Energy-saving Technology for Railway Traction Systems Using Onboard Storage Batteries

Motomi Shimada
Yoshihiro Miyaji
Takashi Kaneko
Keita Suzuki

OVERVIEW: The first application for onboard storage batteries came with the commercialization of series hybrid drive systems that reduced the fuel consumption of diesel trains. Storage battery control has also been used for the absorption of regenerative electric power and to implement the regenerative brake with extended effective speed. Further progress has since led to the development of an efficient regeneration system for making effective use of electric power. Now, Hitachi has conducted operational trials of the regenerative brake with extended effective speed using storage batteries to boost the DC voltage at the inverter input, achieving an increase in regenerative electric power of up to 12.5% (for a 300-V boost). In the future, Hitachi intends to encourage the wider use of onboard storage batteries by achieving a good balance of return on investment, and by working on new energy-saving technologies that are closely aligned with customer needs.

INTRODUCTION

HITACHI is developing railway systems that use storage battery control technology to save energy and reduce carbon dioxide (CO_2) emissions.

The first application for onboard storage batteries came with the commercialization of series hybrid drive systems that reduced the fuel consumption of diesel trains on non-electrified railway lines. While collecting field data, Hitachi has also developed an efficient regeneration system to improve energy efficiency on trains, and has verified its effectiveness through operational trials.

This article gives an overview of storage battery technologies for railways, and describes a regenerative brake with extended effective speed control, which extends the operating speed range for regenerative braking by using storage batteries to increase the direct current (DC) voltage of the inverter, and which is used in the efficient regeneration system.

STORAGE BATTERY TECHNOLOGY FOR RAILWAYS[1]

Development of Hybrid Drive System

In collaboration with the East Japan Railway

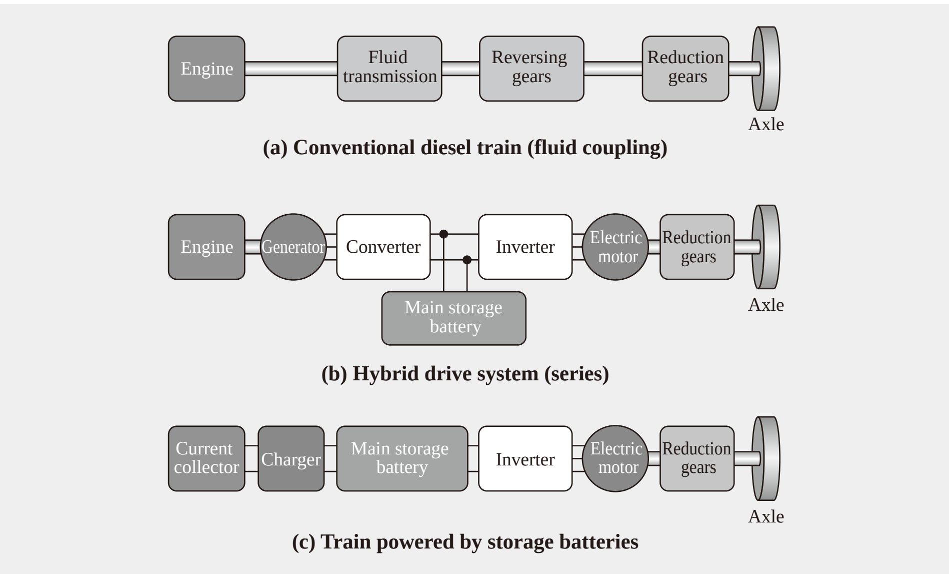


Fig. 1—Traction System for Non-electrified Railway Lines.
Trains that are powered by storage batteries and use a hybrid drive system have fewer mechanical components than conventional diesel trains. They also significantly reduce maintenance work through the standardization of major components between trains.

