Power Electronics Technologies for Railway Traction Systems

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OVERVIEW: To satisfy a growing global market, Hitachi supplies a wide range of railway traction system products to meet diverse customer needs that extend from commuter to high-speed trains. This has included the development and commercialization of a standard medium-capacity inverter with a mass and external dimensions that are less than those of previous models by 20% or more. For high-speed rolling stock, Hitachi has developed an inverter that has roughly double the output of Japanese models, and that is designed for use with rolling stock, motors, and other components that comply with European specifications. This inverter is currently undergoing field trials. To improve rolling stock energy efficiency further and reduce maintenance requirements, Hitachi has also developed a traction system with 35% lower inverter losses, including the development of a highly efficient enclosed induction motor (efficiency improved from 91% to 95%) and SiC hybrid modules that combine SiC diodes with Si IGBTs.

INTRODUCTION

THE international trend toward energy efficiency is making railways increasingly important, and there is a need for the timely supply of a diverse range of traction systems that are not only highly efficient and reliable, but also satisfy the market requirements of each country.

In addition to offering a wide product range that meets these needs, Hitachi has also responded to the growing demand for energy savings by developing new traction technologies, including a highly efficient enclosed induction motor and silicon carbide (SiC) hybrid inverter.

This article describes the features of Hitachi's range of electrical components for the traction circuits used in traction systems for both conventional and high-speed trains, and also newly developed next-generation traction circuit technology.

HITACHI'S TRACTION SYSTEMS FOR ROLLING STOCK

Table 1 lists Hitachi's range of traction systems for rolling stock. The range extends from small-capacity models, used in applications such as monorails, up to units for use in the Shinkansen and other high-speed trains. The following sections describe the different types of systems.

MEDIUM-CAPACITY SYSTEMS

Hitachi offers four different medium-capacity traction systems to suit different applications. The following sections describe their technical features and examples of their use.

Standard Systems

Hitachi supplies a range of standard inverters[(1)] that are smaller, lighter, and easier to maintain than previous models thanks to use of components such as low-loss/low-noise insulated-gate bipolar transistors (IGBTs) and highly efficient cooling systems, the adoption of unit-based designs that make effective use of built-in components, and the elimination of components such as fans that have a limited operating life (see Table 1).

(1) Series 209 experimental train of East Japan Railway Company (MUE-Train)

TABLE 1. Hitachi's Range of Traction Systems for Rolling Stock
The six different types differ based on parameters such as control capacity and functions.

Small-capacity systems	Medium-capacity systems				High-capacity systems
	Standard	With brake chopper	For low-floor rolling stock	AC system / AC-DC dual system	
Subways, monorails, etc.	Urban transportation	Urban transportation (without regeneration)	Linear subways	Intercity transportation	High-speed rolling stock

AC: alternating current DC: direct current

MUE-Train: multi-purpose experimental train

Fig. 1—Series 209 Experimental Train (MUE-Train).
The MUE-Train commenced field trials in October 2010 using a standard inverter adopted for use in the next-generation rolling stock control system.

The East Japan Railway Company is developing a next-generation rolling stock control system for the experimental Series 209 [the multi-purpose experimental train (MUE-Train)]. The inverter for this system is a standard inverter for which the East Japan Railway Company was the first user. The control system uses Ethernet to transmit control signals (see Fig. 1).

(2) Additional units of the East Japan Railway Company's Series E233-3000

A standard inverter adopted for additional units of the Series E233-3000 featured smaller size and lighter weight than the inverter used in the earlier units (see Table 2 and Fig. 2). Despite this, the old and new inverters are mutually compatible in terms of installation and performance.

Systems with Integrated Brake Chopper

For urban services outside Japan, where it is often difficult to achieve an adequate regenerative load, Hitachi has commercialized an inverter for use with brake-generators that incorporates the brake chopper in the same housing. Integrating the brake chopper has reduced the weight by 14% compared to previous equipment.

Systems for Low-floor Rolling Stock

The restricted amount of space available for installing equipment below the floor of subway cars equipped with linear motors places a limit on the height of the inverter. Accordingly, Hitachi's range of standard models has been extended by revising the location of components, modifying the cooling system design, and optimizing the placement of parts inside the inverter unit to suit low-floor rolling stock, resulting in an inverter unit with a height of only 500 mm (24% less than standard model).

