Next-generation Inverter Technology for Environmentally Conscious Vehicles

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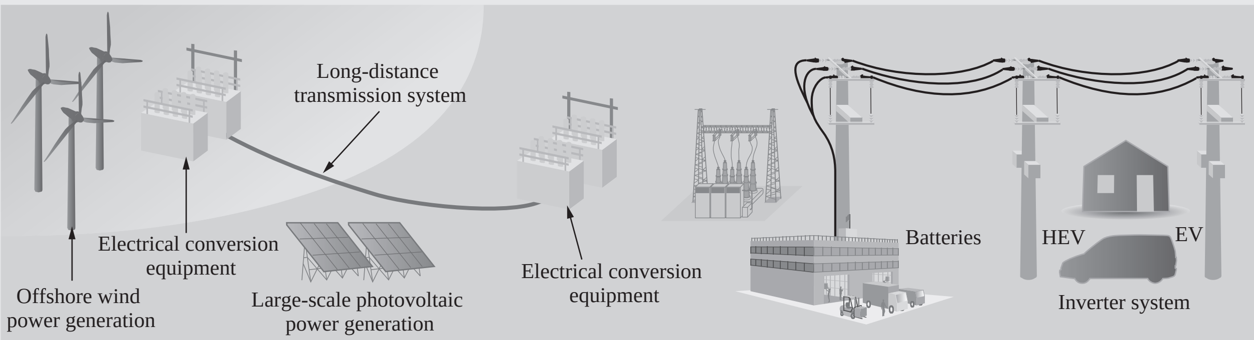
OVERVIEW: Realizing a sustainable society will require a reduction in CO_2 emissions, and energy efficiency is being urged on many different sectors of the economy, including the electric power business, industry, and consumer and transportation businesses. In the transportation sector, in particular, environmentally conscious vehicles that use power electronics will be essential as replacements for conventional vehicles powered by internal combustion engines. The main components used in power electronics include inverters, batteries, and electric motors, and Hitachi is working on the development of specific technologies intended to make these components even smaller and more efficient than before.

INTRODUCTION

WITH steps being taken to reduce carbon dioxide (CO_2) emissions to help achieve a sustainable society, the transportation sector is seeking to improve energy efficiency and reduce CO_2 emissions by switching from conventional vehicles powered by internal combustion engines to hybrid electric vehicles (HEVs) and electric vehicles (EVs). Meanwhile, the power generation sector that produces electric power from primary energy sources is hastening the construction of large power generation systems to increase the amount of power produced from renewable energy sources such as wind and photovoltaic power generation. The construction of smart cities capable of making efficient use of clean and renewable primary energy sources such as these for transportation, industry, and consumer purposes will require small, highly efficient inverter systems, as well as battery systems that will be available when needed for regenerated energy and other surplus electric power (see Fig. 1).

Inverter systems in particular can convert direct-current (DC) electric power from batteries or other sources into alternating-current (AC) electric power, generate this power at the frequency needed for the vehicle speed and other system control requirements at the time of conversion, and accelerate or decelerate the vehicle by controlling the motor revolutions per minute (RPM), torque, power consumption, and other parameters. The features required by electric drive systems such as these in HEVs, EVs, and other vehicles include small size to make them easier to fit inside the vehicle, high efficiency to extend the



HEV: hybrid electric vehicle EV: electric vehicle

Fig. 1—Inverter Systems Using Renewable Energy.
Smart cities capable of making efficient use of clean and renewable primary energy for transportation, industry, and consumer purposes require small, highly efficient inverter systems and battery systems able to store regenerated energy and other surplus electric power.

vehicle's range, high output to enhance the vehicle's performance, and high reliability to withstand the harsh automotive environment[(1), (2)].

To satisfy these diverse requirements, Hitachi developed direct water cooling in 2007 and succeeded in achieving higher inverter performance and smaller size by utilizing implementation and analysis techniques it had built up in numerous other fields such as the electric power, industrial, and consumer sectors. This development has continued, with ongoing work aimed at making further reductions in the size of electric power conversion equipment by using direct, double-sided water cooling in which the entire cooling fin surface is immersed in coolant[(3), (4)] (see Fig. 2).

