Development of a Traction Circuit for Battery-powered and AC-fed Dual Source EMU and Running Test Evaluation of the On-board Battery Performance

Yoshiaki TAGUCHI  Satoshi KADOWAKI  Takayuki NAKAMURA
Traction Control Laboratory, Vehicle Control Technology Division

Masaki MIKI
Traction Control Laboratory, Vehicle Control Technology Division

Kenji HATAKEDA  Yoshimasa ARITA
Kyushu Railway Company

We have converted an existing AC electric multiple unit train (EMU) into a battery-powered and AC-fed dual source EMU (test train) to allow interoperable service between AC electrified lines and non-electrified lines. This paper describes the features and the test results of the developed traction circuit. Results of the on-board battery performance evaluation are also reported, as follows: 1) the running distance, without recharging, of the test train fed by the on-board lithium-ion battery (1382V-83 kWh) was approx. 20-30 km, 2) the maximum temperature of the battery was 51.5℃ leaving a sufficient margin before the upper limit of 65℃, 3) the time required for quick charging increases when the battery is in low temperature conditions. The running test results demonstrate that the on-board battery performance is sufficient to permit interoperable services between AC electrified and non-electrified lines.

Keywords: Battery powered EMU, AC electrified line, Lithium-ion battery, Running tests

1. Introduction

Passenger transport on non-electrified lines relies on diesel motor cars. Yet electric multiple unit train (EMU) have a lower impact on the environment, and cost less in fuel. However, the high cost of electrification which would be required to introduce EMUs instead of diesel cars poses a problem. In 2003, hybrid trains with both a diesel motor and battery were put into revenue service, which improved environmental performance of diesel multiple units (DMUs). Since 2004, a trolley and battery hybrid vehicle (battery powered EMU) has been developed, whereby the train is charged from the trolley, and has no diesel motors [1, 2, 3]. Then in 2014, the East Japan Railway Company developed and commercialized a DC feeding trolley and battery hybrid train: Series EV-E301 [4].

Before this development, however, a hybrid train powered by an AC feeding trolley and battery had not developed. Therefore, the authors developed a battery-powered and AC dual source EMU [5, 6]. In this paper, the features of the developed traction circuit and battery system are described. Then, the results of the running tests in 3 seasons, spring [7, 8], summer and winter, aimed at evaluating the characteristics of the on-board battery system, are reported.

2. Outline of the developed EMU

2.1 Specification of the EMU

The overview of the developed EMU (test train) is shown in Fig. 1. Two suburban cars were converted into the battery powered and AC-fed dual source EMU. The traction battery was installed under the floor of the trailer car. As shown in Table 1, the traction battery is a high-voltage and large-capacity lithium-ion battery, whose ratings are 1382 V, 83 kWh. Since the developed traction battery system is compact, the increase in rate of the total weight of the EMU is only 6%.

Table 1 Typical specification of the battery-powered EMU

| Type                  | Series 817-1000 |
|-----------------------|-----------------|
| Train set             | 2 cars (Mc-Tc)  |
| Tare weight of the    | 63.2 t (before conversion) |
| train                 | 67.1 t (after conversion) |
| Traction motor        | 3 phase induction motor 150 kW × 4 |
| Traction battery      | Lithium-ion battery (Mn type) |
|                       | 1382 V - 83 kWh (Nominal ratings) |

Fig. 1 Overview of the developed dual source EMU

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2.2 Configuration and control of the developed traction circuit

The traction battery is directly connected to the DC-link of the traction circuit, as shown in Fig. 2. Since the existing PWM rectifier operates as the charge/discharge controller of the traction battery, no additional power controller is necessary.

The representative modes of operation are shown in Fig. 3. In the battery-powered mode, as in Fig. 3 (a), the pantograph is folded and the power for the traction inverter and auxiliary load is supplied only from the traction battery. It is one of the features that the power from the battery to the auxiliary load is supplied via the traction transformer. The dual-powered mode is shown in Fig. 3 (b), (c). In terms of powering, the required power is fed from the trolley only. For regeneration, the power from the traction inverter returns into the traction battery. Then, during coasting and stopping at stations, the battery is charged from the trolley, if needed.

