Current and Future Applications for Regenerative Energy Storage System

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OVERVIEW: Railways are a key form of public transportation, yet the electric power shortages resulting from factors such as the impact of the Great East Japan Earthquake on nuclear power plants have made it more necessary than ever that they seek to save electricity. Another issue is the action being taken around the world to deal with the problem of global warming. Hitachi has developed a system for the storage of regenerative power that uses the same lithium-ion batteries as hybrid cars to store and reuse this energy in trains. The system was commercialized in 2007. In some cases, the installation of this system produced savings of more than 10% in power consumption. Hitachi intends to accelerate the deployment of this system to reduce railway power consumption in Japan and other markets.

INTRODUCTION

INITIATIVES involving the use of electrical storage devices in the wayside systems of direct-current electric railways have a long history, with battery posts being used in Japan between 1912 and 1928 to augment the unreliable power supplies of that era. Along with an increase in the demand for electric power from railways, the expansion of transportation capacity during Japan's rapid economic growth also brought problems such as loss of regenerative braking power and voltage drops in feeder circuits. One countermeasure to this was the development of electric power storage systems that combined electrical storage and conversion equipment, and such a system entered practical use in 1988 using a flywheel for storage.

Production of hybrid vehicles by the automotive industry has been rising since 2008, and the batteries that have a core role in these vehicles are a subject of ongoing technical innovation and cost reduction.

In 2004, Hitachi developed a system that uses automotive lithium-ion batteries for the storage of regenerative power (system storing regenerative electric power in wayside storage batteries). The system subsequently underwent successful field trials on the Seishin-Yamate Line of the Kobe City Subway, leading to the installation of a commercial system at the line's Itayado substation in 2007. Another system supplied to Seoul Metro9 subway in South Korea commenced operation in 2011.

This article gives an overview of the system, describes an example of its use outside Japan, and considers its future prospects.

PRODUCT OVERVIEW

System storing regenerative electric power in wayside storage batteries uses lithium-ion batteries of the same type as those in hybrid vehicles to store regenerative power (see Fig. 1).

A feature of regenerative power from trains is that it is produced as a sudden surge. This means that, along with the discharge characteristics, the charging characteristics when absorbing electric power are a key consideration in the choice of storage battery. After collecting data on battery life and other properties to compare the different types of secondary (rechargeable) batteries in terms of these characteristics, Hitachi selected lithium-ion batteries for use in this system.

The features of lithium-ion batteries that make them superior to the alternatives include being small and light with a higher energy density than other

Fig. 1—Lithium-ion Battery.
The system uses the same lithium-ion batteries as hybrid cars.

TABLE 1. Specifications of System Storing Regenerative Electric Power in Wayside Storage Batteries
The table below lists the main specifications.

Rated voltage*1 (V)	Rated capacity (kWp)	Rated current (A)	Load pattern*2	Lithium-ion battery			
				Module rating	Module configuration	Rating	Storage capacity
820 V	500	600	600 A 10 s + 300 A 10 s charging 300 A 30 s discharging	173 V 5.5 Ah	2S×10P	346 V 55 Ah	19 kWh
820 V	1,000	1,200	1,200 A 10 s + 600 A 10 s charging 600 A 30 s discharging	173 V 5.5 Ah	2S×20P	346 V 110 Ah	38 kWh
820 V	2,000	2,400	2,400 A 10 s + 1,200 A 10 s charging 1,200 A 30 s discharging	173 V 5.5 Ah	2S×40P	346 V 220 Ah	76 kWh
1,650 V	1,000	600	600 A 10 s + 300 A 10 s charging 300 A 30 s discharging	173 V 5.5 Ah	4S×10P	692 V 55 Ah	38 kWh
1,650 V	2,000	1,200	1,200 A 10 s + 600 A 10 s charging 600 A 30 s discharging	173 V 5.5 Ah	4S×20P	692 V 110 Ah	76 kWh
1,650 V	3,000	1,800	1,800 A 10 s + 900 A 10 s charging 900 A 30 s discharging	173 V 5.5 Ah	4S×30P	692 V 165 Ah	114 kWh

*1 Initial charging and discharging voltages can be varied on site (remote setting function available as an option).
*2 Standard pattern (for a 180-s interval period)

options such as electric double-layer capacitors or nickel-metal hydride batteries. Together with the fact that they are manufactured for applications that require repeated rapid charging and discharging, these features make them the ideal choice for railway loads. Technologies are also being developed to extend battery lifetime, including improvements to materials and optimum control of charging and discharging.

