Practical Application of a Hybrid Drive System for Reducing Environmental Load

Kazuo Tokuyama
Motomi Shimada
Kiyoshi Terasawa
Takashi Kaneko

OVERVIEW: As part of our efforts to address energy and environmental issues, Hitachi, Ltd. is actively involved in reduction of energy consumption by means of compactization, improving efficiency of equipment, and regenerative braking. However, as for DMUs running in non-electrified regions, on top of the fact that regenerative braking cannot be applied as a system for direct drive by diesel engine, reduction of NO_x *and* CO_2 *gases contained in exhaust is a challenge. Accordingly, we have practically applied a hybrid drive system that can reduce environmental load by means of applying secondary batteries to store regenerative energy and by running the engine at maximum rotational frequency (at which efficiency is high) and switching to electrical energy. What's more, as technical expansion applying rechargeable batteries, we have developed (1) a diesel high-speed-train hybrid system (planned to be deployed on long-distance high speed railways) and (2) a battery-type sequential regenerative system (for realizing stable performance and low energy consumption in regards to electric-train-use drive systems).*

INTRODUCTION

HITACHI, LTD. has been developing hybrid drive systems — aiming to reduce environmental load — since 2001.

In collaboration with East Japan Railway Company (hereafter referred to as JR East), Hitachi constructed a series hybrid drive system — combining a diesel engine and high-energy-density lithium-ion batteries — and by mounting this system in a test train called "NE Train," we have performed verifications (such as demonstration of reduction of fuel consumption and assessment of operational lifetime of the rechargeable battery) aimed at practical application of the system on commercial trains.

In the present work, utilizing the results obtained with the NE Train, we accepted an order for, and subsequently manufactured, a "hybrid drive system for the *Kiha* E200 DEMU (diesel electric multiple unit)" from JR East (see Fig. 1).

This report describes the hybrid drive system for

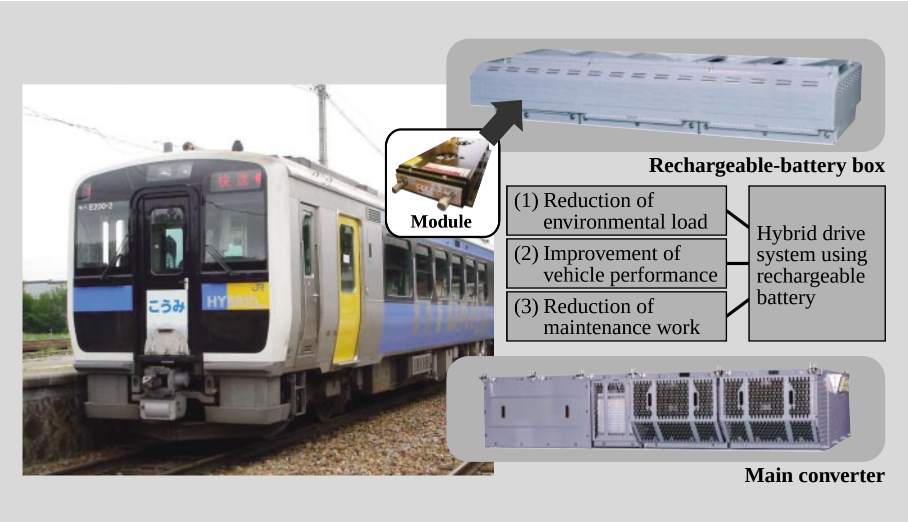

Fig. 1—Hybrid Drive System.
The world's first practical application of a hybrid drive system for commercial vehicles was achieved. Hitachi will push ahead with development of railway-vehicle system technology that takes the environment into account.

the *Kiha* E200 and describes part of the railway-system developments aimed at applying rechargeable batteries under the higher order goals of reduction of environmental load, improvement of vehicle performance, and reduction of maintenance work.

CURRENT BUSINESS CLIMATE OF SECONDARY-BATTERY HYBRID SYSTEMS

Background Concerning Development of Hybrid Drive Systems

In recent years, accompanying energy issues such as fossil-fuel depletion, environmental issues, such as atmospheric pollution from auto emission generated by various power sources and global warming due to carbon-dioxide emissions, have been generating a great deal of concern. To address such concerns from society, while continuing to improve the environmental performance of existing engines, all car manufacturers are developing clean motive systems to replace conventional ones.

At the same time, in regard to the railway field as well, to deal with energy and environmental issues, reduction of electrical-power consumption, by weight saving, efficiency improvement of equipment, and regenerative braking, has been aggressively pursued. However, as for railway cars running between non-electrified zones, regenerative braking as a method for direct driving has not been possible with diesel engines. Given that fact, as a way of enabling regenerative braking on railway trains, a hybrid drive system aims to reduce fuel consumption while cutting harmful waste emission.

