Components and Systems for Electric Vehicles (HEVs/EVs)

Fuel efficiency improvements, compliance with emission regulations, and global environmental protection measures are becoming mandatory requirements for today's vehicles. To help meet these evolving requirements for 'sustainable mobility,' Hitachi Automotive Systems Co., Ltd. is working as a system supplier providing electric powertrains for hybrid electric vehicles and other electric vehicles. It is contributing to the environmental compatibility of vehicles by providing inverter, motor, and battery products along with solution technologies that combine these products. As vehicles evolve, electric powertrains are becoming smaller and lighter while gaining higher power density. They will continue to evolve to expand mobility that is compatible with the global environment.

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1. Introduction

The internal combustion engines long used in vehicle powertrains have been continually evolving, but with environmentally motivated CO_2 reduction initiatives being promoted globally since the turn of the century, the limit of regulatory compliance achievable with conventional combustion-engine vehicles alone is expected to arrive some time between 2020 and 2025. As a result, the introduction of hybrid electric vehicles (HEVs) and electric vehicles (EVs) as environmentally conscious alternatives is expected to grow worldwide.

Hitachi Automotive Systems Co., Ltd. has been developing and supplying electric powertrains for these electric vehicles since the 1990s, and it continues to develop technologies and improve performance in anticipation of the future proliferation of environmentally compatible vehicles.

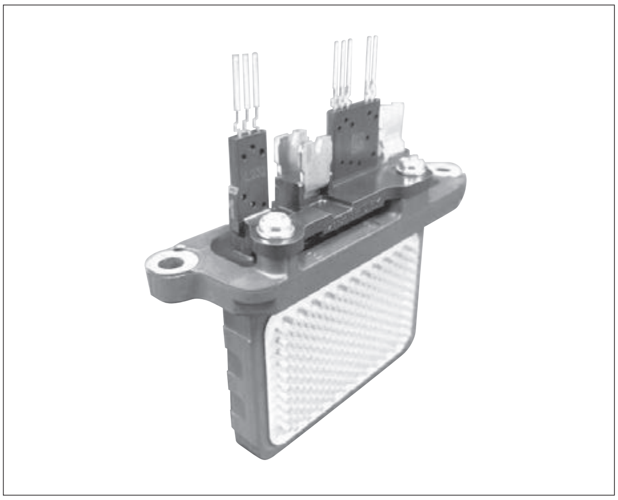
This article discusses some of the electrical component technologies used in the inverters, motors, and batteries that make up the electric powertrains of these electric vehicles, along with the simulation-driven analysis technologies that are used to rapidly create optimum combinations of electrical components.

2. Compact Inverter Technology

Onboard inverters apply pulse width modulation (PWM) control to convert direct current (DC) power stored in an onboard battery into alternating current (AC) power to drive the motor when drive power is needed, and apply an energy regenerating operation to charge the battery when power regeneration is needed. Since the available space in vehicles is very limited,

Figure 1 — Double-sided Cooling Power Module

The structure enables direct double-sided cooling of power semiconductors with cooling water, reducing heat resistance, and improving power density.



smaller inverters are demanded for automotive applications. Accordingly, developing high power density technology for the main circuit of an inverter (chiefly composed of the power module and capacitor) has been an ongoing task. At the same time, there is also demand for high-performance control circuit technology that provides functions linked directly to the basic power performance of HEVs and EVs by features such as drive torque control, motor speed control, and energy regeneration control enabled by communication with vehicle controllers, while enabling features such as anomaly detection, failure diagnosis, and the functional safety measures specified in ISO 26262.

In order to realize these onboard application demands, innovations in high-voltage main circuits and high-performance control circuits, along with the evolution of the structural design technology used to mount these components in a compact package while enabling durable onboard applications that are resistant to vibrations and heat are needed.