Product Specifications

The specifications of the system storing regenerative electric power in wayside storage batteries are listed below.

(1) Standards compliance: International Electrotechnical Commission/European Norm (IEC/EN), Japanese Electrotechnical Committee
(2) Rated capacity: 3,000, 2,000, 1,000, or 500 kWp
(3) Rated voltage: 1,650 or 820 V (the initial charging/discharging voltage can be varied.)
(4) Control method: Constant voltage control with current limiter

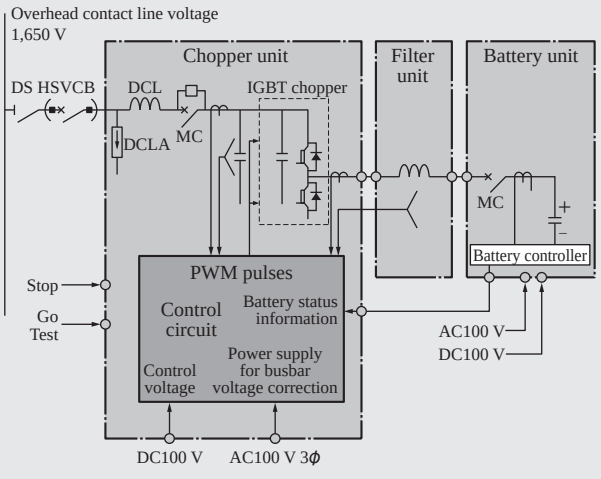
Other specifications are listed in Table 1.

Circuit Configuration

This regenerative energy storage system consists of chopper unit (including the filter units) and storage battery unit blocks. Fig. 2 shows the circuit diagram. A major feature is that it can be installed anywhere without creating space constraints.

The converter uses 3,300-V, 1,200-A insulated-gate bipolar transistors (IGBTs) on the 1,500-V system, consists of multiple bidirectional choppers, and is designed to minimize the flow of ripple current to the feeder power supply and batteries. It is also designed for quick recovery in the event of a fault, with a traceback function that can be used to analyze fault causes.

The system has been standardized on the use of lithium-ion battery modules, with the 1,500-V system using four cells in series. A sufficient number of these modules are installed in parallel to provide the capacity to absorb the required amount of current. Each lithium-ion battery has a battery controller that handles protection and monitors operating status parameters such as the state of charge (SOC), state of hysteresis (SOH) (an indicator of battery deterioration), and battery temperature. These data are also sent to the chopper unit to ensure optimum control of how the lithium-ion batteries are used.



DS: disconnecting switch HSVCB: high-speed vacuum circuit breaker
DCL: direct-current reactor DCLA: direct-current lightning arrester
IGBT: insulated-gate bipolar transistor MC: magnet contactor
PWM: pulse width modulation AC: alternating current DC: direct current

Fig. 2—Circuit Diagram.
This is the circuit diagram of the production model.

Operational control performed by the chopper unit includes feeder power supply voltage control, which involves charging or discharging the lithium-ion batteries, and SOC control, whereby the SOC is reduced when the system is idle in preparation for the next sequence of charging (absorption of regenerative power). This keeps the feeder power supply voltage constant while also managing battery operation to ensure a long operating life. To prevent overcharging or over-discharging due to fluctuations in the voltage from the power collection system, system storing regenerative electric power in wayside storage batteries also includes a voltage correction function that incorporates power collection system voltage elements into the system.

Optional functions include a schedule control function, a function for changing voltage settings from power management, and an emergency drive mode to provide traction power for the train in the event of an outage on the feeder power supply.

EXAMPLE OVERSEAS INSTALLATION—SEOUL METRO9

In recent times, central and regional governments in South Korea have identified railways as a form of transportation that helps prevent global warming, including through the reduction of carbon dioxide (CO_2) emissions. In their pursuit of greater energy efficiency, they have expressed considerable interest in technologies for utilizing the regenerative power produced when trains stop or decelerate. Some railway operators in South Korea have already installed systems for absorbing regenerative power that use electric double-layer capacitors for storage, and are trialing their effectiveness.

