

# Development of Technology for Electrically Driven Powertrains in Hybrid Electric Vehicles

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*OVERVIEW: Hitachi supplies a wide range of environmentally friendly products in its role as a supplier of motors, power inverters, and batteries (made by Hitachi Vehicle Energy, Ltd.) for EVs and HEVs. In addition to increasing the output and reducing the size of its products, Hitachi has also in recent years developed technologies for simulating the overall fuel consumption of HEVs. In the future, Hitachi intends to continue contributing to the realization of a low-carbon society by supplying products and offering system solutions optimized for use in EVs and HEVs.*

## INTRODUCTION

RECENT years have seen many different initiatives aimed at bringing about a low-carbon society and it is anticipated that, in the automotive field, HEVs (hybrid electric vehicles) that offer significant improvements in fuel consumption will precede EV (electric vehicles) in becoming the mainstream of future vehicle markets. HEVs achieve low fuel consumption and powerful performance by combining an engine and electric motor with control that operates each in its optimum range.

Hitachi has traditionally been strong in the field of technology for electric motor development and in addition to three-phase AC (alternating current) motor control systems that are typically supplied in the form of power modules, Hitachi also supplies vehicle system solutions and has developed small, lightweight, highly efficient, and low-cost HEV systems.

This article describes system simulation technologies and the trend toward smaller size and higher output in the electric motors and power inverters used in electric drive systems for HEVs.

## HEV SYSTEM DEVELOPMENT TECHNOLOGY

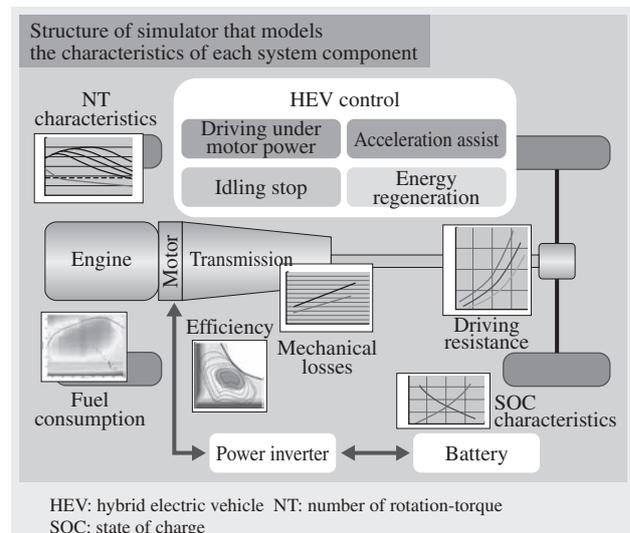
Hybrid vehicles achieve better fuel consumption by using the electric motor, power inverter and battery as the main form of propulsion and operating these in harmony with an engine and transmission.

A technique used by Hitachi in the development of these systems for HEVs is to model each of these elements and use simulation analysis of the operating conditions to determine the characteristics of the control techniques, components, and other elements

that help improve fuel consumption.

## Analysis of Fuel Consumption

In the field of fuel consumption improvement technology, Hitachi has developed a simulator that takes as input the characteristics of the engine, transmission, motor and power inverter efficiency, battery performance, driving resistance and so on, and can determine parameters such as the fuel consumption and the operating conditions of each component under different driving conditions (see Fig. 1).



*Fig. 1—Simulator for Analyzing Fuel Consumption. Which systems contribute the most to improving fuel consumption can be determined by developing a simulation model that incorporates the characteristics of the various components that measure the performance of HEV systems, and then using this model to investigate the system characteristics and perform sensitivity and operational analyses.*

The simulator also analyzes the effect on fuel consumption of changes to the characteristics of the components that make up this system or to enhancements to the control logic used in energy management.

This approach can also be used to analyze the frequencies, operating ranges, and other engine and electric motor parameters under the driving modes defined for Japan, North America, and Europe [10-15, JC08, UDDS (urban dynamometer driving schedule), and NEDC (new European driving cycle)].

