1. Introduction

Currently, there is a tendency to select commodities and facilities that will achieve a dramatic reduction of power cost and energy saving. While hybrid vehicles and electrical vehicles are being introduced in the automobile field against the backdrop of advanced technologies, such as secondary batteries and fuel cells, we must work on further energy saving also in the railway field; even though it is generally known today that railway is more energy efficient and environmental friendly mode than automobiles. And we shall continue to make an effort in order that rail transportation remains an attractive transportation mode in the future. [1],[2],[3],[4]

Under these circumstances, Japan Freight Railway Co., Ltd. and Toshiba have jointly developed a series hybrid shunting locomotive, type HD300, to replace the diesel hydraulic locomotive type DE10, mainly used for shunting freight cars in freight yards, and have the sufficient field test results by reducing toxic exhaust gases, lowering the exterior noise level, and reducing CO2 emissions.

2. Development Objectives

The design goals in the development of the type HD300 were to reduce toxic exhaust gases, lower the exterior noise level, and reduce CO2 emissions, based on the concept of an "ECO-friendly, clean locomotive." Compared with the conventional diesel hydraulic locomotive type DE10, the followings were aimed at: reducing toxic exhaust gases by more than 30% to 40%, lowering the exterior noise level by more than 10 dB(A). Reduce CO2 emissions dramatically through efficient operation of the engine and by the use of regenerative braking.

2.1 Innovative Technologies for Realizing Objectives

To achieve the design goals, we attempted to reduce environmental load by introducing the following technologies. We intended to save energy during shunting by introducing a series hybrid system, employing an energy accumulation system with high-capacity main battery, applying permanent magnet synchronous motors, and introducing a modular concept.

The series hybrid system, which performs dynamic power coordination with electrical power, has superior control responsiveness and each equipment can be easily integrated in modules. Because the engine, serving as the power source, is only used for generating electric power, it is easy to take countermeasures against exhaust gases and noise.

For the energy accumulation system, a highly promising lithium-ion battery was used. The main battery is designed to make it possible to exchanged to meet future development to the optimum battery.

High-efficient permanent magnet synchronous motors (PMSM) were employed for the traction motors, and lower heat generation in PMSM enables the use of a totally enclosed structure, thereby eliminating the need for cooling blowers, which contributes to a reduction in auxiliary power.

We also adopted a modular concept in which each device is modularized to make it easier to introduce future new technologies, such as replacing the engine-generator module with a fuel cell, without considerable changes on vehicle body fittings, once practical high-capacity main battery or fuel cells for railway vehicles become available.

3. System Configuration and Arrangement of Electrical Equipments

Each electrical equipment of the locomotive type HD300 is integrated in modules by its function.
Challenge A: A more and more energy efficient railway

The module layout is shown in Fig. 3.1.1, the structure of the main electrical circuit is shown in Fig. 3.1.2, and the main features of the type HD300 is shown in table 3.1.

This hybrid system uses an engine-generator to generate three-phase AC. The power output is rectified by a converter and then combined with the power output from the main battery connected directly to the intermediate DC link. The power is then fed to each PMSM via the inverter in the main converter module.

![Module layout for type HD300](image)

**Fig. 3.1.1 Module layout for type HD300.**

![Structure of main circuit of type HD300](image)

**Fig. 3.1.2 Structure of main circuit of type HD300.**

<table>
<thead>
<tr>
<th>Item</th>
<th>Main features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Self-weigh</td>
<td>60 tons</td>
</tr>
<tr>
<td>Axle arrangement</td>
<td>4 axles (Bo-Bo)</td>
</tr>
<tr>
<td>Max. tractive effort</td>
<td>20 kgf</td>
</tr>
<tr>
<td>Max. tractive output</td>
<td>500 kW</td>
</tr>
<tr>
<td>Max. speed</td>
<td>55 km/h</td>
</tr>
<tr>
<td>Locomotive length</td>
<td>14,300 mm</td>
</tr>
<tr>
<td>Locomotive width</td>
<td>2,950 mm</td>
</tr>
<tr>
<td>Locomotive height</td>
<td>4,088 mm</td>
</tr>
</tbody>
</table>

**Table 3.1 Main features of type HD300.**

3.1 High-performance, High-capacity Lithium-ion Battery

The main battery, the key component in this hybrid system, has the following features.

1. The main battery outputs capacity high enough to start driving even in cold regions and regardless of deterioration of the modules over time.
2. Safety devices, such as a circuit breaker and devices for monitoring the states of each cell and battery modules, are accommodated in
a single box to reduce the maintenance work.
3. The main battery has a capacity high enough to absorb regenerated energy.
4. The main battery is endowed with some redundancy by forming multiple banks, so that operation can be continued by cutting out the defective bank in the event of a fault.
In this way, we have realized the main battery in the form of a lightweight lithium-ion battery with high output and high output density. The ratings and structure of the main battery are as follows:

![Image of lithium-ion battery module]

**Battery structure:** 26 modules in series
(3 banks in parallel)
Rated voltage: 750 V
Energy capacity: 67kWh

For the type HD300, the main battery serves as the main power for the locomotive, and the maximum power required while the locomotive is accelerating can be supplied with the main battery alone.