Company, Hitachi started developing a series hybrid drive system in 2001 that combined a diesel engine and lithium-ion batteries with the aim of reducing the fuel consumption and harmful exhaust emissions of diesel trains running on non-electrified railway lines (see Fig. 1). The system reduces fuel consumption and noise by using storage batteries to implement regenerative braking, engine idle stop, and constant engine speed operation, features that are not possible on diesel multiple units.

Implementation of Hybrid Drive System

A hybrid drive system has been built for use in the Series Kiha E200 trains of the East Japan Railway Company. The main storage batteries used in the system are high-output lithium-ion batteries designed for use in hybrid cars.

The Series Kiha E200 trains became the world's first hybrid trains to commence commercial operation when they entered service on the Koumi Line in July 2007. Hitachi then went on to develop a hybrid drive system for the Series HB-E300 resort trains in 2010. The Series HB-E300 operates in Aomori Prefecture (Tsugaru and Ominato Lines), Akita Prefecture (Gono Line), and Nagano Prefecture (Shinonoi and Oito Lines), where they are helping reduce the load on the environment in ways that include providing quieter and more energy-efficient operation (see Fig. 2). The system used in the Series HB-E300 is the successor to the series hybrid system implemented for the Series Kiha E200, and it has been designed to suit the requirements of a resort train. This includes providing redundancy in the auxiliary power supply (increased capacity and support for power supply induction), enhancing tolerance of low temperatures and structural strength for coping with snow, and providing additional traction capacity.

Storage-battery-powered Train

Trains powered by storage batteries charge their large-capacity onboard storage batteries while on electrified sections of railway line, and then use storage battery power only to drive the train and supply power to auxiliary systems. Because this eliminates the need for an internal combustion engine, these trains should be significantly more energy efficient than diesel trains, with better environmental performance and lower maintenance requirements. With the rapid growth in the market for storage batteries for use in vehicles, industry, and other applications in recent years, storage battery performance (capacity and output) continues to improve while costs are falling, and this has opened up the potential for trains powered by storage batteries to be built for use on railway lines where the terrain is gentle and the length of non-electrified line is short. As capacity is more important than output for main storage batteries, it is appropriate to use the lithium-ion batteries with high energy density produced for use in electric vehicles and industry. Utilizing the increased capacity, higher voltages, and control and monitoring techniques for lithium-ion batteries that it

Fig. 2—Series HB-E300 Resort Train.
This is the successor to the series hybrid drive built for the Series Kiha E200 trains. It features high-output lithium-ion batteries (15.2 kW).

has built up through its hybrid drive systems, Hitachi is proceeding with development work aimed at the early commercialization of trains powered by storage batteries.

EFFICIENT REGENERATION SYSTEM[2]

Concepts for Achieving Energy Efficiency

Hitachi is building railway systems that are taking the lead in moving to an energy-efficient society by improving the total efficiency of the traction drive in train systems (see Fig. 3).

Specifically, this is being achieved through the following three technologies:

(1) Improvements to equipment efficiency
(2) Use of control to improve efficiency
(3) Utilization of regenerative energy

This section describes the technologies for an efficient regeneration system that utilizes regenerative energy.

Improving Efficiency of Regenerative Braking

Regenerative braking works by using the traction motor as a generator during deceleration. The regenerative energy produced as a result is fed back to the overhead contact lines so that it can be reused to accelerate a nearby train. However, this regenerative energy may not be used fully during off-peak times when there are few nearby trains. The problem is how to use regenerative braking under light load conditions. To prevent the filter condenser voltage from rising in this situation, the inverter controls regeneration under light load in a way that throttles the regenerative current. Although this has the effect of minimizing the rise in the filter condenser voltage, it also reduces the regenerative braking force, and while this can be compensated for using the pneumatic brakes, it results in less regenerative energy being produced.

The energy efficiency benefits are maximized when all of the braking force required to decelerate a train to a stop are provided by the regenerative brake. At high speeds, however, regenerative braking force is limited by the motor output characteristics. As this component of the braking force that the regenerative brake is unable to supply at high speeds is provided by the pneumatic brake instead, the energy savings are smaller than they might have been. Accordingly, the problem is the performance limitations of the motor characteristics.