Expansion of Applications of Rechargeable-battery Technology

As for railway cars, a drive power of over 400 kW per car is needed. Consequently, in the case of the developed NE train, as an advantageous equipment configuration for shouldering this high power, even in the case of rechargeable batteries, a series hybrid method was adopted. With the successful main converter of JR East's general electric trains as our basis, we considered reduction of the amount of maintenance work by sharing of main components. Moreover, to inherit high acceleration/deceleration performance, a lithium-ion battery for use in hybrid passenger cars (combining high energy density and high power density) has been adopted for the rechargeable battery system.

The NE train is presently in its second stage of development, and the series hybrid system is fitted in a fuel cell battery vehicle (with the diesel engine replaced with fuel cells), which is currently undergoing running tests. From now onwards, while expanding the commercialization of the hybrid drive system, through application of the rechargeable battery system, we will continue to push ahead with development of next-generation railway systems that can enjoy heretofore impossible added value.

HYBRID DRIVE SYSTEM FOR KIHA E200

Configuration of Hybrid Drive System

The basic components of this hybrid drive system for *Kiha* E200 are taken from the series hybrid system developed with the NE train. However, in consideration of use in commercial railway vehicles, countermeasures against transportation disorders and assurance of passenger facilities have become necessary. Accordingly, as for the hybrid drive system for *Kiha* E200, equipment was made compact and system redundancy has been achieved (see Fig. 2).

The main structural components of the hybrid drive system are summarized as follows.

(1) Main converter

The main converter is composed of an inverter circuit for driving an induction motor, a converter circuit driven by generated power output from a generator, and an auxiliary circuit for supplying power to air-conditioners and so on (see Fig. 3).

(2) Rechargeable-battery box

The rechargeable-battery box integrates eight lithium-ion battery modules as a unit, and two boxes are attached to the roof of a train car (see Fig. 4). As a two-group configuration, a line breaker for releasing

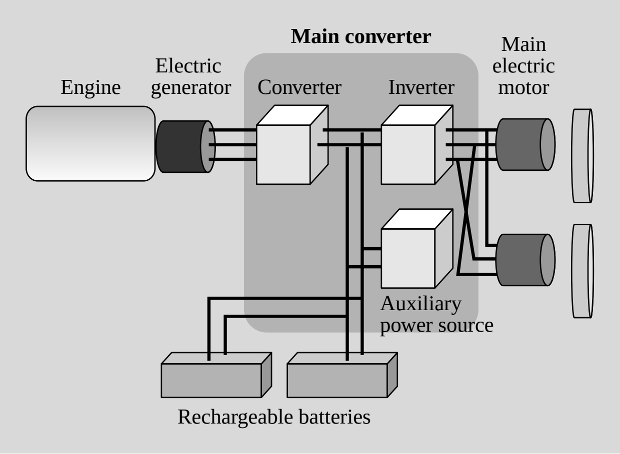

Fig. 2—Hybrid Drive System for Kiha E200.
The main storage battery was developed as a duplex system in consideration of redundancy.

Fig. 3—Main Converter.
The inverter equipment, converter equipment, and SIV (static inverter) are combined, thereby achieving compactness and weight-saving.

Fig. 4—Rechargeable-battery Box.
Since the rechargeable-battery box is fixed on the roof of the train carriages, heat-shield plates are set up to prevent rise in temperature of equipment due to direct sunlight.

failed groups at malfunction times is equipped.

(3) Main electric motor

With a three-phase induction motor of a general train (to be also used on Tokyo's Yamanote Line trains) as a base, the main circuit was revised in accordance with main circuit voltage.

(4) Electric generator

The electric generator is based on a three-phase induction motor. Aiming at noise reduction, an aluminum rotor was used for the first time. In addition, in the case of the NE Train, connection of the generator to the engine output shaft was done by a coupling mechanism; however, in the case of *Kiha* E200, a direct coupling to the engine is adopted in consideration of making the equipment more compact.

Control of Hybrid Drive System

(1) System overall control

In regard to the unit for system overall control, electrical output in each part of the system is monitored, electric charge of the rechargeable batteries is managed, and commands are sent to each part according to these statuses. Moreover, protection coordination during malfunctions is carried out by the system overall-control unit — a key role of the system.

(2) Energy management

By controlling engine power generation in response to the SOC (state of charge) level of the main regenerative storage battery and the speed of the train, running performance that maintains the correct amount of charge is assured. To put that more concretely, engine power generation is controlled in the following manner.

(a) During train stops: To prevent noise while stopping at stations and improve fuel consumption, the engine power generation is shut off.

(b) Departing from stations: Powering of the train is done by the batteries only up to approximately 30 km/h.