The developed traction circuit could potentially be made to function using the contact-wire and battery simultaneously, however, because of the short-term nature of this development, for the present study, this function was not added to the test train.

3. Features of the developed traction system

3.1 Disuse of the additional power controller

The rated voltages of proven battery systems for commercialized railway vehicles are 600V-700V, which are classed as low-voltage. Assuming a low-voltage battery system, it is essential to use a boost chopper to adjust the battery voltage to the original DC link voltage of 1800 V. Installing an additional power converter is difficult in the small vacant underfloor space on the 2-car AC EMU. Consequently, a high-voltage battery system was adopted instead, which can then be directly connected to the DC link. The typical specifications of the battery system are shown in Table 2.

The rated battery voltage of 1382 V was determined in consideration of the available underfloor space, electric insulation, and energy capacity for 30-km running distance. The voltage of the DC link in the battery-powered mode is less than 1800 V in the trolley-powered mode. So in the battery-powered mode, the designed tractive effort of the EMU is less than that in the trolley-powered mode, on high speed sections. However, the designed tractive effort of the EMU is larger than that of Type 47 existing diesel motor cars.

Table 2 Specifications of the traction battery system

| Positive-electrode active material | Lithium manganese oxide |
|-----------------------------------|-------------------------|
| Rated capacity                    | 30 Ah / cell            |
| Rated cell voltage                | 3.6 V / cell            |
| Mass                              | Approx. 2.0 kg / cell   |
| High voltage protection           | 4.3 V / cell (Maximum)  |
| Low voltage protection            | 2.5 V / cell (Maximum)  |
| Over current protection           | 300 A / bank            |
| High temperature protection       | 65 ℃ (Maximum)          |
| Configuration of the battery system | Whole system = 2 banks in parallel |
|                                   | 1 bank = 48 modules in series |
|                                   | 1 module = 8 cells in series |
| Ratings of the whole system       | 604.8 V – 120 Ah (83 kWh) |
| Cooling                           | Forced air cooling with fans |

3.2 High-voltage traction battery system

The voltage of the traction battery (in Table 2) was set much higher than proven on-board battery system for railcars. As a result, the traction battery monitoring system must satisfy electric insulation characteristics. The design of the power line insulation for the traction battery is based on the half value of the total battery voltage, because the neutral point of the DC link is connected to the ground (car body).

The whole battery system consists of two banks, which makes it possible to isolate a malfunctioning bank. Moni-
The monitoring system tracks the cell voltage, the module temperature, the bank current and the stability of the communication line. The forced air-cooling fans, located behind the battery modules, are connected to a simultaneous ON-OFF control. The control is based on whether the maximum module temperature exceeds 45°C or falls below 35°C.

### 3.3 Compact battery protection circuit

The battery protection circuit was designed to be as small as possible, to optimize battery capacity in the confined space. The number of high-speed circuit breakers (HB), which are quite large, was kept down to only one. The HB trips when there is a short-circuit outside the traction battery box. For short circuits or grounding inside the battery box, several small-sized fuses were incorporated at adequate points on the battery strings, as shown in Fig. 4. When battery box crashes, the fuses prevent a large-scale short circuit between the upper-arranged batteries and lower-arranged ones. The line breakers (LB), although they are relatively large, are arranged to allow the two battery banks to be connected or disconnected independently.

![Fig. 4 Examples of short circuit protected by fuses](image)

**Fig. 4** Examples of short circuit protected by fuses

### 4. Evaluation of battery performance through running tests

#### 4.1 Outline of the running tests

The conversion of the existing EMU was completed in March, 2013. The running tests were conducted during three seasons of the year, on the electrified Chikuhō main line (40 days in total) and the non-electrified Hitahikosan line (6 days in summer), as shown in Fig. 5. The 1st test was executed in May, 2013 (springtime), the 2nd test in Aug. and Sep., 2013 (summertime) and the 3rd test in Jan. and Feb., 2014 (wintertime). A typical diagram of the running tests is shown in Fig. 6. Battery endurance tests were conducted in the section between Nakama and Keisen station. The marker “QC” indicates the point where the quick charging function was tested. Moreover, energy consumption was measured on each occasion to analyze differences between running conditions.

