

EVS29 Symposium
Montréal, Québec, Canada, June 19-22, 2016

Development of Power Control Unit for Compact-Size Vehicle

Masaru Nakashima¹, Takaji Kikuchi¹, Osamu Kitazawa¹, Hajime Kosugi¹, Takahisa Kaneko²

¹ TOYOTA MOTOR CORPORATION 1 Toyota-cho, Toyota, Aichi Prefecture 471-8571, Japan,

²DENSO CORPORATION, 1-1 Showa-cho, Kariya, Aichi Prefecture 448-8661, Japan,

Summary

Toyota Motor Corporation has developed a new compact hybrid vehicle (HV) incorporating a new more fuel-efficient hybrid system. This paper describes the development of a new smaller, lighter, and more efficient power control unit (PCU) for this system, focusing on the measures adopted to increase the adaptability of the PCU for use in different models to facilitate the greater popularization of HVs in the future.

Keywords: HEV (hybrid electric vehicle), inverter, efficiency, DC-DC, power density

After the most recent wave of global motorization, vehicles have become a key part of the foundation supporting societies and economies around the world. However, vehicles are also a contributing factor to environmental issues such as global warming due to CO₂ emissions and air pollution. For this reason, automakers regard the development of hybrids (HVs) and other fuel-efficient, low-emission environmentally friendly vehicles as an urgent task. Toyota Motor Corporation has a long history of efforts to develop and popularize HVs, starting with the launch of the world's first mass-production HV in 1997, which was approximately twice as fuel efficient as a contemporary conventional gasoline powered vehicle. The second generation of this HV that was launched in 2003 featured a boost converter system that helped to increase both the power and fuel efficiency of the vehicle. The 3rd generation HV in 2009 included a larger displacement engine and higher output motor that improved performance and fuel efficiency at high speeds. The development of smaller and lighter components resulted in a more versatile hybrid system that was easier to adopt in different models. The recently launched 4th generation HV is the first vehicle to adopt a platform based on the Toyota New Global Architecture (TNGA). This HV achieves high fuel efficiency (40.8 km/L in the JC08 test cycle/ 56mpg in the combined test) and an even more enjoyable driving experience by adopting smaller and lighter powertrain components, as well as a lower center of gravity. This paper describes the 4th generation power control unit (PCU) that was developed for this HV system.



Fig.1: 4th generation PCU

1 PCU Specifications and Structure

1.1 HV System Specifications

Fig. 2 shows the configuration of the latest HV system. The basic configuration is unchanged from the previous generation. The main changes are the locations of the main and auxiliary batteries. Fig. 3 compares the layout of the 3rd and 4th generation HV systems. The new configuration helps to lower the vehicle center of gravity and increase the size of the luggage compartment.

Table 1 shows the main specifications of the system. The following items contribute greatly to the 18.2% improvement in fuel efficiency (JC08 test cycle) achieved by the HV system.

- Higher gasoline engine thermal efficiency
- Lower HV system losses
- Lower current by increasing the rotation speed of the motor

