High-power-density Inverter Technology for Hybrid and Electric Vehicle Applications

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OVERVIEW: Green vehicles have become familiar sights on the road in recent years, with growing sales of HEVs and the arrival of the first mass production BEVs. With environmental regulations on CO_2 (fuel economy) and exhaust emissions also becoming increasingly stringent, sales of these green vehicles are set to increase further in the future. Consequently, because electric drive systems are made up primarily of electric motors, inverters, and batteries, inverters are being called on to fulfill increasingly diverse roles and there is a need to decrease their size and cost while increasing their output. Along with supplying inverters for HEVs and EVs that are an ideal match with customer requirements, Hitachi also intends to continue contributing to progress toward a low-carbon society by developing technologies that will help make inverters more widely used.

INTRODUCTION

WITH the aim of creating a sustainable society, vehicle fuel economy standards are becoming progressively tighter year by year in order to reduce carbon dioxide (CO_2) emissions. It is forecast that the proportion of the total market accounted for by electric vehicles (EVs) and hybrid electric vehicles (HEVs) will grow significantly by 2020. HEVs have been commercialized in a variety of forms. Hitachi draws on its strengths in power electronics to supply inverters that suit diverse customer requirements.

There has been demand in recent years to increase the output and reduce the size of inverters so that they can fit into the limited space available in vehicles. In response, Hitachi has developed new power modules with double-sided direct cooling that deliver considerably higher power density than past models. Hitachi has also developed a standard power electronics platform for mounting these power modules, and has commercialized it in the form of a standard inverter.

This article describes the power modules with double-sided direct cooling used in automotive inverters, the configuration of the standard inverter, Hitachi's own direct current (DC) converter that is integrated into the inverter, and the steps Hitachi is taking to increase inverter output further.

PAST WORK

Automotive inverters accelerate or decelerate the vehicle by converting the DC power from the batteries to alternating current (AC) at the frequency required for vehicle speed and other system control to control the electric motor speed, drive torque, and power. The performance requirements for these electric drive systems for HEVs and EVs are small size (important for ensuring that the system can be installed in the vehicle), high efficiency to extend EV range, high output to provide suitable acceleration performance, and reliability to operate in the harsh environment inside a vehicle.

By utilizing its technologies for package structure of power module to develop a direct water cooling system, Hitachi has succeeded in delivering both small size and high performance. It is also working on making its inverters smaller still by adopting a double-sided cooling method with direct water cooling and fully immersed cooling fins (see Fig. 1).

Depending on the type of drive used, electric drive systems require an inverter capable of driving one or two electric motors. For compatibility with the motor and battery, they also need to operate at a variety of system voltages, such as 60 V or less, or 100 – 450 V. Hitachi commenced full-scale production of HEV inverters with direct cooling in 2005, producing models capable of driving one or two motors and operating at 42 V. Power modules with single-sided direct cooling were used up to the second generation, and double-sided direct cooling was adopted from the third generation onward. Hitachi has also developed its standard inverter to achieve greater sharing of parts between models (see Fig. 2).

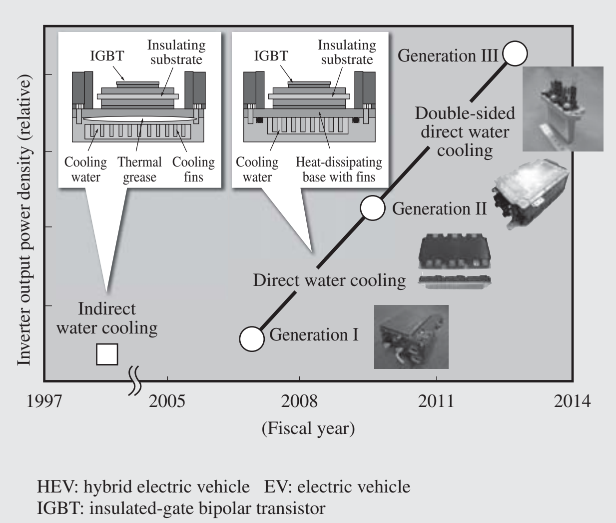


Fig. 1—Development Roadmap for HEV/EV Inverters.
To satisfy the diverse requirements for automotive use, Hitachi is achieving smaller size and higher performance by utilizing engineering and analytical technologies taken from numerous different fields, including the electric power, industrial, and consumer sectors, to develop direct water cooling.

