itself is a little larger than that of a core with electrical steel sheets because its magnetostriction is relatively larger compared with that of a core with electrical steel sheets. Therefore, vibration reduction was the main issue for developing the new reactor.

In this reactor, cores are fixed to the lower case through silicon resin. The result is that the core and case do not directly contact. There is no vibration transmission because of the floating structure. As a result, the new model is much quieter than the current model.

Fig14 shows the floating structure and Fig15 shows the comparison of vibration acceleration between the floating structure and the conventional one in which the core touched the case directly.

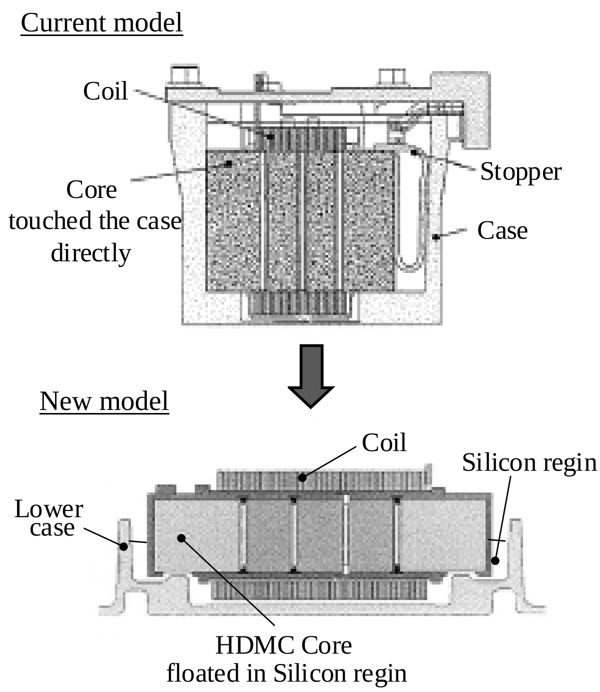


Fig. 14 The floating structure of a new reactor

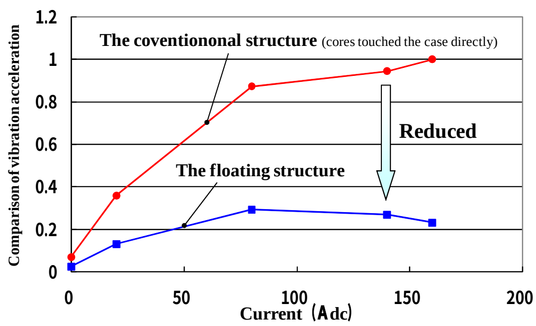


Fig. 15 Comparison of vibration acceleration between the floating structure and the conventional one.

A new silicon resin, with high thermal conductivity and high heat-resistance, has also been developed to improve the cooling efficiency.

3.3 Capacitor module

The capacitor module consists of the smoothing capacitor and the filter capacitor. These capacitors are used to smooth the voltage to control motor and the input voltage from the battery respectively. As for the smoothing capacitor, the motor control modification has enabled the capacitance to be reduced by 30%, and using a smaller capacitor. Moreover, further downsizing of the capacitor has been achieved by adopting much thinner, newly developed PP films optimized to the each capacitor. Additionally, the volume and mass has been decreased greatly by enlarging the elements of the capacitor and applying much thinner copper bus-bars(t0.8). As a result, the volume and the mass of the capacitor module have reduced by 33% and 40 % respectively, compared with the one used in the current model, as shown in Fig.16.

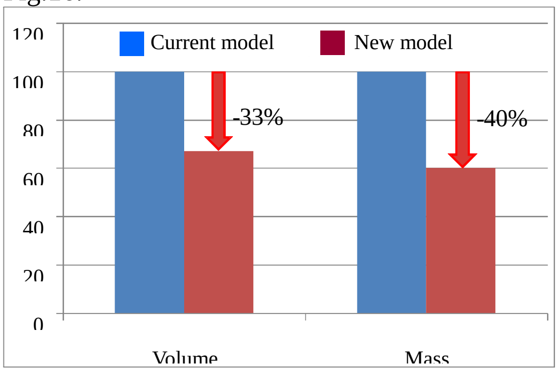


Fig.16 Comparison of the volume and the mass of the capacitor module (vs. Current model)

4 Conclusion

We have developed the 3rd generation PCU for midclass vehicles leading to size reduction, lighter weight and higher efficiency by the newly developed technologies below.

・Adopting higher boosted voltage of 650V

・Development of the direct cooling structure of IPM

・Development of trench-gate type thinner IGBT with low loss

・Development of HDMC core for Reactor

This means it becomes much easier to apply the PCU to multiple models and we can prepare for the expected rapid popularization of HV.

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