Development of Catenary and Battery-powered hybrid railcar system
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Abstract- JR East has been developing "Catenary and Battery-powered hybrid railcar system" to decrease environmental impact by diesel railcars that have been operated in non-electrified lines. The development of the experimental car and battery charging system on ground was started 2008, the experimental railcar was completed Oct. 2009 and we tested concerning to subjects of running performance, control system, and battery characters. Based on the classification of the circuits, we constructed the battery charging facilities last year. From Feb. 2011, we started total system performance test of the catenary and battery-powered hybrid railcar system, using both of charging facilities and experimental railcar.

This paper shows development method and typical result of these test programs.

Index Terms—hybrid system, battery charging

1. Introduction
From FY2000, JR East started development of a diesel and battery hybrid railcar to decrease environmental impact from, and the commercial operation has been started July 2007. After that, aiming for further reduction of environmental impact, we started development of "Catenary and Battery-powered hybrid railcar system".

In electrified lines, the catenary and battery-powered hybrid railcar (hereafter ‘hybrid railcar’) runs by power received from the catenary, and charges batteries at the same time. In non-electrified lines, hybrid railcar runs by the electric power of the batteries. The battery charging facilities (hereafter ‘facilities’) are installed at some stations in non-electrified lines, and the electric power is charged to onboard batteries when hybrid railcar stopping. (Fig.1)

An experimental railcar which equipped new hybrid system was completed in September 2009, and test run was started from October. Synchronous to the test run of the hybrid railcar, we also developed the battery charging system on the ground. Facilities are completed in Oct. 2010 and placed at the train depot in Jan. 2011. Then we started total performance test of this system.

2. Development of the experimental car
The composition of the experimental railcar is shown in Fig.2, and the main specifications are shown in table 1. The main circuit of the hybrid railcar receives DC 1500V in the electrified line, converted into DC 600V with DC/DC converter, and supplies to batteries, traction motors, and the auxiliary power supply unit. (Fig.2)

Between DC/DC converter and VVVF inverter, there are no contactors to switch the current in DC 600V circuit with which the batteries are connected. The current volume and direction are controlled with the converter by adjusting output voltage. (exp. when charging batteries, output voltage adjusted to high, when discharging, the voltage adjusted to low.)

Batteries are mass-produced lithium-ion type and capacity of each cell is 30Ah. The total capacity of batteries is 73kWh. However, considering the longevity, the range of SOC have to confined between 20-95%. So the available capacity becomes about 54kWh.

Fig.1 Catenary and Battery-powered hybrid railcar system

Fig2. Composition of experimental car
Table 1. Main specifications of experimental car

<table>
<thead>
<tr>
<th>Item</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car dimensions  (length x width x height)</td>
<td>19500mm × 2800mm × 4052 mm</td>
</tr>
<tr>
<td>Car weight</td>
<td>43.2 t</td>
</tr>
<tr>
<td>Max. speed</td>
<td>100 km/h</td>
</tr>
<tr>
<td>Cruising range</td>
<td>Approx. 25 km (flat sections, not including power consumption while stopped at stations)</td>
</tr>
<tr>
<td>Pantograph</td>
<td>Prototype mounted on roof that can collect large current from catenaries while stopping</td>
</tr>
<tr>
<td>Power converter</td>
<td>Bi-directionally converts between DC 1,500V of catenaries and 600V for batteries</td>
</tr>
<tr>
<td>Battery for main circuit</td>
<td>Four lithium-ion battery units mounted onboard: 600V, 73kWh</td>
</tr>
<tr>
<td>Motor controller</td>
<td>VVVF inverter system (input: DC600V)</td>
</tr>
<tr>
<td>Motor system/output</td>
<td>Two 95 kW asynchronous motors (mounted on one bogie)</td>
</tr>
</tbody>
</table>

3. Development of the battery charging facilities on the ground

A. Composition of the Facilities

In non-electrified lines, the hybrid railcar charges its batteries only when stopping at a station. Because the time when the railcar is stopping is usually short, it is necessary to supply large current to complete the charge in a short time. The current is almost same as the current that general E.M.U. consumes in electrified lines. Therefore, the same supply ability as a usual substation in electrified lines is necessary for the battery charging facilities. On the other hand, the train driving interval in non-electrified lines is fewer than in electrified lines. Moreover, the time that the facilities supplies power to the railcar is only when the railcar is stopping, the use of the facilities becomes intermittent. (Fig.4) However, the supply power is large, the facilities become inefficient.

Therefore, we examined to install batteries at the facilities to decrease electric power from electric company. Batteries at the facilities are charged at small current during the railcar is away from the station. (Fig.5) As a result, the capacity of the transformer and the rectifier can be reduced. When batteries on the railcar are charged from batteries of the facilities, it is able to charge while the railcar is stopping at the station by discharging the batteries of the facilities rapidly. (Fig.6) The load is leveled as shown in Fig.7.

Moreover, it is also possible to combine renewable energy such as photovoltaic and wind power with the facilities in the future. (Fig.8) We decided to advance the plan by this composition.
B. Circuit of the Facilities

The facilities are chiefly composed of rectifying circuit, battery circuit, and supply circuit. About each circuit, we compared circuit combination based on the voltage. (Fig.9, 10)

C. Comparison of circuit

Based on the table 2, we compared features of 2 kind of circuits, and evaluate. As a result, we decided that circuit 1 is available in the following reasons.