(c) During powering: Output power is complemented by engine power generation.

(d) During regenerative braking: Engine power generation is stopped, and regenerative output power is taken up by the rechargeable batteries.

(e) During holding braking: When the SOC exceeds the charge limit, engine braking is used, and overcharging is prevented.

(3) Gradient-prediction control

Although the fundamental energy-management control is inherited from the NE Train, to further improve fuel consumption, gradient-prediction control (which highly efficiently uses potential energy) is newly added. This function recognizes the position of the train itself and controls energy in response to the inclination of the railway track (i.e. uphill inclination, flatness, and downhill inclination).

(a) In downhill sections: During powering or coasting, secondary-battery energy is given priority for use; on the other hand, during braking and holding braking, more electrical charging is done and regenerative-energy is raised.

(b) In uphill-inclined and flat sections: With a SOC at which charging starts lower than that for the NE Train, the charge/discharge region is expanded.

APPLICATION OF SECONDARY-BATTERY SYSTEM

Hybrid System for High-speed Diesel Trains

Aimed at improvement of environmental friendliness such as fuel-consumption reduction in main line DELs (diesel electric locomotives) and DMUs (diesel multiple units) operating on the UK's main line, long-distance high-speed railways, a large-capacity hybrid system for handling high-speed DELs and DMUs has been developed.

This system enabled electric regenerative braking that had been impossible up till then, and boosted energy saving through regenerative energy reuse and increased acceleration by battery assistance.

(1) Drive system

The configuration of the power-generation system

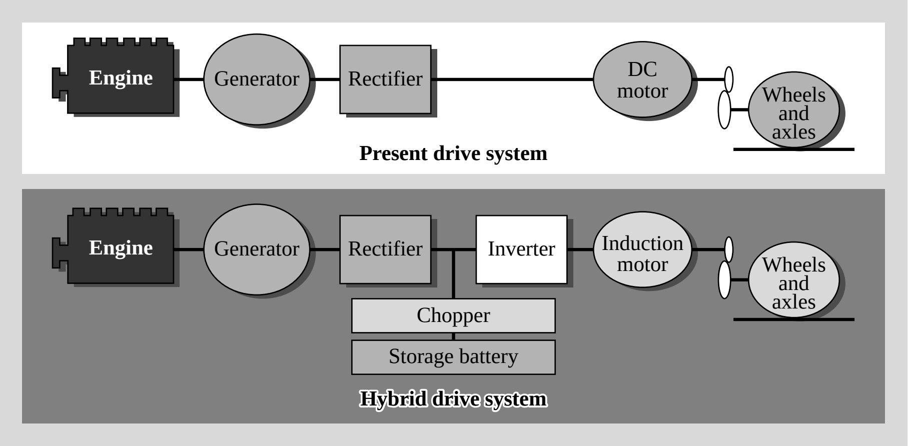

Fig. 5—Developed Hybrid-type Drive System.
The main regenerative storage battery enables electric-power regeneration during braking and electrical assistance during powering.

(consisting of a current diesel engine, electric generator, and rectifier) is unchanged, and AC (alternating current) power obtained from these devices is converted to DC (direct current) power by a VVVF (variable-voltage, variable-frequency) inverter, and an induction motor is driven by that DC power (see Fig. 5).

(2) Storage system

To attain regeneration of electrical power during braking, a storage system is added to the main circuitry, and electrical power generated by braking is drawn into the storage battery, and this power is reused as part of the running power. Since the battery is a lithium-ion type, it is small and lightweight.

To acquire equivalent power for current vehicles, the voltage of the DC components (i.e., rectifier output) must be set to around 1,400 V. Accordingly, by means of a step-down/up chopper, the storage-battery voltage (about 700 V) and the main-circuit voltage (about 1,400 V) are accommodated.

(3) Test train “V-train 2”

In cooperation with a British railway operator, we have mounted the developed hybrid system in an existing HST (high-speed train). This test train — called V-train 2 — is incorporated into the existing railway network, and is undergoing repeated running tests throughout the UK (see Fig.6).

Battery-type Sequential Regenerative System

Rechargeable-battery technology acquired by the development of the hybrid drive system is being exploited, and development of a low-energy-consumption, low-maintenance drive system for electric trains is continuing. In contrast to traditional drive systems for electric trains, the battery-type sequential regenerative system is aimed at adding the following features.

Fig. 6—Test train “V-train 2.”
The test train—fitted with the hybrid system—has undergone repeated running tests incorporated into the existing railway structure in the UK.

(1) Realization of stable running performance

If power is cut off from the collector instantaneously, acceleration-performance reduction by lowering DC voltage and deceleration variation by regenerative-braking lapses will both occur. Accordingly, as a power-source backup by means of storage batteries, the battery-type sequential regenerative system prevents DC-voltage reduction and regenerative braking lapses.

