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Demonstration Testing and Evaluation of a Train Running Under its Own Power Using a Stationary Energy Storage System

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OVERVIEW: Hitachi has supplied SESSs using lithium-ion batteries to seven sites (as of June 2014) since the first system was delivered in 2007. While this system is intended to save energy by utilizing the regenerative power produced by rolling stock, there has also been growing demand in recent years for a way of providing emergency power. That is, enabling a train that has been stranded between stations by a major power outage or other incident to propel itself to the nearest station to allow the passengers to exit safely. To satisfy this requirement, Hitachi has run trials in collaboration with Tokyo Metro Co., Ltd. to demonstrate the ability of a train to propel itself using only this system.

INTRODUCTION

ENERGY-saving systems that return the power generated by regenerative brake systems on rolling stock to the feeder line so that it can be used by other trains have been widely adopted by railway companies for new rolling stock. When no other trains are available to use regenerative power, however, the excess power causes the line voltage to rise, giving rise to a situation called “regeneration cancelled.” Wayside equipment can be installed to prevent this, such as a regenerative inverter or a resistive load that can absorb the excess power.

In response to this issue, Hitachi utilized lithium-ion batteries of the type used in hybrid cars to develop a stationary energy storage system (SESS) in 2004 to make better use of regenerative power. The system was commercialized in 2007.

Since a power outage over a wide area caused by an unexpected event, such as a major disaster, interrupts the supply of electric power to substations, and the outage will bring to a halt any electric trains that lack their own means of propulsion. If this results in a train being stuck between stations, potentially on a bridge or in a tunnel, the passengers can be evacuated more quickly and safely if a wayside power source is available that will allow the train to proceed to the nearest station. While the use of SESS to provide such an emergency power supply has previously been studied in principle, Hitachi recently installed a test system at a substation belonging to Tokyo Metro Co., Ltd. and succeeded in powering a train using only lithium (Li) batteries.

The following section describes the SESS and the results of this operational testing.

SESS

Since regenerative braking on rolling stock produces a comparatively sharp rise in power output when the brake is engaged, this characteristic needs to be taken into account if the SESS is to utilize the power produced. As with the previous regeneration system, which did not include energy storage, it is necessary for the control system to maintain a constant voltage on the feeder lines. Hitachi’s SESS takes full account of these system requirements.

Energy Storage Medium

This characteristic of the comparatively sharp-rising regenerative power produced by rolling stock means that the energy storage medium must be capable of handling repeated rapid charging and discharging, while also having a comparatively high energy density. To satisfy these criteria, Hitachi selected Li batteries of the sort used in hybrid cars (see Fig. 1).

Compared to electric double-layer capacitors and nickel-metal hydride batteries, the characteristics of Li batteries include high energy density, small size, and light weight. This, together with the fact that they are produced to handle repeated rapid charging and

Fig. 1—Lithium-ion Battery.
The system uses lithium-ion batteries for hybrid cars.

discharging, means they are ideal for supplying loads in electric railways. The technology for extending the life of the batteries has also been improved by improving the materials used and optimizing the control of charging and discharging.

System Configuration

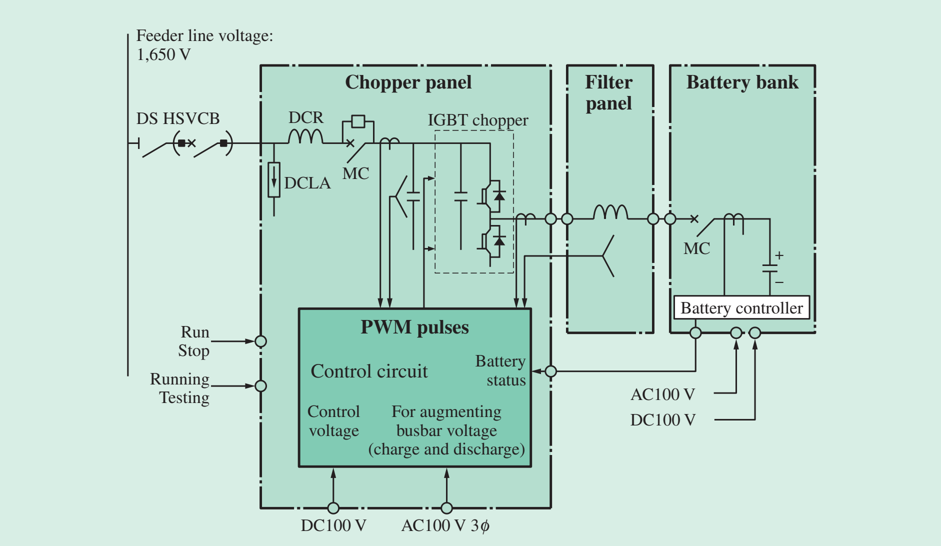
The SESS consists of a chopper panel (including the filter panel) and battery bank blocks. Fig. 2 shows the circuit diagram.