2. 1
High Power Density and High-voltage Main Circuit

Most of the volume of inverters for HEVs and EVs with standard 450 Vdc-class batteries comes from the high-voltage main circuit, so improving main circuit component parts is the key to reducing inverter size. Hitachi Automotive Systems has achieved a major reduction in inverter size by developing double-sided cooling power module technology that uses cooling water without thermal grease to enable direct cooling of the high-voltage power module, which generates most of the inverter heat (see **Figure 1**). The direct double-sided cooling structure greatly reduces heat resistance, enabling a higher current and higher power density. The current output of this double-sided cooling power module can also be scaled to conform to different vehicle weight classes by changing the mounted chips and some of the packaging components. The module's two-in-one structure enables a more compact design, the main circuit inductance can be reduced to reduce power generation loss, and the configuration ensures a degree of freedom in the layout within the inverter package.

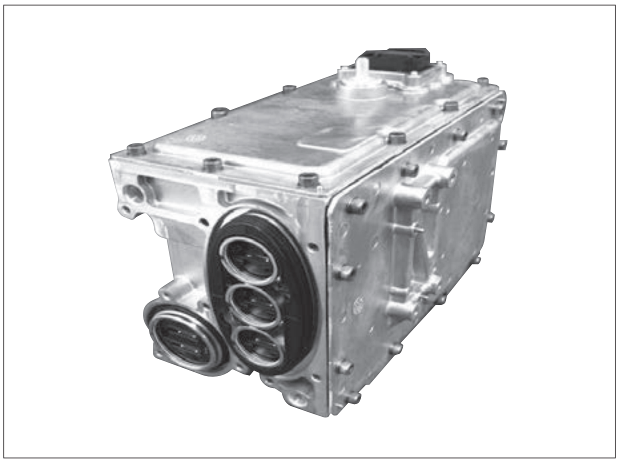
2. 2
High-performance Control Circuit

Onboard inverters require high-performance vector control operations that use variable voltage, current, and operation frequency as demanded by the basic operations for the electric vehicle to start, accelerate/decelerate, and stop. These inverters also need to support functions such as high-capacity, high-speed communication, anomaly detection, torque security, failure diagnosis, and functional safety by using Controller Area Network (CAN) or FlexRay.

To meet these demands, Hitachi has developed high-performance motor control circuit technology

Figure 2 — Traction Inverter for Environmentally Compatible Vehicles

It provides the functions needed in an onboard inverter, while the compact, high-reliability package reduces the size 40% and increases the output relative to previous Hitachi Automotive Systems products.



with a built-in high-performance central processing unit (CPU) and compact function circuits. And, gate control circuits that respond to drive signals from the control circuits to operate the main-circuit power module. They need to operate at speeds and currents high enough to keep up with the latest performance evolution in power devices, while ensuring protective operation. To meet these demands, Hitachi has developed a compact gate control circuit driven by a high-performance integrated circuit (IC).

2. 3 Compact, Highly Reliable Package Structure

The technologies described above have been used in a compact, highly reliable package structure that Hitachi has developed and applied to products. It achieves high reliability and durability while meeting the needs of onboard mounting. The example product shown in **Figure 2** achieves a 40% reduction in size with higher output relative to previous Hitachi Automotive Systems products. And, a high-efficiency DC/DC converter with a maximum efficiency of 94% has also been concurrently developed for this product.

Ongoing evolution in power modules and drive systems along with the use of next-generation low-loss SiC power elements should reduce inverter size and increase EV driving range and the number of available electric vehicle variations in the years ahead.

3. High-efficiency Motor Technology, Elemental Technologies

The concept behind the standard motor is to reduce the development workload and to standardize components, production equipment, and manufacturing practices by designing standard motor specifications that will suit a variety of different types of electric vehicles, such as HEVs, EVs, and plug-in HEVs (PHEVs), as well as different size classes of vehicles, while still providing features such as small size, light weight, high output, high efficiency, quiet operation, and low vibrations. The development approach was to develop a low-cost motor while also improving development efficiency. Meeting these requirements will require physical dimensions that will allow vehicle layouts to be designed in a standardized way over different classes of vehicles, output characteristics that satisfy a wide range of output requirements, time ratings that suit the characteristics of different types of electric vehicles, and a range of model variations to suit different end uses.

