Development of Standard Motor for Green Vehicles

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OVERVIEW: Against a background of environmental problems, there is growing demand in the automotive industry for the electrification of vehicle powertrains. However, there are a number of different configurations that can be used for electrification, including HEVs, EVs, and PHEVs, each of which has different requirements for the electric motor specifications, such as output, torque, or physical dimensions. Seeking to satisfy these different requirements separately for each new motor would end up significantly increasing the costs, effort, and time involved in motor development. Hitachi Automotive Systems, Ltd. is devising its own proprietary technologies in response to this challenge, such as the RR-rotor, while also developing a standard electric motor for powering green vehicles that will be suitable for a range of different uses.

INTRODUCTION

THE tightening of standards for fuel economy and exhaust emissions in response to global environmental problems has directed attention toward the electrification of vehicle powertrains. For this purpose, Hitachi has in the past adopted interior permanent magnet (IPM) synchronous motors that feature small size, light weight, high output, and high efficiency, and has developed electric motors that deliver high torque relative to their bulk. It has also succeeded in delivering high performance and shorter development times by drawing on know-how built up over many years in fields such as insulation technology, and by adopting digital engineering techniques such as using the Large-scale Universal Vector Electromagnetic Fields Numerical Simulator (LUVENS) for tasks such as designing motor core shapes and optimizing magnet positions. LUVENS was developed in-house and features advanced functions and high speed. However, customer requirements for electric powertrain motors cover a range of different configurations, such as hybrid electric vehicles (HEVs), electric vehicles (EVs), and plug-in hybrid electric vehicles (PHEVs), each of which has different requirements for specifications such as output, torque, and physical dimensions. Because developing each of these motor types individually would involve huge cost and effort, while also slowing down the development process, Hitachi is developing a standard motor for green vehicles (vehicles that use electric drive) that will be able to satisfy all of these different specifications.

This article gives an overview of the standard motor for green vehicles currently being developed.

OVERVIEW OF STANDARD MOTOR FOR GREEN VEHICLES

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 electrically powered vehicles, such as HEVs, EVs, and 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 aim is to develop a low-cost motor while also improving development efficiency. The requirements for realizing this concept include 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 electrically powered vehicles, and a range of model variations to suit different end uses. The following sections describe the thinking behind the methods adopted to achieve these objectives.

Stator Winding Design for Standard Motor

To achieve small size and high torque density, wave winding using square-profile wire was chosen for the stator windings on the standard motor. Compared with the distributed windings with circular-profile wire used in the past, those with square-profile wire provide an approximately 20% improvement in packing factor (conductor cross-section/slot cross-section) and an approximately 15% improvement in motor output

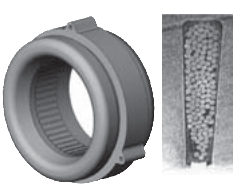
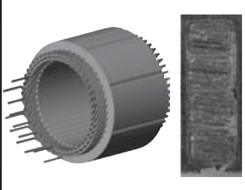
	Distributed winding with circular-profile wire (previous motors)	Wave winding with square-profile wire
Slot cross-section		
Torque density	60–70 (Nm/L)	70–80 (Nm/L)
Packing factor	40–45 (%)	60–65 (%)

Fig. 1—Stator Windings for Standard Motor.
Use of wave winding with square-profile wire provides high packing factor, small size, high torque, and high efficiency.

torque density (output torque/ stator core $D^2 \times L$) (see Fig. 1).

Selection of Motor Diameter

The term "electrically powered vehicle" covers a range of configurations, with different motor layouts in each case. For the standard motor, Hitachi focused on the following two typical motor layouts.
(1) Long cylindrical type intended for use in conjunction with a reduction gear. Used primarily in EVs.
(2) Flat cylindrical type intended to be built into the transmission or located between the engine and transmission. Used primarily in HEVs.

Looking first at the thinking behind the selection of motor diameter for the long cylindrical type used in EVs, this type of motor is typically used in conjunction with a reduction gear and is located under the bonnet in place of the engine and transmission in a conventional vehicle. This type of motor also typically uses water cooling, with a water jacket forming part of the motor case through which water can be circulated. Accordingly, an external diameter of 200 mm was selected for the stator core to satisfy these conditions together with the minimum ground clearance.