(2) Improvement of energy saving

As for the regenerative braking, if no trains are running in the same power-feed zone, regenerative-power ratio is lowered (since regenerative-braking power cannot go back to the overhead power line). The sequential regenerative system absorbs the portion of the regenerative power that cannot go back to the power line, thereby increasing regenerative-power ratio.

(3) Improvement of mobility

In places such as rail yards, to assure safety of

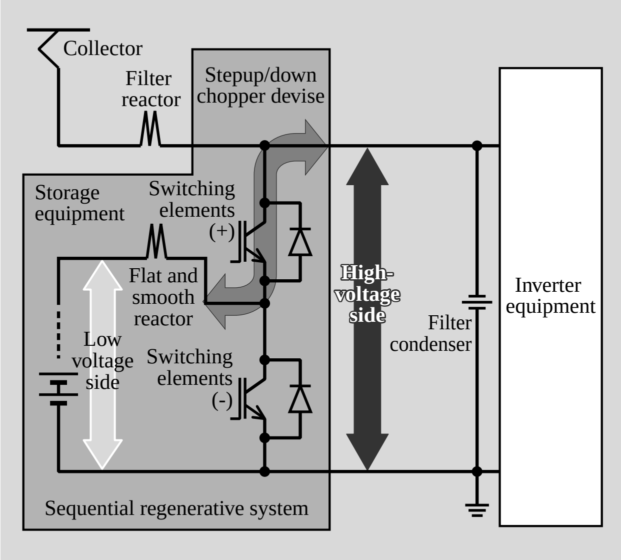

Fig. 7—Battery-type Sequential Regenerative System.
Terminal voltage of the storage device is adjusted by a stepup/down chopper, and charge and discharge of the storage device are controlled.

maintenance work, there are often zones with no power-supply facilities like overhead power lines. The sequential regenerative braking system enables the train to be run by means of battery-stored power in zones without power-supply facilities. With this system, therefore, we are aiming to create a railway system with high mobility — namely, one that enables trains to run wherever there are rails. With the main-circuit voltage of the inverter as the high-voltage side, we have developed a simple configuration that adjusts the terminal voltage of the storage battery on the low-voltage side by the step-up/down chopper and controls charge and discharge of the storage equipment. In response to each of features (1) to (3) above, charge-recharge control of the storage batteries is performed appropriately, and the functions of the sequential-regenerative system are realized (see Fig. 7).

The battery-type sequential regenerative system can be considered an auxiliary power-source system for handling lines on which trains run at relatively low speeds — that is, even on lines that do not hold much promise for sufficient regenerative-power generation.

CONCLUSIONS

This report described applied technologies for a diesel hybrid drive system and a rechargeable battery as technology for reducing environmental load associated with railway vehicles. In regard to global environmental issues, Hitachi, Ltd. intends to continue to be engaged in developing technologies for preempting the needs of railway vehicles and strive to realize clean railway transport systems.

REFERENCES

(1) T. Kaneko et al., “Easy Maintenance and Environmentally-Friendly Train Traction System,” *Hitachi Review* **53**, pp. 15–19 (Feb. 2004).

(2) M. Shimada et al., “Energy Management and Control of Fuel-cell Vehicles”, Institute of Electrical Engineers of Japan, Industrial Applications Meeting (Aug. 2007).

ABOUT THE AUTHORS

Kazuo Tokuyama

Joined Hitachi, Ltd. in 1992, and now works at the Rolling Stock Engineering Department, the Rolling Stock Systems, the Transportation Systems Division, the Industrial Systems. He is currently engaged in coordination of vehicle systems.

Motomi Shimada

Joined Hitachi, Ltd. in 1995, and now works at the Transportation Systems Development Center, the Mito Transportation Systems Product Division, the Transportation Systems Division, the Industrial Systems. He is currently engaged in coordination of development of vehicle control systems. Mr. Shimada is a member of the Japan Society of Mechanical Engineers.

Kiyoshi Terasawa

Joined Hitachi, Ltd. in 1993, and now works at the Rolling Stock Electrical Systems Design Department, the Mito Transportation Systems Product Division, the Transportation Systems Division, the Industrial Systems. He is currently engaged in designing of traction converters for railway vehicles. Mr. Terasawa is a member of the Institute of Electrical Engineers of Japan (IEEJ).

Takashi Kaneko

Joined Hitachi, Ltd. in 1993, and now works at the Rolling Stock Electrical Systems Design Department, the Mito Transportation Systems Product Division, the Transportation Systems Division, the Industrial Systems. He is currently engaged in designing of traction converters for railway vehicles.