Seoul Metro9 is South Korea's first urban railway provided in the form of a public capital development project utilizing private investment. The rolling stock, power system, and mechanical equipment are managed by Seoul Metro Line 9 Corporation under contract to Seoul City, with operation and maintenance outsourced to Seoul Line 9 Operation Co., Ltd.

Hitachi's partner for the installation of system storing regenerative electric power in wayside storage batteries is POSCO ICT, a major South Korean engineering company that has an energy service company (ESCO) contract with Seoul Metro9. The business model involves collecting a base fee, the level of which was determined from simulations conducted by POSCO ICT of the energy savings that would result from installing this system.

Table 2 lists the specifications of the installed system. Because it is intended for use outside Japan, it complies with the IEC 60146 (semiconductor converters) standard.

The system was installed at two substations, numbers 909 and 921 (see Fig. 3), both of which are located underground. As the access provided for subway construction had already been closed off, the system had to be delivered to the site via ordinary stairways. Accordingly, the equipment was transported to the site in dismantled form.

Fig. 4 shows the waveform for the system storing regenerative electric power in wayside storage batteries in operation at substation 921. The system regulates the output current from the rectifier during discharging so that electric power is supplied preferentially from the system. This suppresses the amount of electric power drawn from the power company during traction and also has the effect of cutting peak demand.

While the results of simulating the installation of the system on this line estimated annual power savings of 510 MWh at substation 921, the actual savings in the first month of operation were 94 MWh (including savings at adjacent substations), indicating that performance will surpass the initial predictions. The results of this month of operation also included a reduction in rush hour power consumption, demonstrating the ability of the system to cut peak demand. Currently, POSCO ICT is continuing to assess the energy savings provided by the system.

Table 2. Specifications
The table below lists the specifications of the system storing regenerative electric power in wayside storage batteries.

Parameter		Value	Remark
Rated capacity		1,000 kWp	
Rated voltage		1,650 V	2,000 V max.
Rated current		600 A	606 A (current limit)
Batteries	Type	Lithium-ion battery	
	Module	4 series × 10 parallel	
	Rated voltage	692 V (173 V / module)	
	Rated current	55 Ah	
	Maximum charge/discharge current	±1,500 A	
Converter	Configuration	1S × 2 A × 4 units	
	Control method	Multi-carrier PWM control	
	Cooling	Heat pipe natural cooling	DCL forced air cooling
	Frequency	720 Hz	Synthesizing frequency: 2,880 Hz

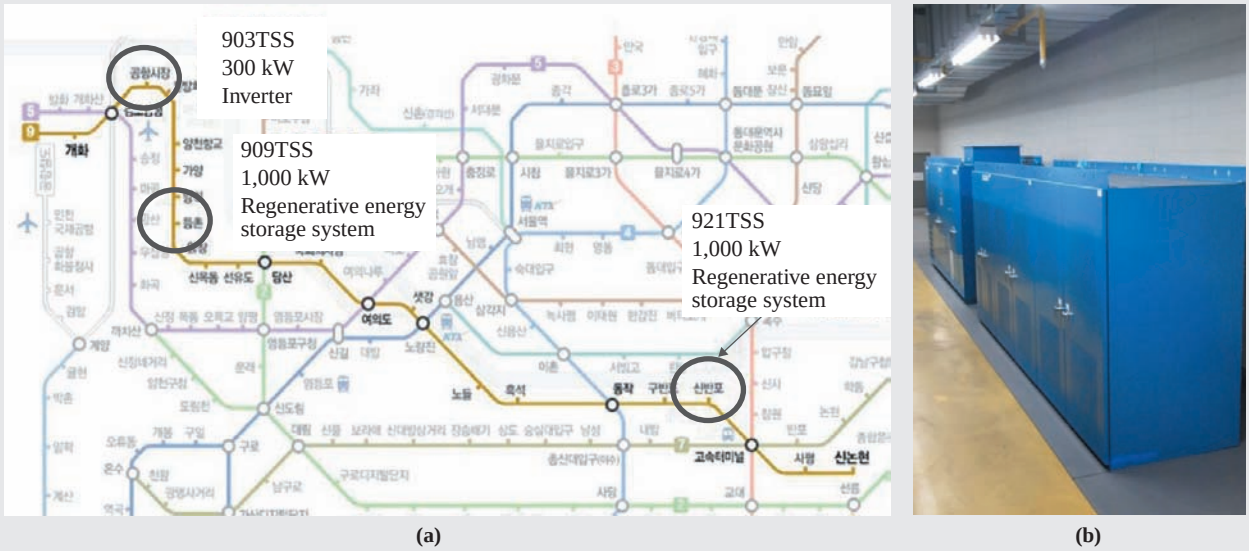


Fig. 3—Map of Seoul Metro9 (a) and Hardware (b).
The map shows the sites where systems storing regenerative electric power in wayside storage batteries were installed and the photograph shows a system that has commenced operation at the substation 921. Stations 909 and 921 are both located underground. From the left rear, the equipment shown in the photograph (b) comprises the chopper unit (a bank of filter units) and the battery unit respectively.