3. 1 Stator Winding Method for Standard Motor

To achieve small size and high torque density, wave winding using square wire was chosen for the stator windings on the standard motor. Compared with the

Figure 3 — Outer Diameter and Number of Coils per Slot in Each Stator Design

Designs compatible with various motor characteristics were created by keeping the stator inner diameter constant and varying the stator outer diameter and number of coils in each slot.

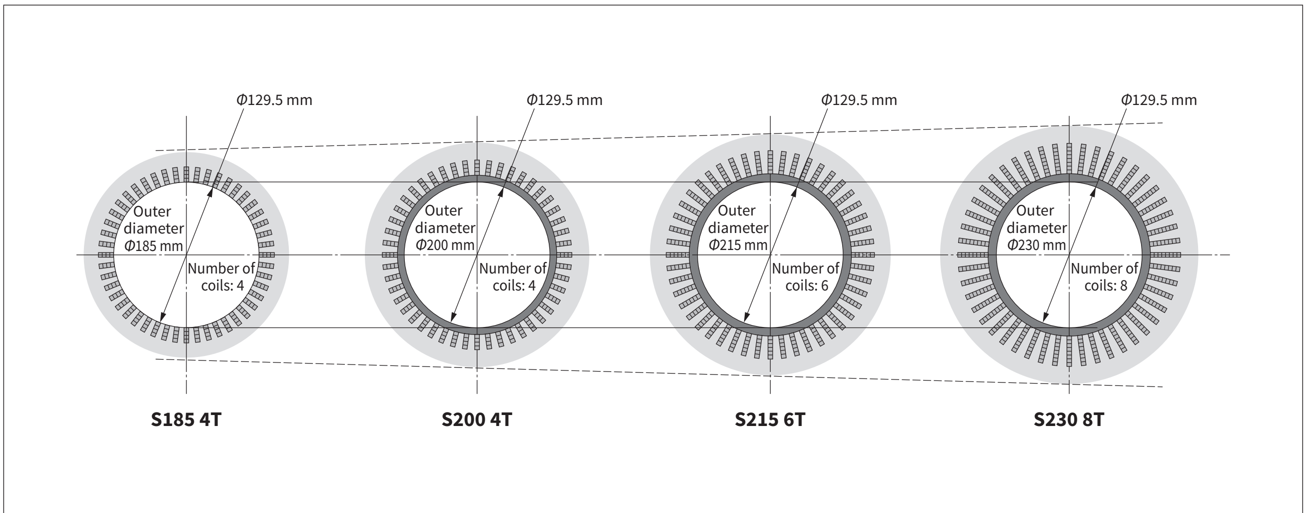
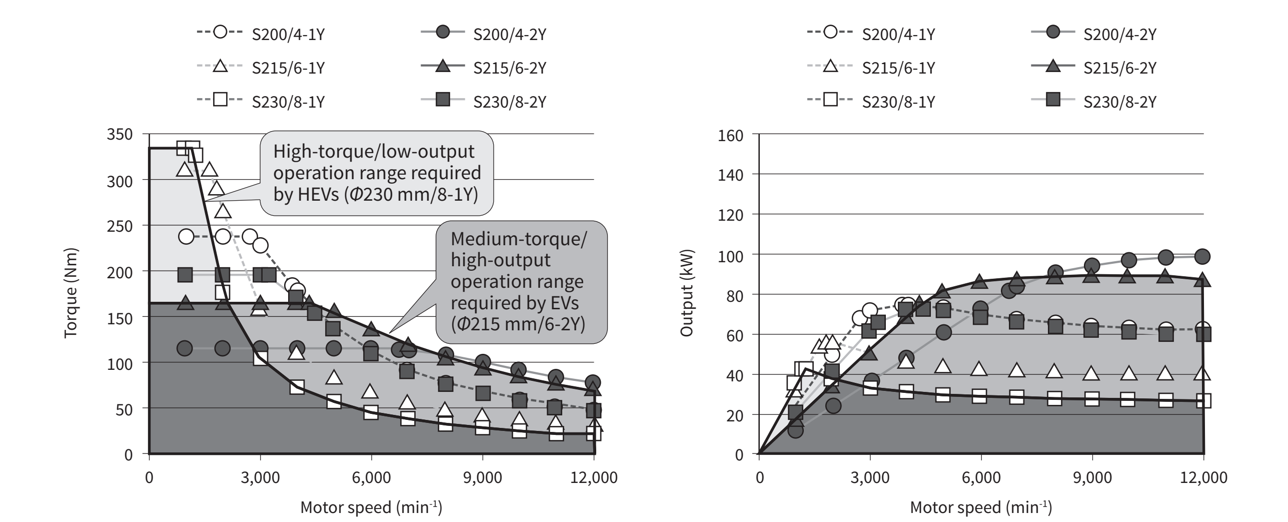