TECHNOLOGIES FOR INVERTERS WITH HIGH POWER DENSITY

Features of High-power-density Inverter

The requirements for automotive inverters include control performance that extends from low to high motor speeds, robustness to withstand a harsh environment (heat and vibration), electromagnetic compatibility (EMC) performance to minimize the radiation of electromagnetic noise due to heavy current switching, ease of installation (small size and light weight), failsafe functions in the event of a fault, long life with respect to thermal fatigue, excellent water and dust proofing, and insulation performance at high altitude. The inverters also need to satisfy these demanding requirements at a low cost.

Automotive inverters incorporate a wide variety of components, including insulated-gate bipolar transistor (IGBT) power devices, power modules, high-voltage DC line capacitors, main circuit busbars, a power module drive circuit board, a motor control circuit board, three-phase current sensors, and DC and heavy-current AC connectors. Delivering the expected high performance has in the past required the use of special-purpose components. The components used in the high-voltage and heavy-current power sections of the inverter required a high level of insulation and the ability to withstand high voltages.

As a result, Hitachi has set out to reduce costs by standardizing components, and is seeking to satisfy diverse customer needs by designing inverters that use these standardized components.

The newly developed high-power-density inverter has the following features.

(1) Use of power modules with low thermal resistance, and IGBTs and diodes with low losses and high performance

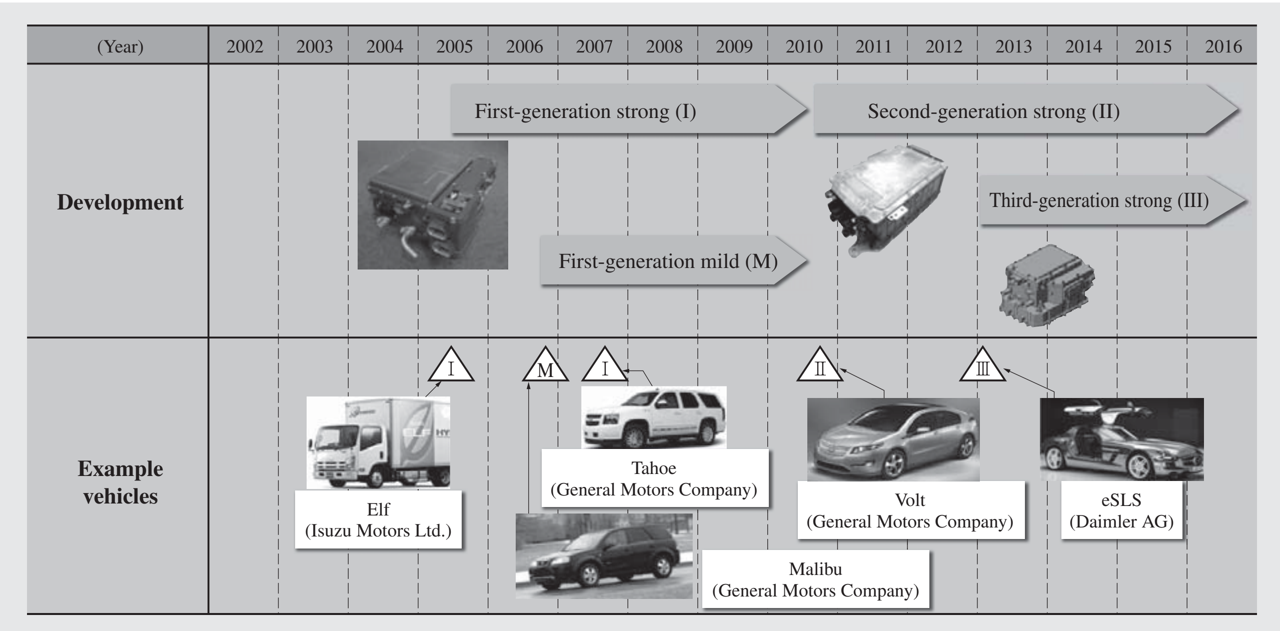


Fig. 2—Use in HEVs.
Hitachi commenced full-scale production of inverters with direct cooling in 2005, and has supplied three generations of high-output inverters to date.