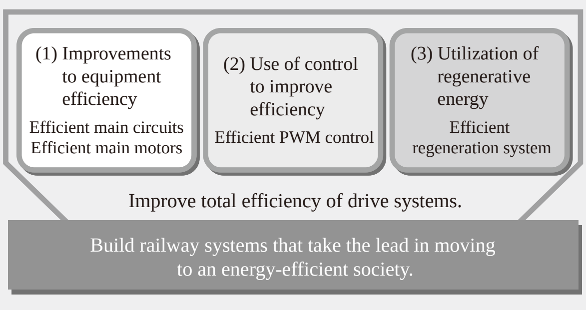
The efficient regeneration system uses the following methods to overcome these two problems.

(1) Solution for regenerative braking under light load conditions

The function for absorption of regenerative electric power uses storage batteries to absorb regenerative electric energy when there are no other trains able to receive it. The energy is then reused to power acceleration (see Fig. 4). The two potential locations for the storage batteries are onboard the train or on the wayside.

(2) Solution for performance limitations of the motor characteristics

The regenerative brake with extended effective speed extends the operating range of regenerative braking into higher speeds by using storage batteries to boost the DC voltage of the inverter, thereby increasing the output of the motor and inverter without changing the current through the various components. As shown in Fig. 5, this has the effect of increasing the voltage/frequency (V/f) top speed.



PWM: pulse width modulation

Fig. 3—Concepts for Achieving Energy Efficiency.
Hitachi is building railway systems that are taking the lead in moving to an energy-efficient society by improving the total efficiency of drive systems.

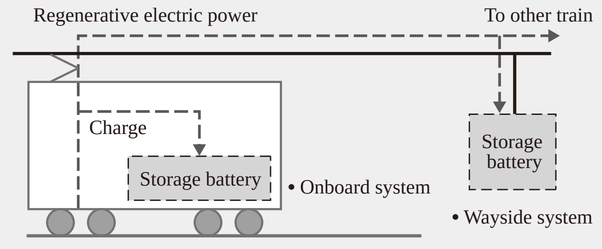


Fig. 4—Function for Absorption of Regenerative Electric Power.
Storage batteries absorb any regenerative electric power that cannot be returned to the overhead contact lines. The stored regenerative electric power is reused the next time the train accelerates to reduce power consumption by the inverter.

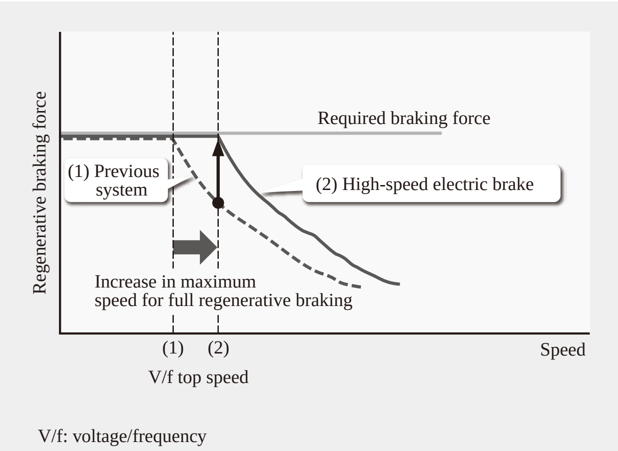


Fig. 5—Regenerative Brake Characteristics.
The storage batteries are used to extend the operating range of regenerative braking into higher speeds by boosting the DC voltage of the inverter, thereby increasing the output of the motor and inverter.

The efficient regeneration system is implemented by operating the function for absorption of regenerative electric power and regenerative brake with extended effective speed in an appropriate manner. Fig. 6 gives an overview of how the equipment operates.