Figure 4 — Torque-output Characteristics of Stators With Φ200 mm, Φ215 mm, and Φ230 mm Outer Diameters
Varying the outer diameter and stack length of the stators enables compatibility with various motor characteristics.



EV: electric vehicle HEV: hybrid electric vehicle

distributed windings with round wire used in the past, those with square wire provide an approximately 20% improvement in space factor (conductor cross-section/slot cross-section) and an approximately 15% improvement in the motor's output torque density (= Output torque / (Stator core diameter)^2 × Stator core length). Wave winding segment coils can be flexibly adapted to stator stack length variations by changing the length of the coil's straight portion.

3. 2 Selection of Motor Outer Diameter Size

To use the wave winding method to create motor specifications compatible with different size classes of vehicles and a variety of different types of electric vehicles, such as HEVs, EV and PHEVs, Hitachi Automotive Systems designed stators with 4 different outer diameters, each having a different number of coils per slot.

Figure 3 shows the stator outer diameter and number of coils per slot for each design. The standard design has 4 coils per slot and a stator outer diameter of ϕ200 mm. The first variation adds 2 coils to the outside of the standard design (6 coils per slot total), and has a stator outer diameter of ϕ215 mm. The second variation adds 4 coils of the outside of the standard design (8 coils per slot total), and has a stator outer diameter of ϕ230 mm. The third variation adds 2 coils to the inside and subtracts 2 coils from the outside of the standard design (4 coils per slot total), and has a stator outer diameter of ϕ185 mm.

The 129.5 mm stator inner diameter was used for the smallest outer diameter (185 mm) as the standard, enabling equipment to be shared by using a 2-coil jig on the core inner diameter side when mass-producing stators with outer diameters of ϕ200 mm, ϕ215 mm, and ϕ230 mm.

These four stator designs can be produced on the same equipment. They support various output characteristics and motor outer diameters, ranging from elongated cylindrical-type EV motors to flat-type HEV motors (see **Figure 4**).

Tailoring the designs as described enables a variable outer diameter and using wave winding enables a variable stator stack length, so that motor specifications requirements for various electric vehicles can be supported using the same production equipment.

4. Next-generation Lithium-ion Battery Pack

4. 1 Electric Vehicle Market Forecast and Initiatives

Mild hybrid systems have recently been attracting interest as a technology for improving fuel consumption. These systems use a gasoline engine for travel

Figure 5 — 48 V Lithium-ion Battery Pack for Mild Hybrid Vehicles
The battery pack developed consists of mainly a battery module, BMS, and junction box.

BMS: battery management system

assistance, along with battery and motor power. Global production of mild hybrid vehicles is forecast[7] to grow from about 450,000 units in 2016 to over 12.8 million units in 2023. Particularly rapid growth of mild hybrid systems is expected in Europe and China, driven by 48 V lithium-ion batteries that can improve fuel consumption relatively inexpensively. Hitachi Automotive Systems has responded to these trends by announcing the development of a 48 V lithium-ion battery pack for mild hybrid vehicles in March 2016. The development work will bring together lithium-ion battery cell manufacturing technology for hybrid vehicles and battery management system (BMS) technology.

