Power Electronics Component Technologies for Green Mobility

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OVERVIEW: As an application systems technology which deals primarily with the use of power semiconductors for electrical conversion and control, power electronics is essential to achieving better energy efficiency. The component technologies used in the field include inverters, batteries, and motors. Hitachi researches and commercializes advanced power electronics technology in a wide range of fields extending from power devices to power system control. Through technologies that utilize direct water cooling to improve the power density of inverters, techniques for reducing the losses in power semiconductors, materials technologies for increasing the energy density of lithium-ion batteries, and optimum design techniques that help make motors smaller, lighter, and more efficient, Hitachi is playing a part in the field of green mobility, including EV systems that achieve low fuel consumption and emissions.

INTRODUCTION

GIVEN the need to reduce CO_2 (carbon dioxide) emissions to help prevent global warming, it is important to encourage energy efficiency in the transport and consumer sectors as well as the effective use of wind, photovoltaic, and other new sources of energy in the power generation sector. Another problem that has arisen is the shortages of electricity, fuel, and other essentials of daily life following the Great East Japan Earthquake. In the future it is anticipated that demand will grow for systems in which features such as low fuel consumption and the ability to store power in an emergency are achieved by utilizing new energy sources as well as technologies such as HEVs (hybrid electric vehicles) and EVs (electric vehicles).

In the transport sector, energy and fuel savings can be anticipated from a switch away from vehicles powered by internal combustion engines toward HEVs and EVs. In power generation, the installed capacity of wind and other new forms of energy can be increased by the use of power system control (which compensates for the variable output of wind turbines) and batteries or other electrical storage devices which absorb these fluctuations. Further, it is feasible that these batteries and generators fitted in HEVs and EVs together with the new energy sources and electric storage devices adopted in the power generation sector could provide a temporary power supply in a time of emergency.

By constructing the power electronics systems needed to make this possible, outputs such as motor power can be obtained from the input power supplied from generation equipment or the grid. That is, it is possible to use power electronics technology to build an electric drive system in which the main components are a battery that can store the input power after it has been converted to direct current, an inverter that converts the direct current to variable-frequency alternating current, and a motor that rotates at a variable speed proportional to the applied frequency (see Fig. 1).

This article describes Hitachi's component technologies used in power electronics systems.

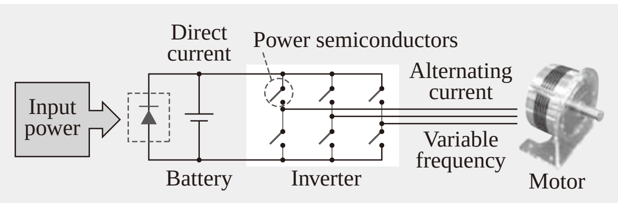


Fig. 1—Configuration of Electric Drive System Using Power Electronics.
The system consists of a battery which stores direct-current power, an inverter which converts a direct current to a variable-frequency alternating current, and a motor which rotates at a variable speed proportional to the applied frequency.

INVERTER TECHNOLOGY

The following discussion of inverter technology deals with the electric drive systems used in HEVs and EVs. Suitability for installation in a vehicle is an important factor for these inverters and lighter weight, higher efficiency for longer driving range, higher output to improve vehicle performance, and better reliability to withstand harsh automotive conditions are key considerations in development. An inverter is a system for synthesizing an alternating current at a desired frequency by switching a direct current. The following sections describe the inverter system and the power semiconductors used for switching.

Inverter

Because the inverter that drives the motor is typically fitted in the limited space of the engine compartment, the reliability and mounting density of the internal power electronics components are important considerations. An inverter typically contains several hundred components, the main ones being the power module on which the power semiconductors are mounted, a capacitor used to smooth the battery output, and a microcomputer and associated control circuits. Hitachi has put a lot of work into developing the power module which uses switching to control the current output to the motor. It has made progress on increasing the current density and enhancing reliability through improvements such as reducing the losses on the internal power semiconductors and achieving better heat dissipation performance(1). In doing so it has succeeded in increasing the power density and halving the volume of automotive inverters over a period of five years (see Fig. 2).

