Trends and Recent Studies on Hybrid Railway Vehicles

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Recently, diesel-battery hybrid railway vehicles have been introduced into operation on commercial lines, which enable on-board battery charging through regenerative energy and discharging. Furthermore, battery-mounted EMUs have been manufactured for use in transition zones between electrified and non-electrified sections. Thus, a variety of hybrid railway vehicles with energy storage devices have appeared over recent years. This report describes the trends in and recent studies on these hybrid railway vehicles.

Keywords: hybrid vehicle, bi-mode vehicle, battery-powered train, fuel cell vehicle, lithium-ion battery

1. Introduction

Rail transport has low running resistance and is more energy-saving than other means of transport such as cars and airplanes. In Japan, about 60% of all the sections are electrified, on which electric trains are running. The latest generation of electric trains uses regenerative brakes, which convert kinetic energy into electric energy during braking. Regenerative braking offers drastic energy saving compared with non-regenerative vehicles using a resistance control system. At the same time however, non-electrified sections of track have mainly diesel railcars running even now, where kinetic energy generated in braking is lost as heat. Nevertheless, owing to increased interest in energy saving triggered by various factors, such as introduction of the revised Energy Conservation Law, which came into force in 2006, and improvement in battery technology, hybrid technologies which are already widespread in the automobile industry are being applied to railway vehicles. This has led to the introduction of diesel hybrid rail vehicles on some non-electrified sections, which convert kinetic energy from braking into electric energy which is then stored in an onboard battery. New battery equipped vehicles have recently also been introduced on lines where they run directly between electrified and non-electrified sections, and the new diesel hybrid vehicles run directly between AC electrified and DC electrified sections. This report therefore discusses trends in and recent studies on these hybrid railway vehicles.

2. Changes in electric vehicle traction systems

Electric vehicle traction systems have progressed mainly in their main circuit systems; they started with a resistance control system, and passed through chopper control and field added excitation control. The Japanese National Railways adopted a combination of an AVAF (adjustable voltage adjustable frequency) inverters and induction motors, using GTO elements, for the type 207-900 series trains, which was launched in 1986. Use of the IGBT elements began in 1990, and more recently the SiC elements appeared and started to be used on some of new train vehicles. Meanwhile, studies on effective use of regenerative electric power have been conducted since around 2000 as a countermeasure against frequent occurrence of regeneration cancellation or throttling in braking, and in response to growing interest in energy saving. Studies of battery application technologies began as one of the items in the abovementioned studies. Batteries are required to have rapid charging performance to absorb regenerative power effectively. However, nickel-cadmium (NiCd) batteries, which were the highest-performing batteries at that time, did not have sufficient rapid charging performance, and nickel-metal hydride batteries and lithium-ion batteries had only just begun to be used in a handful of applications.

Afterwards, lithium-ion batteries were applied to automobiles on a trial basis. The Kiya E991 series (first generation of NE trains) a diesel hybrid test vehicle from East Japan Railway Company (JR East) was developed in 2003, followed by the LH01 (Lithiey Trammy), a battery test vehicle, from RTRI. The lithium-ion batteries applied to the Kiya E991 series were small, and used high-power cells usually employed for hybrid automobiles. For the LH01, large-capacity, high energy type cells for electric automobiles were upgraded to have higher-power. These were the pioneering model hybrid vehicles, which opened the way for many other test vehicles tried in running tests.

3. Types of hybrid vehicle

3.1 Past hybrid vehicles

Table 1 shows different types of hybrid vehicle (including bi-mode vehicles) loaded with energy storage devices, except for lead-acid storage batteries and NiCd batteries, on the Japanese market. The strict definition of “hybrid” is a system that achieves higher-quality performance by combining two or more power sources at a certain moment. Generally, “hybrid” is differentiated from “bi-mode”, which is a system that switches between electrical power from overhead contact lines and engines to run directly between electrified and non-electrified sections. A system called “dual-mode” in the main circuit system has the same meaning as “bi-mode”. “Bi-mode” is used below to avoid confusion with a “dual mode vehicle (DMV)” which run both on the railway and the road. Table 1 lists the ve-
Table 1  Hybrid vehicles which have been tested in Japan