CONTROL OF REGENERATIVE BRAKE WITH EXTENDED EFFECTIVE SPEED[3]

Overview

The efficient regeneration system has two functions. Operational trials have already been conducted for one of these: the absorption of regenerative electric power. The following section describes the operational trials and associated results for the other function: the regenerative brake with extended effective speed.

Principle of Operation

The performance of a regenerative brake for rolling stock deteriorates at high speed because of limitations in the motor output characteristics (once maximum voltage is reached, the braking force is inversely proportional to the square of the speed).

Although the input DC voltage for the inverter is determined by the voltage of the overhead contact line, it is possible to use the voltage from storage batteries to boost this input voltage, thereby increasing the voltage applied to the motor and allowing the output of regenerative braking to exceed the previous restriction. Fig. 7 shows the principle of operation for the regenerative brake with extended effective speed.

Circuit Design for Implementing Function

Fig. 8 provides an overview of the control mechanism and shows the circuit design for the system. The system works by inserting the storage batteries in series between the earth and the negative input terminal of the inverter. This pulls down the voltage at the negative input terminal from the earth voltage by an amount equal to the battery voltage (ΔV), thereby increasing the voltage applied to the inverter by the same amount. This voltage boost can be continuously varied between 0 V and ΔV by the

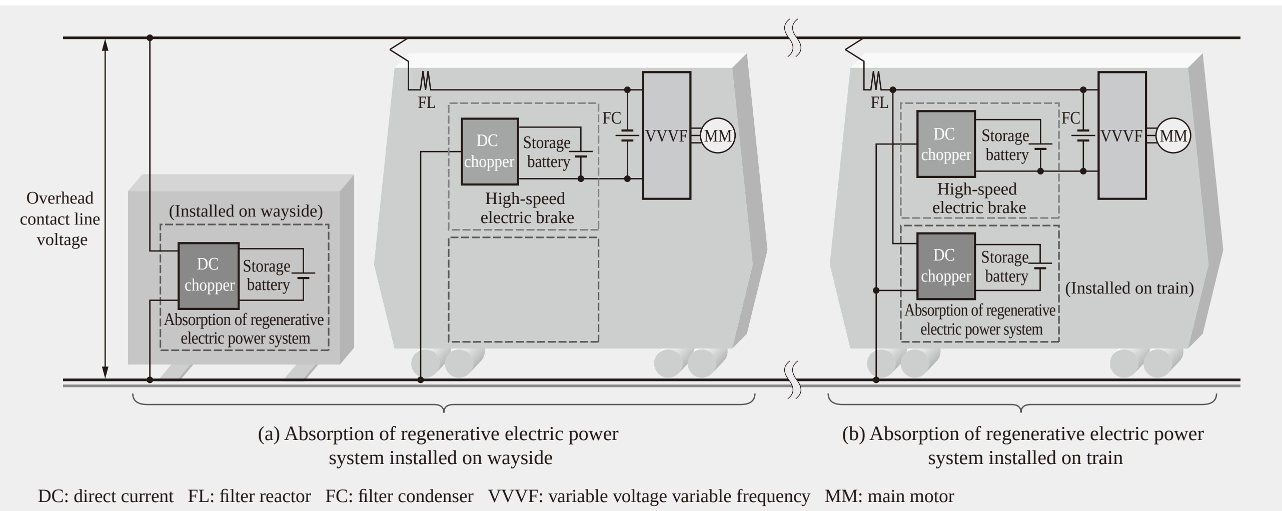


Fig. 6—Hardware Configuration of Efficient Regeneration System.
The storage batteries are inserted in series at the negative input terminal of the inverter when the regenerative brake with extended effective speed is used, and in parallel with the inverter via the step-up/step-down DC chopper when absorption of regenerative electric power is used.