In the case of the flat cylindrical type for HEVs, the external diameter of the transmission case needs to be considered when selecting the motor dimensions since it is assumed that the motor will be located between the engine and transmission or inside the transmission case. Also, although this type of motor is typically cooled using the transmission fluid, to allow for the possibility of water cooling, an external diameter of 245 mm was selected for the stator core to leave room for a water jacket to be fitted around the exterior of the motor.

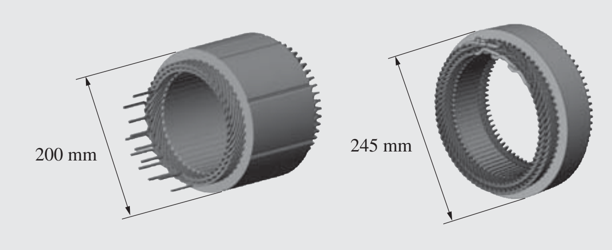


Fig. 2—Dimensions of Standard Motor.
The two standard stator core diameters selected were 200 and 245 mm.

By standardizing these two stator core diameters based on these considerations, Hitachi was able to make development more efficient (see Fig. 2).

MOTOR SPECIFICATIONS AND FEATURES

IPM synchronous motors are widely used for vehicle drive, with advances in motor control

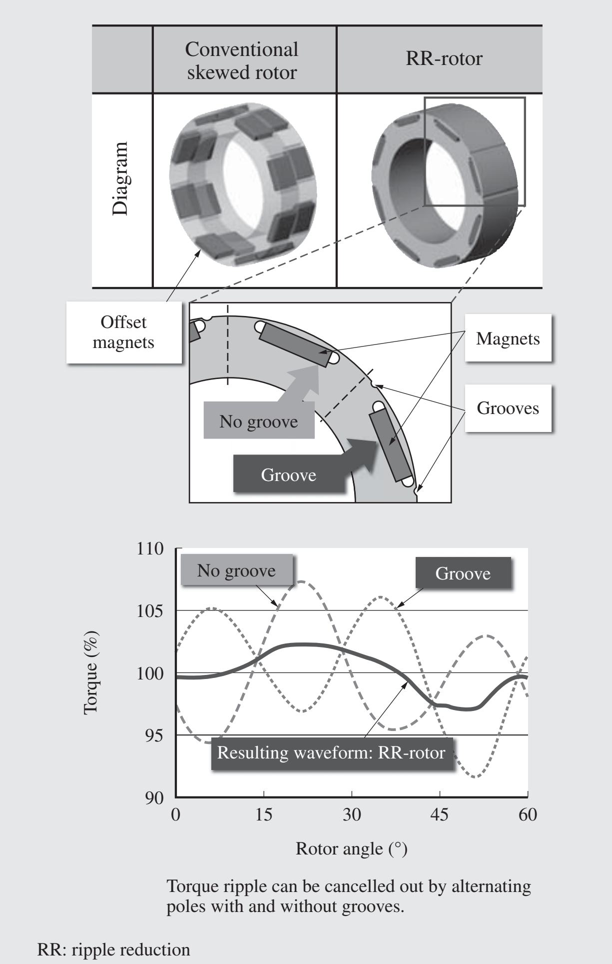


Fig. 3—RR-rotor.
By adding grooves to alternating poles around the circumference of the rotor, torque ripple can be reduced without splitting the magnets in the axial direction.

techniques in recent years delivering smooth driving performance. However, a structurally inherent feature of these motors is that the torque they produce includes a torque ripple component. This ripple can be a cause of pulsation at low speed or noise and vibration at high speed. The following sections describe proprietary techniques adopted by Hitachi for the rotor and stator respectively to minimize these effects.

RR-rotor

The conventional method for minimizing the torque ripple due to the rotor of an IPM motor is the offset skew technique in which the magnets are split and offset along the length of the rotor core (see Fig. 3). However, this approach increases costs because the greater number of magnets increases magnet machining costs and makes rotor assembly more difficult. In its place, Hitachi has devised the ripple-reduction (RR) rotor that reduces ripple without the use of skewing.

Torque ripple is pulsation of the output torque that results from variation in the intensity of magnetic flux. It occurs because of the interaction between the magnetic flux produced by the stator winding and that produced by the magnets. Also, the geometry of the stator slots and rotor poles are contributing factors. Accordingly, it is possible to cancel out the ripple in the output torque waveform by generating an opposite-phase ripple in the torque.