FUTURE PROSPECTS

Another application for the regenerative energy storage system that has arisen in Japan due to concern about electric power shortages caused by the shutdown of nuclear power plants after the Great East Japan Earthquake is the use of stored electric power to provide emergency traction power for trains in the event of a power outage. However, providing emergency traction power takes more than just installing storage batteries in the power system; it also requires discharge control, power system control, and traffic control in cooperation with other railway systems when a power outage occurs. As a total system integrator for railways, Hitachi plans to undertake further work on building

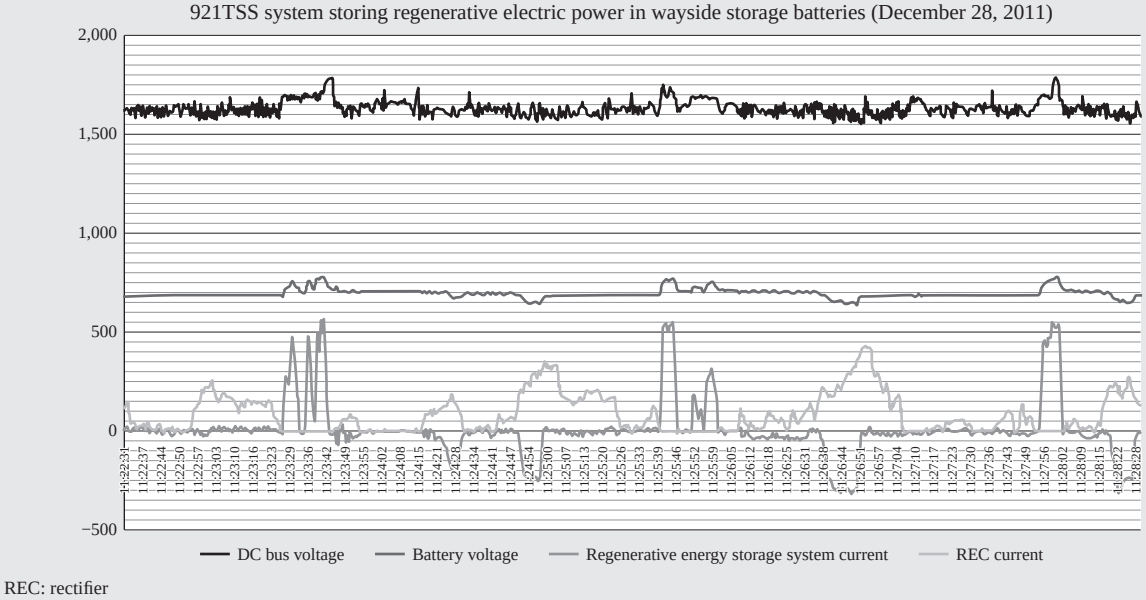


Fig. 4—Sampling Graphs of On-site Measurements.
The output current from the rectifier is regulated when regenerative energy storage system is discharging to cut peak demand.

railway systems capable of implementing such an emergency traction power capability.

System storing regenerative electric power in wayside storage batteries can also provide what is needed to construct a direct current smart grid. Rather than deploying the system as just another item of substation equipment, Hitachi intends to use the system as a core device for providing comprehensive energy management that enhances energy efficiency through interoperation with other railway systems in order to implement the sort of railway smart grids that only a total system integrator for railways could deliver.

CONCLUSIONS

This article has given an overview of the system storing regenerative electric power in wayside storage batteries, described an example of its use outside Japan, and considered its future prospects.

It is anticipated that demand for the prevention of global warming and other energy efficiency measures will strengthen further in the future, in markets both in Japan and elsewhere. Hitachi intends to continue contributing to overcoming environmental and energy problems through technical innovation in this field.

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