JR East EV-E301 Catenary and Battery-Powered Hybrid Railcar

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As development of hybrid and electric vehicles progresses in the automobile industry, in 2000, JR East started development of a new power system using the *New Energy Train* (NE Train) test car, putting the Series *Kiha* E200 diesel hybrid railcar into commercial service in 2007. Subsequently, we fitted the NE Train with high-capacity storage batteries in 2008 and started development of a catenary and battery-powered hybrid railcar that can run on non-electrified sections. This was followed by various tests until March 2012 when practical use was shown to be feasible, so we produced Series EV-E301 pre-production cars and introduced them on some sections of the Tohoku main line and Karasuyama Line in March 2014.

This article overviews the Series EV-E301, particularly development of the battery-powered hybrid railcar system.

Introduction

Railways are said to have high energy efficiency compared to other transport modes. However, much of the energy railway operators use for operations goes to running trains. For that reason, curbing energy consumption and reducing CO_2 emissions is an important issue. Measures taken to make rolling stock more energy efficient have included reducing weight, making drive systems more efficient, and utilizing regenerative braking effectively.

Diesel railcars running on non-electrified sections cannot, in principle, be equipped with regenerative braking systems, so they are less efficient than EMUs. They also have problems with exhaust gases and noise. Consequently, we decided to develop the NE Train test car in an effort to reduce the environmental load of rolling stock running on non-electrified sections through innovations in drive systems. The success of the NE Train was demonstrated in July 2007 with the introduction of the Series *Kiha* E200 on the Koumi Line for practical use as a diesel hybrid railcar. This was followed by the Series HB-E300 introduced from October to December 2010 as 'resort hybrid railcars' in the Nagano, Akita, and Aomori areas.

Meanwhile, battery performance in areas such as output and capacity has been increased tremendously in the automobile industry with progress in development of hybrid and electric automobiles, and price has dropped. Against this backdrop, JR East shifted its focus to the feasibility of fitting trains with high-capacity batteries for running on non-electrified sections using electrical energy stored in batteries. We modified the NE Train into a catenary and battery-powered hybrid railcar (dubbed '*Smart Denchi Kun*') in 2008 using knowledge gained from diesel hybrid railcar development, and started development of a catenary and battery-powered hybrid railcar system including wayside charging facilities. This system supports operation on both electrified and non-electrified sections, thereby increasing rolling stock operational efficiency. Other effects include reduced maintenance by reducing mechanical parts such as engines and transmissions, reduced engine exhaust, and reduced CO_2 emissions and noise. Various tests were performed subsequently until March 2012, showing practical use to be feasible, so we produced Series EV-E301 pre-production cars and introduced them on some sections of the Tohoku main line (Utsunomiya to Hoshakuji) and Karasuyama Line in March 2014.

Trainset and Rolling Stock Performance

The Series EV-E301 has EV (Energy storage Vehicle) as its rolling stock type, indicating that it is a catenary and battery-powered hybrid railcar. It is a two-car fixed trainset with car No. 1 at the Utsunomiya end being a Type EV-E300, and car No. 2 at the Karasuyama end with two pantographs being a Type EV-E301. Each car can carry 133 passengers.

In terms of performance, the maximum speed is 100 km/h; the acceleration is 2.0 km/h/s, and the deceleration is 3.6 km/h/s.

Hybrid System using Overhead Catenary and Batteries

In electrified sections, the trainset raises its two pantographs to run on power from the overhead catenary and charge its batteries.

At the Hoshakuji Station junction between the electrified and non-electrified sections, the pantographs are lowered and the train runs on battery power in the

Exterior view of EV-E301 Hybrid Railcar (JR East)

non-electrified section.

Arriving at Karasuyama Station, the pantographs are raised for quick charging at the new charging facility there.

In this way, the Series EV-E301 raises and lowers its pantographs depending on the presence of overhead catenary at the running section to allow direct service between electrified and non-electrified sections. The frequency of pantograph raising and lowering is greater than with ordinary rolling stock. Furthermore, electrical current restrictions differ at quick charging by charging facilities depending on the catenary conditions, such as charging at greater collection currents than with ordinary overhead catenary. For this reason, the Series EV-E301 has equipment for identifying the type of overhead catenary, which receives location information from the wayside so the train itself automatically recognizes the type of overhead catenary at the running location.

Design

The overall concept of the Series EV-E301 is to be 'next-generation rolling stock leading to a people-friendly future', expressing the innovation of the catenary and battery-powered hybrid railcar system. The carriage design theme also reflects the image of the region along the Karasuyama Line where it has been introduced.