To generate this opposite-phase torque waveform, Hitachi modified the rotor geometry to create structurally induced variation in the flow of magnetic flux and produce a consequent linkage in the flow of magnetic flux at the stator. Specifically, by adding grooves in the rotor surface on each side of the magnets for alternating poles, the torque ripple waveform produced by the poles with a groove is opposite in phase to the torque ripple waveform produced by the poles without a groove (see Fig. 3). The result is reduced torque ripple due to the two ripple waveforms canceling each other out[1].

HR-winding

Hitachi devised the harmonic reduction (HR) winding technique for stators as a means of reducing torque ripple and achieving quiet operation. Reducing the harmonic components of the magnetomotive force and induced voltage play an important role in reducing electromagnetic hum and torque ripple in motors. Accordingly, Hitachi devised a new winding technique designed to achieve these goals (see Fig. 4).

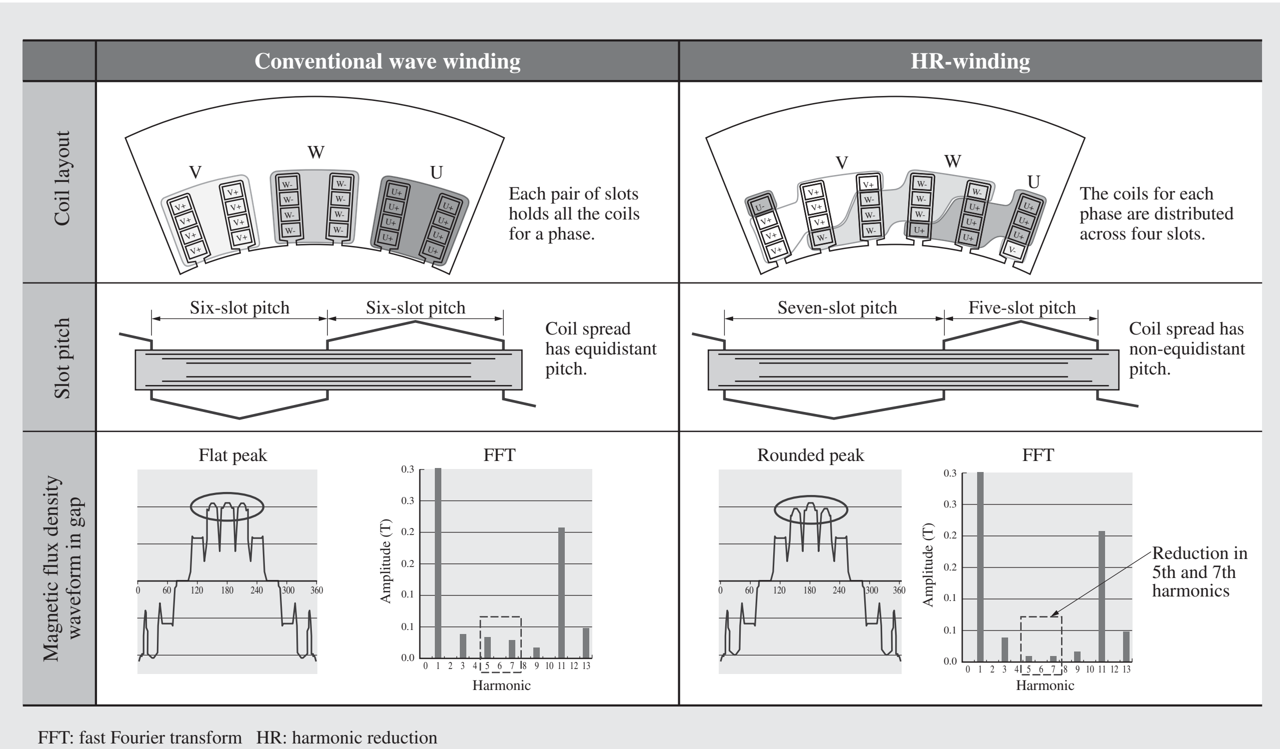


Fig. 4—HR-winding.
Low torque ripple and quiet operation can be achieved by reducing the harmonic components of the magnetomotive force and induced voltage.