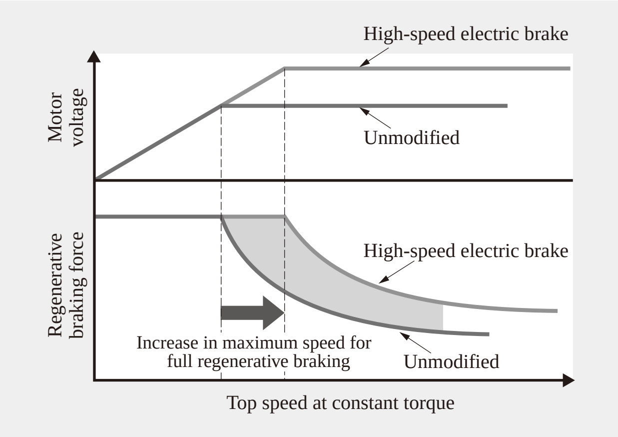


Fig. 7—Principle of Operation of Regenerative Brake with Extended Effective Speed.
As using the voltage from storage batteries to boost the DC voltage increases the regenerative braking power by an amount proportional to the voltage boost, the top speed for full regenerative braking is increased.

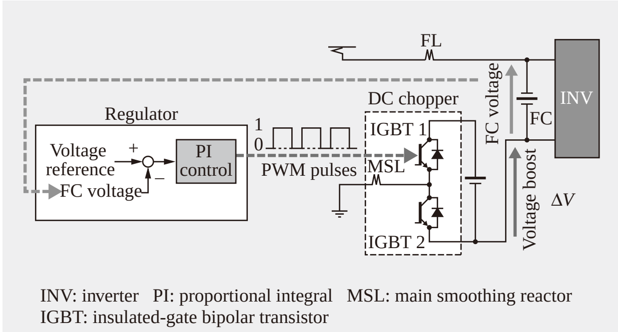


Fig. 8—Circuit Diagram of System and Overview of Control Mechanism.
The amount of storage battery voltage boost is adjusted to keep the DC filter condenser voltage equal to the voltage reference.

DC chopper to increase the filter condenser voltage by whatever amount required.

Field Testing of Prototype

A prototype of this system was installed on a 5050 Series train operated by Tokyu Corporation and operational trials were run between Tsukushino Station and Tsukimino Station on the Den-en-toshi Line. Fig. 9 shows the connection diagram for the main circuit. To simplify installation in the existing train, the prototype connected a DC chopper on the second of two 1C4M variable voltage variable frequency (VVVF) inverters, which control four motors each.

Lithium-ion secondary batteries with high energy density and output density were selected for the storage batteries. Two modules were connected in series to provide a maximum voltage boost of 340 V, each battery module having a maximum voltage of 170 V (see Fig. 10).

Energy Savings Achieved in Operational Trials

The inverter input voltage without boosting was 1,600 V. Fig. 11 shows a comparison of the regenerative electric power produced when braking to a stop from approximately 100 km/h for this and three other patterns in which the inverter voltage was boosted to 1,750 V, 1,850 V, and 1,900 V respectively. The results demonstrated that the higher the voltage boost, the wider the scope for regenerative braking and the greater the amount of regenerative electric power produced.