(2) Design with a low-inductance main circuit and optimized DC capacitance
(3) Water channel design that combines efficient cooling with low pressure loss
(4) Use of an application-specific integrated circuit (ASIC) with built-in protection functions for gate drive
(5) Motor control circuit board designed for functional safety
(6) Compact package design with small size and light weight
(7) Miniaturized auxiliary inverter (option)

Double-sided Direct-cooling Power Module

Power Devices

The IGBT and freewheeling diode (FWD) power devices need to deliver the performance required by the vehicle when operating at its maximum limits. As power devices account for the bulk of losses in an inverter, they have a significant impact on electrical efficiency. Accordingly, the power devices need to have low losses. Hitachi has achieved low losses by adopting the latest device technology available at the time for each of its inverter generations (see Fig. 3).

As the maximum DC link voltage is about 400 V (assuming no voltage booster is used), IGBTs need to be rated for 650 to 700 V. Other likely design requirements are an effective current of 300 to 400 Arms and a carrier frequency of 5 to 12 kHz. To achieve low losses under these operating conditions, and to reduce inverter size, Hitachi has adopted field-stop, trench IGBTs for its third-generation models.

Power Modules

The requirements for power modules are to minimize inverter floor space and to get the best performance out of the power devices. Hitachi has been using direct cooling since its first- and second-generation models. For direct cooling, the fins on the base of the module are immersed in cooling fluid. This improves heat dissipation because it dispenses with the heat sink thermal resistance and the thermal grease used in the past between the base plate and heat sink (see Fig. 4).

The pin fin design is critical to direct cooling. While having more fins reduces the thermal resistance, it increases the pressure losses in the cooling water channels. Hitachi uses a genetic algorithm to optimize the design of its pin fins (see Fig. 5). The optimum pin fin design needs to be selected based on the required thermal resistance and the pressure loss determined by the requirements specified for the electric drive system's cooling system. By applying this optimization, the single-sided cooling systems used in the first- and second-generation inverters achieved a 30% improvement over indirect cooling, as measured by the thermal resistance from the device junction to the cooling fluid (for a flow rate of 10 L/min and a pressure loss of 20 kPa).

This cooling method was further developed in the third generation with the adoption of double-sided

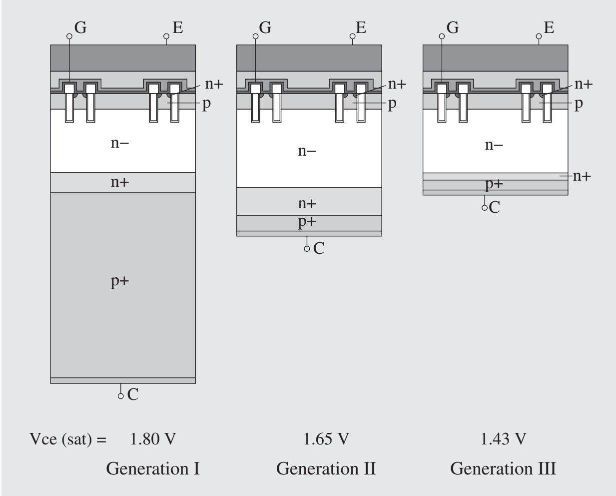


Fig. 3—Evolution of IGBT Device Structure and Vce (Saturation Voltage).
As IGBT losses account for the bulk of inverter losses, losses have been reduced with each successive generation. Non-punch-through devices were used for the first generation, punch-through devices for the second, and field-stop devices for the third.