This article describes the physical circuit designs needed to make the inverters used for control of electric power smaller and more efficient, and analysis and design techniques that achieve a high level of reliability, including cooling and vibration resistance.

NEXT-GENERATION INVERTER

The challenges to be overcome in achieving higher inverter performance and smaller size include designing electric power wiring that is compact and highly flexible, reducing losses in the power modules, improving cooling system performance, and providing greater reliability, including for the circuit board that contains the control computer. The following sections describe the electric power wiring layout of the next-generation inverter together with a power module design that allows highly efficient, high-speed switching.

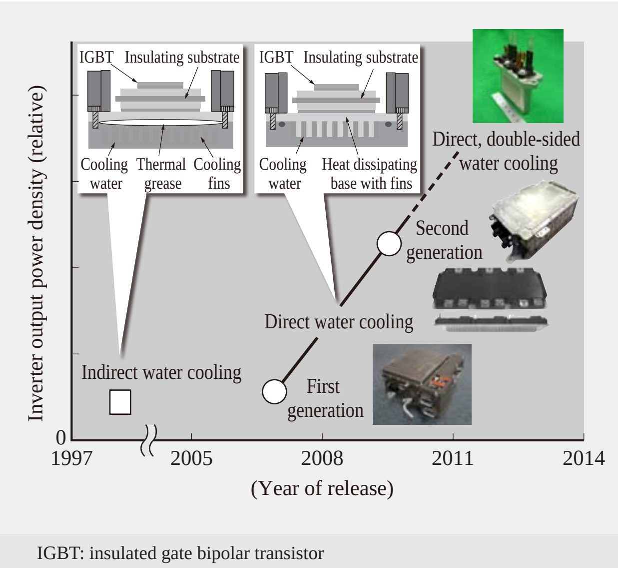


Fig. 2—Development Roadmap for HEV and EV Inverters.
To satisfy the diverse requirements associated with use in a vehicle, Hitachi has developed direct water cooling to achieve smaller size and higher performance by utilizing implementation and analysis techniques derived from numerous other fields, such as the electric power, industrial, and consumer sectors.

Use of Compact Electric Power Wiring to Reduce Inverter Size

The inverters used in HEV systems are typically mounted in the restricted space of the engine compartment, and this often results in more complex internal routing of electric power and a larger housing size in order to improve the ease of connection to the battery, electric motor, and other components. The ideal electric power wiring layout is one that allows the relative positions of the motor and battery wiring to be easily modified, and minimizes the influence of factors such as conversion losses and noise (see Fig. 3).