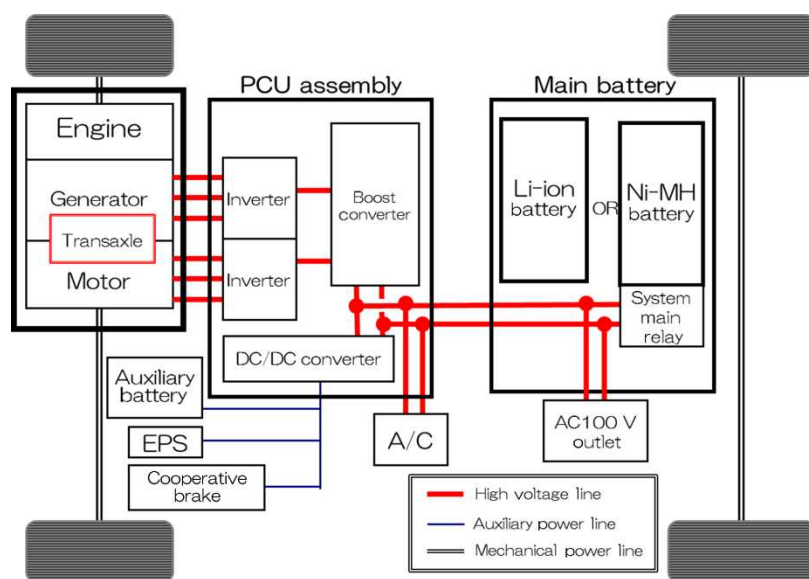


Fig.2: Configuration of 4th generation HV system

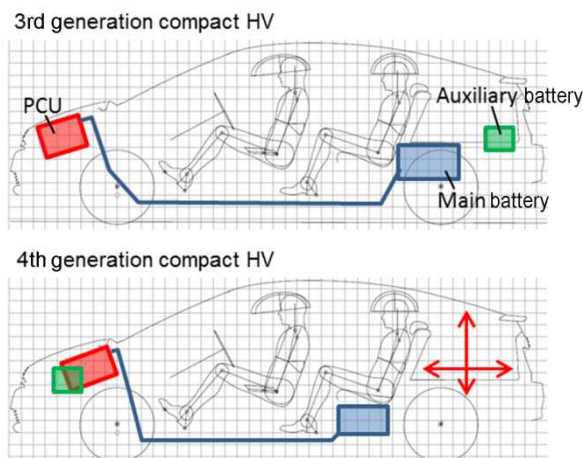


Fig.3: Layout of 4th generation HV system

Table1: Main specifications of HV system

	Previous model (3rd generation)	New model (4th generation)
Boost voltage	650 V	600 V
System max. output	100 kW	90 kW
Motor max. output	60 kW	53 kW
Motor max. rotation speed	13,900 rpm	17,000 rpm
Engine displacement	1.8 L	1.8 L
Engine max. power	73 kW	73 kW
Improvement rate of fuel efficiency	-	18.2%

1.2 PCU Mounting

Following the concept of the TNGA, the PCU mounting space is not designed independently for every vehicle type, but to enable application on a range of models. For this reason, the PCU is mounted directly on the transaxle (Fig. 4). This configuration helps to widen the applicability of the PCU by achieving the following improvements.

- (1) Shorter high voltage cables (reduced weight)
- (2) Simpler brackets (reduced size and weight)
- (3) More robust insulation performance against impact damage

In contrast, the main technical issue of mounting the PCU directly on the transaxle is the transfer of high-frequency engine vibration to the PCU. The following structural countermeasures were adopted to help resolve this issue.

- 1 A rubber bushing was added to the installation bracket to shield the transaxle from engine vibration.
- 2 A stiffer aluminum case was adopted to increase the resonance frequency of the PCU.
- 3 A vibration absorbing structure was designed for the connectors on the control board to improve vibration resistance.

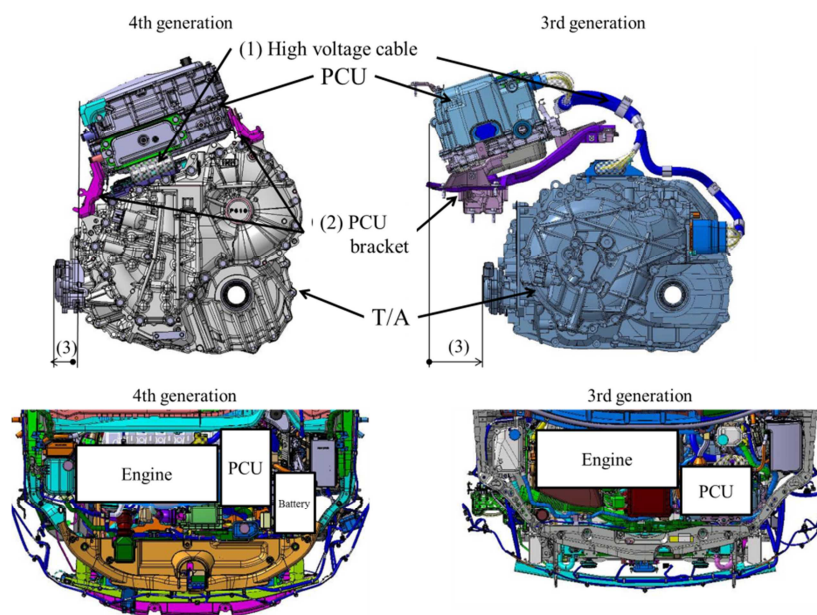


Fig.4: 4th generation PCU mounting structure

1.3 PCU Specifications

Table 2 lists the specifications of the PCU. The developed PCU is 33% smaller in volumetric terms than the previous model and 12% lighter, which corresponds to an improvement in maximum output density of 36%. This was achieved by optimizing the PCU internal layout and reducing the size of each component.

Table2: PCU specifications

	Previous model (3rd generation)	New model (4th generation)
Max. total output	177.8 kVA	162.2 kVA
Max. boost voltage	650 V	600 V
Motor max. current	170 Arms	180 Arms
Generator max. current	88 Arms	75 Arms
Weight	13.5 kg	11.9 kg
Volume	12.5 liters	8.4 liters
Max. output density	14.2 kVA/liter	19.3 kVA/liter

The main measures that helped to achieve this improvement are as follows.