<table>
<thead>
<tr>
<th>Model (abbreviated name)</th>
<th>Kiya E991 NE train</th>
<th>LH-01 Lithiey Trammy</th>
<th>Mo 562</th>
<th>313 series</th>
<th>Kuya R291</th>
<th>Class 602</th>
<th>Class 2103</th>
<th>Kumoya E995 NE train</th>
</tr>
</thead>
<tbody>
<tr>
<td>Owner</td>
<td>East Japan Railway Company (JR East)</td>
<td>RTRI</td>
<td>Fukui Railway</td>
<td>Central Japan Railway Company (JR Central)</td>
<td>RTRI</td>
<td>Fukui Railway</td>
<td>Kawasaki Heavy Industries (KHI)</td>
<td>JR East</td>
</tr>
<tr>
<td>Power supply system</td>
<td>Diesel engine and lithium-ion battery (10 to 15.2 kWh)</td>
<td>Lithium-ion battery (33 kWh), and afterwards loaded with overhead contact line power collector</td>
<td>Switching between overhead contact line and lithium-ion polymer battery (15 kWh)</td>
<td>Overhead contact line and electric double layer capacitor (1.4 F - 0.28 kWh)</td>
<td>Fuel cell (120 kW) or overhead contact line, switching</td>
<td>Switching between overhead contact line and lithium-ion polymer battery (45 kWh)</td>
<td>Switching between overhead contact line and nickel-metal hybrid battery (92 kWh)</td>
<td>Fuel cell (65 kW x 2) and lithium-ion battery (19 kWh)</td>
</tr>
<tr>
<td>Remarks</td>
<td>Mo 3300 class remodeled, loaded with inverter and induction motor</td>
<td>Commercial vehicle applied to test</td>
<td>Changed to two-car train and hybridized battery (36 kWh) in May 2008.</td>
<td>Use of giga cells</td>
<td>Remodeled Kiya E991.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Commercial operation</td>
<td>Only temporarily in operation</td>
<td></td>
<td></td>
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<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Model (abbreviated name)</th>
<th>Kiha E200</th>
<th>Kiha 160 Inno Tech Train</th>
<th>LH-02 Hi-tram</th>
<th>SWIMO-X</th>
<th>Class 555</th>
<th>3000 series</th>
<th>Kumoya E995 Smart Denchi-kun</th>
<th>Kiha 122</th>
</tr>
</thead>
<tbody>
<tr>
<td>Owner</td>
<td>JR East</td>
<td>Hokkaido Railway Company (JR Hokkaido)</td>
<td>RTRI</td>
<td>KHI</td>
<td>Mitsubishi Heavy Industries (MHI)</td>
<td>Odakyu Electric Railway</td>
<td>JR East</td>
<td>West Japan Railway Company (JR West)</td>
</tr>
<tr>
<td>Power supply system</td>
<td>Diesel engine and lithium-ion battery (15.2 kWh)</td>
<td>Diesel engine and lithium-ion battery (7.5 kWh)</td>
<td>Overhead contact line and lithium-ion battery (72 kWh)</td>
<td>Overhead contact line and nickel-metal hydride battery (86.4 kWh)</td>
<td>Overhead contact line and lithium-ion battery (18 kWh)</td>
<td>Overhead contact line or lithium-ion battery (from 168 to 72 kWh)</td>
<td>Diesel engine and lithium-ion battery (18 kWh, used only for auxiliary machines)</td>
<td></td>
</tr>
<tr>
<td>Remarks</td>
<td>The world’s first hybrid commercial vehicle</td>
<td>Parallel hybrid system</td>
<td>Use of giga cells</td>
<td>Remodeled fuel cell vehicle.</td>
<td>Mild hybrid system</td>
<td></td>
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</tr>
<tr>
<td>Commercial operation</td>
<td>Started</td>
<td></td>
<td></td>
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3.2 Hybrid configurations and effects

The hybrid vehicles listed in Table 1, subject to a few exceptions, are broadly classified into three categories. The configuration, effects and purposes of those categories are as follows:

1. Diesel hybrid vehicles

   These are hybrid vehicles equipped with diesel engines and batteries. Originally they were developed and introduced for the main purpose of replacing diesel railcars in chronological order of appearance on the market, except the remodeled or other vehicles which do not have a specific time of introduction and for which the dates of publications in which they appear have been used instead. Please note that there could be slight deviations from the times of their actual appearance in operation or some missing data.
running in non-electrified sections. Many had a “series hybrid” system consisting of a generator directly connected to a diesel engine, and the traction system was a combination of an inverter and an induction motor like an EMU. The main advantages of these vehicles are that regenerative energy is used in non-electrified sections and idling is enabled during parking in stations. HD300 vehicles from the Japan Freight Railway Company (JR Freight) have a smaller sized diesel engine and idling of shunting locomotive contributes to energy saving because waiting times are longer than other railway vehicles.

(2) Overhead contact line and battery hybrid vehicles

These hybrid vehicles collect electric power from overhead contact lines in electrified sections, and supply running power and battery charging power. They also charge the batteries with regenerative braking reducing cancellation and throttling of regeneration, and thus contributing to energy saving. The battery-powered trains obtain their power in non-electrified sections by discharging the batteries. This property also allows this type of hybrid vehicle to continue running even in case of electric power failures, and is a countermeasure against regeneration cancellation. Vehicles of this type are in operation on some revenue lines and are still under research and development.

(3) Fuel cell vehicles

Fuel cell vehicles are hybrid vehicles loaded with fuel cells and batteries. They are under research and development to replace diesel railcars running on non-electrified sections. Making use of the high-energy exchange efficiency of fuel cells, regenerative power is employed by making a hybrid structure in combination with a battery. Estimates indicate that energy consumption of this type of vehicle could be less than a half that of conventional diesel railcars. There are insufficient natural hydrogen resources for it to serve as fuel, however, it could be used as a fuel if other sources are used, such as hydrogen generated as a by-product of industrial manufacturing, from natural gas, or produced from renewable energy sources such as sunlight and wind power. It is environmentally-friendly and versatile and is expected to be a component of a sustainable energy society in the future.

4. Recent research and development of hybrid vehicles

4.1 Development trends in lithium-ion batteries

Many of the vehicles listed in Table 1 are loaded with lithium-ion batteries. This paper therefore briefly describes the development trend of lithium-ion batteries, which have had a heavy influence on the development of hybrid vehicles.

(1) Safety improvement

A lithium-ion battery consists of metallic oxides containing lithium ions in the positive electrode, carbon-based material in the negative electrode, and the electrolyte which is an organic electrolyte solution containing lithium salt.

The initial lithium-ion batteries, which used cobalt oxide in the positive electrode, were high performing and had energy density. However, the thermal runaway start temperature was relatively low, at approximately 200 degrees centigrade. This meant that they could catch fire easily. Thermal runaway is caused by heat generated through decomposition of the electrolyte solution or by the destruction of insulating material due to a needle-like precipitation of lithium metal formed on the surface of the negative electrode when a battery floating charge exceeds the fully charged threshold. Many lithium-ion battery fires were triggered in cell phones and personal computers being charged with unsuitably designed floating charges which did not take those lithium-ion battery properties into account, or because of internal short-circuiting due to insulation damaged from being dropped, etc.

Manganese (thermal runaway start temperature is 300 degrees centigrade or higher, and does not catch fire even after thermal runaway) or iron phosphate (safer than
manganese products) products are used in the positive electrodes of more recent lithium-ion batteries. Besides, the proper design of the charger floating charge voltages and sophistication of safety devices prevent conditions which could lead to a fire. Still, if an internal short-circuit or similar incident due to an accident etc. should occur, the decomposition of the internal electrolyte solution and gas generation will cause an increase in pressure, which could result in the release of a safety plug, and a gas discharge. Consequently, batteries on commercial vehicles should be installed outside passenger areas (on roofs or under floors).

(2) Increase in capacity (decrease in weight)

For battery-mounted vehicles which go directly into non-electrified sections, increasing the capacity of onboard batteries is crucial for extending travel distances. Commercial vehicles are equipped with 600 V battery systems, while the input voltages of the main converters for conventional EMUs are in the 1,500 V range. This trend in voltage increase is geared to increase battery capacity.

