

Energy Storage System for Effective Use of Regenerative Energy in Electrified Railways

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OVERVIEW: Hitachi is working on the development of energy-saving systems for rolling stock that use lithium-ion batteries to help reduce the environmental impact of railway systems. Two issues associated with regenerative braking are regenerative braking under light load conditions and limits on performance due to motor characteristics, and in response Hitachi has developed respectively an absorption of regenerative electric power function and a regenerative brake with effective speed extended function, proposed an efficient regeneration management system for determining when to operate these functions, and is currently commercializing these technologies. For the function to absorb regenerative electric power, Hitachi has developed the wayside B-CHOP system and on-board sequential regenerative brake system to provide systems that are appropriate to the line and other operating conditions where the system is to be installed. Hitachi will continue to enhance the functions of its energy-efficient systems to meet diverse customer needs.

INTRODUCTION

HITACHI is working on the development of railway systems that utilize storage battery control technology to help the railway industry become more energy-efficient and emit less CO₂.

Hitachi has developed an absorption of regenerative electric power function and regenerative brake with effective speed extended function which provide technologies for eliminating the weaknesses of regenerative braking and further enhancing its energy-saving benefits. The key point about these technologies is how to operate appropriately the absorption of regenerative electric power function that stores the power generated by braking in a storage battery if there is no other train able to use it and the regenerative brake with effective speed extended function that extends the operating range of the regenerative brake to higher speeds by using the storage battery to boost the DC (direct current) voltage of the inverter and increase the output of the electric motor, inverter, and other components.

To implement the absorption of regenerative electric power function, Hitachi developed the wayside B-CHOP system and on-board sequential regenerative brake system. The significant energy savings achieved by installation of the wayside system have already been demonstrated in practice and the benefits of the on-board system have been confirmed in main line trials.

This article describes the features and benefits of these systems for absorption of regenerative electric power.

EFFICIENT USE OF REGENERATIVE ELECTRIC POWER

Issues Associated with Regenerative Braking

(1) Regenerative braking under light load conditions

Regenerative braking uses the traction motor as a generator during deceleration. The regenerative energy obtained from this process is returned to the power supply line so that it can be reused in any other trains on the line that are currently accelerating. However, during off-peak and other times when there are few trains able to take the regenerative energy produced during braking, this energy has nowhere to go. This

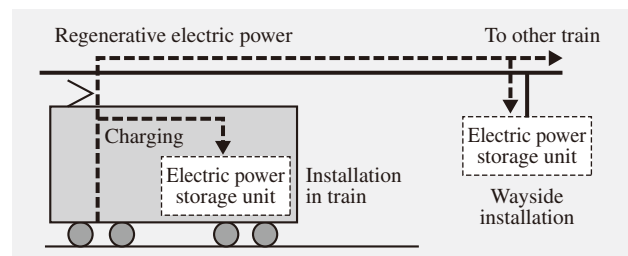


Fig. 1—Absorption of Regenerative Electric Power. Regenerative electric power that cannot be returned to the power line is collected in a storage battery. The collected energy is then reused in the next acceleration to reduce the power consumption of the inverter.

is called “regenerative braking under light load conditions.” As this causes the filter condenser voltage to rise, the light load regeneration control implemented on the inverter to suppress this rise operates to throttle back the regenerative current. Although the light load regeneration control suppresses the rise in the filter condenser voltage, in doing so it reduces the effectiveness of the regenerative brake which means it must be augmented by the air brake, reducing the regenerative energy.

(2) Limits on performance due to motor characteristics

The energy savings are maximized if regenerative braking can provide all of the braking energy needed to decelerate to a halt. At higher speeds, however, the amount of regenerative braking is limited by the motor output characteristics. As the additional required braking not able to be supplied by regenerative braking in this high speed range is provided instead by the air brake, the energy-saving benefits are reduced (“limits on performance due to motor characteristics”).

Proposed Solutions

(1) Absorption of regenerative electric power function

Hitachi has developed the absorption of regenerative electric power function as a solution to the problem of regenerative braking under light load conditions. When no other trains are available to make use of the regenerative energy, the energy is collected in a storage battery so that it can be reused for acceleration (see Fig. 1). There are two options for locating the electric power storage unit: one in which it is installed in the train and the other in which it is installed by the wayside.