AC and AC-DC Dual Systems

By applying technologies from standard models to alternating current (AC) and AC-direct current (DC) dual systems, these have been made smaller, lighter,

TABLE 2. Comparison of Inverters Used on Series E233-3000
The table below compares the dimensions and weight of the old and new inverters used on the Series E233-3000.

Parameter	Initial rolling stock	Additional rolling stock
External dimensions (W × D × H) (mm)	3,390 × 740 × 725	2,950 × 740 × 650 (-22%)
Weight (kg)	1,030	790 (-24%)

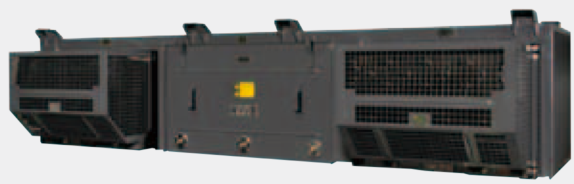

Fig. 2—Inverters Used on Additional Series E233-3000 Units.
The inverters used for additional Series E233-3000 units were standard models. They were smaller and lighter than the inverters used on earlier units.

and easier to maintain than previous models. These systems include both converters that convert single-phase AC to DC and converter-inverter systems that incorporate an inverter.

A feature of Hitachi's converter-inverter systems is that they use T-shaped three-level converters to minimize power supply harmonics and noise. To make them smaller and more efficient, the T-shaped three-level converters have a simple design that also uses proprietary Hitachi circuit techniques to eliminate the clamping diodes used on previous three-level traction circuits(2).

The converter-inverter system on the East Japan Railway Company's Series E657 express trains for the Joban Line that entered commercial operation in March 2012 combines the T-shaped three-level converter with a DC rolling stock inverter power unit from the same series as that described above.

The converter power units for the Kyushu Railway Company's 817-2000 and 817-3000 Series use this three-level traction circuit and incorporate low-noise, snubber-less traction circuit technology that is implemented in the inverter. Thanks to the small size and UV phase integration, the converter-inverter system consists of two independent sub-systems to provide redundancy even on short trainset configurations.

TRACTION CIRCUIT FOR HIGH-SPEED ROLLING STOCK

While trains speeds are increasing to more than 300 km/h throughout the world, the following are the main differences between Japan and other countries.

In Japan, the proportion of driving wheels is increasing to reduce the mass per axle and ensure an adequate level of adhesion. The purpose is to reduce the effect on the railway track. As a result, individual converter-inverter systems tend to have a smaller output, with the control of four 300-kW motors being a typical configuration. Development trends include environmental considerations such as higher efficiency and making devices smaller and lighter while retaining the same capacity.

Overseas, meanwhile, where track foundations tend to be firmer, the main rolling stock configuration is to use central traction systems of the type used in Europe that have a high mass-per-axle. Even when a distributed traction system is used, the proportion of driving axles tends to be lower than in Japan and a higher capacity converter-inverter system, requiring a high-capacity configuration that controls four motors in the 600-kW range. The following sections describe examples of these two different types of system.

Small, Lightweight Systems for Use in Japan

Since the adoption of IGBTs in 1997 on the Central Japan Railway Company's Series 700 Shinkansen rolling stock, the predominant configuration for converter-inverter systems for the Shinkansen has consisted of three-level converter-inverters with 3.3-kV IGBTs.

The East Japan Railway Company's Series E5 Shinkansen rolling stock, which entered commercial operation in March 2011, is intended to be connected with the new Series E6 Shinkansen rolling stock (scheduled to commence commercial operation in the spring of 2013) that will operate through-train services on an existing line. There are plans to operate the Series E5 and E6 Shinkansen connected, with speeds to increase progressively up to Japan's maximum speed of 320 km/h after services commence.

Hitachi has prepared a common design for the converter-inverter systems used in both the Series E5 and E6 Shinkansen rolling stock, and has made the operation and maintenance of traction circuit equipment more efficient. Because the Series E6 Shinkansen rolling stock will also run on conventional lines, they require a small converter-inverter system to suit their small carbody.

The power unit of the converter-inverter system for the Series E5 has an integrated configuration consisting of two converter phases and three inverter phases. Its design, which allows the system to be attached to or removed from the side of the vehicle, not only makes effective use of the available installation space and helps make the equipment smaller, it also provides a significant improvement in ease of installation. The system is also designed to facilitate work on internal equipment that needs inspection or maintenance, with an inspection cover fitted on the air intake that is on the mountain-side of the converter-inverter system and all of the main internal devices being located together. The size of the system is also reduced by utilizing free space inside the converter-inverter system for components such as filter condensers and resistors that do not require frequent inspection (see Fig. 3).