![Fig. 5 Area covered by running tests](image)

**Fig. 5** Area covered by running tests

**Fig. 6** Typical diagram of the running tests

#### 4.2 Energy consumption tendencies

Battery-powered EMUs often require frequent charging every 1-2 hours, and have a lower energy capacity margin than the DMU’s fossil fuel. It is therefore important to understand the energy consumption patterns of the developed EMU. Measured and calculated electrical energy points are shown in Fig. 7. Directly measured electric energy $W_2$, $W_4$ and $W_5$ are used to calculate $W_p$ and $W_i$ which are not measured directly, due to limited space. Bi-directional power flow points represent electric energy consumption, which is powering electric energy minus regenerative electric energy.

During the springtime tests, the developed EMU ran locally between Nakama and Keisen stations. Figure 8 compares electric energy consumption at the traction inverter input, $W_i$, under several running conditions, when the acceleration value is 1.5 km/h/s, which is almost the same as the Type 47 DMU. As seen in Fig. 8, the energy consumption of condition A is 1.4-1.5 times larger than that of condition B. This is because the maximum speed under condition A was around 90 km/h in two inter-stations out of a total of five inter-stations, whereas the maximum speed under condition B was always around 60 km/h. The maxi-
explained by the double of between the north bound and the south bound are almost
ergy. Acceleration is 9.8 m/s
(=g), the difference in potential en
ergy between the two stations Nakama and N
bound, which is explained by the difference in potential en
the north bound was smaller than on south
consumption by running direction of the EMU. Energy
traction inverter.

Moreover, Fig. 8 shows the difference in energy consumption by running direction of the EMU. Energy consumption on north bound was smaller than on south bound, which is explained by the difference in potential energy between the two stations Nakama and Nōgata. Given that the difference in elevation of the two stations is 5.2 m (=Δh), the mass of the EMU is 70 t (=M), and the gravity acceleration is 9.8 m/s² (=g), the difference in potential energy ΔU is derived as follows:

$$\Delta U = Mg\Delta h = 3.57\text{MJ} = 0.99\text{kWh}$$  \hspace{1cm} (1)

The differences in energy consumption, 1.5-2.8 kWh, between the north bound and the south bound are almost explained by the double of ΔU.

The energy consumption values in Fig. 8 represent the

Fig. 9 Complete waveforms of the battery endurance tests

4.3 Traction battery endurance

Battery endurance tests were conducted by running trains as far as possible on just battery power between Nakama and Keisen stations. The purpose of these tests was to determine the maximum running distance of the battery without recharging, control characteristics when the battery reaches a low charge state and to measure rises in temperature.

The complete battery endurance test chart is shown in Fig. 9, for when air-conditioning was not used, during springtime. The SOC (State Of Charge) of the traction battery was 91.6% at the time of departure. After 30.4-km battery-powered running, the SOC had decreased to 19.1% on arrival at Keisen station, which means that the target distance of 30 km could be reached, without recharging. The time-expanded waveforms in Fig. 10 indicate the effectiveness of the low-voltage limit control of the traction battery. More specifically, around the time point 1:57, the voltage of the traction battery reached the limit value of 1248 V, then the traction inverter decreased the motor torque. This control helps to prevent a sudden power outage due to the depletion of the battery. Such a function in normal revenue service however, would not be suitable because the decrease in motor torque could cause delay on arrival.

In Fig. 11, the running distance without recharging and the remaining SOC at the end of the battery-powered run are shown for summertime and wintertime. The set value of the low voltage limit was determined to 1152 V in summer and winter, lower than the springtime 1248 V. Due to the electric power required for air-conditioner operation, there were many cases where the EMU could not reach Keisen station unless fed by the external AC power...
supply when the outside air temperature was over 30°C in summer, and under 10°C in winter. The minimum running distance without recharging was approximately 20 km, which was found when the outside air temperature was under 10°C and the maximum speed was over 80 km/h in most inter-station sections.

4.4 Temperature rising of the traction battery

The upper limit of the on-board traction battery temperature is 65°C. When temperatures reach around 65°C, the degradation is promoted rapidly, and extremely high temperatures may cause high-temperature gas to be blown out from the safety vent hole. Low temperatures on the other hand restrict output/input power because they increase inner resistance. The optimal operating temperature therefore is between 25 to 45°C.