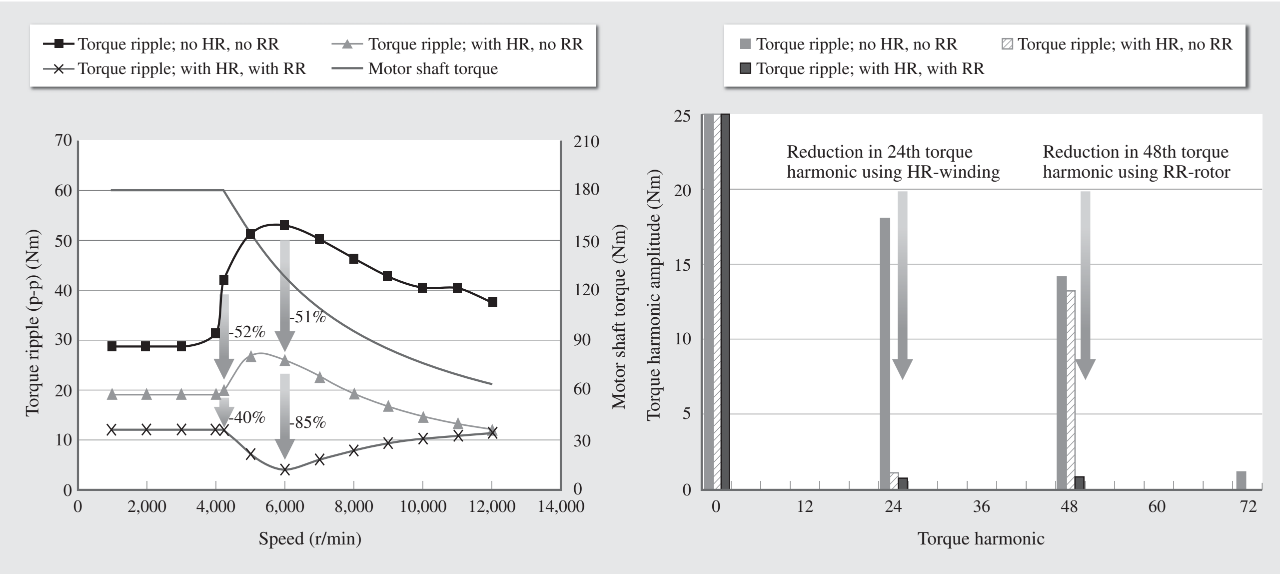


Fig. 5—Benefits of Torque Ripple Reduction.
A magnetic field simulation was used to demonstrate the benefits of the HR-winding and RR-rotor for a motor with maximum torque of 180 Nm. Use of HR-winding reduces torque ripple by 51% and use of the RR-rotor reduces torque ripple by 85%. Note that these results were calculated assuming a sinusoidal current waveform.

Previous winding techniques used the same slot pitch for all coils, with a stator cross-section in which all of the coils for each phase were located together in two slots. In contrast, the new HR-winding technique uses coils with seven-slot and five-slot pitches to distribute the coils for each phase across four slots and spread the magnetic flux produced by the coils over a wider area. This creates a rounded peak at the leading edge of the magnetic flux waveform in the gap between the inner circumference of the stator and outer circumference of the rotor and makes the overall waveform closer to a sine wave, thereby suppressing the harmonic component by reducing the amplitude of the fifth and seventh harmonics.

Benefits of RR-rotor and HR-winding

To demonstrate the benefits of the RR-rotor and HR-winding, Fig. 5 shows the results of using a magnetic field simulation to calculate the torque ripple for a motor with maximum torque of 180 Nm.

The horizontal axis represents motor speed and the vertical axis represents torque ripple. Use of HR-winding reduces torque ripple by up to 51% compared with that of previous designs. If the RR-rotor is also used, it is anticipated that torque ripple will be reduced by up to 85% compared with when HR-winding is used on its own. Meanwhile, fast Fourier transform (FFT) analysis of the torque waveform showed that the harmonic at which the benefits occur is different in each case, with HR-winding reducing torque ripple for the 24th harmonic of rotation and the RR-rotor reducing it for the 48th harmonic.

OUTPUT ADJUSTMENT FOR STANDARD MOTOR

While two different stator core diameters (200 mm and 245 mm) were selected for the standard motor, because customers' motor performance requirements are diverse, Hitachi also intends to use the two motor performance adjustment methods described below to satisfy these various requirements (see Fig. 6).