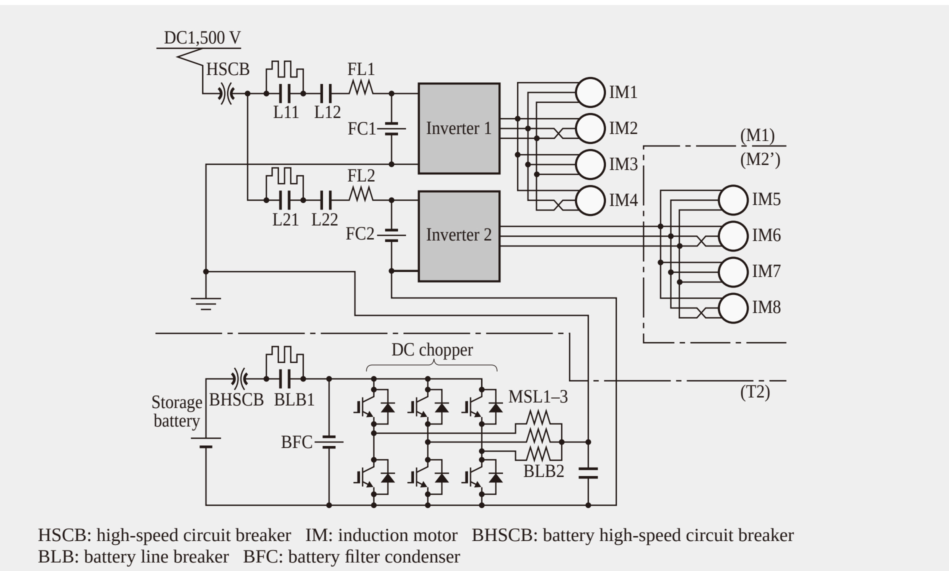


Fig. 9—Connection Diagram of Main Circuit.
A DC chopper is connected to the second of two 1C4M VVVF inverters to boost the voltage.

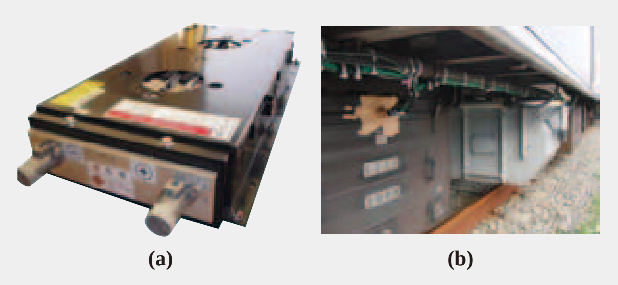


Fig. 10—Hardware for Control of Regenerative Brake with Extended Effective Speed.
The system uses 16 lithium-ion battery modules (a). Photograph (b) shows the chopper (front) and MSL (rear).

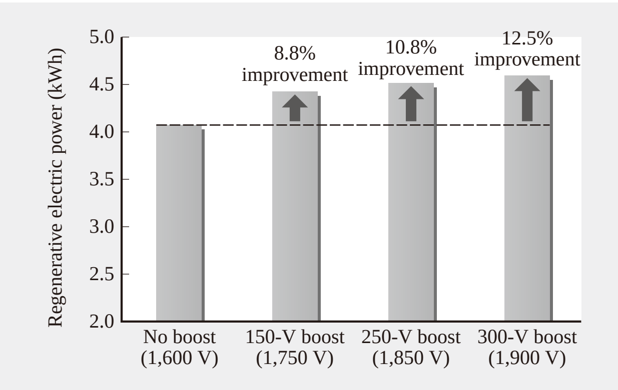


Fig. 11—Comparison of Regenerative Electric Power Produced for Different Voltage Boosts.
Increasing the voltage boost increases the maximum speed for full regenerative braking. The results of this trial, in which the train braked to a stop from 100 km/h, demonstrated that the amount of regenerative electric power increases the higher the voltage boost.

Hitachi is now working on enhancing energy management control and making the system smaller and lighter to ready it for use in commercial trains.

FUTURE ENERGY SAVING TECHNOLOGIES USING STORAGE BATTERIES

In actual rolling stock systems, trains on the same feeding section are supplied from the same substation via the overhead contact lines. In the near future, if all trains are fitted with storage batteries, in addition to considering the benefits of energy efficiency in terms of individual trains, it will also be possible to utilize the network of overhead contact lines to optimize the onboard storage battery systems by, for example, having nearby trains share stored electric power via the overhead contact lines.

Following this approach, Hitachi has developed a railway integration evaluation system that can be used to study systems optimization for the case when more than one vehicle fitted with storage batteries is present on the same feeding section.