Fig. 2 shows example analysis results.

It is possible to determine the sensitivity of fuel consumption to various elements and conditions, such as weight, efficiency, and control technique, by using methods such as analyzing the effects that differences between component characteristics have on fuel consumption and the change in fuel consumption when driving in each mode, and this can be used to improve the system performance when the components are combined.

### Analysis of Component Operation

Although the simulator described above analyzes fuel consumption based on a model of the entire vehicle, separate analysis of the particular operation of individual components can be performed using a simulator that incorporates a detailed model of the electric motor, power inverter, or battery only.

Fig. 3 shows an example of this in the form of a temperature analysis.

Performing these detailed analyses of the interaction between the electric motor, power inverter, and battery helps identify problems, investigate how to deal with them, and improve reliability.

Hitachi will continue making improvements to the performance of HEV products based on system development technology with the aim of encouraging the wider use of HEVs and thereby making a social contribution to the global environment.

## TECHNOLOGY FOR ELECTRIC MOTOR DEVELOPMENT

With vehicle fuel economy and exhaust gas emission regulations being strengthened in response to global environmental problems, attention has focused on the use of electric drive systems in vehicles. Hitachi has had a long involvement in the development of electric motors with high output-to-weight ratio and has adopted the IPM (interior permanent magnet) synchronous motor for use as an

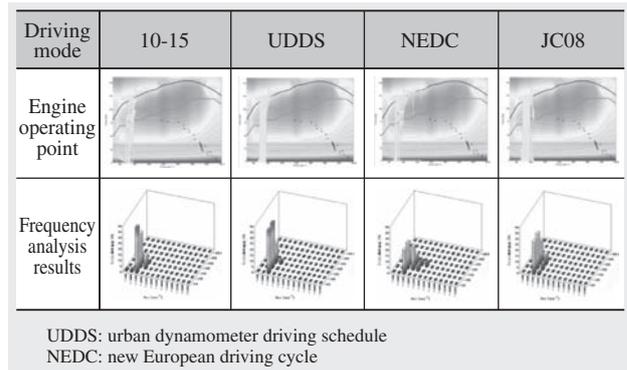


Fig. 2—Simulation Analysis Results.

An analysis was conducted of the frequency and operating points for an HEV engine and electric motor under Japanese, North American, and European driving modes, and improvements were made that increased the efficiency of the overall system.

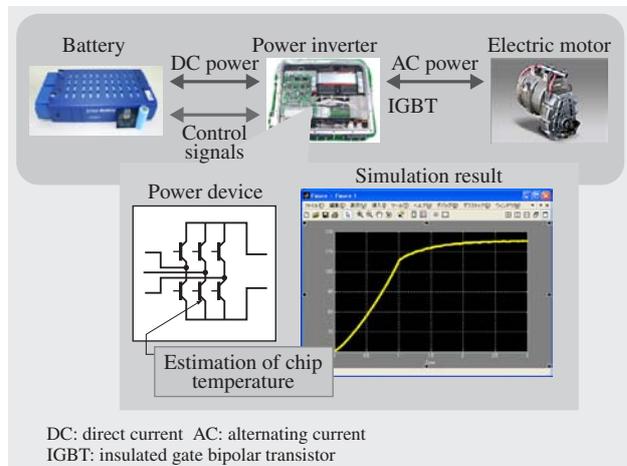


Fig. 3—Analysis of Component Operation.

Simulation using models of the system components (battery, power inverter, and electric motor) allows detailed analysis of phenomena that are difficult to study experimentally and analysis of operation under complex test conditions.

electric drive motor for vehicles. IPM synchronous motors combine small size, light weight, high output and high efficiency. The high performance of these motors is made possible by insulation technologies accumulated over many years and by optimization of design features such as core shape and magnet arrangement achieved through use of the group's optimum magnetic circuit simulation technology. However, factors such as vibration and acoustic noise are concerns because of the high energy density that results from the increased output densities of these motors.