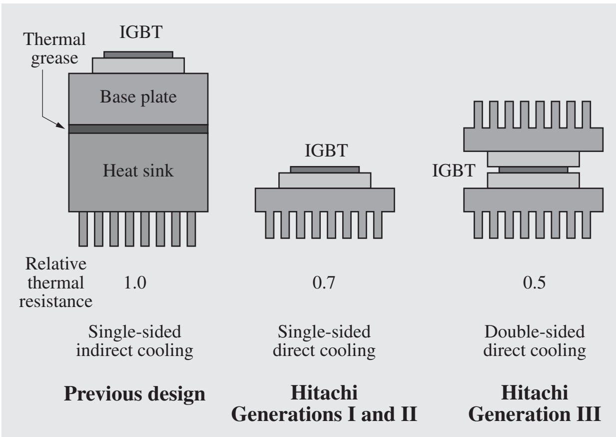
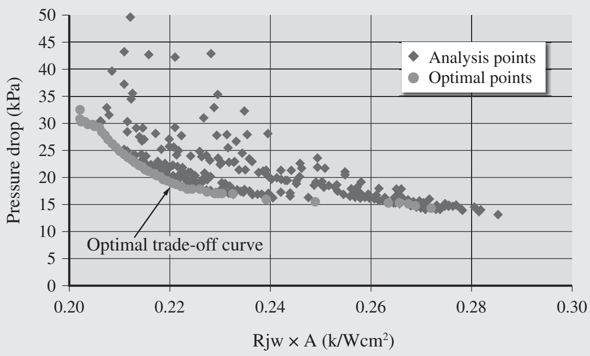
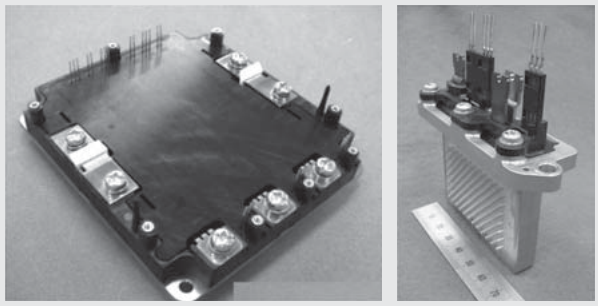


Fig. 4—Advances in Power Module Cooling Design.
Whereas past designs dissipated heat via grease to a heat sink, Hitachi has since its first-generation models adopted direct cooling in which the heat-dissipating fins are immersed in cooling water, allowing the IGBT current density to be increased. From the third generation onwards, Hitachi has developed a new double-sided cooling method in which fins are located on both sides of the chip.



Pressure drop: Drop in pressure in cooling water channels for 50% long life coolant (LLC), 50% water
Rjw × A: Thermal resistance per unit area between junction temperature and cooling water temperature

Fig. 5—Pin Fin Optimization for Power Modules.
The thermal resistance of the power modules is improved at the expense of increasing the pressure loss in the cooling water channels. As this increases the resistance to water flow in the channels, the optimal point can be selected based on the cooling capacity. Hitachi used a genetic algorithm to determine the optimal curve for the fin shape parameters (number of fins, fin spacing, and fin height).



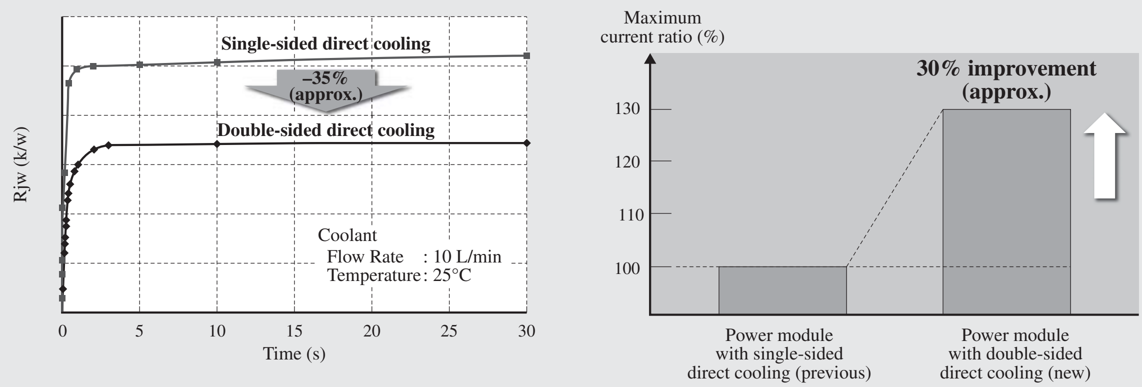
(a) Power module with single-sided direct cooling **(b) Power module with double-sided direct cooling**

