Series Hybrid Locomotive Equipped with Energy-Saving Electrical Equipment for European Market

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Japan and other countries have set a target of reducing greenhouse gas emissions to net zero by 2050, that is, carbon neutrality by 2050.

Toshiba Infrastructure Systems & Solutions Corporation has been engaged in the development of technologies for hybrid locomotives equipped with both a diesel engine generator and lithium-ion batteries as a power source, in order to realize rolling stock with improved energy saving and reduced exhaust gas emissions for the Japanese market. Taking advantage of our accumulated experience in this field, we are responding to the need for further emission reductions worldwide by developing key technologies for energy-saving electrical equipment, including a traction battery system, a power conversion cubicle, and a traction motor, with the aim of introducing series hybrid locomotives to the European market, which is characterized by a high level of environmental consciousness. We have applied a highly efficient, easy-to-maintain permanent magnet synchronous motor (PMSM) as the traction motor. Tests on the traction motor in combination with the power unit have verified that it achieves a high efficiency of 97.4%.

1. Introduction

In both Japan and Europe, it is becoming more important than ever before to save energy and reduce exhaust gas emissions using new technologies. For decades, the railway industry has been using diesel-powered locomotives in places where overhead electricity is unavailable. As the automobile industry has undergone a shift in focus toward hybrid vehicles, the railway industry has also been engaged in the research and development of hybrid locomotives powered by a diesel engine in order to save energy.

Toshiba Infrastructure Systems & Solutions Corporation has been developing hybrid locomotives combining a diesel engine generator and a lithium-ion battery pack as a means of saving energy and reducing exhaust emissions. We have already delivered Class HD300 hybrid locomotives jointly developed with Japan Freight Railway Company, contributing to a reduction in environmental burden[(1)]. Participating in the Hybrid Electro-Mechanical Shunter (HELMS) Project to convert the BR294 locomotive with a hydraulic transmission into the BR1094 hybrid locomotive, we supplied electrical equipment to Europe, including traction battery systems and power conversion cubicles.

This report describes the series hybrid locomotive that we are developing for the European market and the features of its energy-saving electrical equipment while referring to the related European Norm (EN) standards.

2. Overview and development targets of hybrid locomotives for European market

As part of the Diesel-Electric Hybrid Locomotive (DEHLo) Project undertaken by DB Cargo AG, a subsidiary of Deutsche Bahn AG and the largest rail freight transport operator in Europe, we received a contract for the design and manufacture of a hybrid locomotive named the Toshiba HDB 800 (hereinafter the T-HDB 800). We have commenced the development of the T-HDB 800, with the aim of achieving more than 30% higher fuel efficiency than the current diesel locomotives of DB Cargo AG. The traction battery system for the T-HDB 800 has an output of 750 kW and uses the SCiB™ rechargeable lithium-ion battery developed by Toshiba Corporation. The traction motors are permanent magnet synchronous motors (PMSMs) featuring high efficiency and ease of maintenance[(2)].

Figure 1 shows an artist's rendition of the T-HDB 800, and **Figure 2** shows the configuration of its main circuit system. In order to increase robustness to the failure of one component, the T-HDB 800 provides dual modular redundancy, with each replication consisting of a diesel engine and a generator. Four traction motors are individually controlled by four inverter circuits.

There are two different types of hybrid systems: parallel and series. As is the case with the Class HD300 hybrid locomotive, we have employed a series hybrid architecture for the T-HDB 800. A series hybrid system uses an engine only to generate electricity by means of a generator

Figure 1. Rendering of T-HDB 800 hybrid locomotive
We aim to achieve more than 30% higher fuel efficiency than existing diesel locomotives.

