Development of an Energy-Saving Light Rail Vehicle Powered by Large Lithium Ion Battery*

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Abstract
A light rail vehicle (LRV) powered by a large Mn-type lithium ion battery (LIB) module was developed to run on a local railroad in Japan. A 60 kWh LIB module weighing 640 kg was used, and the relationship of running time with voltage, current, and consumed electric power was investigated in detail. The LRV was run while the LIB module was discharged between 660 V and 600 V. On a single charge, the LRV could run for 40 km by consuming around 40 kWh of energy. The running performance of the LRV with the LIB module was equivalent to that of an LRV powered electrically via an overhead contact wire. However, electrical power consumption of the LRV improved by 22% after charging the LIB with regenerative energy. The lifecycle of the LIB were examined by performing rechargeable tests. The initial capacity of the LIB was maintained at greater than 90% at 3 C (state of charge: 20%) after 3000 cycles.

Key words: Battery, LRV, Energy Saving, Contact-Wireless, Regenerative Energy

1. Introduction

Recently, it has been noted that rechargeable batteries can be applied to running contact-wireless types of railcars and light rail vehicles (LRV)\(^1\)(\(^2\)). The advantages of contact-wireless rail vehicles are as follows: (1) townscapes are improved by removing the overhead contact wires running above rail lines and level crossings; (2) maintenance costs would be significantly reduced if overhead contact wires are fewer; (3) battery-powered vehicles are not affected by power supply failure from damage to overhead contact wires from natural disasters or traffic accidents; (4) a drastic reduction in carbon dioxide emissions, when compared with diesel-powered railcars, especially as nitrogen oxides and suspended particulate matter are not discharged; and (5) charging batteries with regenerative energy results in energy savings and improves the running performance of the railcar. The lithium ion battery (LIB) is expected to be a useful power source because it has the highest energy density and power density among the various types of rechargeable batteries. In the application to DC type electric railcar, the use of large LIBs is effective as an alternative method of driving a regular diesel railcar because LIBs enable railcars to run on sections of rail line that have different voltage standards.

In an effort to develop a railcar that exhibits satisfactory running performance and generates energy savings with such an LIB, we conducted running tests of a DC 600 V railcar that uses a large Mn-type LIB module, on a local railroad in Japan. It was found that the running performance of the LIB railcar was equal to that of a contact wire-type railcar, and energy consumption was reduced\(^3\)(\(^4\)). At present, variable voltage variable frequency
(VVVF) inverter type railcars use mainly regenerative braking systems to convert kinetic energy of the railcar into electricity that is fed back into the overhead contact wire. Although the VVVF inverter has also been used for LRVs to improve energy savings while running, regenerative energy is often lost because it is not routed to other nearby railcars on the same line. The use of an LIB is anticipated to solve this problem\(^\text{5,6}\). To date, the rechargeable properties of large LIBs and their application to large transport systems have been rarely reported. We developed a novel LIB with high power density, high energy density, and low ac impedance for running a railcar. The weight of the LIB was also reduced by modifying the lithium ion cells and battery case. In this paper, we present the energy savings and running performance of an LRV in which regenerative energy was charged to an LIB as. Furthermore, we describe the rechargeable properties of the LIB required for effective LRV operation.

2. Experimental Procedure

2.1 LIB

A sheet type lithium ion cell was prepared before the production of the LIB. Spinel lithium manganese (LMO) powders were used as the cathode materials of the lithium ion cell. LMO has a poor operational lifetime due to the dissolution of Mn ions at temperatures greater than about 40 °C. Therefore, to use LMO for transport applications, such as electric vehicles, buses, and railcars, it is necessary to solve the problem. It is known that doping with metal ions such as \(\text{Al}^{3+}\) increases the operational lifetime of LMO cathodes. Accordingly, we added 5 mol % of \(\text{Al}^{3+}\) ions to the LMO cathode during production of the lithium ion cell to improve its operational lifetime. The LMO cathode was prepared using 88 wt % LMO powder, 6 wt % acetylene black, and 6 wt % fluorine resin. A mixture of hard carbon and graphite (1:1 w/w) was used as the anode. Porous polypropylene sheets were used as the separator. As the electrolyte, 1 M LiPF\(_6\) in ethylene carbonate/1,2-dimethoxyethane (1:1 v/v) was used. Sheet type lithium ion cells (323 mm × 130 mm × 7 mm; 570 g; 16.8 Ah; 3.8 V) were produced in a glove box under an argon atmosphere. A single LIB (323 mm × 240 mm × 160 mm; 100 Ah; 11.4 V) consisted of 18 lithium ion cells. Three cells were connected in series and six 3-cell series were connected in parallel. Aluminum battery cases with ventilation slits were used to allow heat dissipation from the lithium ion cells during charge and discharge cycles. The LIB was also lightened to 10 kg. Protection circuits were installed in all LIBs to avoid overcharge or overdischarge, conditions that can cause ignition and smoke emission. The LIB module (Fig. 1) consisted of 54 LIBs connected in series to provide 620 V (60 kWh). The LIB module specifications are listed in Table 1. The rechargeable capacity and cycle life of the LIB were measured by a rechargeable tester (60 V, 300 A).
Table 1. LIB module specifications.