Exterior design

- Expressing innovation
  A simple impression is created through the new front shape and striped livery expressing innovation.
- Expressing environmental friendliness
  The silver/green livery expresses consideration for the environment, harmony with the wayside scenery, and freshness.
- Expressing catenary and battery-powered hybrid railcar system
  The under-floor battery boxes for the traction circuit and the pantographs are coloured green to harmonize the exterior. This promotes the Series EV-E301's main characteristic of being a catenary and battery-powered hybrid railcar system.

Interior design

- Innovation
  We aimed to create an image of an innovative cabin not seen before on commuter trains. This includes aspects such as indirect LED lighting arranged continuously, new

ACCUM Logomark (JR East)

ceiling cross-sectional shape, and cabin interior featuring a black upper area at end walls to clearly identify the information display space to passengers.

- Next-generation service
  Keeping in mind the concept of universal design used for the Series E233, we aimed to make the cars easy for anyone to use. This included enhancing wheelchair spaces.
- Potential of Karasuyama Line
  Elements with a feel of greenery, colour, and vibrancy were employed for the seat and floor design. These elements include features of the wayside scenery offering a feel of the seasons, traditional crafts typified by Japanese paper, and the *Yamaage* festival enlivening the Karasuyama area.

Logomark

The public was asked to submit suggestions for the nickname of the Series EV-E301, and 'ACCUM' was chosen (from accumulator or storage battery). The car's exterior bears the ACCUM logomark with an image of the flow of energy between the overhead catenary, battery, and motor.

Body Structure

Main dimensions

The straight body is 19,570-mm long, 2800-mm wide, and 3620-mm high. The total height with pantograph retracted is 3980 mm to run through smaller tunnels. The floor height is 1130 mm.

Construction

The body is a lightweight stainless-steel construction except in part of the underframe where strength is needed, and the head structure is reinforced at the front as a countermeasure to damage in level-crossing accidents. Reinforcement was added as necessary to improve body strength because the Series EV-E301 is heavier than conventional cars despite use of lighter materials due to the onboard batteries. On the other hand, the weight had to be reduced as far as possible to keep battery consumption down. Consequently we changed materials to aluminium, added holes to reduce weight, and took other measures to make the body as light as possible while confirming body strength.

Passenger Cabin

Structure and equipment

Both cars in the Series EV-E301 two-car trainset have the same longitudinal seating arrangement with equipment room at the rear. Each car has seating for 48 passengers with 12-person seats between the three doors on each side.

The seats are cantilever type with heaters and air conditioning/electrical equipment housed under them, having independent cover-type risers. Sinuous springs are used for the seat face to improve cushion comfort. These springs are integrated into the attachment frames to make attaching and removing easier. Seat cushions and backs are bucket type with an effective width of 460 mm to clearly identify the seat spacing for each passenger.

Interior of EV-E301 passenger cabin (JR East)

Interior lights are indirect LEDs to cut power consumption and give continuous unbroken lighting for the entire length of the cabin, offering a never-before-achieved cabin image. The side ceilings have a new three-fold cross sectional shape with a design aspect of one face being black with a *washi* Japanese paper feel. Cabin decorative panels are mostly melamine.

As a measure to further enhance accessibility functions, an LCD fare display that also serves as an on-board guide for information such as the next station is located at the top centre of the wall behind the driver's cab. A chime sounds when doors open and close and a red lamp flashes, giving guidance to passengers with vision and hearing impairments. The door side edges also use yellow door-stop rubber to make doors more visible from both inside and outside the train.

Hand straps and luggage racks are 50-mm lower at part of the front 12 seats, which include priority seats, allowing easier access by shorter passengers. Moreover the stanchion poles in the priority seat area have a curved shape and non-slip surface, making them easier to use. Aluminium round pipes are used for the luggage racks to make them lighter.

A wheelchair space at the back end features an emergency intercom at a level where passengers can communicate with crew while seated in a wheelchair.

Windows and doors

The side windows are separated into top and bottom sections with the top section able to slide down to open. Sufficient window area was secured by combining with fixed windows. The windows use UV-absorbent glass; FRP window frame covers are set on the interior side of side windows.

The side sliding doors use stainless steel panels on both the interior and exterior, with a honeycomb core between them for lightness and strength. The effective width of the doors is 1300 mm.

The end sliding doors at the gangway between cars close naturally thanks to tilted door operating equipment. They have an 800-mm effective width, so wheelchair users can pass through, taking into account limited door operation by one-person crew.

Cab Equipment

The only crew cabin is the one-person operation driver's cab with no corridor connection to the passenger cabin. To protect the driver in an impact, the body front has a

Cab equipment of EV-E301 (JR East)

reinforced structure as well as a rescue port behind the cab.