4. 2
Development of 48 V Lithium-ion Battery Pack for Mild Hybrid Vehicles

Lithium-ion batteries charge and discharge using the movement of lithium ions to and from the electrode material. Battery output density has so far generally been increased by reducing the electrode film thickness to decrease resistance. But the decrease in storable energy that results as output density increases is a problem. The new lithium-ion battery pack improves the cell electrode structure at the micron level to create a structure that enables easier lithium ion flow. This structure reduces resistance without reducing film thickness, increasing output density. The material composition of the positive and negative electrodes has also been improved, increasing energy density by increasing the amount of lithium that can be stored per unit weight. These technologies have increased output density by 25% and energy density by 50% relative to previous products[8].

The need for a cooling fan has been eliminated by lowering heat generation and resistance within the cells, and by using metal with high heat conduction and dissipation properties in the lithium-ion battery pack casing. These advances improve quietness and enable a thinner design with more installation freedom (see **Figure 5**).

The output density improvement enables better torque characteristics during motor acceleration assistance, achieving a maximum output of 12 kW that enables powerful performance when accelerating from rest. A maximum input of 15 kW is also possible, enabling a large amount of regenerative energy to be recovered instantaneously during sudden deceleration, and reducing energy loss. This combination of better input/output characteristics and higher energy density helps improve fuel economy (see **Table 1**).

Hitachi Automotive Systems' lithium-ion battery also has outstanding durability, low environmental impact, and safety. These features are being exploited for the development and release of a lithium-ion

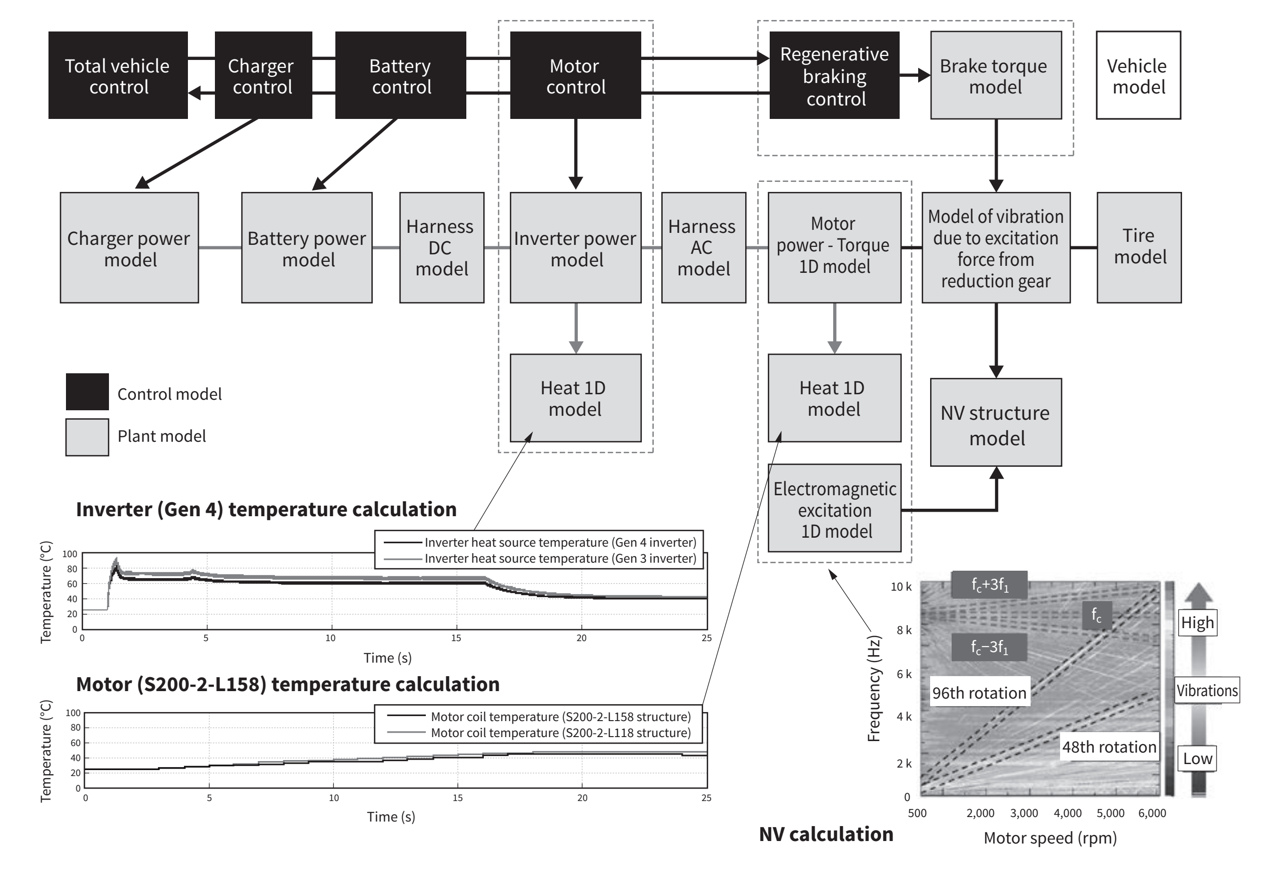
Table 1 — Main Specifications of 48 V Lithium-ion Battery Pack for Mild Hybrid Vehicles
The table below shows the main specifications of the developed battery pack.