Meanwhile, although HEVs combine an electric motor and gasoline engine, the distance that these vehicles are able to travel in EV mode where they are powered by the electric motor only is increasing. It is

anticipated that the commercial availability of pure EVs and the practical realization of plug-in HEVs that can be recharged from the power supply in the home are not far away. In the future, motor vibration and acoustic noise will become significant issues as use of electric motor power grows as a proportion of total vehicle mileage. The following sections describe techniques for achieving low vibration and acoustic noise in electric motors by reducing torque ripple which is one of the problem's causes.

### Standard Method for Reducing Torque Ripple

IPM motors are widely adopted by other manufacturers of vehicle drive motors and recent advances in motor control technology can achieve smooth driving performance. However, the nature of these motors is such that a torque ripple naturally occurs in the motor output and this is one of the causes of pulsation at low speed and of vibration and acoustic noise at high speed. The standard method for reducing the torque ripple produced by an IPM motor is to split the magnets as shown in Fig. 4 and to incorporate an offset skew into the rotor core in the axial direction.

However, using an offset skew raises the cost of the motor because increasing the number of magnets makes production more expensive and because it makes the rotor assembly more complex. It also tends to reduce the output and torque of the motor. In response to these problems, Hitachi has devised a ripple reduction rotor that can reduce torque ripple without using skew.

### Principles and Design of Ripple Reduction Rotor

Torque ripple is a phenomenon whereby a pulsation occurs in the output torque caused by the interaction of the magnetic flux due to the stator winding and the magnetic flux due to the magnet, and results from how the distribution of magnetic flux density is influenced by design characteristics such as the stator slot shape and rotor pole shape. The torque ripple can be cancelled out by generating a torque waveform with opposite phase to the torque ripple. The method used to generate this opposite-phase torque waveform is to modify the rotor shape to achieve a structural change in how the magnetic flux varies and thereby to change the flow in the magnetic flux linkage to the stator. Specifically, grooves are added to the circumferential surface of the rotor near the edges of the magnets immediately under the rotor

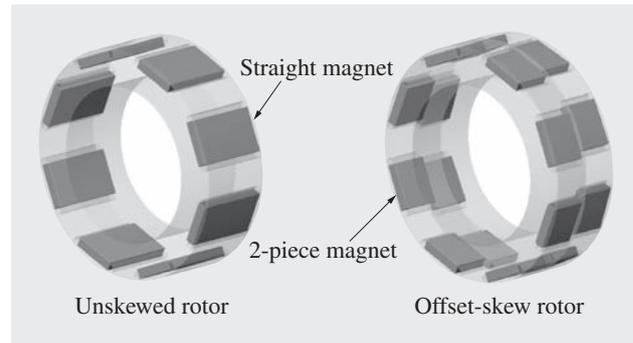


Fig. 4—Diagram of Offset-skew Rotor.

This method reduces torque ripple by splitting the magnets in the axial direction and offsetting the split surfaces in the circumferential direction.

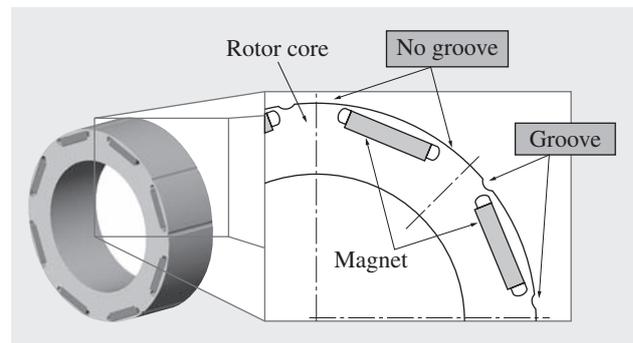


Fig. 5—Structure of Ripple Reduction Rotor.

Grooves are added to the outer circumference of the rotor near the edges of the magnets under the rotor surface. The grooves are added to every other rotor pole.

surface as shown in Fig. 5. Because the grooves are only added to every other magnetic pole, this results in the torque ripple waveform generated by the poles with grooves having opposite phase to the torque ripple waveform generated by the poles without grooves.

