Special edition paper

Assessment of the Vehicle System in Catenary and Battery-powered Hybrid Railcar System


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In an effort to achieve a catenary and battery-powered hybrid railcar system, we modified the NE Train (New Energy Train) to be equipped with that system in 2009. Other than batteries and the DC/DC converter used for purposes including charging the batteries, the system was based on the concept of the existing main circuit system. Major objectives of the system development were driving in non-electrified sections by electric power charged to the onboard main circuit batteries and allowing quick charging of those batteries at turn-back stations and other places. Assuming practical use of the system in DC-powered sections, we carried out stationary tests, running tests, and tests on the combination with wayside equipment. With the completion of verification and assessment for practical use, all the scheduled tests were finished with running tests on the Karasuyama line in March 2012, confirming that the developed system could be put into commercial operation without problem.

●Keywords: Catenary and battery-powered system, Lithium-ion battery, DC/DC converter

1 Introduction

Assessment of the Vehicle System in Catenary Battery performance has increased tremendously in recent years with progress in development of hybrid and electric vehicles in the automobile industry. In the railway sector too, development of light rail vehicles (LRV) that can run in non-electrified sections by new onboard large-capacity batteries has been advancing.

Battery output (power density) and capacity (energy density) of batteries have increased and cost of batteries has dropped to less than that at the time of development of the diesel hybrid cars. And with that, feasibility of rolling stock systems for running in non-electrified sections on electrical energy stored in batteries alone has come into view.

In light of those circumstances, we took on development of a catenary and battery-powered hybrid railcar system where trains can run in electrified sections on electric power from the catenaries just like with conventional trains, and in non-electrified sections on power from batteries alone with the pantograph lowered. This is seen as a new measure to reduce environmental load in non-electrified sections.

2 Overview of the Battery-powered EMU

2.1 Configuration of the Railcar System

The railcar is a third-generation test car type E995, which was modified to a fuel cell hybrid car in 2006 from the type Kiya E991 NE Train test-produced in 2003 for the development of diesel hybrid railcars. Modification to a catenary and battery-powered system was in 2008. Table 1 lists the major specifications of that car. Nominal battery voltage is 600V, and the car has a DC/DC converter that converts catenary voltage to voltage for charging/discharging the batteries with capacity sufficient to allow supply of power both for battery charging and driving.

Initially the car had nine units of main circuit batteries (163 kWh). The number of the battery units was reduced to four in August 2010 because running test results clarified the appropriate capacity and taking into account issues such as equipping batteries in future commercial operation.

The main circuit battery units were initially set up vertically in the cabin, but one of those units was housed under the seats in 2011, taking into account of the conditions for equipping batteries in commercial operation. Fig. 1 shows the car appearance and equipment locations and Fig. 2 the mounting of the main circuit batteries.

Table 1 Major Vehicle Specifications

Item	Description
Car dimensions (length × width × height)	19500 × 2800 × 4052 mm
Car weight	39.9 t
Maximum speed	100 km/h
Pantograph	Prototype pantograph on car roof to handle large current while stopped
DC/DC converter	Two-way conversion between catenary DC 1,500V and battery 600V
Main circuit battery	Four lithium-ion battery units in the cabin: 600V, 72 kWh
Control unit	VVVF inverter type, input voltage 600V
Main motor type and output	Two 95 kW induction motors

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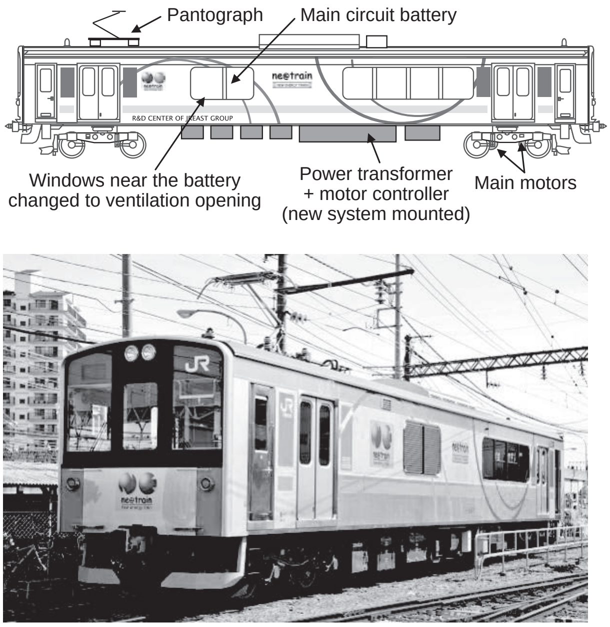


Fig. 1 Car Appearance and Equipment Locations

Fig. 2 Mounting of Main Circuit Battery Units
(Left: Vertical setting, Right: Mounting under seats)

2.2 Vehicle Control Mode

The 600V circuit connected to the batteries between the DC/DC converter and the VVVF inverter has no contactor or similar device for switching current. Instead, it controls current direction and value by controlling DC/DC converter output voltage according to battery voltage (output voltage high for battery charging, low for battery discharging).