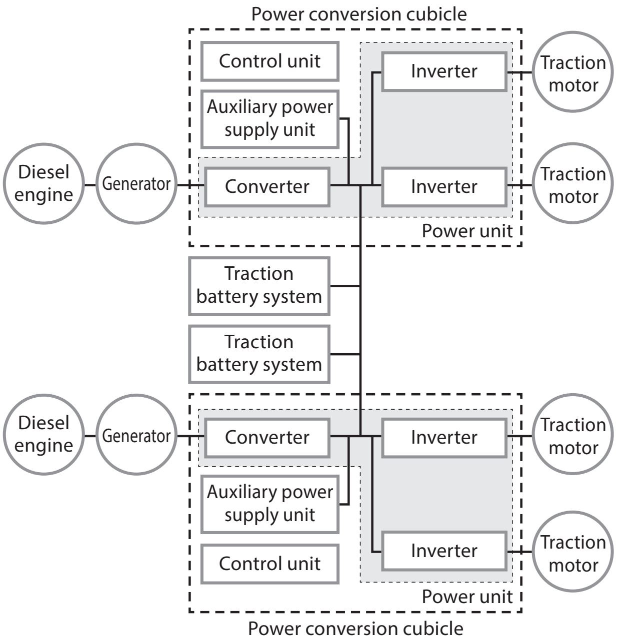

Figure 2. Configuration of main circuit system of T-HDB 800
A series hybrid system uses an engine to drive a generator, which generates electricity to run the traction motors. The traction battery system is charged and discharged as necessary.

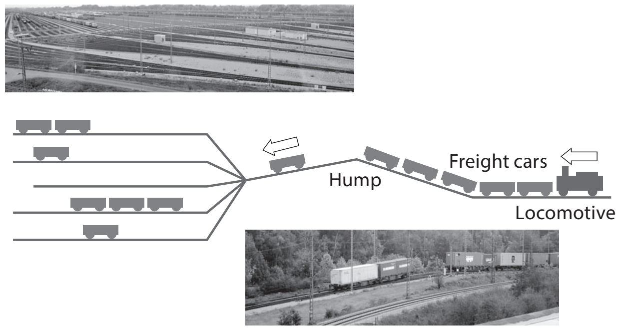

Figure 3. Shunting operation in freight yard
A heavy load is placed on the traction motors because the locomotive has to continuously propel the cars on a rising gradient at low speed.

and propels the vehicle with traction motors. The series hybrid system eliminates the need for the conventional mechanical transmission elements; namely, the gearbox and transmission shafts. It is therefore easier to reduce the size and weight of a series hybrid system compared with a parallel hybrid system, enabling reductions in parts count and system failure rate.

The main role of the T-HDB 800 is to separate freight trains onto one of several tracks in a shunting yard according to their destinations. **Figure 3** illustrates a shunting yard called a hump yard, which is commonly found in Europe. A hump is an artificially built hill over which a locomotive pushes freight cars from behind at low speed. The freight cars are uncoupled at the crest of the hump so that they roll by gravity onto their destination tracks. This process of shunting in a hump yard operation exerts the greatest load on the traction motors.

The T-HDB 800 is designed to be able to run on a main line for a short distance in order to travel between different yards. A hybrid system has a significant energy-saving effect on the shunting operations in a yard. Powering and braking are repeatedly performed during shunting operations. Since a diesel engine is not suited to sudden acceleration, a traction battery system compensates for the energy deficiency during powering. Conversely, the regenerative energy generated during braking is converted into electricity to charge the battery. In this way, a hybrid system helps to save energy.

Since the T-HDB 800 runs both on the shunting yard and the main line, it requires sufficient electrical ratings so as to be able to run on low-speed and high-speed sections without interruption. However, conventional traction motors generate considerable heat. We have solved the heat problem by using a low-loss material for the traction motors of the T-HDB 800.

3. Overview, development concepts, and features of electrical equipment

We have developed the electrical equipment in Japan. For the traction battery system requiring particularly high safety, we have utilized SCiB™ battery modules and their peripheral devices certified for Safety Integrity Level 4 (SIL 4), a measurement that represents system safety performance based on the EN 50126 and EN 50129 standards[3]. **Figure 4** shows the SIL 4 certification mark.

