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Running Characterization of Light Rail Vehicle Powered by Lithium Ion Battery

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Received May 13, 2009 ; Accepted September 6, 2009

A lithium ion battery module was applied to the running of light rail vehicle for 3 years. The battery was a 15 kWh Mn type lithium ion battery and the relations between running time and voltage, current and integrating electric power were investigated in detail. A running test was carried out during light rail transit to investigate charge performance due to regenerative energy. The lithium ion battery module was quickly charged three times at 150 A by use of a regenerative braking system. Energy savings were estimated at around 22% when charging the lithium ion battery from regenerative energy. From a practical viewpoint, the capacity and cycle performance of the lithium ion battery submodule was examined over a 3-year period and although discharge capacity decreased to about 70% of initial capacity, the battery exhibited good cycle stability.

Key Words : Lithium Ion Battery, Light Rail Transit, Regeneration Energy, Energy-Saving

1 Introduction

In recent years, fuel cells and rechargeable batteries such as lithium ion or nickel hydrogen batteries have been applied to the running of railcars.^{1,2)} The application of these batteries is expected to confer the following advantages when light rail vehicles (LRVs) are used as railcars. (1) The townscape is improved in the vicinity of railway roads. (2) The maintenance cost of overhead contact wires is reduced. (3) It is possible to utilize the battery as an emergency power source in the case of accident or disaster causing power supply failure. (4) The discharge of carbon dioxide, nitrogen oxides and sulfur oxides can be drastically reduced compared with diesel type railcars. (5) The energy-saving effect for the running of the LRVs is improved by regenerative energy with the use of rechargeable batteries. In efforts to develop a railcar showing satisfactory running performance and energy-saving effects with such battery, we have been conducting running tests of a DC 600 V type railcar using a large Mn type lithium ion battery on the business lines of Echizen railway and Fukui railway in Japan.³⁻⁵⁾ It was found that the running performance of the railcar with a lithium ion battery was equal to that of a contact wire type railcar and mileage was improved. At present, new variable voltage variable frequency (VVVF) inverter type railcars are using regenerative braking systems where the kinetic energy of the railcar is converted to electricity that is fed back into the contact wire. The VVVF inverter has been also used for LRVs to improve energy savings during running. However, loss of the regenerative energy occurs frequently since the regenerative energy is not charged to other railcars running nearby on the line. The use of a lithium ion battery is anticipated to solve this problem.

The use of regenerative energy for energy savings has been reported in the running of electric vehicles and hybrid electric vehicles.^{6,7)} In the present work, the energy-saving effects and running performance were investigated using a VVVF type LRV in which the regenerative energy was charged by a lithium ion battery. A quick charge test of the lithium ion battery which assumed running of the LRV on the Fukui railway is described and the performance of lithium ion battery discussed.

2 Experimental

Aluminum doped lithium manganate ($\text{LiAl}_{0.05}\text{Mn}_{1.95}\text{O}_4$) cathode materials were produced by large-scale spray pyrolysis equipment (RH-6, Ohkawara Kakohki Co., Ltd.). It is known that the addition of aluminum ions confers high stability on the life cycle of a lithium manganate cathode, and the optimum content of aluminum was determined to be 5 mol%.⁸⁾ The rate of powder production was 1 kg/h in this equipment. LiNO_3 , $\text{Mn}(\text{NO}_3)_2$ and $\text{Al}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ were used as starting materials. LiNO_3 , $\text{Mn}(\text{NO}_3)_2$ and $\text{Al}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ were weighted out to attain the metal component molar ratio (Li:Mn:Al) of 1:1.95:0.05 and were dissolved in double distilled water to prepare aqueous solutions of 1.0 mol/dm³. A mist of aqueous nitrate solution (10 μm average droplet size) was generated using a two-fluid nozzle atomizer at a flow rate of 10 dm³/h. The pyrolysis temperature was 700 °C. As-prepared powders were produced and then calcined for 10 h at 800 °C to remove a few weight % of undecomposed metal nitrates which were detected by differential thermal analysis-thermogravimetric analysis (DTG-60, Shimadzu). The cathode was prepared using 85 wt % $\text{LiAl}_{0.05}\text{Mn}_{1.95}\text{O}_4$ powder, 10 wt % acetylene black

Fig. 1 (a) Lithium ion battery module and (b) light rail vehicle (LRV) used in this study.

Table 1 Specifications of 15 kWh lithium ion battery module.

Battery system : Mn type lithium ion battery
Average output voltage (V) : 620
Operation voltage range (V) : 480 - 660
Capacity (Ah) : 32
Dimensions (mm) : W600 × L700 mm × H600
Weight (kg) : 180
Components of module : 18 submodules in series