The basic circuit configuration of the VVVF inverter to drive the main motor was not changed from that of a direct current EMU, with just the input voltage being changed from 1,500V to 600V. The main circuit operation for each driving mode is as follows.

(1) Electrified Section
The DC/DC converter steps down the catenary voltage to supply driving power, and it charges the batteries when their state of charge (SOC) is low. The regenerative energy by braking is used to charge the batteries first. However, when SOC is high, it is also returned to the catenary.

In situations such as electrified sections with low catenary voltage, the vehicle can run on the power assisted from the batteries. When a station is located at the end of an uphill gradient, the vehicle can give priority to running on battery power until that station so as to secure the capacity to absorb regenerative power when subsequently going downhill.

(2) Non-electrified Section
In sections that are not electrified, the DC/DC converter stops and the vehicle runs simply on the power from the batteries. The regenerative power by braking is charged to the batteries and to the auxiliary power source.

(3) Charging in Non-electrified Section
When stopped at stations with charging facilities, the vehicle raises its pantograph for quick charging. After completing charging, it car lowers the pantograph and starts running.

3 Test Using Actual EMU

3.1 Test Details and Schedule

After the basic performance check on the test track of the Omiya General Rolling Stock Center, we started the operation on a commercial line from January 2010. After conducting performance checks for powered running, braking, safety and other equipment, we completed all of the scheduled assessment tests such as assessment of battery characteristics, power consumption in powered running, and charging by regenerative braking, characteristics of charging from a wayside facility up to March 2012.

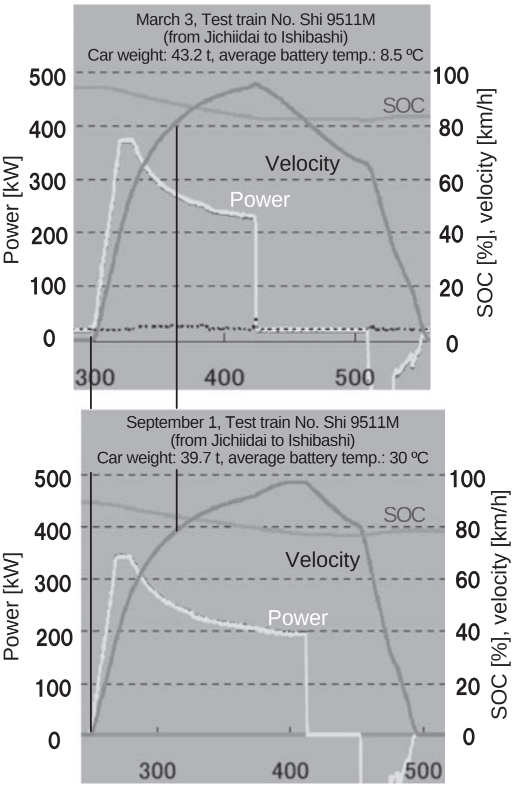
3.2 Test Results

(1) Vehicle Performance
Running tests confirmed that vehicle performance and control was as designed. As the charging and discharging performance of the batteries varies according to the ambient temperature, we carried out running tests on the same section (between Jichiidai and Ishibashi Stations on the Tohoku Line) in summer and winter, confirming that basic performance did not change (Fig. 3).

(2) Power Consumption in Running
With the catenary and battery-powered hybrid railcar system, the distance to be covered using the limited onboard batteries is an important assessment point. Fig. 4 shows a breakdown of the power consumed in operation at a maximum speed of 65 km/h in an approx. 20 km non-electrified section between Hoshakuji and Karasuyama Stations on the Karasuyama Line of (altitude difference approx. 50 m), stopping at every station.

The inbound Karasuyama Line (Karasuyama to Hoshakuji) mainly consists of uphill gradients that require more power in powered running and generate less regenerative electricity compared to the outbound line (Hoshakuji to Karasuyama), thus the power consumed on the inbound line was approx. 2.6 times that of the outbound line. However, the tests demonstrated that power consumption of the four battery units used (72.5 kWh) still left leeway of 18.7 kWh up to the SOC bottom limit of

20%, even on the inbound line. The running tests carried out in winter under the same running conditions showed that the power consumed in running did not vary according to the ambient temperature.



Required time to accelerate from
0 to 80 km/h was almost the same.