Power Semiconductors

Power semiconductors are implemented in a power module in which they are cooled via heat transfer to a coolant.

Reducing the losses on power semiconductors is important for reducing the size of the cooling system and improving vehicle driving efficiency. Achieving lower losses requires faster operation to reduce switching loss and a reduction in the conduction loss which occurs when the devices are carrying a current. While improvements in semiconductor miniaturization have been used to increase output current density in the past, this approach makes the devices more prone to breakdown because they are unable to limit excessive current flow. Hitachi has solved this problem by developing a HiGT (high-conductivity insulated gate bipolar transistor) which can handle a higher output current density when operating close to rated current and limit excessive current flow while also reducing the voltage when conducting(2). Hitachi also plans to reduce conduction loss further by using SiC (silicon carbide) which has a breakdown electric field strength approximately 10 times that of Si (silicon) devices such as IGBTs (insulated gate bipolar transistors).

Two issues for the power module on which the power semiconductors are mounted are how to achieve efficient cooling of the losses from the power semiconductors used in the circuit and how to limit the surge voltage that occurs in high-speed switching. The wiring board in the module uses materials such as SiN (silicon nitride) and other ceramics and polymer insulators with high heat conduction. In a previous design, the heat resulting from the losses that occur in the power semiconductors flowed through this wiring board to the heat dissipating base and then via thermal grease to be cooled by the cooling fins on the inverter case. Hitachi has now developed a direct cooling method that eliminates the use of thermal grease by integrating the cooling fins on the inverter case into the heat dissipating base(1). The

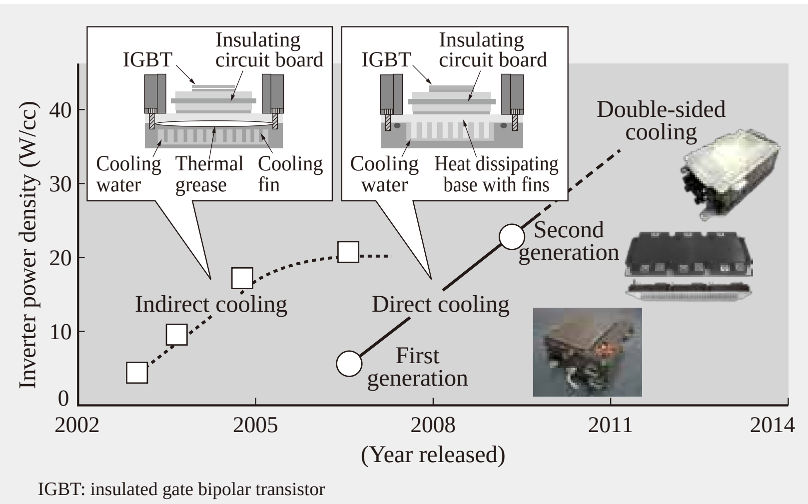


Fig. 2—Ongoing Development of Hitachi Automotive Inverters.
The power density has increased year by year. Direct cooling of the power module has been the key to this improvement.