Since the outputs (kW) and energies (kWh) are not be separately designed for batteries, high power types have been applied to the hybrid railway vehicles up to today because they are advantageous in dealing with high power in acceleration and braking. Over the past few years however, high-energy types have also been studied for the above-mentioned purpose. Since the internal resistance of high-energy types is higher than that of high-output types, verifications need to be made on high-energy batteries to check heat generation and increases in temperature rise.

For lithium-ion polymer batteries that use polymer electrolytes, aluminum laminate film is used for exterior packaging. Recently, aluminum laminate film has even been applied with encapsulation technology, creating the expectation that it becomes even more lightweight.

4.2 Recent research and development at RTRI

(1) Method for estimating battery temperature rise

The lithium-ion batteries mounted on many hybrid vehicles degrade due to age (calendar) and charge and discharge cycles. Deterioration due to aging in particular is known to depend on battery temperature. However, no simplified method for estimating the temperature rise has been established. Therefore, RTRI explored a simplified method for doing this using a thermal model constructed using a thermal network method [1]. Figure 1 shows an example of a constructed thermal network. Comparison between the obtained test data and the calculation results based on this method indicate that the errors were about 2 K. Since this method enables estimation of the temperature prior to performing an actual running test, it is expected to contribute to the calculation of length of serviceable life.

(2) Hybrid vehicle running simulation

RTRI has developed the software Hybrid SPEEDY [2] by adding the energy evaluation function, hybrid-vehicle supporting function and operating-notch specifying function to the existing train performance calculation software SPEEDY. Figure 2 shows an example of estimated hydrogen consumption by performing a running simulation of fuel cell vehicles, using this Hybrid SPEEDY, which is expected to contribute to prior a study to verify if specifications such as energy saving effect and battery capacity are sufficient to design hybrid vehicles if introduced.

(3) Evaluation of fuel cell deterioration

Evaluation of fuel cell deterioration is critical in practical applications of fuel cell vehicles. RTRI made an assessment to see which parameter correlates most with deterioration factors by using a 100 kW level fuel cell mounted on the test train [3]. The voltage retention rates at a given current were used as an evaluation index. The voltage retention rate was approximately 94% as a result of about 10 years of use. The factor which correlated most with deterioration was the number of times the battery was started and stopped. Figure 3 shows an example evaluation of deterioration in the light of voltage retention rates and the number of start and stop times.

5. Conclusion

Hybrid vehicles developed so far differ in construction, purpose and target. However, they are all designed to improve railway vehicle performance, compared with conven-
Two luxury trains have been announced for 2017: one is the “TRAIN SUITE Shiki-Shima” comprising bi-mode vehicles in combination with an overhead contact line and diesel engine from JR East, and another is the “TWILIGHT EXPRESS Mizukaze” which is a diesel battery hybrid vehicle from West Japan Railway Company (JR West). At the same time, battery-powered trains for interoperation between AC electrified and non-electrified sections will appear on the Oga Line operated by JR East and on the Chikuho Main Line -Wakamatsu Line operated by JR Kyushu Railway Company (JR Kyushu). This shows that hybrid vehicles are a growing feature of revenue line operations. Moreover, Kinki Sharyo announced the appearance of the “HARMO” [4] composed of one bi-mode vehicle which uses a combination of power from an overhead contact line and a diesel battery. These railway vehicles will bring about significant advances to the conventional railway system which mainly had diesel railcars and electric trains, improvement in terms of convenience and energy saving, as well as a more enjoyable means of transit.

Moreover, the fuel-cell automobile “MIRAI” that Toyota Motor Corporation launched at the end of 2014 is considered to have affected the railway systems greatly. In 2015, Alstom and China Railway Rolling Stock Corporation announced the production plans of the railway vehicles with fuel cells manufactured by Hydrogenics and by Ballard Power Systems by 2020 respectively.

RTRI also intends to not only continue developing such systems as smaller and lighter fuel cell systems but also promote development and improvement of the laws and rules for using hydrogen as fuel of railway vehicles and realize practical application of fuel cell vehicles, thus to commit itself to achievement of a sustainable energy railway system.

References


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