The converter uses 3,300-V, 1,200-A insulated-gate bipolar transistors (IGBTs) (for a 1,500-V system), with multiple bidirectional choppers to minimize harmonics on the feeder line and ripple current on the battery side. It is also designed to ensure rapid recovery in the event of a fault and incorporates a trace-back function (a function that records data for a certain period of time after a specified event occurs) for fault cause analysis.

The batteries (for a 1,500-V system) are standardized on blocks of four Li battery modules in series, with sufficient blocks connected in parallel to handle the level of charging current. A battery controller incorporates a protection function and monitors the state of charge (SOC), state of health (SOH), battery temperature, and other operating parameters for each Li battery, with this internal status data being sent to the chopper unit so that it can control operation in the way that best suits the Li batteries.

The chopper unit incorporates automatic voltage regulation (AVR) and charging rate control to control the operation in a way that maximizes battery life while also maintaining a constant feeder line voltage. AVR keeps the feeder line voltage constant during charging and discharging of the Li batteries, and charging rate control is used while the batteries are idle to keep the batteries at the correct SOC setting in readiness for the next time they are charged with regenerative power. A function is also included to adjust the voltage at which battery charging or discharging is initiated that includes a device to measure the incoming voltage. This function prevents unnecessary charging and discharging due to fluctuations in the incoming voltage.

Optional functions include a schedule control function that changes the voltage at which battery charging or discharging is initiated according to the time of day and a function to allow this initiation voltage setting to be modified from the power system



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

Fig. 2—Circuit Diagram of Stationary Energy Storage System.
The diagram shows the circuit used in the commercial system.

TABLE 1. SESS Specifications
The table lists the main system specifications.

Rated voltage[*1] (V)	Rated capacity (kWp)	Rated current (A)	Load pattern[*2]	Lithium-ion batteries			
				Module rating	Module configuration	Rating	Storage capacity
820 V	500	600	charging: 600 A 10 s + 300 A 10 s discharging: 300 A 30 s	173 V 5.5 Ah	2 S×10 P	346 V 55 Ah	19 kWh
820 V	1,000	1,200	charging: 1,200 A 10 s + 600 A 10 s discharging: 600 A 30 s	173 V 5.5 Ah	2 S×20 P	346 V 110 Ah	38 kWh
820 V	2,000	2,400	charging: 2,400 A 10 s + 1,200 A 10 s discharging: 1,200 A 30 s	173 V 5.5 Ah	2 S×40 P	346 V 220 Ah	76 kWh
1,650 V	1,000	600	charging: 600 A 10 s + 3000 A 10 s discharging: 300 A 30 s	173 V 5.5 Ah	4 S×10 P	692 V 55 Ah	38 kWh
1,650 V	2,000	1,200	charging: 1,200 A 10 s + 600 A 10 s discharging: 600 A 30 s	173 V 5.5 Ah	4 S×20 P	692 V 110 Ah	76 kWh
1,650 V	3,000	1,800	charging: 1,800 A 10 s + 900 A 10 s discharging: 900 A 30 s	173 V 5.5 Ah	4 S×30 P	692 V 165 Ah	114 kWh

*1: The charging and discharging start voltages can be modified on-site (remote control is available as an option).
*2: Indicates the basic pattern (180-s interval)

supervisory control and data acquisition (SCADA) system. An emergency power mode that can be used to power the rolling stock during a power outage is also available.

Product Specifications

The standard specifications of the SESS are as follows.
(1) Standards compliance: IEC/EN, JEC
(2) Rated capacity: 3,000 kW, 2,000 kW, 1,000 kW, or 500 kW
(3) Rated voltage: 1,650 V or 820 V (voltage at which battery charging or discharging is initiated can be modified)
(4) Control: Fixed-voltage control with current limiter

Table 1 lists these and other specifications. A major feature of the SESS is that it can be installed anywhere.

Sites where SESS is Installed

Investment in energy-saving equipment has been growing in Japan, prompted by the Great East Japan Earthquake of March 2011 among other factors. The system has been supplied to seven sites since the first system was installed in 2007 (as of June 2014, including outside Japan). Table 2 lists these sites.

EMERGENCY POWER TRIAL

Since March 2013, Hitachi has been working on joint research with Tokyo Metro on the EM-B-Traction emergency wayside battery system. The emergency power trial utilized technology developed for use as an SESS, and included planning, equipment design, installation, and inductive disturbance testing (to check for interference with signaling equipment), with the trial itself successfully powering a 10-car train along a 2.7-km section of the Tokyo Metro Tozai Line from Nishi-kasai to Minami-sunamachi Station on January 26, 2014.