Item	Specification
Size (mm)(W×L×H)	300×175×90
Number of cells	12
Weight (kg)	8
Capacity (Ah)	8
Maximum input (kW) (10 seconds, 50% SOC, 25°C)	15
Maximum output (kW) (10 seconds, 50% SOC, 25°C)	12
Cooling method	Natural air cooling

SOC: state of charge

Figure 6 — Energy/NV-coupled Simulator

This simulator analyzes the energy flowing from the battery to the inverter and motor, and provides a simulation analysis of the mechanical phenomena (noise, vibrations, and heat) generated by this energy in a fully coupled state for feedback to product design.



1D: one-dimensional NV: noise-vibrations AC: alternating current DC: direct current

battery module for the ZH200-6 Hybrid Hydraulic Excavator through a joint development project with Hitachi Construction Machinery Co., Ltd.

5. Electric Powertrain Simulation Technology

The key issue for electric powertrain components is how to achieve the desired performance both individually and in combination with the other items they are ultimately used with. Vehicles are collections of many different products, and high performance is unlikely to be achieved from just partial optimization. Hitachi Automotive Systems is using simulation-driven analysis to study product specifications and control technologies suited to particular combinations of these electric powertrain components.

5. 1 Energy/NV-coupled Simulator

Along with being sources of electrically generated power, electric powertrain systems are also mechatronics products that generate torque within the system and contain areas of spinning rotors and similar components.

Optimizing these systems calls for analysis and verification covering both power performance and the noise-vibrations (NV) generated when the system is mounted in the vehicle (a mechatronics issue). Even vehicles with high power performance will not be viable in the market if they generate high noise levels.

Hitachi Automotive Systems has developed an energy/NV-coupled system simulator that enables it to verify electric powertrain component performance during development, and to evaluate NV to make the required design improvements before prototyping.

The old simulation methods that were used often analyzed energy and NV separately, and when these parameters were coupled in a mechatronics product, it was forced to create a prototype to evaluate the generated vibrations, noise, and heat. Major design revisions were sometimes needed as a result. The use of a coupled simulator enables vibrations, noise, and heat to be studied in advance before prototyping, so that improvements can be made at that time. This simulator has made product-phase verification and performance assurance more reliable (see **Figure 6**).

6. Conclusions

This article has discussed the inverters, motors, and batteries used as electric powertrain components in electric vehicles, as well as simulation technology for analyzing combinations of these components.

Electric powertrain components have advanced through refinements in power electronics and micro-processors, and will continue to evolve as automotive power units. Hitachi is working to help protect the environment by developing products that meet the needs of the expanding market for vehicles that are compatible with the environment.

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