<table>
<thead>
<tr>
<th>Item</th>
<th>Specification</th>
</tr>
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<tbody>
<tr>
<td>Average output voltage</td>
<td>620 V</td>
</tr>
<tr>
<td>Operation voltage range</td>
<td>567 V − 660 V</td>
</tr>
<tr>
<td>Operation temperature range</td>
<td>−10 °C to +50 °C</td>
</tr>
<tr>
<td>Capacity</td>
<td>100 Ah</td>
</tr>
<tr>
<td>Components</td>
<td>54 in series</td>
</tr>
<tr>
<td>Dimension of LIB</td>
<td>W 1,000 mm × L 2,000 mm × D 1,000 mm</td>
</tr>
<tr>
<td>Total Weight</td>
<td>640 kg</td>
</tr>
</tbody>
</table>

2.2 LRV powered by LIB

Figure 2 shows a VVVF inverter type LRV (Model 800 Low-floor type LRV, 25 tons, Nippon Sharyo, Ltd.) used in this study. The LIB module was installed in the centre of the LRV and fixed in a metal rack to withstand vibrations when the LRV was running. The LIB module was connected to a 60 kW motor via the VVVF inverter. By adjusting specification for the running in Fukui railway, the regenerative breaking system of LRV has been modified. Regenerative breaking was activated when the LRV decelerated from 60 km/h to 40 km/h. On the other hand, mechanical breaking was activated at speeds less than 40 km/h. In this work, the regenerative energy obtained from the 60 km/h to 40 km/h transition was charged to the LIB module. The running characteristics of the LRV were evaluated on a railroad of the Fukui Railway Company. All changes in voltage, current, and temperature during running were recorded on a personal computer via a data logger installed in the center of the LIB module.

3. Results and discussion

3.1 Running test of LRV

The running characteristics of the LRV with the LIB module were investigated on a local railroad over a 20-km distance around midnight. Outside temperature was about −5 °C. The running condition of the LRV was determined on the basis of a timetable. After charging the LIB module (warmed to 10 °C) at 1 C via the overhead contact wire at 600 V, the LRV was run for the entire distance while patterns of coasting, powered running, and stopping were repeated more than 20 times (Fig. 3). The voltage decreased from 660 V to 600 V over 1800 s, but no voltage fluctuations in the LIBs were observed. A current of 300 A flowed to the LIB module and the voltage decreased when the LRV was accelerated. A current of around −100 A was measured as regenerative energy, suggesting that 100 A of regenerative energy was charged at 1 C to the LIB module by regenerative braking. Temperature of the LIB module increased up to 18 °C during running, which was not regarded as a drastic increase since the rated temperature value for safe use of the LIB has been set at 50 °C. Because the LIB case was made of aluminum, it provided excellent heat dissipation in air, which enabled the LIB to cool between operational periods and return to below 30 °C after the running. In the running test, the LIB showed a high level of stability against the change of temperature during the rechargeable process. This suggested that no dissolution of Mn

![Fig. 2. VVVF inverter type of LRV used in this study.](image-url)
ions from the LMO cathode or degradation of the LiPF₆ electrolyte or organic solvent occurred during running because the temperature of the LIB remained below 40 °C.

Figure 4 shows the relation between running time and energy consumption while running on discharge from the LIB module without regenerative energy (a), and with regenerative energy (b). When the LRV was powered only by the LIB module on a 20-km run, energy consumption was 24.8 kWh. On the other hand, when the LRV was run by repeatedly decelerating from 60 km/h to 40 km/h by regenerative braking, the energy consumption improved to 19.5 kWh. Furthermore, it was found from the difference in consumed energy that the power consumption was improved about 22% (5.3 kWh) by charging with regenerative energy. Although it is effective for energy saving to charge regeneration energy to the LIB module, the lifetime of the module may be decreased, owing to the
Table 2. Rechargeable properties of lithium ion cell.