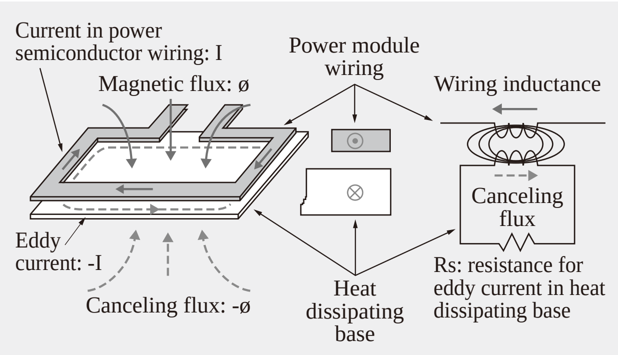
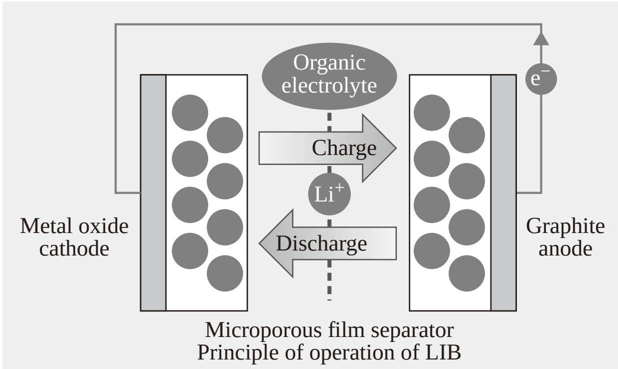


Fig. 3—Technique for Reducing Inductance of Power Module Wiring.
The wiring inductance is reduced by a design that creates flux linkage between the heat dissipating base and the magnetic flux produced by the wiring around the power semiconductor so that the resulting eddy current in the heat dissipating base acts to cancel out this flux.

direct cooling method reduces the thermal resistance by about 25% by making the inverter case part of the water flow path and passing cooling water directly over the cooling fins on the heat dissipating base. Meanwhile, to reduce switching losses it is necessary to reduce the surge voltage that occurs in the power semiconductors by minimizing the inductance of the power module wiring. Hitachi succeeded in reducing the wiring inductance by establishing a magnetic flux linkage between the current in the wiring and the heat dissipating base resulting in an eddy current which acts to cancel the magnetic flux(3) (see Fig. 3). For the future, Hitachi intends to improve cooling performance further by developing a power module that is cooled on both sides.

LITHIUM-ION BATTERY TECHNOLOGIES

Since the early 1990s, Hitachi has participated in a number of projects run by the New Energy and Industrial Technology Development Organization (NEDO) that have involved the development of large LIBs (lithium-ion batteries) and undertaken research and development of LIBs for use in electric power storage and EVs. During this time, Hitachi has applied the results of this research to lead the world in the commercialization of LIBs with high output density for HEVs and LIBs for hybrid trains. Now, in a continuation of this business, Hitachi is developing LIBs for PHEVs (plug-in HEVs) with the aim of achieving 1.5-times higher energy density. Meanwhile, Hitachi is also developing a range of LIBs suitable for use with wind, photovoltaic, and other new sources of energy to encourage its effective use.



Feature	Main issue	Development objective
Cathode material	Cost reduction, reversibility improvement, capacity improvement	Mn cathode improvement
Anode material	Capacity improvement during rapid charging, reversibility improvement	Grain shape optimization
Electrolyte material	Reduction in ion resistance	Solvent composition optimization
Separator	Heat resistance and durability improvement	Ceramic separator
Electrode production process	Reduction in electrode resistance	Kneading, coating optimization

Li: lithium LIB: lithium-ion battery Mn: manganese

Fig. 4—Principle of Operation of LIB and Development Objectives.
LIBs are batteries that produce a flow of electrons by absorbing and releasing lithium ions between a cathode and anode that sandwich a polymer film separator impregnated with organic electrolyte. The cathode and anode are made from materials able to absorb and release lithium ions respectively.

Lithium-ion Battery Development by Hitachi

LIBs for HEVs typically feature high output but low energy density whereas LIBs for EVs have high energy density but low output density. Future LIBs, however, will need to combine high levels of both output and energy density while also satisfying demand for longer life, lower cost, and better safety. These requirements mean there is a need for battery materials suitable for use in LIBs to achieve even higher performance.

LIBs use materials that can absorb and release lithium ions as their cathodes and anodes and the battery is charged and discharged by exchanging lithium ions between cathode and anode (see Fig. 4). Work by Hitachi aimed at achieving high output, high energy density, and longer life includes improving cathode and anode capacity, achieving better reaction reversibility, reducing the ion resistance of the electrolyte, improving the durability of separators and other battery parts, and optimizing the electrode production process.