High-output System for Overseas Use

A number of high-speed trains were developed in China in preparation for the 2010 opening of the Beijing–Shanghai high-speed railway, which is used exclusively for passenger services. As part of this,

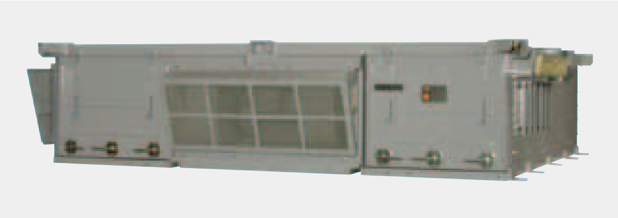

Fig. 3—Converter-inverter System for Series E5 Shinkansen Rolling Stock.
This system shares a common design with the system for the Series E6, with more efficient operation and maintenance of traction circuit equipment.

Hitachi received an order for electrical components for one of the trains built for this purpose, the CRH380CL, from CNR Changchun Railway Vehicles Co., Ltd. The order size was for 25 trainsets. The order for the first trainset was produced at Mito Rail Systems Product Division, and for the second and subsequent trainsets at Hitachi Yonge Electric Equipment (Xi'an) Co., Ltd. (HYEE). The specifications of CRH380CL rolling stock are shown in Table 3.

The CRH3 Series includes the CRH380BL (with an electrical system supplied by Siemens AG), which is produced based on CRH3 rolling stock that is already in service (ICE3 base). The purpose of the CRH380CL to which Hitachi's order related was to be a locally developed train for China that used the structure of European rolling stock as a base. A major issue in the development was that it required the systems to be compatible with rolling stock, motor, converter-inverter, and other components based on European technology (see Fig. 4).

The configuration of the traction system connects two converter-inverter systems to each main transformer, with each converter-inverter system driving four 615-kW motors in parallel. Another feature of the system is that an auxiliary power supply is connected to the intermediate DC section of the converter-inverter system so that, as well as delivering a maximum of 3 × 160 kVA, it has a configuration that enables the auxiliary power supply to operate using regenerative electric power from the inverter when passing through sections. The converter circuit of the converter-inverter system has a dual configuration for higher capacity and uses carrier phase-shift operation to reduce harmonics. Table 4 lists the specifications and main development requirements of the converter-inverter system.

As of September 2011, the first trainset had completed factory testing at the manufacturer's site and was undergoing tuning and field trials on the test line of the China Academy of Railway Sciences in Beijing.

NEW TECHNOLOGIES FOR ENERGY EFFICIENCY

Hitachi is working on a wide range of technology developments aimed at further improving the performance of railway traction systems. This section describes two such new developments: a highly efficient enclosed motor and a low-loss SiC hybrid inverter.

Highly Efficient Enclosed Induction Motor

The demand for making rolling stock motors more energy efficient, and easier to maintain with low noise has been steadily increasing. To achieve this, Hitachi has developed a new, highly efficient enclosed induction motor (see Fig. 5). The features are as follows.

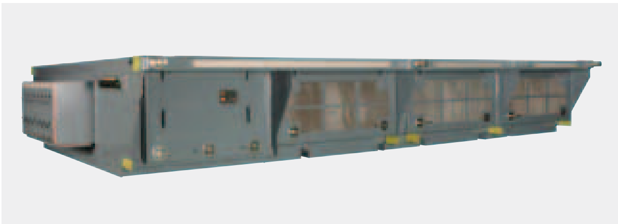

Fig. 4—Converter-inverter System for CRH380CL.
One inverter and two converters are housed in the same unit.

TABLE 3. CRH380CL Rolling Stock Specifications
The CRH380CL was developed specifically for use in China using European rolling stock as a base.

Trainset configuration	16 cars (8M8T)
Trainset mass	1,000 t
Electrification system voltage	25 kV
Performance	Output at wheel: 600 kW × 32 axles
	Maximum operating speed: 380 km/h
Rolling stock manufacturer	CNR Changchun Railway Vehicles Co., Ltd.

M: motor T: trailer

TABLE 4. Development Specifications
The configuration is similar to European rolling stock designs.