<table>
<thead>
<tr>
<th>Item</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Sheet type cell</td>
</tr>
<tr>
<td>Energy density*</td>
<td>120 Wh/kg</td>
</tr>
<tr>
<td>Power density*</td>
<td>4500 W/kg</td>
</tr>
<tr>
<td>Ac impedance*</td>
<td>2.6 mΩ</td>
</tr>
</tbody>
</table>

* 25°C

frequent charge cycling. Therefore, running tests of the LRV were carried out five times over two days. Figure 5 shows the number of runs and the corresponding power consumption of each run. It was seemed that the change of the power consumption was little. However, fluctuation of power consumption occurred as a result of extraneous variables that included adverse weather conditions, such as snow and freezing of railroad surface, because the running test was conducted in the middle of the night during the winter. In addition, we speculate that the power consumption of the LRV was not influenced by the frequent charge cycling of the LIB.

3.2 Performance of the LIB

The rechargeable properties of the lithium ion cell are summarized in Table 2. The energy density and power density of the lithium ion cell were 120 Wh/kg and 4500 W/kg, respectively. The power density was determined as follows. Voltage during 10 s of pulsed current for 1 C was plotted against current and power density at a 50% state of charge (SOC) to obtain a linear relationship. The ac impedance of the lithium ion cells used in our LIBs was less than 3 mΩ, whereas that of regular lithium ion cells produced from commercial LMO cathodes is about 5 mΩ. This suggests that the low impedance may have resulted in the high power density of the array. It was also considered that the 25-ton LRV could run on the lithium ion battery that consisted of lithium ion cells with higher power and lower ac impedance. The rechargeable durability of the LIB was examined on the assumption that the LRV would be powered by the LIB module over a one-year period.

Figure 6 shows the relation between cycle number and LIB capacity at 1 C for 1000 cycles. Depth of discharge (DOD) was determined at 100% and 80%. One thousand cycles were taken to correspond to one year’s use since LRVs are used 3 times daily on the Fukui Railway. The capacity of the LIB gradually decreased in accordance with increasing cycle number at DOD of 100%. The retention ratio of capacity was 89% at DOD of 100% after 1000 cycles. The temperature of the LIB increased from 20°C to 32°C. On the other hand, the capacity of the LIB exhibited excellent cycling stability at DOD of 80%. After 1000 cycles, the retention ratio of capacity was 95% at DOD of 80%. The temperature of the LIB increased from 20°C to 27°C. It was found that the cycling stability and the increase of temperature improved with a lower DOD value. This result suggested that the lithium ion cell had high cycling stability due to the effect of doping the LMO cathode with aluminum ions. Furthermore, the cycle test of the LIB was conducted at room temperature according to a charging and discharging schedule based on the timetable of the LRV. Cycling test of the LIB was examined up to 3000 cycles at 3 C. In Fukui railway, the distance of road area corresponding to contact-wireless

![Fig. 5. Relation between power consumption and number of running.](image-url)
section was 2 km. SOC and DOD of LIB was 20%, respectively. This condition corresponded to the charge of the LIB at the starting station and the discharge for 2-km running. Three thousand cycles were corresponded to about eight year’s use. Figure 7 shows the relation between cycle number and capacity of the LIB. The retention ratio of capacity was maintained above 90% of initial capacity after 3000 cycles. Generally, large LIB will be often used from 50% to 80% of initial capacity. Therefore, it is estimated that the life cycle of the LIB will be further lengthened more than ten years. This showed that the LIB had excellent cycling stability for recharging under low SOC conditions. Given these findings, the use of the LIB module was deemed effective for regular scheduled use on a local railway with low-frequency traffic.

4. Conclusions

A VVVF inverter type LRV powered by a Mn-type LIB module of 60 kWh was developed and a running test was carried out on a railroad of the Fukui Railway Company. A current of 100 A was charged to the LIB module by regenerative braking from 60 km/h to 40 km/h Regenerative braking provided around 5 kWh of total electric power to the LIB which would improve the mileage by 22% when the regenerative energy was charged to the LIB module. In terms of energy savings, it was effective to use both the LIB and regenerative braking. It was also found that the running performance of the LRV with the LIB was equivalent to that of an electric LRV powered via an overhead contact wire, but with improved energy efficiency. This was most likely the result of the Mn-type lithium ion cell having 120 Wh/kg of energy density, 4500 W/kg of power density, and lower ac impedance. The cycling stability of the LIB module was dependent on the condition of DOD; the lower SOC of the LIB led to excellent cycling performance and 90% of the initial capacity was retained at SOC of 20% after 3000 cycles.

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References