Development of Long-life Manganese Cathode

This section gives an example of the development of the cathode, the key material in an LIB. Whereas the main cathode material used in consumer LIBs has Co (cobalt), a scarce resource, as its primary constituent, interest has turned toward the use of Mn (manganese) cathodes in industrial LIBs. Mn is an abundant material with the potential to cut costs. However, conventional cathodes made from Mn spinel were unable to achieve an adequate operating life for two reasons: firstly because charging and discharging caused the volume of the crystal to expand and contract leading to the breakdown of the crystal structure, and secondly because acid present as an impurity in the electrolyte caused the Mn to dissolve.

Noting this, Hitachi tried replacing some of the Mn with different elements to stabilize the crystal structure and mixing it with a composite oxide with a laminar structure and excellent acid resistance. This achieved reductions of about 50% in both dissolution of Mn into the electrolyte and change of volume during the charging and discharging reactions. The result was a halving of the fall in capacity with repeated charge/discharge cycles and an estimated battery life of 10 years or more(4).

Also, because the requirements for power storage systems differ for different applications, such as wind and photovoltaic power generation or PHEVs, construction machinery, rolling stock, and other vehicles, Hitachi is working to optimize battery materials for each of these applications.

MOTOR TECHNOLOGY

Small size, light weight, and high efficiency are key factors for the electric motors used in EVs, HEVs and trains. Also, optimum design techniques incorporating simulation are essential to achieving the best possible design in the limited development time available. This section describes these optimum design techniques and what Hitachi is doing to achieve small size, light weight, and higher efficiency.

The problem with making motors smaller while maintaining output is that the associated reduction in surface area for dissipating heat leads to higher temperatures inside the motor. This causes the magnets to suffer an irreversible loss of magnetism and higher losses. Accordingly, a motor characteristics calculation that takes account of this temperature rise and its use to optimize the motor shape are needed if motors are to be made smaller. Hitachi has developed technology for performing optimization calculations that use the motor characteristics along with temperature values obtained by a coupled magnetic field and thermal analysis(5).

The optimization calculation was trialed on a 3.7-kW [5-HP (horsepower)] permanent magnet synchronous motor. The specifications for the motor were the same as those for Hitachi's first ever product, a 5-HP induction motor built in 1910. In conjunction with the optimization calculation, Hitachi is also designing and prototyping permanent magnet motors that make active use of its advanced motor materials. These include magnets, enamel wire, and organic materials. By optimizing the motor design in a way that takes account of temperature rise, Hitachi has succeeded in producing a motor with a high 94%

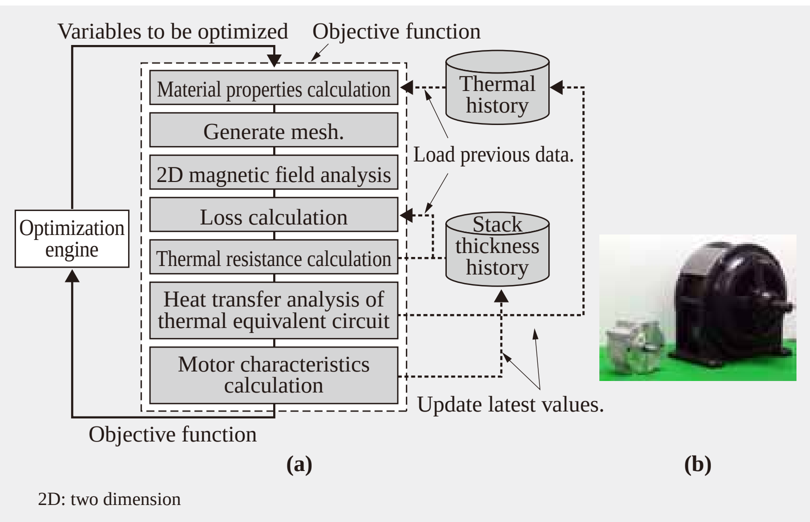


Fig. 5—Flow Chart of Coupled Thermal and Magnetic Field Analysis (a) and Hitachi's First Electric Motor Next to a Prototype Motor (b).
The prototype motor is approximately one-fifteenth the size of Hitachi's first electric motor [a 5-HP (horsepower) induction motor, Hitachi's first ever product].