Equipment Specifications

Hitachi determined the Li battery capacity needed to power a 10-car train on the Tokyo Metro Tozai Line

TABLE 2. SESS Installation Sites
The system has been supplied to seven sites since the first installation in 2007.

Customer	Project	Voltage (V)	Capacity (kWp)	Quantity	Delivery
Kobe City Transportation Bureau	Itayado traction substation, Seishin-Yamate Line	1,500	1,000	1	2007
POSCO ICT (South Korea)	Traction Substations 909 and 921 of Seoul Metro Line 9	1,500	1,000	2	2011
East Japan Railway Company	Haijima substation, Ome Line	1,500	2,000	1	2013
Osaka Municipal Transportation Bureau	Tsuruhashi substation, Sennichimae Line	750	1,000	1	2014
East Japan Railway Company	Okegawa substation, Takasaki Line	1,500	2,000	1	2014
Keio Corporation	Horinouchi substation, Sagamihara Line	1,500	2,145	1	2014

TABLE 3. Specifications of EM-B-Traction Trial System
Hitachi specified the EM-B-Traction emergency wayside battery system using an SESS to have sufficient capacity for the trial.

Parameter	Specification
Rated capacity	1,000 kW (2,000 kWp in emergency power mode)
Load pattern	Class S Charging: 600 A 10 s + 300 A 10 s Discharging: 300 A 30 s (Load pattern is not used in emergency power mode)
Cooling	Natural air cooling using boiling-cooling method
Battery configuration	231 Ah (4 S × 42 P)
Storage capacity	160 kWh

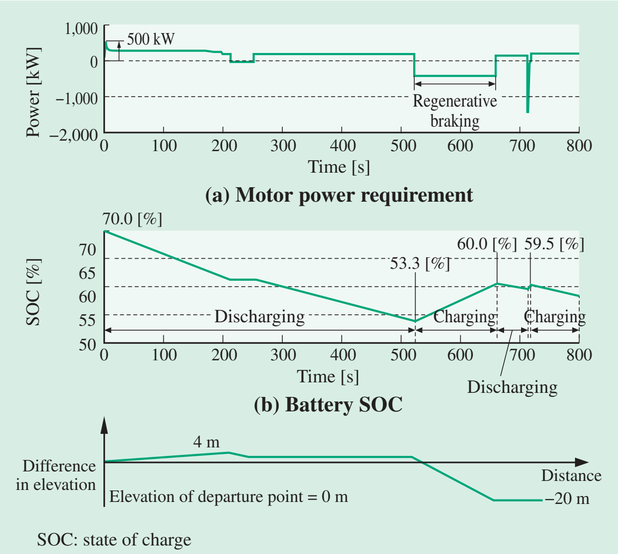


Fig. 3—Battery Capacity Simulation.
The battery capacity was selected based on factors such as the line gradient.

based on factors such as the traction characteristics of the rolling stock and the gradient of the line. Table 3 lists the specifications of the EM-B-Traction system used for the trial.

Whereas normal operation mode involves operating the SESS for energy efficiency, with charging at 1,000 kWp and discharging at 500 kWp, the system was designed to allow discharging at 2,000 kWp in emergency power mode. Six choppers were used, in the same configuration as the standard 2,000-kW model.

Preliminary Testing

Unlike during normal operation, the SOC range needs to be extended to its maximum extent in emergency power mode, where the aim is to discharge as much of the energy stored in the Li batteries as possible. Fig. 3 shows the results of preliminary simulations conducted while assuming these conditions.

The results indicated that the Li battery capacity selected would be adequate for the trial.

Emergency Power Trial

After the last train of the day on January 26, 2014, the EM-B-Traction system was turned on and a 10-car train departed Nishi-kasai Station at 1:39 AM on January 27, arriving at Minami-sunamachi Station at 1:48 AM. Fig. 4 shows the measured waveforms.