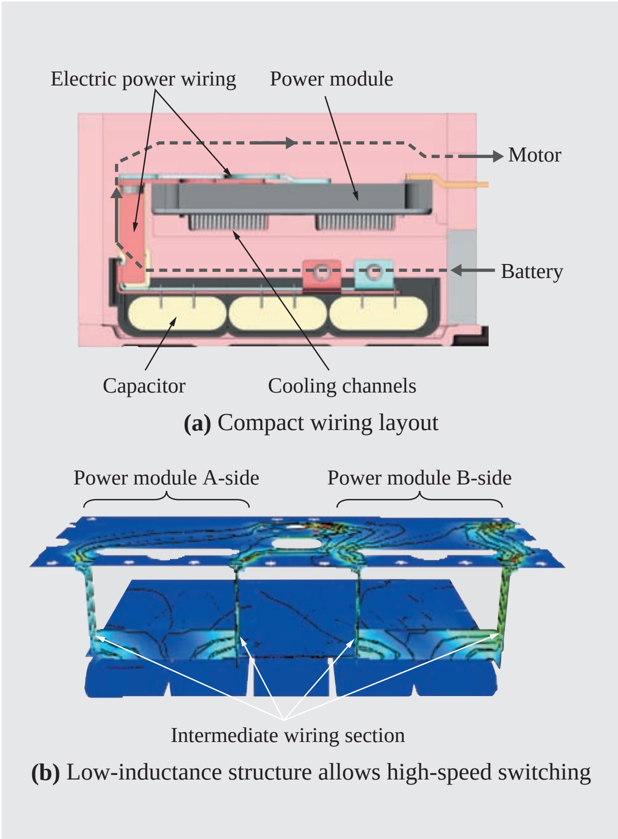


Fig. 3—Wiring Layout and Low-inductance Structure of Next-generation Inverter.
The inverter consists of three areas with cooling water channels running down the center. The design significantly reduces the area required for wiring by providing a compact flow of electric current in the housing. It also provides more flexibility for attaching external connections, and reduces inductance by controlling the current density distribution in the intermediate wiring section.

Fig. 3 (a) shows an outline of how electric power is routed in the second generation inverter developed by Hitachi. A feature of this inverter is that it is made up of three areas, including cooling channels that run down the center, a capacitor underneath, and a power module on top, with the capacitor area providing a highly flexible layout for connection of the battery wiring. This design significantly reduces the wiring area by providing a compact flow of electric current through the housing, as indicated by the dotted line, while also improving the inverter output power density and the flexibility with which the battery wiring can be connected. This increases the inverter output and reduces its size by a factor of more than three compared to the previous model.

Power Module Capable of High-speed Switching

To reduce inverter losses, it is necessary to reduce the power module conduction loss and the switching loss caused by transient changes in voltage and current. In turn, reducing switching loss requires that the inductance of the electric power wiring be reduced to allow high-speed switching(5). Typically, inductance can be reduced by adopting a parallel board layout so that the currents for opposing phases cancel out the magnetic flux. However, connecting the capacitors and power modules to a pair of parallel boards tends to make the housing larger. In response, to reduce the size of the second-generation inverter, Hitachi succeeded in reducing the inductance to the A- and B-side power modules by splitting the electric power wiring between the capacitor area and power module area, connecting four pairs of intermediate wiring to form a small parallel board arrangement between these areas, and providing adequate spacing between them. Fig. 3 (b) shows the results of a current distribution analysis for the electric power wiring. The analysis demonstrated that the effect of the intermediate wiring was to reduce the inductance by spreading the current across the full extent of the electric power wiring in each area, thereby reducing power module losses and minimizing surge voltage, a cause of noise.

OPTIMUM DESIGN TECHNIQUE FOR PIN FIN HEAT SINKS

To cool the power semiconductors and improve reliability, most automotive inverters fitted in vehicles use cooling water to carry the generated heat to the radiator at the front of the vehicle so that it can be dissipated into the air. Especially in the case of HEV and EV inverters that required smaller size and higher performance, the heat generated by the power module is greater relative to volume than it is in industrial and other systems, and therefore a high-performance cooling system is required to remove the heat from the power module. Accordingly, direct cooling is used whereby pin-shaped fins that have excellent heat transfer characteristics with respect to cooling water are formed directly on the heat-dissipating base of the power module.

The challenges for this pin fin heat-dissipating base are how to improve the efficiency of the vehicle's overall cooling system, and how to combine low pressure losses with a high rate of heat transfer from the fins. The performance of the pin fins is largely determined by the shape of the fins, and it is necessary to optimize the fin's shape parameters to satisfy the specifications for both pressure loss and heat transfer rate. The design technique used in the past required a very large number of different combinations to be tested, resulting in a considerable amount of work. In this case, a multi-objective optimization technique was used to improve the performance of the pin fin heat-dissipating base.

To use this multi-objective optimization technique, it is necessary to define objective functions. In the case of the power module, the thermal resistance (R) and pressure loss (P) provided suitable objective functions. Similarly, the pin fin shape parameters served as the design variables. The four variables were height (H), diameter (D), flow-parallel pitch (X/D), and flow-perpendicular pitch (Y/D) (see Fig. 4). The analysis also specified fin height H < 8 mm and minimum fin spacing > 1 mm as constraints. The analysis involved varying the design variables within the above constraints to find a shape that satisfied the objective functions for both R and P.