Fig. 3 Comparison of Powered Running Performance in Summer and Winter

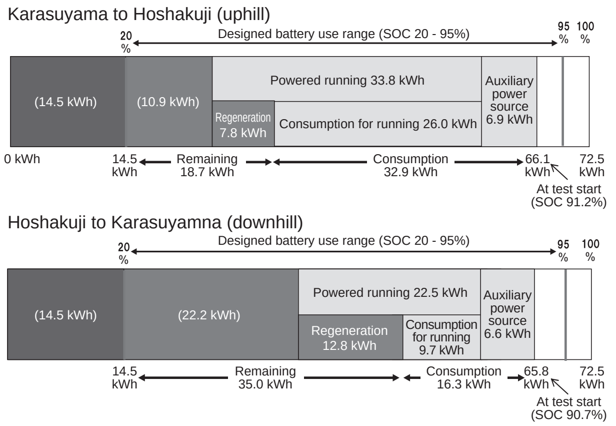


Fig. 4 Power Consumption Measurement Results (on the Karasuyama line)

(3) Absorbing Regenerative Energy to Batteries

Table 2 shows a comparison of regenerative factors with and without batteries. Charging regenerative electricity to the batteries improved the regenerative factor from 12.8% when returning the power only to the catenary to 16.7%.

Checking the absorption of regenerative electricity by holding braking on a downgrade on the Nikko line confirmed that all regenerative energy could be charged to the batteries.

Table 2 Regenerative Power Absorption Effect

Line	Section	Powered running	Regeneration	Regenerative factor	Note
Utsunomiya Line	Koganei to Utsunomiya	44.6 kWh	7.5 kWh	16.7 %	With battery
		42.5 kWh	5.5 kWh	12.8 %	Without battery
Nikko Line	Nikko to Utsunomiya	19.3 kWh	23.1 kWh	119.4 %	SOC 19.9 to 48.5 %
		22.7 kWh	22.4 kWh	98.9 %	SOC 47.7 to 74.2 %

(4) Running Assisted by Power from Batteries

Fig. 5 shows a comparison between running only on the power from catenaries and running assisted by the power from batteries (assistance rate 35%). The fluctuation of the catenary voltage was kept under control in assisted running, so we can expect effects from battery assistance such as control of powered running performance degradation and elimination of the need of increasing power transforming equipment.

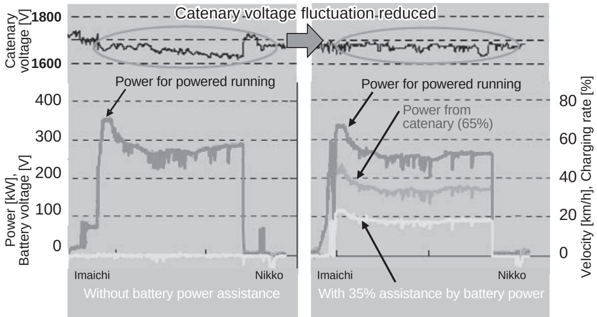


Fig. 5 Effect of Running Assisted by Battery Power

(5) Charging Time (While Running)

Charging tests while running revealed that the time required until fully charged (charge rate: SOC 95%) was around 20 minutes. The batteries could thus be charged during through service from a non-electrified section to an electrified section so as to be able to run in the next non-electrified section (Fig. 6).

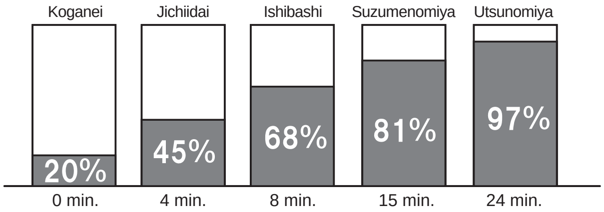


Fig. 6 Charging Time While Running

(6) Charging Time (While Stopped)

Charging tests using an actual EMU with the wayside facilities clarified that the charging time could exceed the target charging time (around seven minutes with new batteries) depending on the battery temperature. As shown in Fig. 7, long charging time is required when SOC is high. We thus lowered the upper SOC use limit by 5% and carried out charging tests. The test results showed the prospect that charging could be completed within the target time at around 15 ºC battery temperature (Fig. 8). However, we have to increase battery capacity by around 5%

because lowering the SOC upper use limit reduces the usable capacity.