3.1 Traction battery system using SCiB™

The SCiB™ uses lithium titanate oxide for the anode. Despite being classified as a lithium-ion battery, the SCiB™ features enhanced safety, long life, low-temperature operation, rapid charging, high input/output power, and a wide effective state-of-charge (SOC) range. We therefore adopted the SCiB™ for the T-HDB 800.

The traction battery system of the T-HDB 800 is designed in such a manner that, in the event of a fault,

Figure 4. Safety Integrity Level (SIL 4) certified by TÜV Rheinland
We have obtained safety certification for the SCiB™ and its peripheral components from TÜV Rheinland, a third-party testing organization.

the faulty component can be disconnected. The traction battery system consists of 56 SCiB™ modules connected in series. The traction battery system is duplicated to provide a total capacity of 120 kWh. As is the case with power conversion cubicles, the traction battery system is water-cooled to reduce any rise in battery temperature in order to achieve long life.

3.2 Traction motors (PMSMs)

The EN 13749 standard stipulates the requirements for the strength of a bogie on which traction motors are mounted. We analyzed the strength in accordance with EN 13749 using the motor model shown in **Figure 5**. Taking manufacturing variations into consideration, we have secured sufficient safety for the traction motors by applying a safety factor according to the FKM Guideline (Fracture Mechanics Proof of Strength for Engineering Components) widely used in Germany.

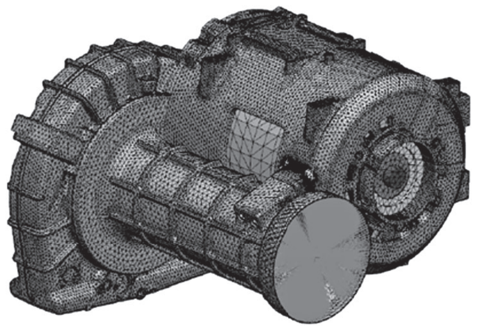

Figure 5. Finite element method (FEM) analysis model of PMSM
We have performed a strength analysis in accordance with EN 13749 and the FKM Guideline.

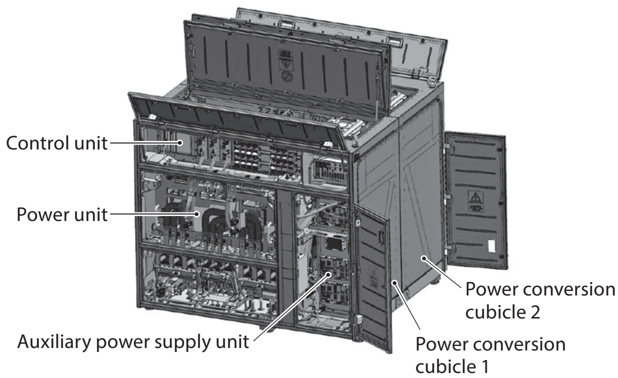

Figure 6. Power conversion cubicles
Two identical power conversion cubicles are mounted back-to-back.

3.3 Power conversion cubicle

Figure 6 shows the power conversion cubicles that drive the traction motors using electric energy generated by generators. Each power conversion cubicle incorporates a power unit consisting of one converter and two inverters as well as a control unit for the power unit and an auxiliary power supply unit.

The features of the power conversion cubicle are as follows:

(1) In order to ensure uninterrupted locomotive operation, the power converter is duplicated to provide redundancy in case one should fail. In addition, the power unit provides an inverter for each of the traction motors so that they can be disconnected individually.
(2) The T-HDB 800 is equipped with a forced water cooling system to reduce the size of the power conversion cubicle.
(3) Even though each traction motor is controlled by a dedicated inverter (Figure 2), the control functions are optimally split between the control and power units so that one control unit can control one converter and two inverters. As a result, we have succeeded in further reducing the size of the power conversion cubicle.
(4) The power unit provides extra space to add an insulated-gate bipolar transistor (IGBT) in case any need arises to receive a power supply via an overhead wire.