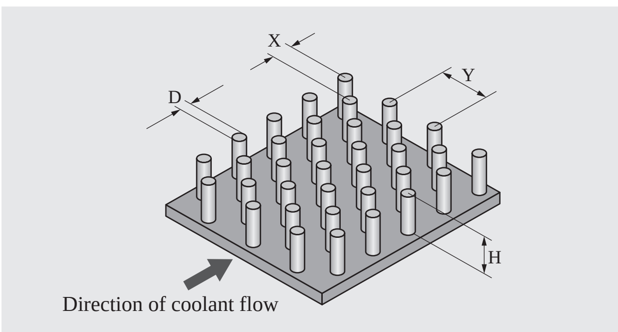


Fig. 4—Definition of Heat Sink Design Variables with Respect to Direction of Coolant Flow.
The variables are the pin height (H), diameter (D), and the pitches in the directions parallel and perpendicular to the flow (X and Y respectively).

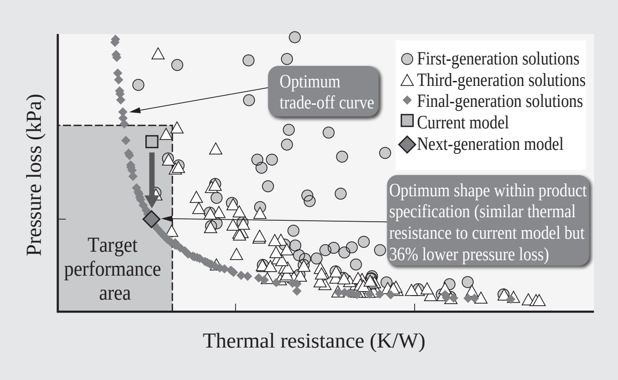


Fig. 5—Results of Multi-objective Optimization Calculation.
A genetic algorithm was used to perform an analysis to minimize the trade-off between pressure loss and thermal resistance. The graph in the figure plots the characteristics of different shapes. While the solutions for the first generation were widely scattered, they had started to concentrate at the bottom left by the third generation. When the process of natural selection was repeated and analysis continued to the final generation, the set of solutions that remained formed a curve representing the optimum trade-off.

The search used a genetic algorithm that repeated 100 iterations of 100 pairs of combinations over the entire analysis range. The result of automatic calculation was to obtain a solution with a thermal resistance (R) similar to that of the heat sink produced by the previous design technique and a pressure loss that was roughly 36% lower. In addition to improving the performance of the cooling system, this technique is also making a major contribution to shortening the design time in ways that include being able to respond quickly to specification changes (see Fig. 5).

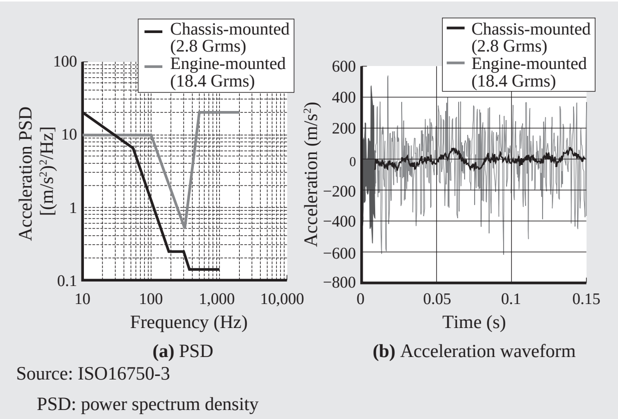


Fig. 6—PSD Representing Intensity at Each Frequency of Random Wave, and Example of Actual Acceleration Waveform.
The vibrations to which an inverter is subject differ significantly depending on factors such as where it is mounted, whether the vehicle has an engine, the engine type, and suspension performance.