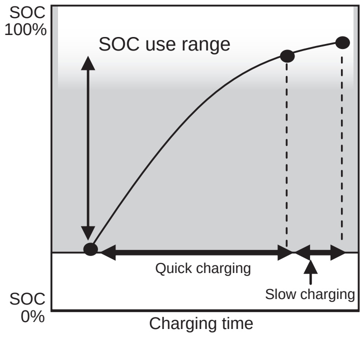


Fig. 7 Relation of Charging Time to SOC

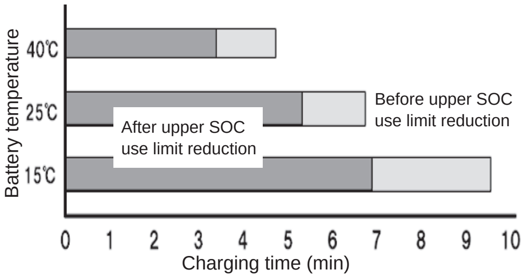
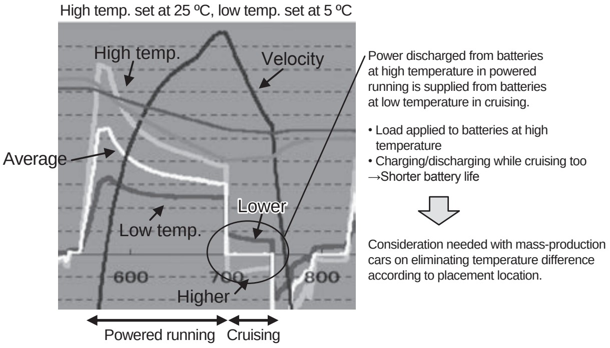


Fig. 8 Charging Time Reduction by Reducing Upper SOC Use Limit

(7) Battery Temperature Difference Tests
Battery temperature difference pushed up the charging/discharging frequency, causing shortened service life. Equipping according to the temperature environment was confirmed to be necessary (Fig. 9).



Power discharged from batteries at high temperature in powered running is supplied from batteries at low temperature in cruising.

- Load applied to batteries at high temperature
- Charging/discharging while cruising too

→Shorter battery life

Consideration needed with mass-production cars on eliminating temperature difference according to placement location.

Fig. 9 Behavior of Charging/Discharging Current

(8) Check of Housing Battery Unit Under Seats
Taking into account equipping conditions with commercial operation, we mounted a battery unit to under the seats and checked equipping convenience and temperature. Running tests on the Karasuyama Line showed that the battery temperature had leeway of more than 10 ºC in terms of the specified upper limit, even though the batteries were of a sealed structure.

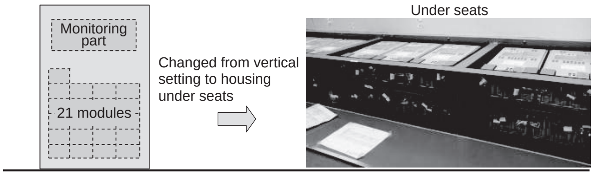


Fig. 10 Battery Unit Housed Under Seats

(9) Battery Temperature Change at Low Ambient Temperature
In order to see how much the battery temperature lowers when a vehicle is left at low ambient temperature without voltage applied, we checked temperature change of the batteries housed under the seats. Taking into account actual rolling stock operation, we started measurement of battery temperature at 45 ºC. After the assumed overnight parking time of five hours, the battery temperature was confirmed to be 27 ºC, within the battery use temperature limit.

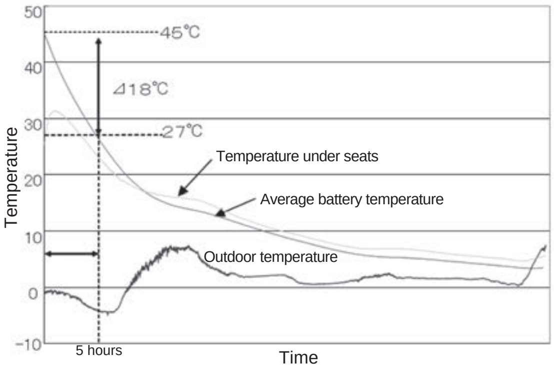


Fig. 11 Battery Temperature Change at Low Temperature

4 Conclusion

We installed a catenary and battery-powered system to the NE Train and carried out running tests from 2009 to investigate running performance on battery power, charging time using wayside facilities, and other factors. With tests using an actual EMU up to March 2012, we have completed all the scheduled tests, confirming that the system can be introduced to trains in commercial operation.

We next will make proposals and recommendations on specifications when used on commercial trains in view of putting the system into practical use.

Reference:

1) Kenichi Shibanuma, Koji Yoshida, "Development and Evaluation of Storage Battery Hybrid Train System," *Proceedings of Translog 2010* (August 2010)
2) Kenichi Shibanuma, Koji Yoshida, Hidetoshi Kitanaka, Kazuki Konishi, Masaaki Mima, Atsushi Nishida, "Chikudenchi Kudo Densha System no Kaihatsu [in Japanese]," *Proceedings of Translog 2011* (December 2011)