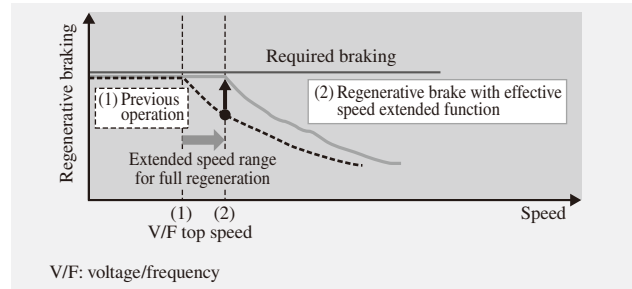


Fig. 2—Regenerative Brake Characteristics. The storage battery extends the top speed of the operating range for regenerative braking by boosting the DC (direct current) voltage of the inverter and increasing the output of the motor, inverter, and other components.

(2) Regenerative brake with effective speed extended function

Hitachi has developed the regenerative brake with effective speed extended function as a solution to the problem of limits on performance due to motor characteristics. This function extends the operating range of the regenerative brake into higher speeds by using the storage battery to boost the DC voltage of the inverter and increase the output of the electric motor, inverter, and so on without changing the level of the current flowing through each component, thereby shifting upwards the top speed of the V/F (voltage/frequency) range in which full regeneration is possible, as shown in Fig. 2.

Efficient Regeneration Management

Hitachi has developed an efficient regeneration management system to implement the absorption of regenerative electric power function and regenerative brake with effective speed extended function in such

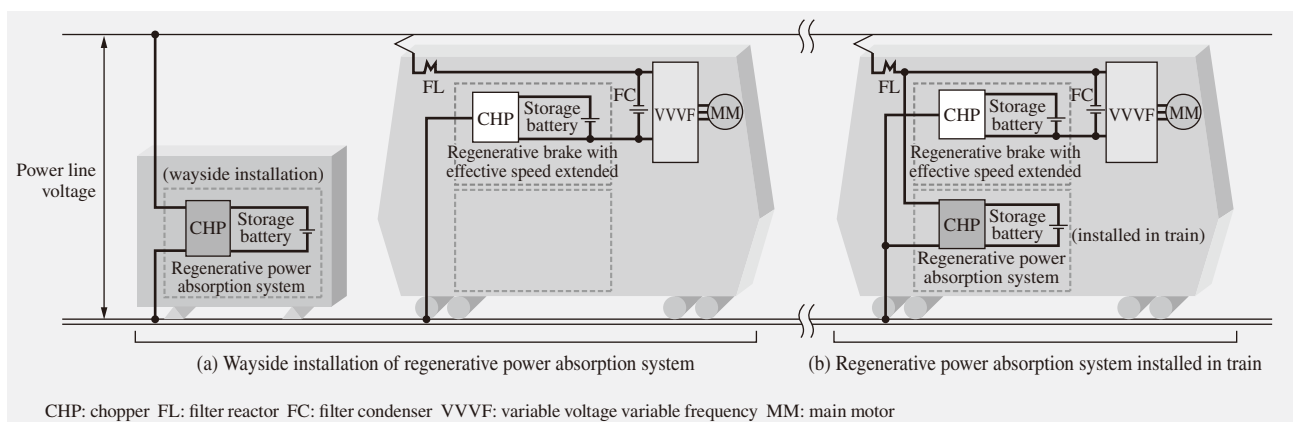


Fig. 3—Outline of Efficient Regeneration System Equipment. A regenerative power absorption system is installed either in the train or on the wayside. When the regenerative brake with effective speed extended function operates, an electric power storage unit is inserted in series at the negative input terminal of the inverter.

a way that they operate appropriately. Fig. 3 shows an outline of how the equipment operates.

The high-speed electric braking system used to implement the regenerative brake with effective speed extended function increases the total voltage across the inverter by the amount of the battery voltage (ΔV) by inserting an electric power storage unit in series between ground and the negative input terminal of the inverter to lower the voltage at the negative input terminal of the inverter by the battery voltage amount (ΔV) relative to the ground voltage. The chopper can vary this additional voltage continuously between 0 V and the battery voltage (ΔV) to ensure that the voltage of the filter condenser remains at its designated voltage.

If the system for absorbing regenerative power is located in the train, a storage battery is inserted in parallel with the main circuit of the inverter via a step-up/step-down chopper. During regeneration, the step-up/step-down chopper is operated as a step-down chopper to use the regenerative power to charge the storage battery, and if the voltage across the filter condenser rises during regeneration and exceeds the designated level, this is treated as a light load condition and limiter control is invoked to prevent any rise above this designated voltage.

On the other hand, the configuration used for wayside installation of the system for absorbing regenerative power is to insert the storage battery in parallel between the power line and ground via a step-up/step-down chopper. For wayside installation, light load conditions are detected using the power line voltage at the point where the system for absorbing regenerative power is inserted.