### 3.2 Compact Engine-Generator

The features of the engine-generator module for generating electrical power to drive the locomotive are as follows:
1. The diesel engine, main generator, and engine auxiliary equipment are accommodated in a single box to reduce the maintenance work and lower noise. In addition, it is designed to allow easy replacement with a fuel cell in the future.
2. To reduce toxic exhaust gases, the diesel engine complies with the Tier3 exhaust gas regulations stipulated by the Ministry of Land, Infrastructure, Transport and Tourism (equivalent to the EPA Tier3 standard in the U.S. and the EU Stage3A standard in Europe).
3. An industrial engine with existing 500,000 results is diverted. This 325 horsepower engine is used at a horsepower of 275 to reduce noise and toxic exhaust gases.
4. Furthermore, the engine output is made variable to find the engine output optimal for shunting in small and medium-size freight stations. It is also designed to meet future upgrades to hybrid vehicles.
5. The engine is designed to operate independently without the main battery, assuming that the main battery may fail. In this case, the maximum tractive output is 114 kW (at the wheel).
6. The main generator is realized by a three-phase induction generator, which needs no excitation system and therefore has a simple structure.

As a result, the type HD300 employs a diesel engine and an induction generator and is rated as follows.

(1) **Engine specifications**
- Rated output: 325 BHP (242 kW), 1800 rpm
  (including the engine radiator 10 BHP)
- Rated rpm: used at 1600 rpm (max. 1800 rpm)

(2) **Main generator specifications**
- Type: three-phase squirrel cage induction generator, direct-drive shaft system, self-ventilated cooling
- Output: used at a constant output of 170 kW
- Rated voltage: 440 VAC (line-to-line)

As discussed in Section 3.1, because the power during locomotive accelerating can be supplied from the main battery because of its high capacity, the engine starts when the main battery capacity
Challenge A: A more and more energy efficient railway decreases, it operates at constant rpm and outputs constant power so as to always operate at the maximum efficiency. Therefore, the engine can be made compact, thereby reducing exhaust gases and noise.

3.3 High-efficiency Permanent Magnet Synchronous Motors

Because of its low loss and small amount of heat generation, PMSM allows the traction motor to have a totally enclosed structure while still ensuring performance close to that of a conventional induction motor and therefore can reduce noise and the frequency of maintenance work. This leads to further energy saving. The type HD300 employs a drive system with PMSMs.

3.3.1 PMSM Specifications

The external appearance of a totally enclosed PMSM for the type HD300 is shown in Fig. 3.3.1, and the specifications and ratings of the traction motor are shown in Table 3.3. The main feature of the PMSM is that it is totally enclosed while producing similar torque with external dimensions and weight equivalent to those of a conventional motor.

![Fig. 3.3.1 Permanent magnet synchronous traction motor.](image)

<table>
<thead>
<tr>
<th>Table 3.3 Specifications of traction motor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main motor system</td>
</tr>
<tr>
<td>No. of phases</td>
</tr>
<tr>
<td>No. of poles</td>
</tr>
<tr>
<td>Cooling system</td>
</tr>
<tr>
<td>Time</td>
</tr>
<tr>
<td>Output</td>
</tr>
<tr>
<td>Voltage</td>
</tr>
<tr>
<td>Current</td>
</tr>
<tr>
<td>rpm</td>
</tr>
<tr>
<td>Frequency</td>
</tr>
<tr>
<td>Weight</td>
</tr>
<tr>
<td>Max. available rpm</td>
</tr>
</tbody>
</table>

3.3.2 Characteristics of PMSM

(1) Electrical characteristics

Because the PMSM employs a permanent magnet for the rotor, no magnetizing current is required, and because the secondary copper loss usually seen in an IM is 0 in the case of the PMSM, the loss of the PMSM is smaller than that of the IM in principle. In addition, this effect is prominent especially in a low-speed region where a high torque and a high electrical current are required, such as at startup time. Fig. 3.3.2 shows a comparison of startup loss between the totally enclosed PMSM that we developed and a conventional open type IM. As shown in Fig. 3.3.2, the loss of the PMSM is about half that of the IM. We confirmed 97.6% as an efficiency and which is 9% better than IM.

![Fig. 3.3.2 Comparison of startup loss between IM and PMSM.](image)

(2) Structure

A Nd-Fe-B magnet with a maximum energy product of 41 [MGOe] is employed for the permanent
magnet, which therefore has heat resistance high enough to endure the temperature increase resulting from the totally enclosed structure.