- 1 Signal line imputes to the board were changed from W/H wiring to Terminal Pin wiring .
- 2 A double-sided cooling module and 2-in-1 power devices were adopted.
- 3 The weight of the reactor was reduced by changing the cooling module.
- 4 The capacitance of the smoothing capacitor was reduced by optimizing the boost converter control.
- 5 The size of the DC/DC converter was reduced by adopting a thick copper foil circuit board.

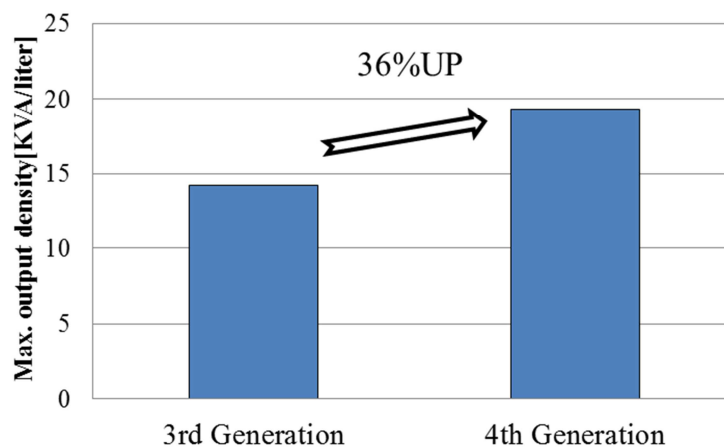


Fig.5: Comparison of specifications

1.4 PCU Structure

Fig. 6 shows the PCU structure. The PCU consists of inverters for the motor and generator, a boost converter, and a DC/DC converter. The new PCU structure is smaller and more easily adopted in other vehicle models than previous generations. This was achieved due to the adoption of a new power module with a double-sided cooling structure.

Fig. 7 shows the structure of the power module, which differs from the single-sided cooling structure used in the previous generation. This double-sided structure is more suitable for use with different engine displacements and system outputs because the number of stacks in the structure can be adjusted to change the output of the system.

This is called the power stack assembly. It consists of power cards, a cooler, insulating plates, and thermally conductive grease. One potential issue with the power stack assembly is an increase in heat flux caused by integrating two power device pairs into one power card. This issue was resolved by improving the cooling efficiency by cooling the power cards from both sides.

The size of the PCU was also reduced by adopting smaller components, and by optimizing the part layout, fixing structure, and wiring. The main changes are as follows. First the signal line input connections to the board were changed from wire harnesses to terminal pins. This was achieved by incorporating the terminal pins into each part and creating an efficient layout in the aluminum housing. Next, the internal wiring connections were changed from bolt tightening to welding, which reduced the amount of fastening structures by 67%. The signal wires were also integrated into each component. These changes helped to reduce the size of the PCU while improving productivity. The improvements described above reduced the size of the PCU by 33% in volumetric terms.

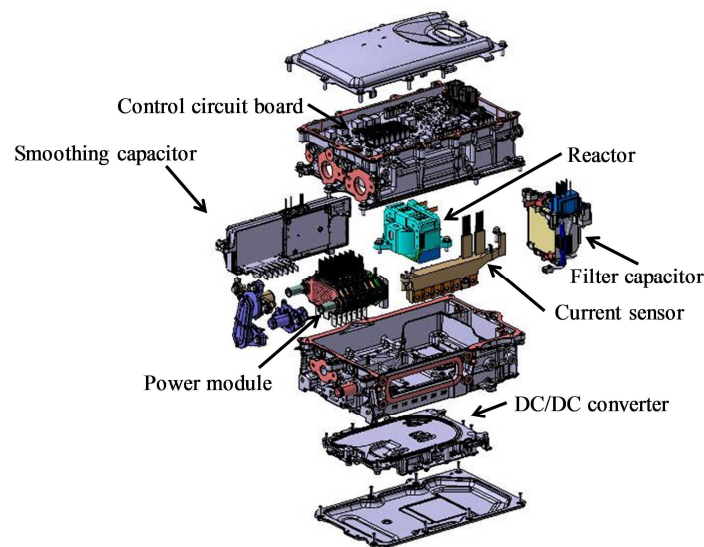


Fig. 6: PCU structure

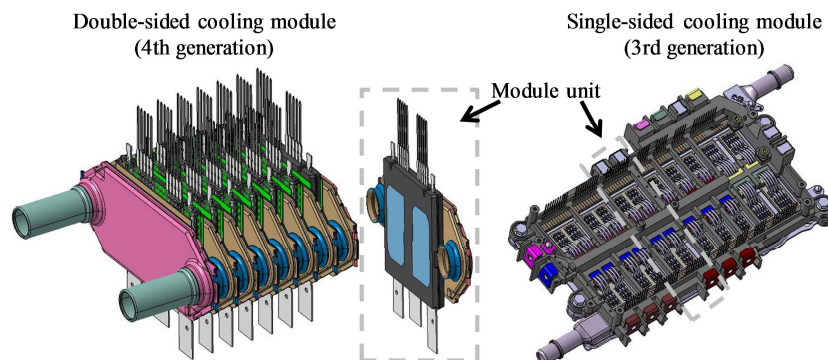


Fig. 7: Cooling structure

2 New Component Technology for Reducing Size and Weight

This section focuses on the size and weight reduction technologies incorporated into the internal PCU components.