### Results of Magnetic Field Analysis of Ripple Reduction Rotor

A magnetic field analysis was conducted to determine the effect of adopting this ripple reduction rotor.

The results are shown in Fig. 6 and Fig. 7.

The results show that superposing the torque waveforms produced by the poles with and without grooves causes them to cancel each other out and thereby reduce torque ripple.

Use of this technique shows that torque ripple can be reduced, without increasing costs, by about 60% compared to rotors without skew. Also, by optimizing the shape and position of the grooves on the outer circumference of the rotor, the torque

ripple can be reduced across the entire range of current phases without affecting the underlying torque characteristics. Development of HEVs and EVs that use motors incorporating this technology is already underway and Hitachi will in the future put further effort into expanding sales of these motors that achieve low vibration and low-noise while also keeping costs down.

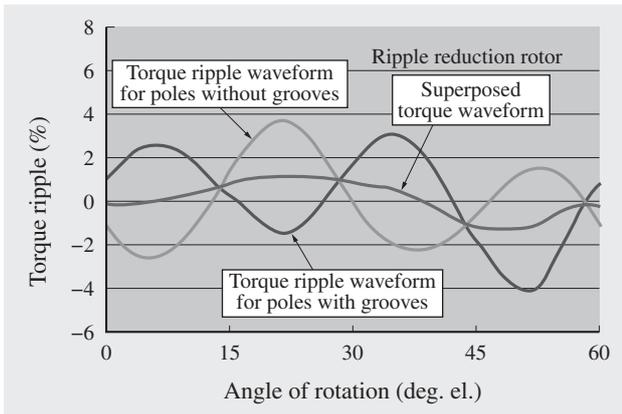


Fig. 6—Results of Analysis of Torque Ripple for Ripple Reduction Rotor. The torque ripple waveforms for poles with and without grooves cancel out when superposed, thereby reducing the torque ripple.

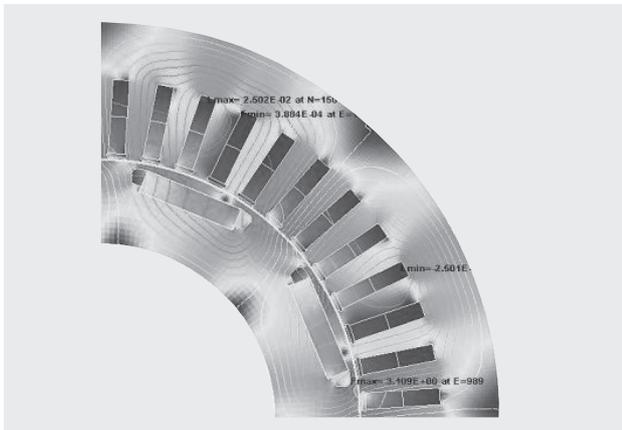


Fig. 7—Contour Diagram of Ripple Reduction Rotor Analysis Results. The effect of the grooves added to the surface of the rotor circumference for every other magnetic pole is to change the flow of the magnetic flux linkage with the stator.

**TECHNOLOGY FOR POWER INVERTER DEVELOPMENT**

The requirements for the power inverters used in HEVs are that they be small enough to fit into the limited space available in a vehicle, have the higher output (capacity) needed to achieve the required vehicle driving performance, and be made cheaper.

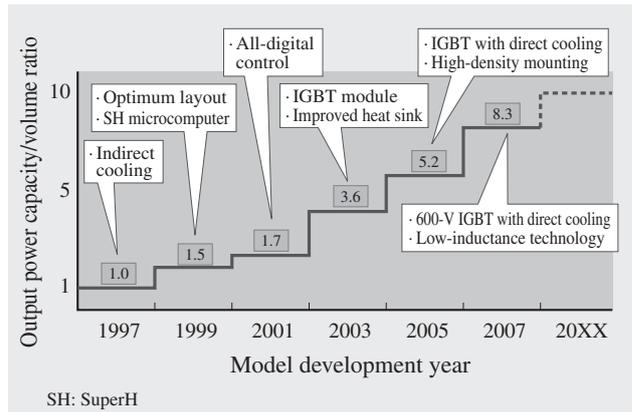


Fig. 8—Progress of Power Inverter Technology Development. The 2007 model combines small size and high output with a power output relative to volume that is approximately 8.3 times that of the 1997 model.