The V-shaped magnetic pole layout and flux barrier structure shown in Fig. 3.3.3 are employed for the magnetic pole layout, and the starting current can be decreased while suppressing the maximum voltage by taking advantage of a reluctance torque due to the resultant saliency.

The structural characteristics of the developed PMSM are as follows.

**Totally enclosed structure:** The PMSM is totally enclosed by dividing the interior of the motor from its exterior with a revolving heat-dissipation partition disc and a bracket labyrinth, thus preventing dust from entering the PMSM. **Bearing-replacement without motor disassembly structure:** This machine is so constructed that the bearing can be replaced without having to disassemble the motor, based on the following two points: (1) it has a totally enclosed structure and is almost free from internal damage or contamination, eliminating the need for internal cleaning, and (2) it has a permanent magnet embedded in the rotor and requires careful handling when the motor is to be disassembled.

Because of this structure, grease replacement and bearing replacement can be completed in the shortest possible period of time, which should contribute to a significant reduction in the frequency of maintenance work.

### 3.4 Main Converter Module

The main converter module of the type HD300 consists of converter circuit, inverter circuits for PMSM drive, an auxiliary power inverter circuit, and a main circuit contactor and is responsible for power conversion and hybrid power coordination control. The characteristics are as follows.

1. The main converter module is so constructed that each motor is controlled individually as the PMSMs are applied and each circuit can be isolated separately by a bogie to secure redundancy in the accident of failure.
2. The auxiliary power supply unit is incorporated in the main converter module, and power is supplied by the intermediate DC link. The power is converted into three-phase AC power by the inverter for auxiliary power supply and is then fed to the loads.
3. Self-cooling of the main converter module can be achieved by employing the above-described compact engine and high efficiency PMSMs, eliminating the need for a cooling blower or a cooling air duct structure. This has contributed to the very compact size of the main converter module and reduction in auxiliary power.
4. The main converter module is responsible for main battery control, engine-generator control, PMSM driving, and hybrid power coordination control.
5. A main circuit system and a control system are designed to make it possible to replace some devices, such as the main battery, in the future.

A photograph of the main converter module without covers is shown in Fig. 3.4, and the structure of the main circuits is shown in Fig. 3.1.2.
4. Cooperative Traction Control System

The type HD300 drives the locomotive via parallel run operation of the engine-generator and the main battery.

The key point of this system lies in how to integrally control the combination of the energy generated by the engine and the energy of the main battery.

1. Placing the highest priority on reduced environmental load, the power-generating engine is operated at the optimal point at which the efficiency is the maximum value possible.

2. To reduce fuel consumption and noise, the engine is stopped as much as possible during certain periods such as at times of low output or when the locomotive is stopping, and the main battery is used up to a high level of depth of discharge.

3. The employed brake is a regenerative brake to take advantage of braking energy to the main battery.

4. The main battery service life of 8 years is secured, even when used in cold regions.

4.1 Engine-Generator Control (Converter Control)

Because the engine used in the hybrid system frequently experiences intermittent operation, the durability is not stable with a starting circuit using a generally available DC series motor. In the type HD300, a main generator in the form of an induction motor is used to operate a traction inverter with a converter, to control engine starting and engine power generation.

When the engine is started, the converter performs a generator startup operation to start the engine via the output shaft of the engine coupled directly to the generator shaft. In addition, after the engine is started, the converter performs a generator regenerative operation to feed the intermediate DC link with electrical power generated from the engine.

4.2 Total Energy Control System (ECOS) for Hybrid Shunting Locomotive

Because this hybrid system manages charging and discharging of the main battery based on the main battery module SOC (State of Charge), the main battery module terminal voltage (total voltage) and discharge current (total electrical current) of the main battery module are monitored by the main converter module to estimate the main battery module SOC.

As shown in Fig. 4.2 and Table 4.2, for total energy control system (ECOS) of the type HD300, engine startup and stopping are controlled based on the main battery SOC, locomotive output, and locomotive speed.
The locomotive is driven with the main battery alone in a region where the main battery SOC is high. When the main battery SOC decreases to a certain level, the engine is started by power running to drive the locomotive via parallel run operation of the main battery and the engine.

When the main battery SOC decreases further, the engine is operated even when the locomotive is not running to charge the main battery for subsequent running.

Furthermore, to operate the engine mainly during running, the full-charge target for the main battery when the locomotive is running is set higher than when it is not running. Thus, the engine can be stopped when the locomotive is not running (idling stop).