efficiency that is approximately one-fifteenth the size of its original induction motor (see Fig. 5).

Based on the optimization calculation, Hitachi has also developed a technique for calculating the speed/torque characteristics subject to various constraints. These constraints are: (1) permitted increase in coil temperature, (2) reversible demagnetization limit within which the permanent magnet retains its magnetism, and (3) upper voltage limit. This technique can calculate the maximum torque that satisfies the three constraints given the speed/torque characteristics of the permanent magnet motor. This constrained torque limit can be represented in terms of the speed/torque characteristics and a quantitative estimate of the performance margin relative to the required performance calculated for the design constraints of each individual motor design (see Fig. 6).

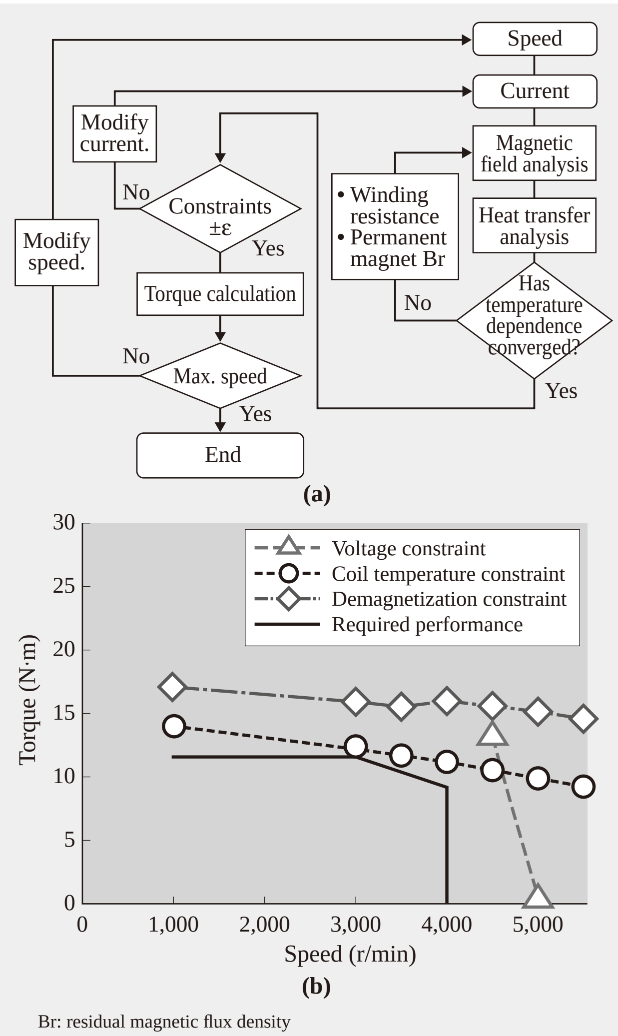


Fig. 6—Flow Chart of Constraint-limited Speed/Torque Characteristics Calculation (a) and Example Calculation of Maximum Torque Possible while Satisfying Constraints (b).
The calculation calculates the speed/torque characteristics for the motor based on three constraints (temperature, magnet demagnetization, and voltage).

CONCLUSIONS

This article has described Hitachi's component technologies used in power electronics systems.

In addition to possessing component technologies including inverters, batteries, and motors, Hitachi intends to continue contributing to green mobility by supplying high-performance power electronics systems based on understanding and balancing overall requirements.

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