Efficient regeneration management is designed to select between three modes based on the power line voltage and train speed: “regenerative brake with effective speed extended function,” “absorption of regenerative electric power function,” and “standard regeneration” (see Fig. 4).

The regenerative brake with effective speed extended function operates when the train speed is high (top speed of V/F range: A km/h or higher) and the power line voltage is at or below the designated voltage (V_{ref}). However, if the speed drops below the top speed of the V/F range (A km/h), the regenerative brake with effective speed extended function turns off and the control system returns to standard regeneration operation. Similarly, the absorption of regenerative electric power function operates if a light load condition occurs and the power line voltage exceeds the designated voltage.

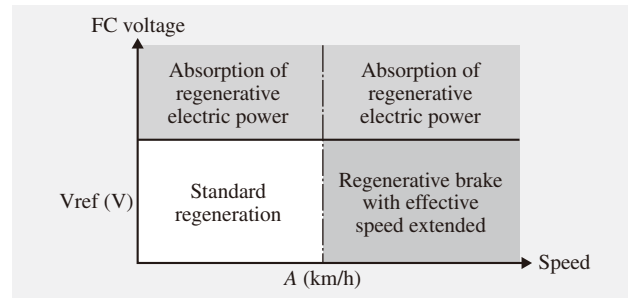


Fig. 4—Control Strategy for Efficient Regeneration Management.

Efficient regeneration management selects between three modes based on the power line voltage and train speed: “regenerative brake with effective speed extended function,” “absorption of regenerative electric power function,” and “standard regeneration.”

SYSTEM IMPLEMENTING ABSORPTION OF REGENERATIVE ELECTRIC POWER FUNCTION

Characteristics of On-board and Wayside Installation of Electric Power Storage Unit

To provide systems to implement the absorption of regenerative electric power function, Hitachi developed the B-CHOP system for wayside installation and sequential regenerative brake system for on-board installation in parallel. It was done this way because Hitachi believed it was important to be able to offer the appropriate system based on the characteristics of the respective systems and on the track and other operating conditions at the railway where the system is to be installed. Table 1 lists the characteristics of the on-board and wayside systems for absorbing regenerative electric power.

TABLE 1. Comparison of Different Electric Power Storage Unit Installation Locations

The respective characteristics of the on-board and wayside electric power storage units are shown.

Parameter	Wayside installation	On-board installation
Absorption of regenerative electric power function	Stores regenerative electric power that is not used by other trains. ○	Stores regenerative electric power that is not used by other trains. ○
Ease of installation	Installation is comparatively easy if space is available by the wayside. ○	Space for installation in train is restricted. Electric power storage units need to be installed separately in each train. △
Regeneration can continue when disconnected from power line.	No ×	Yes ○

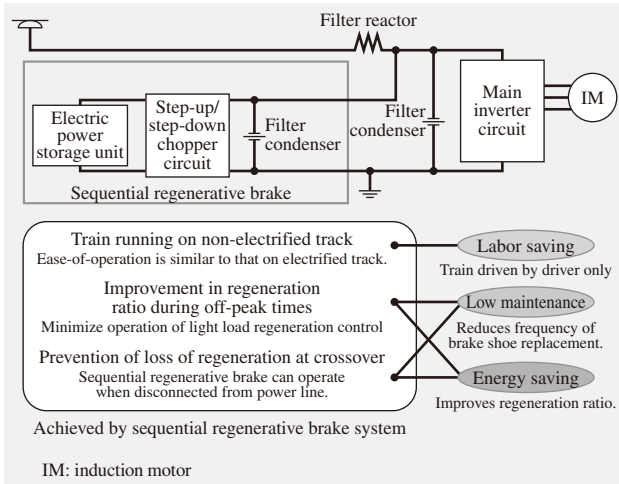


Fig. 5—Block Diagram of Sequential Regenerative Brake System Equipment.

Energy consumption is reduced by charging an electric power storage unit with the regenerative electric power that is unable to be returned to the overhead contact line (third rail conductor system) and then reusing this energy in the next acceleration.

On-board Installation (Sequential Regenerative Brake System)

Sequential regenerative brake system overview

Fig. 5 shows a block diagram of the sequential regenerative brake system. The sequential regenerative brake reduces energy consumption by charging an electric power storage unit with the regenerative electric power that is unable to be returned to the overhead contact line (third rail conductor system) and then reusing this energy in the next acceleration. The step-up/step-down chopper can control the charging and discharging current even if the voltages at the electric power storage unit and inverter differ.