Figure 12 shows temperature variation for a day when the maximum battery temperature was 51.5°C, which is highest among all running tests. Although the cooling fans began to operate when the maximum module temperature exceeded 45°C, the battery temperature continued to increase up to 51.5°C. In the summertime, the cooling fans managed to suppress battery temperature so that the difference with the outside temperature did not exceed 20°C. This confirmed the fan’s ability to maintain battery temperature under the upper limit of 65°C. In wintertime, battery modules in the corners or at the bottom of the battery box tended to have relatively lower temperatures, differing up to approximately 10°C with the temperature of other modules. This means that heat retention and equalization of module temperature should be taken into account for the thermal design of the battery box.

4.5 Time for quick charge operation

Quick charge of the traction battery is required for when the charging time is short and/or the charging capacity is large. Quick charging test results are shown in Fig. 13. The charging time was 480 s, when the battery was hot. On the other hand, the time was 715 s due to the higher inner resistance of the battery, when the battery was cold. In practical situations, it is necessary to be able to estimate the longest charging time under worst conditions.
is 3-order polynomial, the charging time, $T$, is numerically solved. The estimation condition is as follows: $I_{b,cc}$ is 367 A equal to the measured value, $V_{b,occ}$ is 1612 V equal to the measured value, $Q$ is the rated value of 60 Ah, $R_b$ is the measured value at the same temperature as that found when charging stops. The comparison shows that the estimated time $T$ is longer than the measured time when the battery is hot. On the contrary, $T$ is shorter than the measured value when the battery is cold. Although there is room for the improvement of accuracy, the Eq. (4) enables an approximate estimation.

One of the countermeasures for longer charging-times in winter is to adjust the stop-charge SOC, $X_{c}$, so as to make its value lower than usual, bearing in mind of course whether there is enough energy remaining or not. Another countermeasure is to speed-warm the system when it is started.

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![Fig. 14 Evaluation of the estimated charging time](image)

5. Conclusion

The battery-powered and AC-fed dual source EMU (test train) was developed by converting an existing AC EMU. The developed EMU enables interoperable service between AC electrified lines and non-electrified lines, utilizing the AC feeding trolley for charging the traction battery. Special features of the developed traction circuit include its compact-size, thanks to a direct connection between the traction battery became colder. This is because the on-board traction battery were evaluated as follows:

1. The running distance of the developed EMU without recharging was approximately 30 km, from Nakama to Keisen station, when fed by a 83-kWh on-board battery and with no air-conditioning in operation. The running distance fell to a minimum of 20 km when air-conditioning was on high, and with a maximum speed of over 80 km/h. Predicting and reducing energy consumption of the EMU is important, in order to prevent depletion of the battery.

2. The temperature of the on-board traction battery was kept under 51.5°C even in summer, well within the limit temperature of 65°C. In winter, it was revealed that it is important to prevent over cooling of the battery and to suppress temperature differences among battery modules.

3. The time needed for quick charging rose as the traction battery became colder. This is because the inner resistance of the battery increases at low battery temperature. High inner resistance in turn strongly decreases the value of the charge current when the voltage approaches its upper limit. Attention should be paid to the SOC range and management of the battery temperature.

These test results demonstrated that the performance of the developed EMU was sufficient to run uninterruptedly between non-electrified line sections and electrified line sections. Further insight from running test results will be utilized to devise a mass-production design for battery powered EMUs.

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Authors

Yoshiaki TAGUCHI
Assistant Senior Researcher, Traction Control Laboratory, Vehicle Control Technology Division
Research Areas: On-board battery system, Power conversion

Masaki MIKI
Researcher, Traction Control Laboratory, Vehicle Control Technology Division
Research Areas: Energy storage equipment

Satoshi KADOWAKI, Dr. Eng.
Assistant Senior Researcher, Traction Control Laboratory, Vehicle Control Technology Division
Research Areas: On-board battery system, Electromechanical dynamics

Kenji HATAKEDA
Assistant Manager, Kyushu Railway Company
Research Areas: Rolling Stock

Takayuki NAKAMURA
Assistant Senior Researcher, Traction Control Laboratory, Vehicle Control Technology Division
Research Areas: Electromagnetic equipment

Yoshimasa ARITA
Manager, Kyushu Railway Company
Research Areas: Rolling Stock