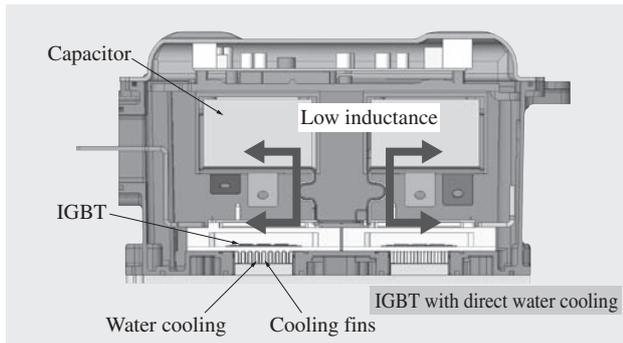
Fig. 9—2007 Power Inverter. Now in full-scale production, this model has external dimensions of 367 × 373 × 162 mm and technical features that include a low-inductance design and IGBTs with direct water cooling.

Hitachi uses PWM (pulse width modulation) inverters that use IGBTs (insulated gate bipolar transistors) as their semiconductor switching devices and is developing both water-cooled and air-cooled versions to suit different vehicle applications.

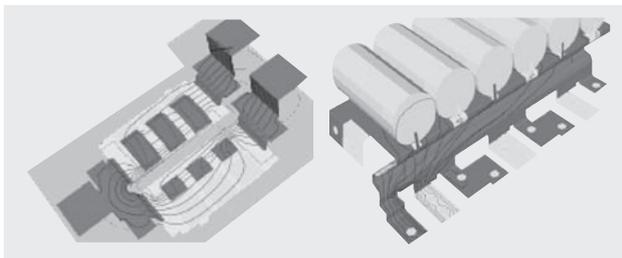
Fig. 8 shows an overview of the development of power inverter technology at Hitachi.

The current status of development is that the development of the 2007 models has completed and development of the next generation of models is in its final phase. The 2007 models feature higher output and smaller size, with a ratio of output power capacity to volume that is approximately 8.3 times that of models from 10 years ago.

Fig. 9 shows a photograph of a 2007 model power



*Fig. 10—Internal Structure of 2007 Power Inverter. A low-inductance design is achieved by directly connecting the bus bar from the capacitor to the IGBT with direct water cooling.*



*Fig. 11—Simulation Technology for Main Power Inverter Circuit (Inductance Analysis).*

*A low-inductance configuration was analyzed using Hitachi's own simulation software to develop a power inverter that is both small and inexpensive.*

inverter and Fig. 10 shows the internal configuration.

Features of the power inverter include a 600-V IGBT with direct water cooling developed by Hitachi and a low-inductance design achieved using technology for simulating the main circuit.

The IGBT with direct water cooling has cooling fins on the lower surface of the base plate to which the semiconductor switching devices are attached and the device size is reduced to achieve small size, high output, and lower costs by immersing these fins directly in the cooling water channels.

A low-inductance design for the main circuit of the power inverter was achieved using simulation technology which is shown in Fig. 11 and is unique to Hitachi. This allows the surge voltage at switching to be reduced and facilitated the successful development of a power inverter using small and low-cost low-voltage components.

Hitachi intends to continue developing power inverters that will meet future market needs based on these development technologies.

## CONCLUSIONS

This article has described system simulation

technologies and the trend toward smaller size and higher output in the electric motors and power inverters used in electric drive systems for HEVs.

The market for HEVs is expanding rapidly. Hitachi will strengthen its activities aimed at realizing a low-carbon society by continuing to press ahead with the development of products that meet customer needs and supplying the best solutions.

## ABOUT THE AUTHORS



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