TECHNIQUE FOR ASSESSING VIBRATION RELIABILITY

Inverters for HEVs or EVs need to achieve high reliability in the harsh environment inside a motor vehicle. Also, to make effective use of the limited space inside the vehicle, the inverter and other electrical components need to be fitted close to the engine or transmission, both major sources of vibration. This means that the key factor when seeking to design an inverter able to withstand vibration is to make it reliable with respect to vibration while also dealing with the heat, electric power, and other challenges within the confined space available. The vibrations to which an inverter is subject can be broadly divided into: (1) The predominantly sinusoidal vibrations generated by large vehicle components such as the engine or transmission, and (2) The predominantly random vibrations associated with road noise. To improve vibration reliability, it is necessary to assess the influence of both types of vibration. Many car makers use random vibration testing schemes based on standards for vibration testing of automotive parts such as ISO16750-3 and JIS-D1601 (see Fig. 6).

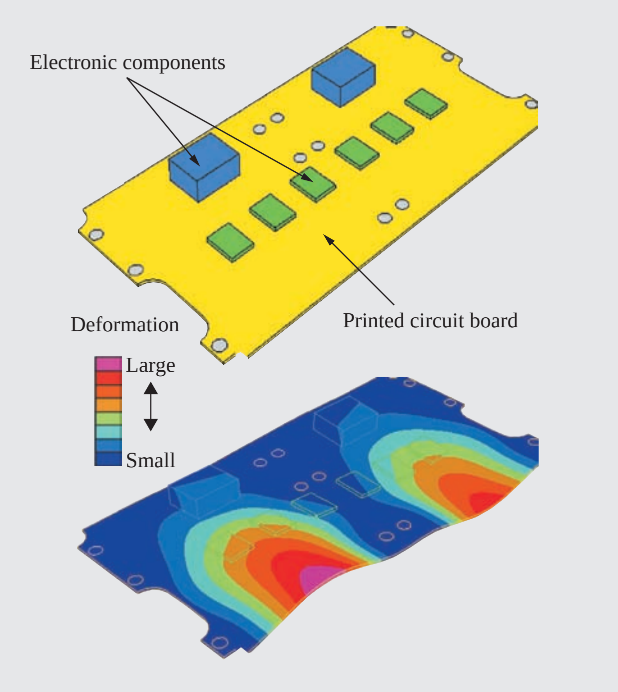


Fig. 7—Vibration Analysis of Inverter Printed Circuit Board.
Used in conjunction with three-dimensional computer-aided design (3D-CAD) software, the technique provides a designer working at a desktop with a workflow that proceeds from shape design to analysis and then uses the assessment results as feedback to the shape.

To allow a range of different types of random vibration to be used, Hitachi has developed an analysis-based random vibration simulation and reliability assessment technique based on vibration simulation techniques that Hitachi has been developing for some time for use with railway, nuclear power plant, and other equipment (see Fig. 7). When combined with three-dimensional computer-aided design (3D-CAD) software, this technique allows the vibration reliability of the inverter to be assessed under a wide range of different vibration conditions. It provides a designer working from a desktop with a workflow in which simulation is used to perform reliability assessments based on shape changes made in the 3D-CAD system, and then this information is used as feedback for the 3D-CAD shape. The technique assesses vibration reliability based on the resonant frequency, deformation, stress frequency characteristics, and other results obtained from the simulation. This assessment can then be used as feedback to the design, including designing appropriate attachment points to minimize unwanted resonance, modifying the structural design to reduce stresses, and vibration isolation design using vibration reduction rubber mounts.

CONCLUSIONS

This article has described the use of Hitachi's analysis techniques for electric power, heat, and vibration to reduce the size and improve the reliability of inverters, a key component of environmentally conscious vehicles.

By making further improvements to these analysis techniques in the future, Hitachi intends to continue working toward achieving a sustainable society by supplying power electronics systems with benefits that include helping to boost the performance of overall systems while reducing the load they impose on the environment.

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