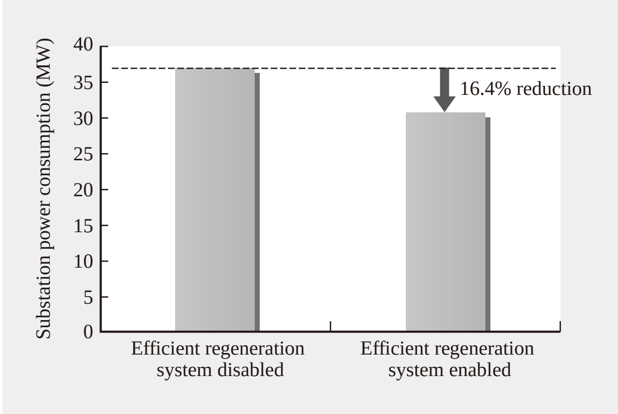


Fig. 12—Benefits of Installing Efficient Regeneration System.
It is anticipated that installing the efficient regeneration system will result in better energy efficiency.

A simulation was conducted to evaluate the benefits of installing an efficient regeneration system on a line with a mean distance between stations of 1.7 km, and assuming use of rolling stock designed for use on urban commuter lines.

The simulation assumed a distance between substations of 5 km, trains running every 5 minutes, and that trains stopped at all stations. Fig. 12 shows the benefits of installing an efficient regeneration system under these conditions. With energy savings of 16.4% compared to conventional inverter drive systems, the results demonstrated the benefits of installing an efficient regeneration system.

CONCLUSIONS

This article has given an overview of storage battery technologies for railways and described regenerative brake with extended effective speed control for inverters, which is used in the efficient regeneration system.

Technology for using onboard storage batteries to save energy was first commercialized in the form of a series hybrid drive system for reducing the fuel consumption of diesel trains running on non-electrified railway lines. In addition to collecting field data, Hitachi has also developed an efficient regeneration system with the aim of further improving the energy efficiency of rolling stock, and verified the energy savings provided by absorption of regenerative electric power and the regenerative brake with extended effective speed through operational trials. In the future, Hitachi intends to encourage the wider use of onboard storage batteries by achieving a good balance of costs and benefits, and by working on new energy-saving technologies that are closely aligned with customer needs.

REFERENCES

(1) K. Tokuyama et al., "Practical Application of a Hybrid Drive System for Reducing Environmental Load," Hitachi Review **57**, pp. 23–27 (Mar. 2008).

(2) M. Shimada et al., "Energy Storage System for Effective Use of Regenerative Energy in Electrified Railways," Hitachi Review **59**, pp. 33–38 (Apr. 2010).

(3) H. Manabe et al., "Development of Technology to Expand High-speed Operating Range of Regenerative Braking in Inverter-driven Rolling Stock," Proceedings of 48th Symposium of the Congress of Japan Railway Cybernetics, p. 526, Congress of Japan Railway Cybernetics (2011) in Japanese.

ABOUT THE AUTHORS

Motomi Shimada

Joined Hitachi, Ltd. in 1995, and now works at the Process Designing Department, Mito Rail Systems Product Division, Rail Systems Company. He is currently engaged in the development of vehicle control systems. Mr. Shimada is a member of The Institute of Electrical Engineers of Japan (IEEJ).

Yoshihiro Miyaji

Joined Hitachi, Ltd. in 1989, and now works at the Rolling Stock Electrical Systems Design Department, Mito Rail Systems Product Division, Rail Systems Company. He is currently engaged in the design of inverters for electric train drive systems. Mr. Miyaji is a member of the IEEJ.

Takashi Kaneko

Joined Hitachi, Ltd. in 1993, and now works at the Rolling Stock Electrical Systems Design Department, Mito Rail Systems Product Division, Rail Systems Company. He is currently engaged in the design of inverters for electric train drive systems.

Keita Suzuki

Joined Hitachi, Ltd. in 1999, and now works at the Rolling Stock Electrical Systems Design Department, Mito Rail Systems Product Division, Rail Systems Company. He is currently engaged in the design of inverters for electric train drive systems. Mr. Suzuki is a member of the IEEJ.