[1] Because the output voltage control of the rectifier is unnecessary, and the simple diode element can be applied, so rectifier can be simple.
[2] Even if the DC/DC converter breaks down, onboard batteries of railcar can be charged directly by rectifier (but current must be limited).
[3] Though the energy efficiency is a little inferior, there is no big difference among others. Therefore, we decided to develop the facilities adopting circuit 1.
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TABLE 2 COMPARISON OF CIRCUIT 1 AND 2

<table>
<thead>
<tr>
<th>Items</th>
<th>Circuit 1</th>
<th>Circuit 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method of charging batteries of facilities</td>
<td>Charging decreased voltage by DC/DC converter</td>
<td>Charging directly from the rectifier</td>
</tr>
<tr>
<td>Adjusting of supply voltage</td>
<td>Discharging voltage stepped up by DC/DC converter</td>
<td>Discharging voltage stepped up by DC/DC converter</td>
</tr>
<tr>
<td>Energy efficiency</td>
<td>83%</td>
<td>85%</td>
</tr>
<tr>
<td>Voltage control of rectifier</td>
<td>Unnecessary</td>
<td>Necessary</td>
</tr>
<tr>
<td>Rectifying device</td>
<td>Diode</td>
<td>IGBT</td>
</tr>
<tr>
<td>Control system</td>
<td>Only for DC/DC converter</td>
<td>Both of rectifier and DC/DC converter</td>
</tr>
<tr>
<td>Robustness in case of DC/DC converter failure</td>
<td>Possible to supply with the rectifier separating the DC/DC converter circuit (Current limitation is necessary)</td>
<td>Impossible</td>
</tr>
</tbody>
</table>

4. Test running
A. Energy consumption
In this system, it is significant to evaluate how long the railcar is able to run with a certain battery’s energy. Fig.11 and Fig.12 show the detail of the energy consumption. The experimental railcar ran about 20km (difference of altitude was about 50m) at maximum speed 65 km/h. It was confirmed 73kWh batteries could afford to supply power and there was room to SOC20%, which is lower limit of the use of the battery.

B. Electric energy for auxiliary power unit
It is necessary to supply electric power for the equipment of the railcar control, lightning and air conditioning by the batteries. Under the intense heat summer, there was a case to consume the twice the electric power of the accessory shown in Fig.11 and Fig.12. The energy saving of the air conditioning that occupies the majority of power consumption is a subject.

D. Battery temperature management
Test run was executed under different temperature between the units of the battery to evaluate the influence of the batteries installed under a different environment. Fig.14 shows the result. When discharging for acceleration, high temperature battery with small internal resistance feeds more current than low temperature battery. Battery doesn’t charged or discharged when the railcar is coating, but because of unbalanced current at accelerating, charge was done from the low temperature battery to the high temperature battery to

Fig.11 Electric power consumption (uphill)

Fig.12 Electric power consumption (downhill)

Fig.13 Total amount of onboard batteries

C. Capacity of battery
The capacity of batteries for the railcar was examined based on the result of test running. In addition to the energy for running and auxiliary power unit, margin when the railcar is stopping at the station or delay by accident is necessary. Moreover, the battery capacity is decreased because of the passing age, and the range of SOC that can be used is limited. Therefore, at the time of operation starts, total amount of onboard battery capacity is shown in Fig.13.
equalize SOC of batteries. This equalizing movement increases charge and discharge frequency and shorten lifetime of batteries. This shows that management of temperature becomes a very important factor when considering rigging design of commercial railcars.

5. Conclusion
[1] To decrease environmental impact, we developed the system which enables the hybrid railcar run only by the energy of batteries in non-electrified lines.
[2] The voltage which hybrid railcar receives is DC 1500V and the voltage of the batteries is DC600V. These voltages are controlled by DC/DC converter. The voltage control by DC/DC converter enables charging and discharging without contactors.
[3] To charge the hybrid railcar rapidly at large current, we install batteries at battery charging facilities.
[4] Estimation of battery capacity based on the result of test run, we have to estimate capacity of batteries both of railcar and facilities.

6. Further development
We start hybrid car and facilities combination test from February. Followings are the latest test programs.
[1] Combination of DC/DC converters
Because DC/DC converters are installed both hybrid railcar and facilities, we are going to examine the charging control.
[2] Verifying temperature
Large current is necessary for shortening the charging time. We are going to verify the rise in temperature of the overhead wire, the pantograph and the batteries with the large current.

[3] Low temperature test
Internal resistance of lithium-ion battery becomes large at low temperature. It causes the charging time to be lengthened. So we are going to examine to raise the temperature of batteries.
Assuming DC/DC converter’s breakdown, we are going to examine to charge railcar from the rectifier of the facilities without using DC/DC converter and batteries of facilities.

Next to above-mentioned tests, we plan to repeat the charging test and running test to examine the endurance of the railcar and the batteries.

Fig.14 Characteristic of the temperature difference between batteries