2.1 Power Module

2.1.1 Conventional Structure of Power Module (3rd Generation)

Fig. 8 shows the structure of the 3rd generation power module that adopted the single-sided cooling structure. This structure consists of insulated gate bipolar transistor (IGBT) and free-wheeling diode (FWD) power semiconductors, an insulating plate, and a cooling plate. This structure utilizes a direct cooling method to improve cooling performance without requiring thermally conductive grease. However, this module is only suitable for adoption in low-power compact vehicles and cannot be used in higher power models that lack the space for a higher number of power semiconductors. Therefore, the 4th generation module adopted a stacking structure with a double-sided cooling module (power cards). This enables the development of a series of cooling modules for use in both lower and higher power vehicles, as well as improved cooling performance by further reducing the size of the power semiconductors.

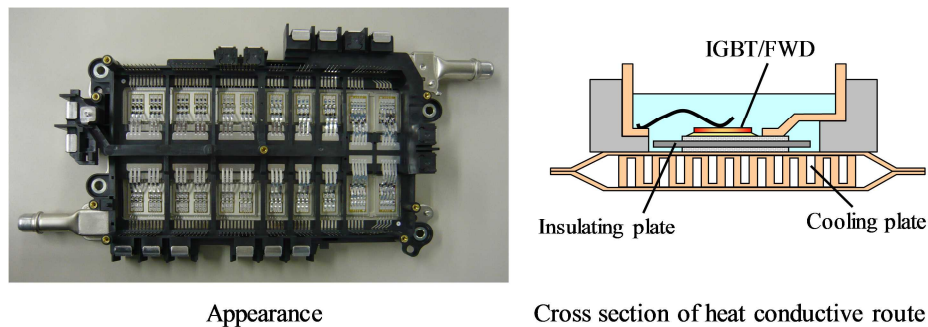


Fig.8: Single-sided cooling module (3rd generation)

2.1.2 2-in-1 Double-Sided Cooling Module (4th Generation)

Fig. 9 shows the differences in the IGBT and FWD packages. The conventional double-sided cooling structure is a 1-in-1 structure consisting of a sealed package with a pair of IGBTs and FWDs. The aims of the newly developed 2-in-1 structure are to facilitate installation in compact vehicles, and to reduce inductance and the number of components. Since fewer power cards need to be installed in vehicles with lower engine displacements and power, a reduction in the inductance and number of parts can be achieved. As the engine displacement and power increases, the number of power cards can also be increased to allow high output current.

Fig. 10 shows a cross-section of the 2-in-1 power card structure. The development of this structure first studied the advantages and disadvantages of U- and N-shaped cross-sections. A U-shaped structure has advantages in terms of size, inductance, and the number of components because the emitter on the upper arm and the collector on the lower arm are integrated to a common heat sink (O). However, an issue of the U-shaped structure is controlling the melting sequence of the solder on the copper (Cu) spacer, which absorbs the lamination tolerance when soldering, since the mounting directions of the power semiconductors on the upper and lower arms are reversed. In this case, the concern is solder overflow around the power semiconductors if a different solder melts during the manufacturing process. Therefore, the solder on the Cu spacer was designed to melt first by using a low-melting point solder on the Cu spacer and adopting materials with different specific heat capacities for some of the soldering tools. However, quality was difficult to control due to the dispersion of the manufacturing process. In contrast, an issue of the N-shaped structure is the reliability of the solder joints that connect between the upper and lower arm, and with the N terminal. Finally, the N-shaped structure was adopted after confirming the fatigue life of the solder joints under repeated heat stress, electro-migration tolerance at high current densities, and other factors.

Figs 11 and 12 show the structures of the 4th generation 2-in-1 power card and power module. Compared to the 1-in-1 structure and assuming equal output performance, the size was reduced by 22% and the inductance between the P and N terminals was reduced by 55% by eliminating the wiring busbar between the upper and lower arms.