4. Hybrid control and simulation technology

In order to realize an energy-efficient hybrid locomotive, it is important to run the diesel engine with the highest efficiency possible. There are two ways to control the engine: (1) continuous engine control, which continuously changes the engine power according to the amount of power required by the vehicle, and (2) discrete engine control, which operates the engine at the point within the maximum battery charge/discharge range that provides high engine efficiency regardless of the amount of power required by the vehicle.

Leveraging our experience in this field, we have been refining simulation technology to achieve optimal engine control. Our enhanced simulation technology is employed to determine the load-sharing ratio between a traction battery system and an diesel engine that provides the lowest fuel consumption based on the vehicle running pattern (i.e., the speed-vs-location profile). This simulation technology is capable of simulating not only the battery cell temperature but also the speed of battery deterioration, contributing to a reduction in the risk of design iteration.

We determined which hybrid control method to use taking both the simulation results and actual efficiency measurements into consideration.

5. Tests and evaluations of test results

5.1 Results of type and combined tests

We performed type tests of the power unit and the traction motor to be mounted on the T-HDB 800 as well as combined tests. These included vibration, efficiency measurement, and temperature rise tests in order to verify that the power unit and the traction motor satisfy their specifications. Electrical equipment for the European market must be tested for compliance with the EN standards. **Figure 7** shows the EN standards that apply to the electrical equipment and rolling stock of a hybrid system. These EN standards stipulate the required tests and test conditions, covering the entire development process of rolling stock from individual parts tests to locomotive tests.

We have completed all of the tests satisfactorily. As a result of a rated load test of the traction motor, the measured efficiency of the traction motor and the power unit was found to be 97.4% as against the design target of 96.0%. This equates to a roughly 5% improvement in efficiency compared with the conventional open-type induction motor.

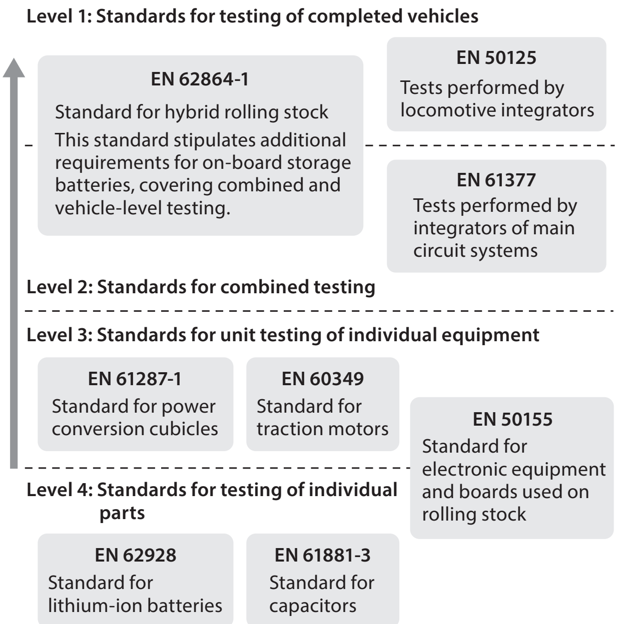

Figure 7. Main test standards system for hybrid locomotives
EN 62864-1 and EN 62928 are specific to hybrid locomotives. The other standards also apply to rolling stock without an on-board battery system.

5.2 Future test plan

We are currently measuring the equipment efficiency at our factory. Thereafter, we will perform combined tests of the entire locomotive system, including the diesel engine generators and traction battery systems, at a delivery site in Europe, followed by optimization of the hybrid control system, various tests, and measurements of overall efficiency.