**Table 4.2 Energy control system operations.**

<table>
<thead>
<tr>
<th>Mode name</th>
<th>Engine power generation</th>
<th>Engine warm-up operation</th>
<th>Powering</th>
<th>Regeneration</th>
<th>Auxiliary power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generation stop mode</td>
<td>Always stop</td>
<td>-</td>
<td>-</td>
<td></td>
<td>Operating</td>
</tr>
<tr>
<td>Generation restriction mode</td>
<td>No change</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard running mode</td>
<td>Starts at 100kW or more</td>
<td>No</td>
<td>Possible</td>
<td>Possible</td>
<td></td>
</tr>
<tr>
<td>Standard stopping mode</td>
<td>No change</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ordinary generation mode</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Powering limit mode</td>
<td></td>
<td></td>
<td></td>
<td>Limited</td>
<td></td>
</tr>
<tr>
<td>Powering prohibition mode</td>
<td></td>
<td></td>
<td></td>
<td>Prohibited</td>
<td></td>
</tr>
<tr>
<td>Discharge prohibition mode</td>
<td></td>
<td></td>
<td></td>
<td>Stop</td>
<td></td>
</tr>
</tbody>
</table>

4.3 Test Results of Cooperative Traction Control

Fig. 4.3.1 shows a chart of a locomotive running test, where the main circuit inverter is stably driven during powering with energy supplied from the main battery and the engine-generator.

It was confirmed that the main battery was stably charged by regeneration and generated energy from the engine-generator, performing stable power control.

Figs. 4.3.2 and 4.3.3 show test results of the ECOS control.

The locomotive is driven with the main battery alone where the main battery capacity is sufficient (region ‘Generation Restriction Mode’ in Fig. 4.3.2). Where the main battery capacity decreases to a certain level (region ‘Standard Running Mode’ in Fig. 4.3.2), the engine is started by the powering operation and the main battery is charged to prevent the main battery capacity from decreasing.

Charging of the main battery stops when the full-charge target value is achieved.

As shown in Fig. 4.3.3 illustrating a 700 tons towing test, idling stop was achieved, where the engine operates while the locomotive is running and stops while it is not running. In addition, the main
battery capacity SOC varies between 70% and 80% during this 700 tons towing. Based on the ECOS control, engine noise during non-running will be eliminated, and a decrease in SOC during towing at the maximum load is also prevented.

Fig. 4.3.1 Type HD300 test chart: powering/regeneration performance (5s/div)

Fig. 4.3.2 Type HD300 test chart: energy control system operations (10s/div)

Fig. 4.3.3 Type HD300 test chart: operation check of engine idling stop (10s/div)

Trq: Tractive effort; EFC: Voltage of intermediate dc link; SOC: State of charge of the main battery; Ibat: Current of the main battery; FR-ENG: Engine rpm; Iq: Torque current of PMSM; FR: Locomotive speed;
5. Verification Results

Under the same conditions, including the same freight station (Tokyo Freight Terminal), the same freight car (container freight car 700 tons), and the same running pattern, the type HD300 and the type DE10 were each equipped with a fuel flowmeter and an exhaust gas analyzer to compare fuel consumption and NOx emissions between the two types. The results are shown in Fig. 5.

The fuel consumption of the type HD300 was lower than that of the type DE10. In addition, NOx emissions were significantly decreased.

A similar test was conducted with a noise meter temporarily installed on the ground to compare the HD300 and the DE10. When noise was measured, the type HD300 was found to produce much lower noise than the type DE10.

6. Environmental Assessment

It was achieved that decrease NOx emissions by 62% by employing a diesel engine in compliance with the Tier3 exhaust gas regulations stipulated by the Ministry of Land, Infrastructure, Transport and Tourism to reduce toxic exhaust gases and by optimizing engine rotation.

It was achieved that reduce the noise level by 22 dB (A), compared with the type DE10, by making
the engine compact and by providing open spaces with an acoustic absorbent or a louver expected to produce a sound reduction effect.

It was achieved that reduce fuel consumption by 36%, due to the effect of intermittent operation based on the hybrid system, where operation is performed only when the main battery capacity decreases, when the locomotive is not running resulting from the compact size of the engine, and idling stop.

Furthermore, it was achieved that achieve reduced power consumption by applying the high-efficiency PMSMs, collecting regenerated energy, and performing high-efficiency operation (constant rotation and constant output) of the engine, thus achieving a fuel cost reduction.

7. Conclusion

Currently, hybrid systems composed of an engine generator and a main battery are used more frequently in practice, not only in automobiles but also in railway vehicles. The needs for such hybrid systems will grow in the future. We could build a basis for hybrid systems by developing the hybrid shunting locomotive system, which is expected to allow hybrid systems to be applied not only to locomotives but also to general railway vehicles.

The Japanese Government, MLITT (Ministry of Land, Infrastructure, Transport and Tourism) supports the development of hybrid systems by subsidiaries to push JRF for green transport.

References