Fig. 6—Power Modules.
A power module with single-sided direct cooling (a) was used for the second-generation inverters, and a power module with double-sided direct cooling (b) was developed for the third generation. The power module with double-sided direct cooling is rated for 700 V, has a maximum current of 325 Arms, and has an insulation resistance of 10 MΩ (500 Vdc) and 2,700 Vdc (1 minute). Its maximum current can also be up-rated to 400 Arms by changing the IGBT chip.

direct cooling (see Fig. 4). In place of the wire bonding used in the past, the lead frame for the emitter side of the IGBT is soldered and the lead frame is joined to the heat sink via insulating material. As the metal leads, insulators, and fins form a single structure, this dramatically reduces thermal resistance.

Also, the third-generation modules have a two-in-one configuration with one module for each phase of the three-phase current (UVW). This facilitates optimization of the inverter design because it provides greater flexibility in where to mount the module (see Fig. 6).

The power modules with double-sided direct cooling have approximately 35% better thermal resistance than the modules with single-sided direct cooling, providing a performance improvement of 30% or more in terms of current flow assuming use of power devices with the same chip size (see Fig. 7).



(a) Comparison of transient thermal resistance **(b) Comparison of maximum current ratios**

Rjw: Thermal resistance (degrees Kelvin/Watt) between junction temperature of power device and cooling water temperature

Fig. 7—Heat Dissipation Performance of Power Module with Double-sided Direct Cooling.
This comparison shows the heat dissipation performance of power modules with double-sided and single-sided direct cooling respectively, assuming the same IGBT chip size. The reduction of about 35% in Rjw thermal resistance increases the maximum current by approximately 30%.

Improvements in the performance of modules with double-sided direct cooling mean less rise in junction temperature, and because the inverter is able to operate with the cooling water at a higher temperature, this simplifies the dedicated inverter cooling system that was required in the past.

Cooling Water Channels, Main Circuit, and Capacitors

While reducing inverter losses requires lower gate resistance and higher switching frequency, these result in higher surge voltage. This means the main circuit inductance needs to be reduced. As the main circuit inductance consists of the module's internal inductance, busbar inductance, and capacitor internal inductance, reducing overall inductance is achieved by optimizing pin locations and overlaying the positive and negative busbar terminals of each component.

Film capacitors of 2.5 μm in thickness are used to improve DC capacitor reliability, and the cells and pin locations have been optimized to reduce the capacitors' internal inductance.

For inverters that use the power modules with double-sided direct cooling, Hitachi also optimized the design of the cooling water channels that house the modules to ensure that the level of pressure loss in these channels is appropriate.

The design also locates the DC capacitance in the space surrounded by the vertical cooling water channels that house the power modules with double-sided direct cooling so that the heat generated by these DC capacitors, which have a low heatproof temperature, is conducted away to the water-cooled jacket. Hitachi has also sought to dramatically simplify the wiring harness to make the inverters easier to assemble and more reliable. An efficient design is used, including the current sensors being mounted directly on the circuit board, eliminating harness and connector components, and significantly reducing the overall component count of the inverter (see Fig. 8).

Gate Drive Circuit Board

The gate drive circuit board is designed to suit the power module layout, with Hitachi having developed an ASIC that includes protection functions for detecting over-temperature and over-current, and that significantly reduces the component count. It has been standardized to obtain maximum performance from the power devices.

Motor Control Circuit Board

Internal permanent magnet synchronous motors (IPM-SM) are widely used in HEVs because of the need for the motors to operate at high torque and speed. Hitachi has developed standard control software and a standard motor control circuit board to implement vector control. These provide the key functions required for automotive inverters, including a resolver interface, dual control area network (CAN) interfaces, motor temperature detection, high-voltage detection, torque security, and fault diagnostics memory. As automotive electronics systems will need to comply with functional safety as defined by ISO 26262 in the future, Hitachi has pre-empted this by designing inverters that satisfy the Automotive Safety Integrity Level-C (ASIL-C) standard of functional safety. Hitachi also uses dual-core central processing units (CPUs) and provides the monitoring functions needed to satisfy functional safety requirements.