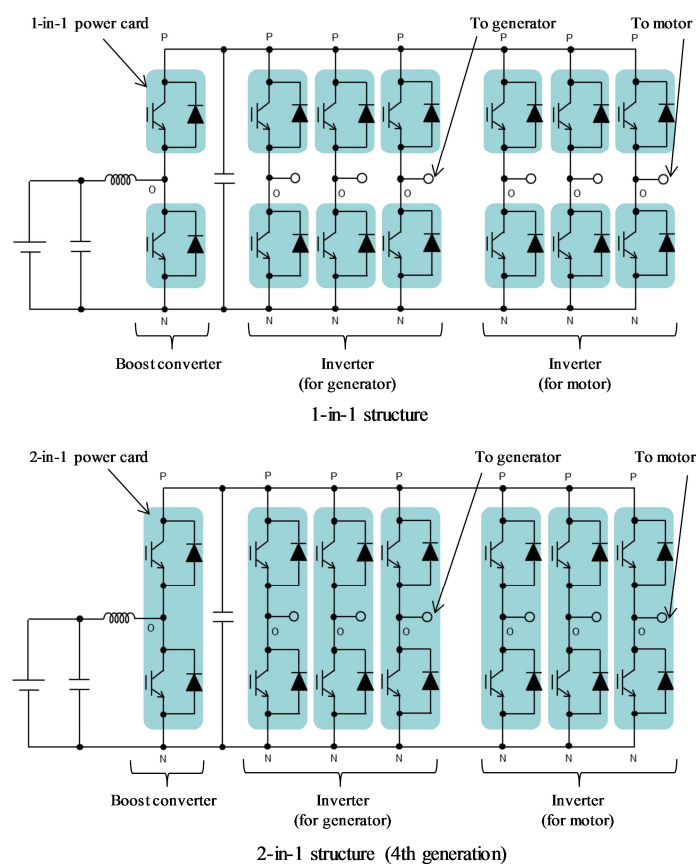


Fig.9: Power semiconductor device packages

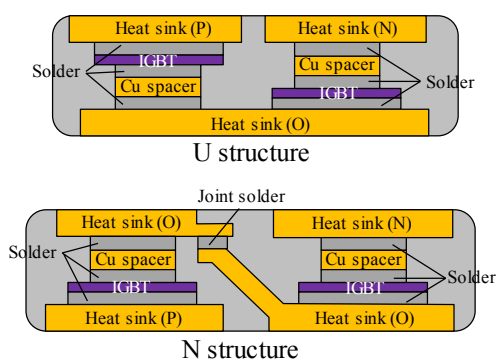


Fig.10: 2-in-1 structure

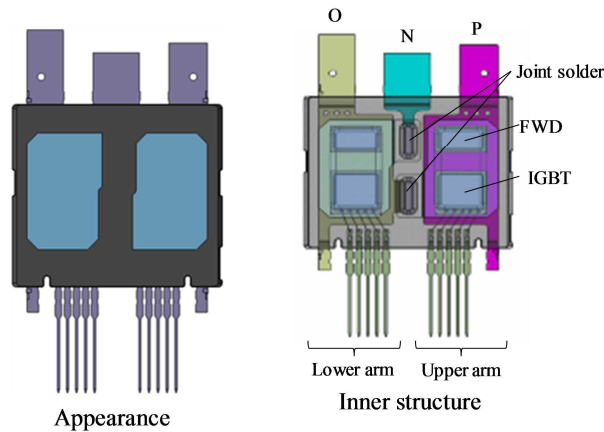


Fig.11: Structure of 4th generation 2-in-1 power card

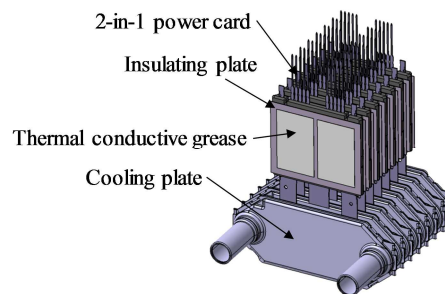


Fig.12: Structure of 4th generation power module

2.1.3 Control Circuit Board

The control circuit consists of an electronic control unit for the motor/generator (MG ECU) and an intelligent power module (IPM) circuit board. The MG ECU calculates the control signals of the IGBTs using sensor output signals and vehicle drive requests from the master ECU. The IPM circuit board contains the IGBT driver circuits and circuits to protect the IGBTs against short circuits or overheating.

The 4th generation PCU design integrates the MG ECU and IPM circuit into a single circuit board. In addition, the power supply to the control board was optimized and the circuit density was increased by adopting hybrid processing ICs. These control circuit board improvements reduced the number of components as well as the number of board layers.

On the control circuit board itself, the microcomputer and reactor current sensor were improved. Adopting a new microcomputer increased the processing speed of the motor control, thereby reducing loss. Adding a reactor current sensor improved controllability and reduced the size of the components around the capacitor.

Reactor

Fig. 13 shows the structure of the 4th generation reactor, which was developed with the aim of reducing weight. The following measures succeeded in reducing the weight by 11%.