In normal operation when the train is braking to a halt (B5S), the electric power storage unit has sufficient capacity to absorb all of the regenerative electric power on its own. The rated voltage was set at 340 V, this being approximately half the 750 V overhead contact line (third rail conductor system) voltage used on the track where testing was performed. The reason for this was to minimize the battery current ripple ratio by controlling the conduction ratio (ratio of on to off times for the switching elements) of the step-up/step-down chopper to be approximately 50%.

Performance testing of the sequential regenerative brake system was conducted on a main line in fiscal 2007 with the cooperation of the Osaka Municipal Transportation Bureau.

Sequential regenerative brake system control and performance testing

The way charging control works is that, when the voltage across the filter condenser rises because regenerative electric power cannot be returned to the overhead contact line (third rail conductor system), part of the regenerative electric power is used to charge a storage battery so as to prevent the filter condenser voltage from exceeding the designated voltage. Also, discharge control supplies traction power preferentially from the electric power storage unit.

Operational testing was carried out to determine the extent of the improvement in regeneration ratio achieved by the sequential regenerative brake system. The testing was conducted on 10A Series trains belonging to the Osaka Municipal Transportation Bureau.

(1) Test procedure

To determine the improvement in regeneration ratio achieved by the system, it was tested under light load conditions with no nearby trains in operation. The regeneration ratio obtained when the brake (B5S) was applied at a speed of 60 km/h was measured.

(2) Test results

Fig. 6 shows a comparison of the improvement in regeneration ratio achieved by turning on the absorption of regenerative electric power function. The black line in the figure shows the waveform when the absorption of regenerative electric power function was turned off and the blue line shows the waveform when the function was turned on.

When the absorption of regenerative electric power function was off, the motor current was throttled down

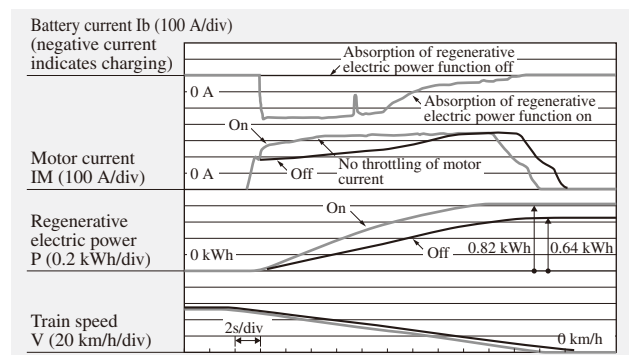


Fig. 6—Improvement in Regenerative Power Due to Absorption of Regenerative Electric Power Function.

Almost no throttling of the motor current occurs when the absorption of regenerative electric power function is on as the regenerative electric power that is unable to be returned to the overhead contact line (third rail conductor system) is used to charge an electric power storage unit.

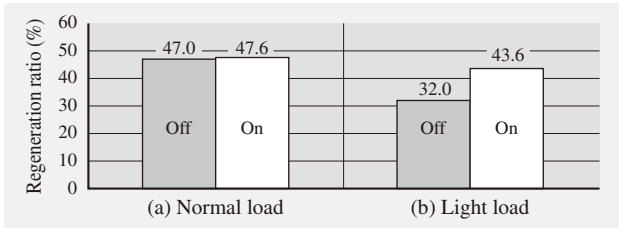


Fig. 7—Improvement in Regeneration Ratio Due to Absorption of Regenerative Electric Power Function. Testing on a main line was conducted by simulating light load conditions. The system’s absorption of regenerative electric power function increased the regeneration ratio by 11.6 percentage points to approximately 44%.

as part of the regenerative electric power could not be returned to the overhead contact line (third rail conductor system). In this test, the traction energy per inverter (driving two motors) was 2.00 kWh and the regenerated energy was 0.64 kWh (regeneration ratio: 32%).

When the absorption of regenerative electric power function was on, there was almost no throttling of the motor current as any regenerative electric power unable to be returned to the overhead contact line (third rail conductor system) was used to charge the electric power storage unit. In this test, the traction energy per inverter was 1.88 kWh and the regenerated energy was 0.82 kWh [regeneration ratio: 44% (approx.)].

Fig. 7 shows a comparison of the regeneration ratios when the absorption of regenerative electric power function was on and off. Under normal load conditions (when the regenerative electric power is used to drive another train), the regeneration ratios were largely the same regardless of whether the absorption of regenerative electric power function was on or off. On the other hand, under light load conditions, the system’s absorption of regenerative electric power function

increased the regeneration ratio by 11.6 percentage points to approximately 44%.