Standard Inverter

Fig. 9 shows Hitachi's latest inverter that utilizes the technologies described above for higher density. Second-generation inverters used modules with single-sided direct cooling and were able to drive two motors. The third-generation models use modules with double-sided direct cooling and feature a power density of 35 kW/L, 5.6 times that of first-generation models. Whereas in the past Hitachi has developed inverters that have been optimized for individual customers, for its third-generation models it developed a new standard inverter that drives a single motor. The aims are to simplify vehicle layout design and shorten development and design times. By using

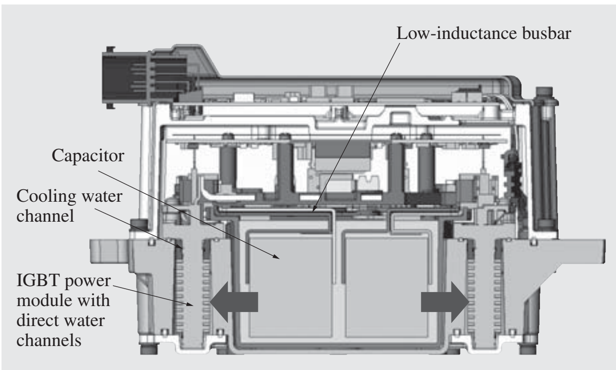


Fig. 8—Internal Design of Inverter Using Power Module with Double-sided Direct Cooling.
Locating the inverter power modules with double-sided direct cooling alongside the capacitors allows cooling of the film capacitors, which have a low heatproof temperature.

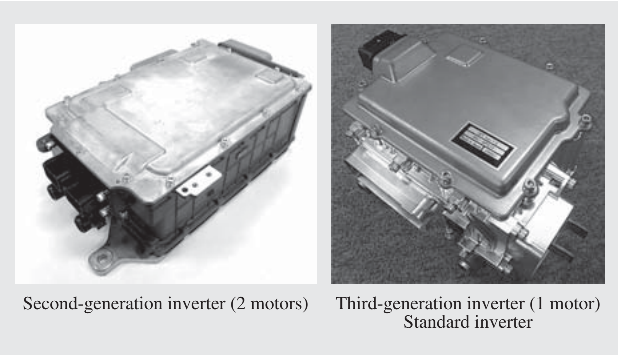


Fig. 9—Design of Latest Inverters.
Hitachi has developed a single-motor standard inverter to its own proprietary specifications. To maintain its general-purpose characteristics while also providing the flexibility to fit in various vehicle layouts, the new inverter uses a standard power section but allows the cooling pipework, heavy-current connectors, signal connectors, and housing (interface) to be designed to suit user requirements.

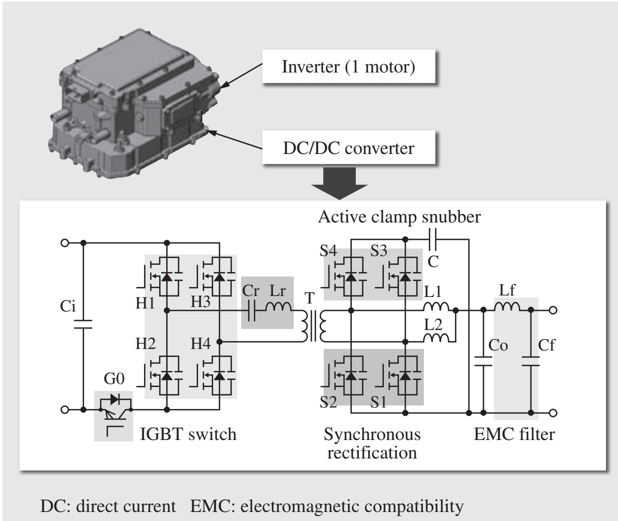


Fig. 10—Inverter with Integrated DC Converter, and DC Converter Main Circuit.
Hitachi has developed a DC/DC converter that can be integrated into the inverter. It achieves small size by sharing the inverter's cooling water channels.