Output capacity	4 × 615-kW motors + 3 × 160-kVA auxiliary power supplies
Converter	2 × two-level, snubber-less converters with IGBTs (4.5 kV/900 A)
Inverter	1 × two-level, snubber-less inverter with IGBTs (4.5 kV/900 A)
Configuration, etc.	• Auxiliary power supplies connect to DC section, installed on anti-vibration rubber mounts • 4,300 × 2,716 × 700 mm, 3,380 kg

IGBT: insulated-gate bipolar transistor

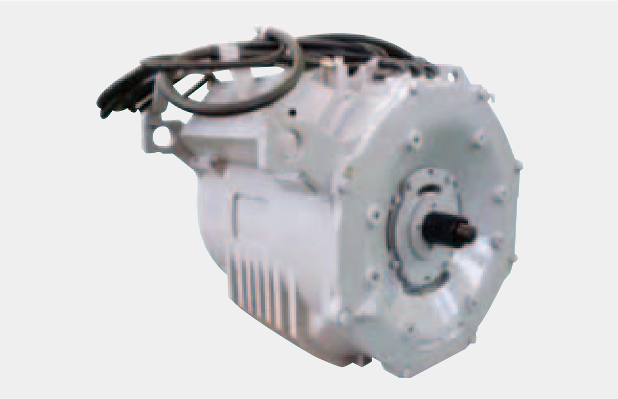

Fig. 5—Enclosed Motor.
An optimized fin layout was designed to cool the air inside the motor efficiently using the natural airflow of the moving train.

Fig. 6—SiC Hybrid Inverter.
The inverter was made 40% smaller and lighter by reducing the size and losses of the switching devices.

(1) Enclosed design with internal fan: Past induction motors have required regular cleaning because they draw in external air for cooling, which can allow dirt to get inside the motor. These motors are also louder because noise from the rotor inside the motor propagates through the cooling air.

In response, Hitachi has developed an enclosed motor that overcomes these problems. The major challenge with adopting this fully enclosed structure was the resulting increase in heat generation as cooling air cannot be drawn into the motor.

To deal with this problem, Hitachi set out to reduce motor losses and improve cooling efficiency. To reduce losses, electromagnetic analysis was used to optimize the design of the stator and rotor and to select a low-loss material for the rotor. This improved the motor efficiency from 91% to 95%. Developments aimed at improving cooling efficiency included using an analysis of air flow and temperature to optimize the design of the internal recirculation duct and external cooling fins, and using an auxiliary fan to improve the cooling efficiency of the bearings. Adopting this fully enclosed design eliminated the need for cleaning the inside of the motor and has reduced noise by 30 dB.

(2) Bearing design allows replacement without disassembly.

Hitachi has also devised a simple new design for the bearings that allows them to be worked on without removing the rotor.

Whereas motors in the past required a crane to remove the rotor, this is not necessary with the new motor because the rotor does not need to be removed. In addition to providing more flexibility in where maintenance work can be performed, this also significantly reduces maintenance time. The simple bearing design means that no special tools are required and this also removes constraints on work such as tool availability.

SiC Hybrid Inverter

Hitachi has developed an inverter that uses new SiC hybrid modules as its semiconductor switching elements (see Fig. 6).

While 1.7-kV SiC semiconductor switching elements had been developed for use with DC 750-V electrification system, there were no 3.3-kV devices suitable for use with the DC 1500-V electrification system common in Japan. This provided a strong incentive for their development.

Now, Hitachi has developed a 3.3-kV SiC hybrid module and used it in an inverter for 1500-V electrification system with a simple two-level configuration. The features of the inverter are as follows.

(1) Lower losses: Hitachi has developed an SiC hybrid module with the aim of reducing both diode switching loss and the turn-on switching loss that occurs when IGBTs turn on by combining SiC diodes with Si IGBTs. The result has been to reduce inverter losses by 35% by cutting diode switching loss to one-sixth and IGBT turn-on loss to less than one-half.

(2) Smaller size and lighter weight: Because of the low losses described above, the SiC hybrid module is only two-thirds the size of previous devices with the same current capacity. Features such as the reduction in heat generation and the smaller size of the cooling system, which was achieved by using thermofluid analysis to optimize the heatdissipating fin and heat pipe layout, have succeeded in reducing the volume and weight of the inverter by 40% compared to the previous model.

CONCLUSIONS

The railway market will become increasingly global in the future, and there will be demand for traction systems that are both easier to maintain and more energy efficient. Hitachi intends to respond to diverse customer needs with newly developed next-generation traction circuit technology and the range of railway traction systems described in this article.

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