We have established Toshiba Railway Europe GmbH in Germany, which will play a leading role in car design, rolling stock system design, car assembly, and testing in Europe.

In Europe, it is mandatory to obtain homologation (type approval) for new locomotives from a third-party testing organization in order to apply for operating authorization. The homologation procedure includes an examination of the results of various tests, such as (1) electromagnetic compatibility (EMC) tests, (2) functional safety tests, (3) brake tests, and (4) noise tests. It is difficult to obtain homologation even for European manufacturers. We are pursuing the DEHLo Project, drawing on our experience with the HELMS Project.

6. Concept of new hybrid locomotive

As mentioned in Subsection 3.3, the T-HDB 800 is being designed so as to be able to receive electric power via overhead wires. In order to enhance the usability of locomotives and achieve a further reduction in exhaust gas emissions, Europe prefers railway lines that operate on electricity without diesel engines in areas where overhead wires are available. To realize such railway lines, triple hybrid locomotives are necessary that are capable of running from three types of power supplies: an overhead wire, a diesel engine generator, and a traction battery system (**Figure 8**).

In order to actualize a triple hybrid locomotive, many challenges must be overcome such as securing sufficient on-board space to mount the required equipment and establishing a technology for switching between the different power modes. It is therefore essential to reduce the size of all locomotive equipment. Of equal importance is to reduce the size and weight of power supplies by minimizing their capacities based on a calculation of their optimal load-sharing ratio according to the operating states.

For example, among our ideas is the use of only one small diesel engine generator solely to generate the energy required for emergency running, depending on the operating pattern of the locomotive, in order to leave sufficient space for the equipment for overhead wire operation and the traction battery system.

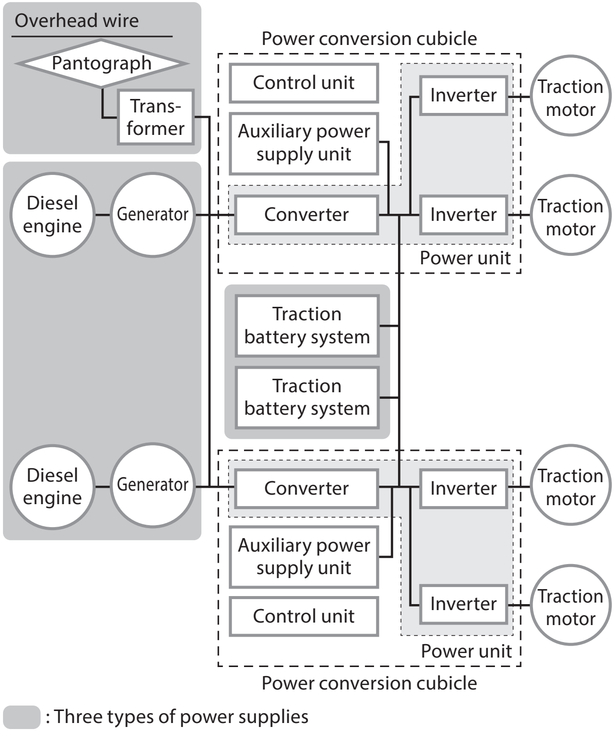

Figure 8. Configuration of main circuit system of triple hybrid locomotive with additional power supply from overhead wire

A power feeder circuit has been added to the main circuit system of the T-HDB 800 in order to supply electricity from an overhead wire via a pantograph and a transformer.

7. Conclusion

This report focuses on the features and development status of the electrical equipment for the T-HDB 800. Henceforth, most of the development work will be transferred to Toshiba Railway Europe GmbH. We will continue our efforts to achieve a more than 30% increase in fuel efficiency.

In order to meet customer requirements for even higher fuel efficiency, the newly developed electrical equipment has been designed in such a manner that it can also support overhead wire operations with minimal modification. We will continue to work on technological development to achieve early realization of a triple hybrid locomotive, thereby contributing to a further reduction in the environmental burden.

References

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