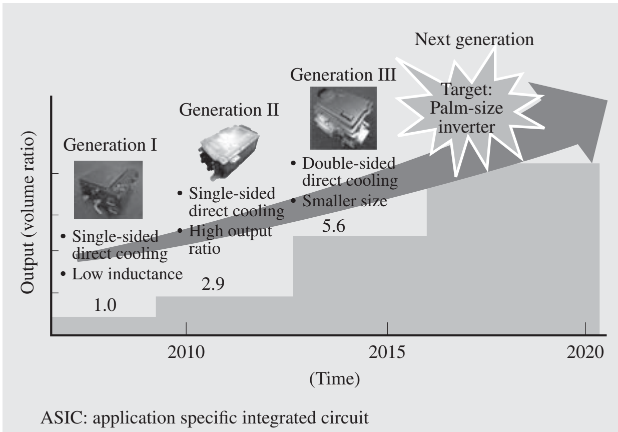


Fig. 11—Future Inverter Development.
To date, Hitachi has developed three generations of small inverters with high output. In the future, Hitachi intends to continue this trend toward higher output and to develop a next generation of ultra-small inverters small enough to fit in the palm of the hand.

power modules with double-sided direct cooling, the size of the new inverter has been shrunk to 3.5 L, making installation in vehicles significantly easier. By selecting from power modules with rated currents ranging from 300 to 400 Arms, the same package can be used to drive motors with a range of outputs, extending from HEVs to EVs.

DC/DC CONVERTER

As HEVs and EVs no longer have 12-V alternator systems, they require a DC/DC converter to supply power from the high-voltage (150- to 450-V) system to the low-voltage (12-V) system. In response, Hitachi has developed its own DC/DC converter that is integrated into the inverter so that it can share features such as the cooling system and high-voltage connectors, making it easier to install in the vehicle (see Fig. 10). This has included developing an active clamp circuit and IGBT switching method to produce a 3-kW DC/DC converter that achieves high efficiency (95% max., 92% or higher under rated conditions) and supports bidirectional operation (back and boost).

CONCLUSIONS

This article has described the power modules with double-sided direct cooling used in automotive inverters, the configuration of the standard inverter, Hitachi's own DC/DC converter that is integrated into the inverter, and the steps Hitachi is taking to increase inverter output further.

In the future, Hitachi intends to continue making advances in automotive inverters primarily through advances in power devices and the design of power modules. As indicated by its inverter roadmap, Hitachi intends to continue making its inverters smaller and to increase their output, with the aim of making the next generation of systems small enough to fit in the palm of the hand (see Fig. 11). It is anticipated that the future of automotive inverters will see new technical innovations made possible by silicon carbide (SiC) and other wide-band-gap semiconductors, and further system integration to reduce in the overall cost of drive systems.

REFERENCES

(1) H. Hamada et al., "Development of Fuel-efficient, Environmentally-friendly Hybrid Electric Vehicle Systems," Hitachi Review **53**, pp. 177–181 (Nov. 2004).

(2) S. Yoshihara et al., "Development of Technology for Electrically Driven Powertrains in Hybrid Electric Vehicles," Hitachi Review **58**, pp. 325–329 (Dec. 2009).

(3) K. Ide et al., "Power Electronics Component Technologies for Green Mobility," Hitachi Review **60**, pp. 310–315 (Oct. 2011).

(4) K. Nakatsu et al., "Development of Technologies to Cut in Half Floor Space Required for Power Modules on Inverters for Electric and Hybrid Automobiles," Hitachi Review **61**, p. 80 (Aug. 2012).

(5) K. Nakatsu et al., "Next-generation Inverter Technology for Environmentally Conscious Vehicles," Hitachi Review **61**, pp. 254–258 (Nov. 2012).

(6) R. Saito et al., "High power density inverter technology for automotive applications," Ingénieurs de l'Automobile, No. 825 (2013).

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