and 5 wt% fluorine resin. The slurry obtained was coated on an aluminum sheet using a doctor blade. A mixture of hard carbon and graphite (1:1 volume ratio) was used as the anode. Porous polypropylene sheet was used as a separator, and 1 mol/dm³ LiPF₆ in ethylene carbonate/1,2-dimethoxyethane (EC:DME in 1:1 volume ratio) was used as the electrolyte. A laminate sheet type lithium ion cell (170 mm × 160 mm × 5 mm, 250 g) was assembled in a globe box under argon atmosphere. Electrical capacity and voltage of the lithium ion cell was 8 Ah and 3.8 V, respectively, and this specification of the cell was designed based on the general specifications of Enax Co., Ltd. Figure 1 shows photographs of the Mn type lithium ion battery module and LRV (Model 800 Low-floor LRV, Nippon Sharyo, Ltd.) used. The Mn type of lithium ion battery consists of 18 submodules, with each submodule (200 mm × 70 mm × 700 mm, 10 kg) consisting of 36 laminate sheet type lithium ion cells. Nine lithium ion cells were connected in series and then were also connected four in parallel. The electrical capacity and voltage of each submodule was 32 Ah and 34.2 V, respectively. An aluminum case was used to release heat from the sheet cell during charge and discharge, and for safety considerations a protection circuit was installed in all submodules to prevent overcharge and overdischarge. The 18 submodules were connected in series to produce a 15 kWh lithium ion battery module with a weight of 180 kg. Table 1 shows the specifications of the lithium ion battery module used. The output voltage of the module ranged from 480 to 660 V. The module was mounted on the front of the LRV fixed to a wooden rack in order to withstand vibration during running. The

lithium ion battery module was charged with an exclusive battery charger (600 V, 130 Ah, Daiken Chemical, Co., Ltd.) via the contact wire. The lithium ion battery module was directly connected to the motor of the LRV. Since the LRV cannot generally run just by the limiter connecting the motor to a battery, the LRV was operated by removing the limiter using software. Changes of voltage, current and temperature of the module during running was stored on a data logger and subsequently transferred to a personal computer.

3 Results and Discussion

The running performance of the LRV with lithium ion battery was examined on Fukubu business line (1.5 km), Fukui railway. After charging the lithium ion battery module at 1C through the contact wire, the LRV was run for the entire distance while patterns of power running, coasting and stopping were repeated three times. Figure 2 shows the change of voltage and current as a function of running time during running. A current of 300 A flowed to the lithium ion battery and the voltage decreased when the LRV was quickly accelerated. When the current decreased down to around 200 A, a rapid reduction in speed from 50 km/h was attempted by regenerative braking. A current of around -150 A was obtained as regenerative energy, suggesting that 150 A of regenerative energy is quickly charged to the lithium ion battery by regenerative braking. Figure 3 shows the change of temperature as a function of running time during running. A thermocouple inserted into the central part of a submodule revealed that the temperature of the lithium ion battery module increased from 17 to 25 °C during running, which was not a drastic temperature increase. Thus, the safety of quickly charging the module is considered relatively high. Figure 4 shows the change of speed and consumed energy after running the LRV powered by the lithium ion battery and contact wire. When powered only by the lithium ion battery, the LRV reached a maximum speed of 60 km/h and battery consumed energy was 2.54 kWh during the 1.5 km run while repeatedly decelerating from 50 km/h by regenerative braking. In contrast, energy consumption when powered only by the contact wire was higher at 3.24

kWh. Thus, the lithium ion battery showed an energy-saving effect of around 22%. It is important to investigate the performance of the used submodules from a practical standpoint. Therefore, the rechargeable performance of the lithium ion battery submodules was also examined after three years of running a DC type railcar. The submodules were regularly charged over the 3-year period and approximately 34 V of voltage was maintained at room temperature. Figure 5 shows the relation between voltage and discharge capacity of the lithium ion battery submodule at 1C. Its initial discharge capacity was 34.2 Ah, but this decreased to 23.9 Ah after 3 years, which is a decrease to about 70% of the initial discharge capacity. Even with this 70% discharge capacity, the battery was able to charge regenerative energy during running. A rechargeable test of the submodules was carried out assuming a running pattern on 2 km of the Fukui railway. Figure 6 shows the cycle stability for rechargeable of the submodule assuming such condition. A 3000 cycle test was conducted at room temperature. According to the service diagram of Fukui railway, this means that 20% of the depth of discharge was continuously charged for 4 min (3C) each day for 24 months in the case that the lithium ion battery is charged 4 times daily. It was clear that the module had high stability for recharge capability. Given these findings, the use of a

lithium ion battery was deemed effective for a service diagram of a local railway without high frequency.

4 Conclusion

The running test of an LRV powered by a Mn type lithium ion battery module of 15 kWh was carried out on the business line of Fukui railway. A current of 150 A was charged to the battery by braking from 60 km/h to 50 km/h at one time. Braking three times provided 0.7 kWh total electric power to the battery. Mileage was improved by 22% when the regenerative energy was charged by the lithium ion battery during running. It was also found that running performance of the LRV with the lithium ion battery was equivalent to that of a railcar powered electrically via the contact wire. Cycle performance of the lithium ion battery submodule exhibited high stability for rechargeable at 3C.

Acknowledgement

This work was supported by the project Strategic Development of Technology for Efficient Energy Utilization, Fundamental Technology Development for Energy Conservation by the New Energy and Industrial

Fig. 2 Change of voltage and current as a function of running time during running of the LRV with lithium ion battery.

Fig. 3 Change of temperature as a function of running time during running of the LRV with lithium ion battery.

Fig. 4 Change of speed and consumed energy as a function of running time during running of the LRV with lithium ion battery.

Fig. 5 Relation between voltage and capacity of lithium ion battery submodule at 1C.

Fig. 6 Relation between cycle number and capacity of lithium ion battery submodule at 3C (DOD 20%).

Technology Development Organization (NEDO).

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