The Series EV-E301 has new switches required by a catenary and battery-powered hybrid railcar, such as quick-charge switches, as well as equipment for identifying the type of overhead catenary. They are arranged to help prevent driver error.

The front window glass is partitioned into two parts with a 2:1 ratio for the driver's side and assistant's side, taking maintainability into account. It is vertically curved large quadratic surface glass

The front marker lights use LEDs located on the top front with two each on the left and right sides. The rear marker lights are placed vertically at the bottom rear to give a characteristic design.

Equipment Layout

Under-floor equipment layout

Auxiliary power sources and related equipment along with electric compressor units are installed on car No. 1, and traction circuit-related equipment, such as power converters, is installed on car No. 2. A total of 10 battery boxes for the traction circuit are located in groups of five in each car.

Rooftop equipment layout

Two pantographs supporting quick charging are installed on car No. 2. Both cars have air conditioners and train radios.

Major Equipment

Main controller and auxiliary power source

DC/DC converters are located under the pantographs to convert the 1500-Vdc overhead line voltage to 630 Vdc. Large-capacity lithium-ion batteries are located in the 630-Vdc intermediary link circuit as traction circuit batteries, and there is also a VVVF inverter and two auxiliary induction motors with 630-Vdc input. Moreover, the auxiliary power source primarily runs on power from the traction circuit batteries. The intermediary link circuit is 630 Vdc to secure safety with the lithium-ion batteries. The Series EV-E301 is a two-car trainset, so a two-group structure is installed to ensure redundancy for the traction circuit system.

Since the intermediary link circuit is 630 Vdc, the VVVF inverter and induction motors are not the same type as used by ordinary EMUs running off 1500-Vdc overhead catenary. During the design stage, we considered a system where the intermediary link circuit was 1500 Vdc

On board display showing energy flow (JR East)

and a DC/DC converter was located upstream from the batteries, but the current system was used so as not to reduce the limited power from the battery energy through voltage-conversion losses.

The drive method with this system differs in electrified and non-electrified sections. At power running on non-electrified sections, motive power is generally electric power from batteries. On electrified sections, the train receives electric power from the overhead catenary while running on electric power from the batteries, so the actual battery state of charge (SOC) does not fluctuate very much.

Regenerative energy from braking is generally stored in the batteries but when the batteries are fully charged, it is returned to the overhead catenary in the same way as an ordinary EMU.

At power running on non-electrified sections, regenerative energy from braking is stored in the batteries and subsequently used as energy for motive power.

The traction circuit performance offers a starting acceleration of 2.0 km/h/s, giving acceleration equivalent to limited-express trains. The maximum speed on the Karasuyama Line is 50 to 60 km/h, but is 100 km/h on the Utsunomiya Line. Two-level inverters are used for the DC/DC converter and VVVF inverter to increase quality by reducing the number of elements. The DC/DC converter and VVVF inverter have an integrated chassis structure to make the devices more compact. Inverter equipment is cooled by air as the train moves, but the DC/DC converter has cooling fins to allow sufficient cooling when the train is stopped at quick charging and there is no air flow.

Main motor

The main motor is a three-phase squirrel-cage open type induction motor. An ordinary EMU induction motor cannot be used because the inverter voltage is 630 Vdc. Consequently, we used the same induction motor as used on Type *Kiha* E200 hybrid railcars with similar battery voltage, and worked to make the equipment common between the two.

Batteries (for motive power)

Battery energy is important with the Series EV-E301, so we decided to use lithium-ion batteries with higher energy density, although the power is weaker than using capacitors. 630 Vdc is supplied from 22 traction circuit batteries in series; arranging 10 banks of these in parallel achieves 190 kWh. Each bank is housed in one box, and a total of 10 boxes are installed under the floor.

The capacity was designed to give leeway in terms of charge failure in addition to energy consumed when running, taking into account situations that might occur, such as schedule disturbances.

To ensure a high safety level for the lithium-ion batteries, the double protection of a battery controller and power converter controller was provided in addition to a structure to prevent battery box rupture in an accident.

Power collection device

A single arm design was adopted for the two pantographs; they feature strengthened contact strips to handle the large current at quick charging. Moreover, the pantograph horn is painted fluorescent green to give distinctive design characteristics and to increase visibility at night.

Brake equipment

The braking system uses electric-command brake equipment combined with regenerative braking equipment. There are five types of brakes: service, emergency, straight air reserve, snowproof, and holding. Each bogie has one brake-operating unit.

Service brakes control each car. By performing electro-pneumatic cooperative control where the trailing bogie braking power is supported as much as possible by the motored bogie regenerative braking, regenerative energy is increased and brake shoe wear is reduced.