- 1 Improving the controllability of the boost converter widened the usable range of the DC superimposition characteristics. This enabled the conventional 4-gap structure to be changed to a 2-gap structure, thereby reducing the number of components and weight of the reactor.
- 2 In the conventional reactor, only the core was resin molded and the reactor cooling structure absorbed coil misalignment using resin potting. This was replaced by a single-molded reactor structure that also incorporates the coil. Cooling is achieved by heat dissipating sheets, further reducing weight.

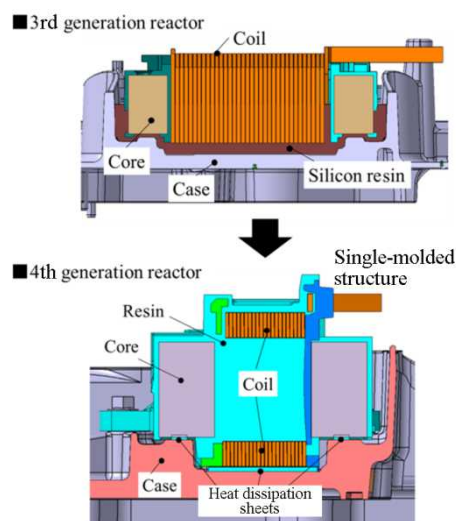


Fig.13: Structure of reactor

2.1.4 Capacitor

The capacitor module consists of smoothing and filter capacitors. These capacitors function to stabilize the PCU voltage input from the battery and the PCU output voltage to the motor. To reduce the size of the power semiconductors, it is necessary to reduce the surge voltage. This requires decreasing the equivalent series inductance (ESL). Functional integration and reducing the size of the components enabled the development of a smaller 4th generation capacitor module with a lower ESL.

Figs 14 to 16 show the circuit diagram of the functional integration and the component parts. The 4th generation capacitor module integrates the 4-phase busbar with the smoothing capacitor. This reduces the length of the wiring and allows the P and N busbars to be laid out close to each other in parallel, thereby reducing ESL.

Reducing the size of the component parts helped to decrease the capacitance of the capacitor module by improving the controllability of the power semiconductors. In addition, a newly developed thin film was used to further reduce size.

These improvements helped to reduce capacitance by 34% and ESL by 58% (Fig. 17).

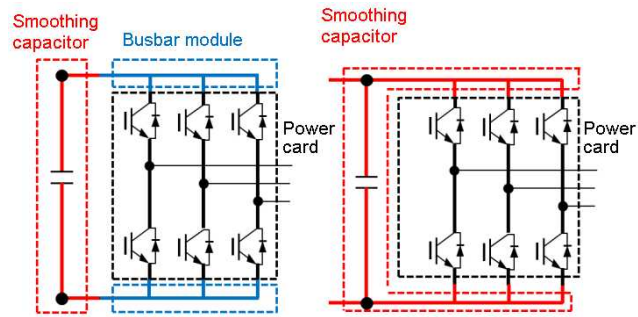


Fig.14: Functional integration of 4th generation capacitor module

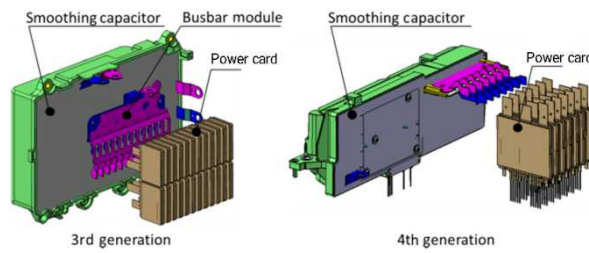
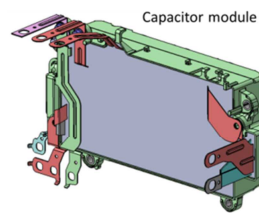


Fig.15: Comparison of structure

■ Previous model



■ New model

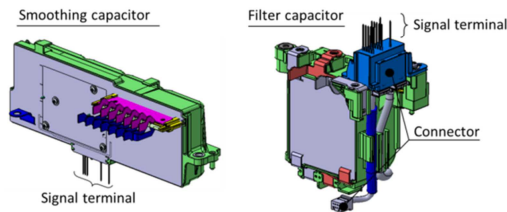


Fig.16: Structure of capacitor modules

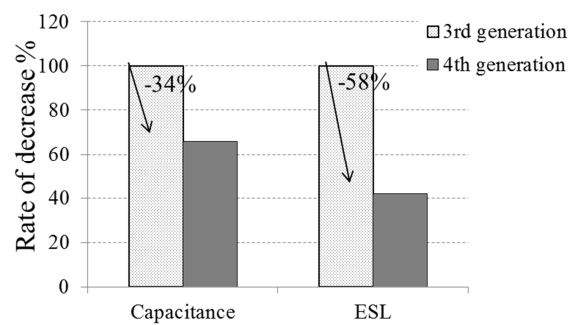


Fig.17: Comparison of specifications

2.1.5 Current Sensor

The current sensor detects and feeds back the input and output current of the motor and generator to the PCU current control. The size and weight of the fourth generation current sensor were reduced by combining functions and adding sensing capabilities. Fig. 18 shows the sensing points of a 4th generation current sensor in the PCU circuit. In addition to detecting the input and output current of the motor and generator, the 4th generation current sensor also detects the input and output current of the boost converter. This helps to both reduce fluctuations in the PCU system voltage and decrease the capacitance and size of the film capacitors.