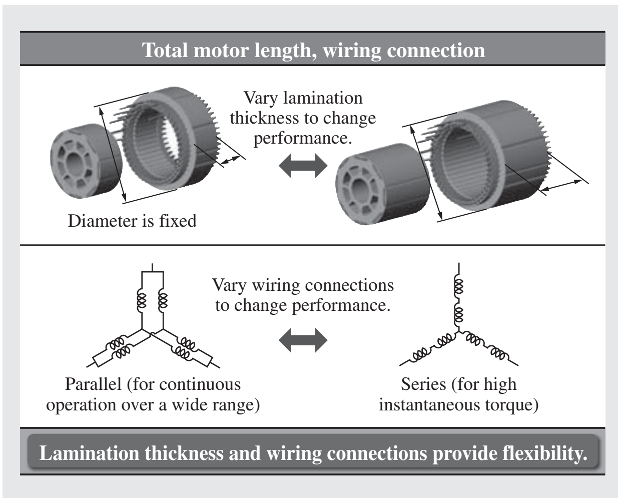


Fig. 6—Stator Variations.
Motor performance can be changed by varying the lamination thickness and wiring connections.

Torque Adjustment by Changing Lamination Thickness

The workload for motor design and development is significantly increased if the magnetic circuit (motor cross-section shape) from the core shape for each new set of customer requirements. On the other hand, once the magnetic circuit design of the motor cross-section is complete, the performance calculation associated with varying the length of the motor (core lamination thickness) is comparatively simple. Moreover, the production equipment can be adapted more easily to changes that consist solely of varying the length of the motor without changing its cross-section shape when using wave winding with square-profile wire than it could when using the distributed windings with circular-profile wire in the past.

For these reasons, Hitachi has chosen to use changes to the core lamination thickness (as shown in the top part of Fig. 6) as a means of varying the torque and other motor performance parameters, without changing the cross-section shape of the core.

Torque Adjustment by Changing Winding Wire Connections

The motor output range and time rating requirements differ for different vehicle models and gear ratios of the associated reduction gear. Because an EV is powered by the electric motor on its own, it needs to be able to operate continuously over a wide range. In the case of an HEV motor, on the other hand, because it provides torque-assist to the engine, it is used to generate high torque over short durations. To satisfy these different requirements, Hitachi uses a standard winding wire configuration but changes the wiring connections in the stator, as shown in the lower part of Fig. 6.

For an EV motor, end-point connections are used to form two winding circuits in parallel and provide low-torque and high-speed motor output characteristics that are matched to the reduction gear ratio. This provides for continuous operation over a wide range when operating in the frequently used medium to low torque range.

HEV motors require high-torque and low-speed motor output characteristics. Accordingly, to deliver high torque, the two winding circuits are connected in series to increase the number of winding loops. Although this results in a shorter permissible operating time because of the large temperature rise while current is flowing, it is adequate for the short-duration torque-assist that occurs in HEVs when accelerating from a halt, for example.

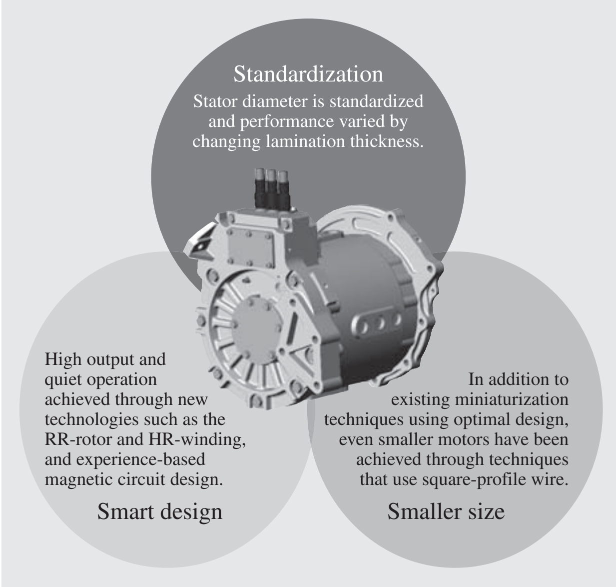


Fig. 7—Standard Motor Developed by Hitachi Automotive Systems, Ltd.
Hitachi is developing small motors that feature high output, high efficiency, and quiet operation, and that have standardized stator core diameters.

Based on these considerations, it is possible to produce a series of motors that share components such as cores, magnets, wires, and insulating paper, and that allow the standardization of production equipment and manufacturing practices.

CONCLUSIONS

Hitachi is currently working on the development of a standard motor for green vehicles that incorporates its proprietary technologies (see Fig. 7). While changes in environmental and fuel economy standards continue, it is anticipated that demand for vehicles with electric drive will increase, and that the technology for a next-generation standard motor described in this article will play a key role in satisfying the need for vehicle electrification.

REFERENCE

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