To prevent increased braking distance and wheel flat generation due to sliding when braking, wheel slide re-adhesive control is provided. Each axle has a tachometer generator to detect speed and if sliding is detected, braking power to the sliding axle is temporarily weakened to promote re-adhesion.

As a feature of the Series EV-E301, emergency braking is applied based on the overhead catenary status determined by the equipment for identifying the type of overhead catenary to prevent entry into non-electrified sections while the pantographs are raised, and movement of the train during quick charging.

Air conditioner and heater

One 33,000-kcal/h air conditioner is mounted on the roof. Sheathed-wire type heaters are located in the passenger cabin longitudinal seat area and wall area of the wheelchair space.

The air conditioning is controlled manually from the monitor screen by selecting heating, cooling, or ventilation. However, when heating or cooling is set, output is selected automatically to maintain the base temperature set for the cabin.

Door operating equipment

The door equipment is a directly operated pneumatic type with a semi-automatic function. At door closing, the closing force is weakened temporarily after closing to allow easy removal of hands, fingers, clothing, bags, etc., that may be trapped in the door.

Monitoring device

The monitoring device supports the driver's management of the catenary and battery-powered hybrid railcar system.

The energy flow screen shows the state of the batteries, and the driver can visualize the flow from the pantograph through the static converter as well as battery charging and running of the motors through the inverter. Energy flow can be confirmed at power running, coasting, braking, and stopping, and the battery charge, and overhead line type, are also displayed.

The monitoring equipment is also compatible with conventional-line digital radio applications, including operation information and rolling stock information display, crew support functions such as one-person crew operation device control, control functions for service equipment such as coolers and heaters, and inspection/repair functions related to failure recording and testing.

Train protection system

The trains are equipped with the ATS-P train protection system. It sends information on overhead catenary status according to the running location from the wayside to the equipment to identify the type of overhead line.

Train destination indicators and cabin guidance displays

Train destination indicators use three-colour graphic LEDs installed at both the front and sides.

There are no cabin guidance displays. The next station, destination station, side with opening doors, operation information, etc., are displayed on the LCD fare display mounted on the wall behind the driver's cab.

Announcement equipment and emergency intercom

The announcement equipment has functions for making announcements in the passenger cabin and outside the train. There is also an automatic system that automatically makes appropriate announcements at locations where needed.

Emergency intercoms allow two-way passenger communications with crew. They are located at two positions in each car, including the wheelchair space.

One-person crew operation equipment

The Series EV-E301 runs with one-person crew on the Karasuyama Line. Equipment to handle one-person crew operation includes an outside one-person crew indicator showing passenger doors, in-cabin ticket-issuing machine, fare box, and LCD fare display (also serving as cabin guidance display). The outside one-person crew indicator and ticket-issuing machine are at the two front and back doors on each side of the car, taking account of the flow of passengers getting on at the back and off at the front during one-person operation.

Bogies

The Series EV-E301 bogies are bolster-less with trailing bogies at the front and powered bogies at the rear.

The wheels are corrugated for the trailing bogies and solid rolled for the powered bogies. The wheel bearings use sealed duplex tapered roller bearings.

The power transmission is a parallel cardan-type drive with main motor and gear units connected by TD joints. The gear ratio is 6.06.

The car suspension system supports the vertical load of the body on left and right air springs attached to the top of the bogie frame. The traction device has a centre pin attached to the body joined to the bogie frame with a single link.

An axle beam type is used for the axle box suspension.

The brake equipment uses a one-sided tread block and disk brakes for the trailing bogie, and a one-sided tread block for the powered bogie.

The lead axle has a ceramic jetting device for slip prevention.

Conclusion

The Series EV-E301 function has been confirmed by performance tests and charging tests, and its crew made training runs before the start of commercial operation using one trainset of pre-production cars on the Karasuyama Line on 15 March 2014. We have high hopes that it will be very popular with users and local residents into the future.

We plan to replace all diesel railcars on the Karasuyama Line with Series EV-E301 cars sometime in the future.

We are working to improve the battery technology as well as accelerate our efforts in catenary and battery-powered hybrid railcars. ■

Further Reading

H. Abiko, 'Development of Hybrid Railcars and Catenary and Battery-powered Hybrid Railcar System,' *JR EAST Technical Review No. 23*

M. Shinbo, H. Abiko, H. Sonoda, K. Shibanuma, 'Utilization of Catenary and Battery-powered Hybrid train system (4-S7-9),' *Proceedings of the 2013 Japan Industry Applications Society Conference*

H. Takiguchi, 'Overview of Series EV-301 Catenary and Battery-powered Hybrid Railcar,' *Rolling Stock & Machinery*, Japan Railway Rolling Stock & Machinery Association (May 2014)

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