In addition, the current sensor was integrated with the output terminals to save installation space and reduce the number of components. Hall ICs were adopted for the current detection devices to reduce the number of mounted components as well as the volume of the circuit board. As a result, the size of the current sensor was reduced by 42% in volumetric terms and the weight by 29% in comparison to the 3rd generation sensor (Fig. 19).

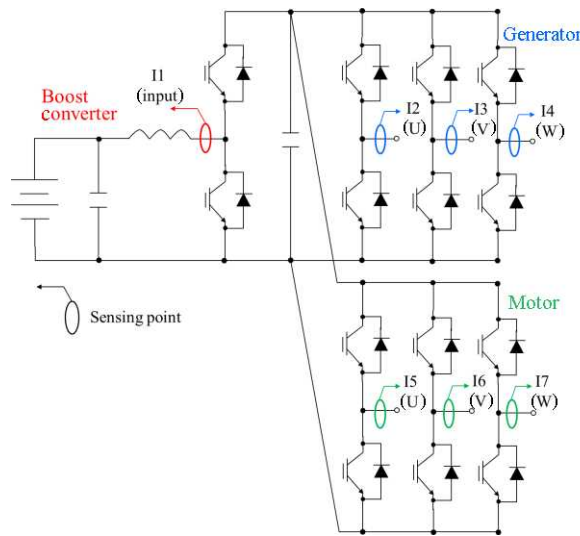


Fig.18: Sensing points of current sensor

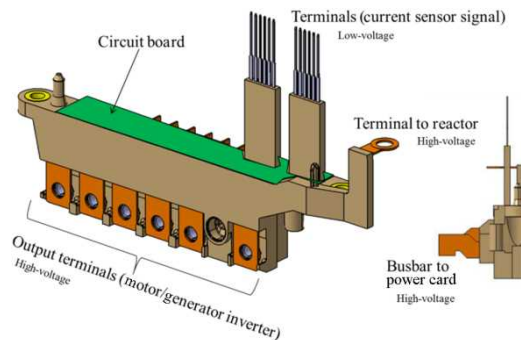


Fig.19: Structure of current sensor

2.1.6 DC/DC Converter

The DC/DC converter in a hybrid system fulfills the role of an alternator in a conventional gasoline engine vehicle. Since the PCU is mounted on the transaxle in the 4th generation DC/DC converter, it was also important to reduce the size and weight of the DC/DC converter.

The 3rd generation DC/DC converter used a conventional busbar connection between components, which increased the number of parts and made weight reduction difficult. Therefore, a new thick copper foil circuit

board was developed to eliminate the need for bus bar connection. A conventional copper foil circuit board requires a high thermal efficiency and is too thin to form a correct pattern by conventional etching techniques. Therefore, a metal stamping process was adopted to allow the formation of a highly precise pattern on a thick copper foil circuit board. This allowed components to be directly mounted onto the thick copper foil circuit board, thereby reducing size and weight (Fig. 20).

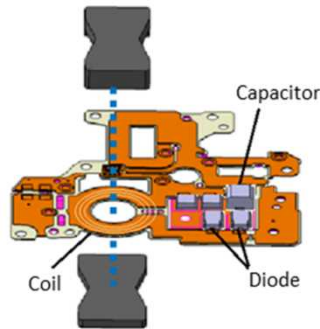


Fig.20: Appearance of thick copper foil circuit board

3 New Component Technology for Reducing Electrical Loss

3.1 Lower Loss IGBT

New IGBT technology was developed for the 4th generation PCU to drive the motor and generator. The 4th generation IGBT is based on the 3rd generation IGBT and features a newly developed low loss structure called a super body layer (SBL). The SBL was developed with trench gate and thin film technology. As shown in Fig. 21, steady-state and switching losses increase when the density of electron holes decreases near the emitter. However, as shown in Fig. 22, the 4th generation IGBT uses the SBL to make it more difficult for electron holes to pass through to the emitter. This improved the trade-off effect between steady-state and switching losses by 16%.