The control system kept the feeder line voltage stable after switching to emergency power mode, and the EM-B-Traction system operated as intended, supplying power without problems through repeated

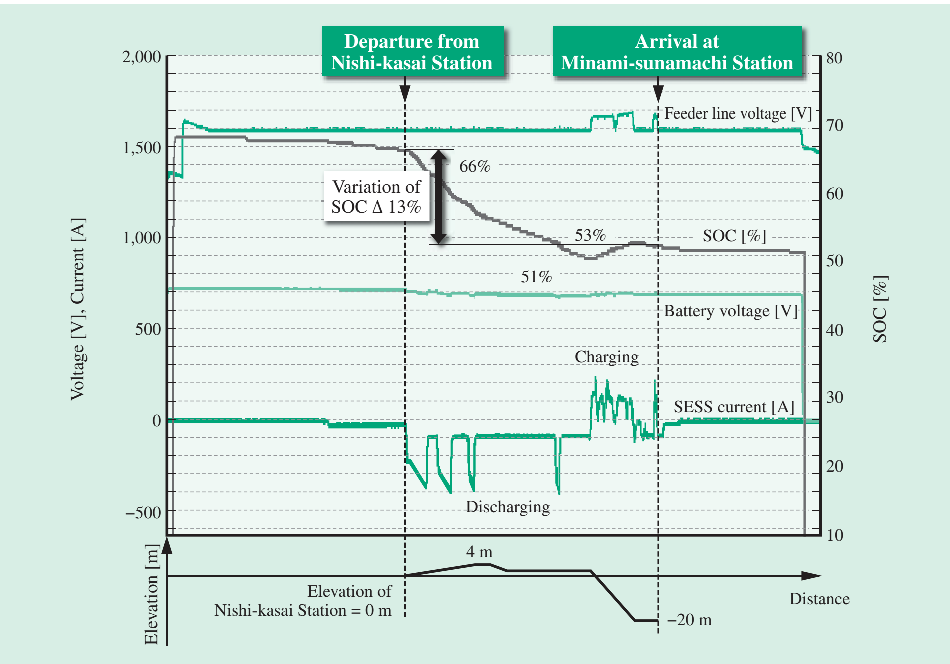


Fig. 4—Waveforms when EM-B-Traction Used to Supply Emergency Power.
The EM-B-Traction controls the feeder line voltage to keep it constant.

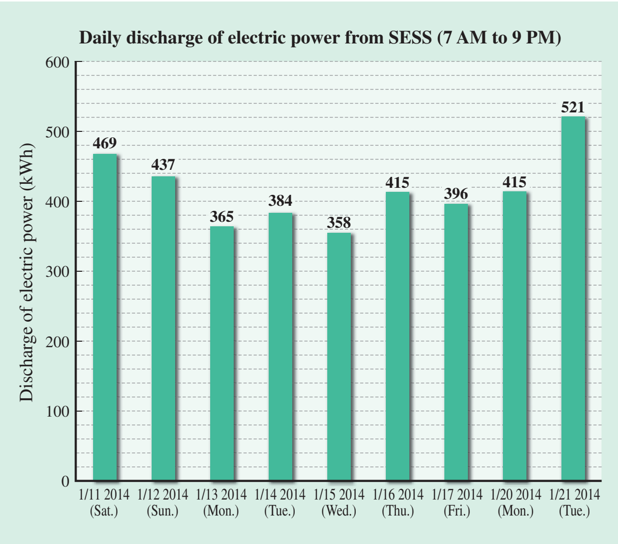


Fig. 5—Energy Savings (Power Supplied by SESS).
The EM-B-Traction system also helps save energy.

periods of coasting, powering, and regeneration. Since the EM-B-Traction system uses a chopper to supply a constant 1,600 V feeder line voltage, it acts to reduce motor current, which allows for a smaller bank of Li batteries.

Energy Savings

During normal operation mode, the EM-B-Traction system helps save energy by operating as an SESS, storing regenerative power and supplying it to power rolling stock. During the trial, the system was operated as an SESS during the day to confirm these savings. Fig. 5 shows the results.

This indicated that a 1,000-kW system could be expected to save an average of 718 kWh on weekdays and 731 kWh on holidays.

FUTURE PROSPECTS

Since the Great East Japan Earthquake, there have been heightened concerns about power outages caused by major disasters or other emergencies, and about how to deal with tsunamis. This has led to growing demand from railway operators throughout Japan for the ability to use stored electric power to provide emergency traction power during such an outage. However, this requires more than just installing energy storage devices on the power system. What is needed is for the battery discharge, power system, and other control functions needed during an outage to be implemented through interoperation between the control center (power system SCADA) and on-site equipment (EM-B-Traction). Hitachi intends to continue working on the system with the aim of building railway systems that provide emergency motive power for trains.

CONCLUSIONS

An SESS provides a useful tool for implementing a smart grid for railway systems that operate on DC power. Rather than seeing it as just another substation device, Hitachi plans to undertake further study of its role in implementing comprehensive energy management to improve energy efficiency by acting as a core device that can interoperate with other railway systems that manage power and traffic. It is also anticipated that demand for such measures as a means of preventing global warming and improving energy efficiency will become even stronger than before in both overseas and Japanese markets. In the future, Hitachi intends to continue contributing to solving environmental and energy problems through technical innovation in these fields.

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