Wayside Installation (B-CHOP System)
B-CHOP system overview

Fig. 8 shows an example of a wayside installation of a system for storing regenerative electric power in a storage battery. As with the on-board system, the energy produced by regenerative braking is collected in a storage battery for reuse when accelerating. In addition to benefits that include avoiding loss of regeneration by keeping the feeding voltage stable, a feature of this system is that it provides a way to keep the feeding voltage stable.

Supplied system in actual operation

A system supplied to the Kobe Municipal Transportation Bureau is currently in operation (see Fig. 9). Annual energy savings of 358 MWh have been achieved by installing the system on lines that have long sections of steep gradient.

Support for System Installation

To make maximum use of regenerative electric power, it is necessary to undertake an optimization that utilizes the respective characteristics of the wayside and on-board systems, and this in turn requires various types of engineering. Hitachi supports this work in a variety of ways including investigating the optimum location for the lithium-ion batteries, whether it be on or off the train, the system capacity, interoperation with peripheral systems, and other factors, and also through the use of simulation to verify the results.

Hitachi utilizes the rolling stock and electrical engineering technologies it has accumulated over many years to undertake preliminary assessments that

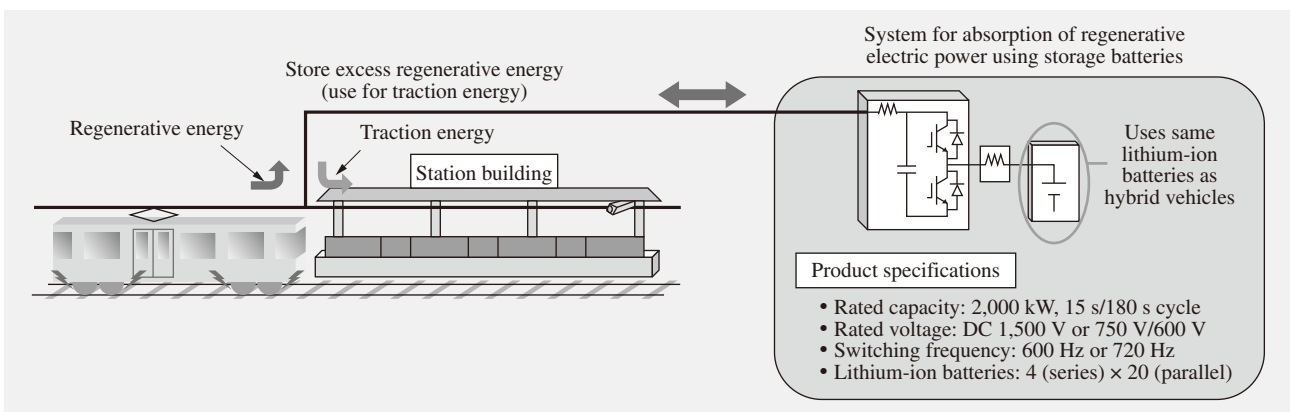


Fig. 8—System for Absorption of Regenerative Electric Power Using Storage Batteries (Wayside Installation). An electric power storage unit installed on the wayside absorbs any leftover regenerative electric power.

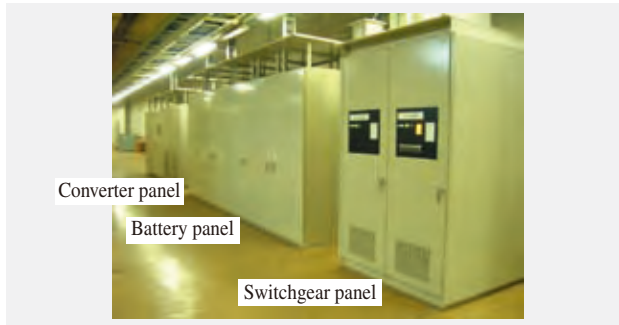


Fig. 9—System for Absorption of Regenerative Electric Power Using Storage Batteries Supplied to Kobe Municipal Transportation Bureau.

The system has demonstrated annual energy savings of 385 MWh.

consider the introduction of optimum regeneration systems to suit customer needs. Hitachi from an early stage developed a simulator for use as a support tool that uses a model of actual operation and which it has used in preparing a large number of proposals.

CONCLUSIONS

This article has described the features and benefits of using on-board and wayside absorption of regenerative electric power.

Based on requests from railway operators, Hitachi has trialed the use of efficient regeneration management, which aims to reduce power consumption by increasing the amount of regenerative electric power regardless of track conditions, and wayside and on-board systems for absorbing regenerative electric power. For the future, Hitachi intends to accelerate the reduction in the environmental impact of railway systems by extending its range of functions for energy-saving systems able to meet diverse customer needs.

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