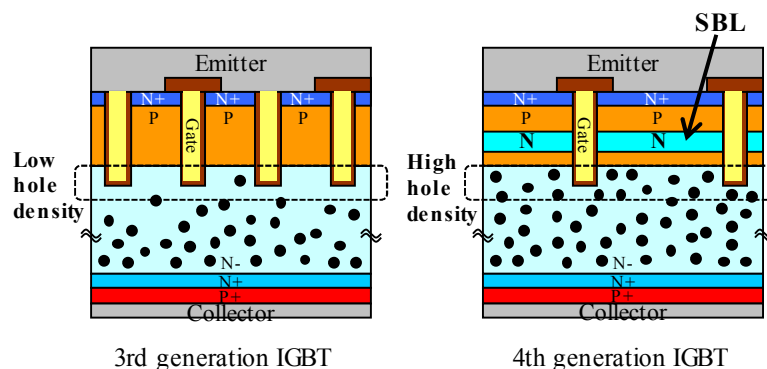


Fig.21: Adoption of low loss structure (SBL)

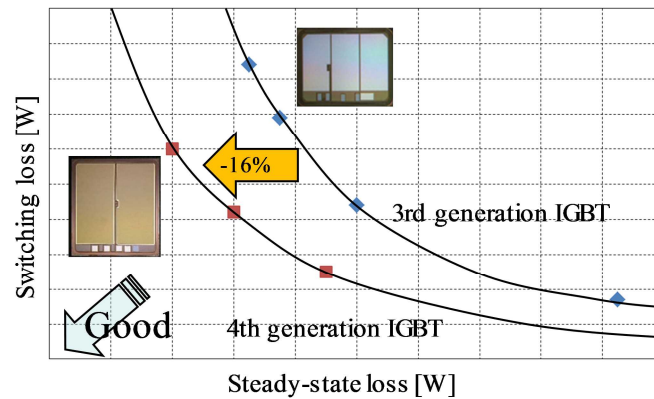


Fig.22: Improvement of loss trade-off

4 Conclusions

A new PCU was developed for a 4th generation HV based on the TNGA. The following measures were adopted to reduce the size and weight of the PCU.

- The high-voltage cables and brackets were simplified by directly mounting the PCU on the transaxle.
- A double-sided cooling structure and 2-in-1 power card module were adopted.
- The size and weight of the control circuit board, reactor, capacitor module, current sensor, and DC/DC converter were reduced.
- Improved sensing technology and higher speed processing stabilized higher voltages and helped to reduce the capacitance of the capacitors.
- The electrical losses of the PCU were improved by developing lower loss IGBTs.

The 4th generation PCU is smaller, lighter, and has lower loss than the 3rd generation component. These improvements help to improve fuel efficiency while ensuring an even more enjoyable driving experience in the latest generation HV.

References

- [1] N. Nozawa, K. Asakura, S. Nozawa, T. Maekawa, *Development of Power Control Unit for Compact-Class Vehicle*, SAE Paper 2009-01-1310, 2009
- [2] Y. Sakai, H. Ishiyama, T. Kikuchi, *Power Control Unit for High Power Hybrid System*, SAE Paper 2007-01-0271, 2007

Authors



Masaru Nakashima
Hybrid Vehicle Power Train Development Div.
TOYOTA MOTOR CORPORATION
1, Toyot-cho, Toyota, Aichi, 471-8571 Japan
Phone: +81-565-94-3420
Fax: +81-565-94-3319
E-mail: masaru_nakashima_aa@mail.toyota.co.jp



Tkakaji Kikuchi
Vehicle Power Train Development Div.
TOYOTA MOTOR CORPORATION
1, Toyota-ho, Toyota, Aichi, 471-8571 Japan
Phone: +81-565-94-3435
Fax: +81-565-94-3319
E-mail: takaji_kikuchi@mail.toyota.co.jp



Osamu Kitazawa
Hybrid Vehicle Power Train Development Div.
TOYOTA MOTOR CORPORATION
1, Toyota-ho, Toyota, Aichi, 471-8571 Japan
Phone: +81-565-94-3436
Fax: +81-565-94-3319
E-mail: hv-kmsupport@mega.tec.toyota.co.jp



Hajime Kosugi
Power Electronics Development Div.
TOYOTA MOTOR CORPORATION
1, Toyota-ho, Toyota, Aichi, 471-8571 Japan
Phone: +81-50-3184-6229
Fax: +81-565-44-9487
E-mail: hajime_kosugi@mail.toyota.co.jp



Takahisa Kaneko
EHV Components Eng. Div. 1, Eng. Dept. 4,
DENSO CORPORATION
1-1, Showa-cho, Kariya, Aichi 448-8661, JAPAN
Phone: +81-566-55-6810
Fax: +81-566-25-4870
E-mail: TAKAHISA_KANEKO@denso.co.jp