Development of High-Efficiency Drive System with All-SiC Inverter and High-Efficiency 8-pole PMSM

As environmental awareness has grown worldwide in recent years, Hitachi has developed a SiC power device with new materials and a new drive system incorporating a multipolarized PMSM in order to enhance the energy saving and compact aspects of its lineup of electrical parts for rolling stock. As a result of commercial operation for a year on a subway line frequently using short distances between stations and low- or medium-speed zones with high potential for energy saving, it was proven to lower energy consumption by 27% compared to systems using standard IM. In addition, for commuter and suburban trains Hitachi commercialized a drive system combining an all-SiC inverter with an IM.

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1. Introduction

As concern for the environment has increased globally in recent years, demand grows for greater energy savings in rolling stock. Hitachi responded to this need of rail companies by developing the following technologies and strengthening its lineup with the aim of making electrical parts smaller, lighter weight, and more efficient.
(1) More compact and lightweight electrical parts via a drive system using low-loss power devices incorporating silicon carbide (SiC) as a new material.
(2) Increased efficiency via a drive system using a permanent magnet synchronous motor (PMSM).

This article describes examples of how these development technologies were applied to products.

2. Drive System with All-SiC Inverter and High-Efficiency 8-pole PMSM

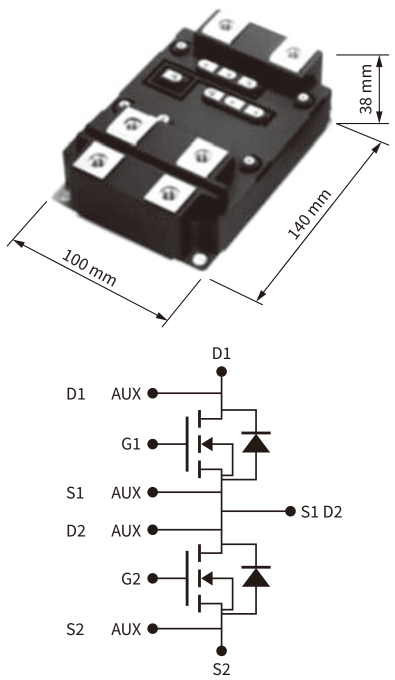
2. 1 Compact Technology for All-SiC Inverter

The size of drive systems for rolling stock has been reduced via the progress of power devices, high-density mounting, better cooling capabilities, and smaller peripheral parts.

Recent years have seen progress in the development of low-loss power devices using SiC as a new material. In this case Hitachi used SiC metal-oxide-semiconductor field-effect transistor (MOSFET) for the switching element, commercializing the world's first high power density all-SiC module in a 2-in-1 configuration with both the upper and lower arm elements in one package (next high power

Figure 1 — All-SiC Module

Shows the exterior and circuit diagram of a high power density, all-SiC module in a 2-in-1 configuration with both the upper and lower arm elements in one package, and equipped with SiC-MOSFET.



D: drain AUX: auxiliary G: gate S: source SiC: silicon carbide
MOSFET: metal-oxide-semiconductor field-effect transistor

density dual: $_{n}$HPD^{2}[1]. The module is 140 mm × 100 mm in size, reducing the element mounting area by approximately 50% compared to previous modules, enabling high-density mounting for the inverter. By making the power unit and unit parts inside the inverter more compact and lightweight, the company substantially reduced the volume and weight compared to previous Si module inverters (see **Figure 1**).

2. 2
Development of a High-Efficiency 8-pole PMSM

Adoption of PMSM is spreading as another means, in addition to standard induction motors (IM), of gaining greater efficiency in the main motors for rolling stock.

For subway lines, which in general frequently use short distances between stations and low- or medium-speed zones, PMSM is efficient in terms of saving energy. Copper is the main loss for the main motor in low- to medium-speed zones, so reducing this will decrease overall loss, thereby gaining greater efficiency. In general, the resistance of stator winding can be lowered by increasing the number of poles in the main motor, so Hitachi considered the use of multiple poles.

Figure 2 shows the exterior of this applied to the main motor. Most standard IM have four poles, while the PMSM in use in recent years tend to have six. Hitachi developed a PMSM with eight poles in order to further pursue energy savings.

Figure 2 — Main Motor Exterior

An 8-pole PMSM developed to achieve 98% efficiency.

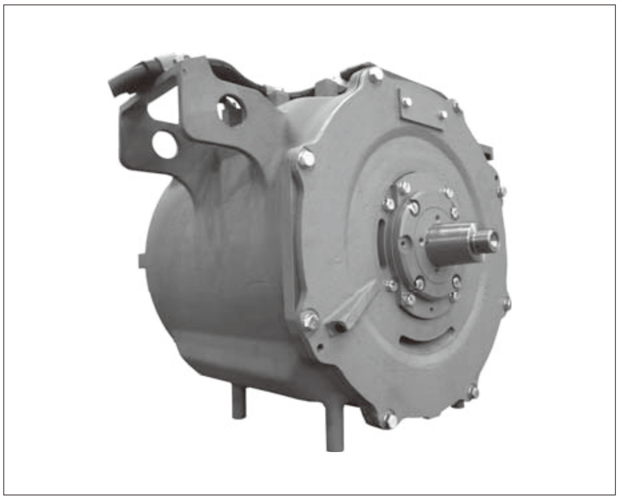


Figure 3 shows the differences in efficiency between the 8-pole PMSM Hitachi designed and a 6-pole PMSM of the same capacity class built to examine the characteristics (efficiency of the 8-pole PMSM vs efficiency of the 6-pole PMSM). The 8-pole PMSM reduced copper loss due to the increased number of poles, and by adopting a low-loss structure optimized for eight poles the company was able to improve efficiency particularly in low- to medium-speed zones, substantially reducing power consumption in operating conditions where such low- to medium-speed zones are frequently found. As a result, whereas the efficiency of an IM of the same capacity class is around 95%, the 8-pole PMSM achieved 98%, gaining a substantial improvement in efficiency.

2. 3
Development of a PMSM Inverter

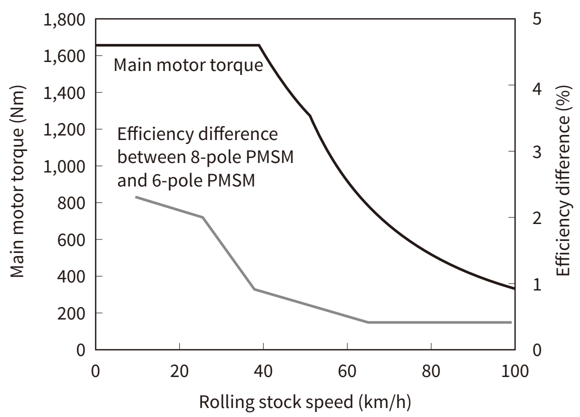
When using multiple poles for the main motor, the inverter frequency controlled by the inverter must be increased to obtain the same torque as the main motor prior to multipolarization. When the 8-pole PMSM was operated at the same switching frequency as before multipolarization, the problems of lower efficiency and worsening control performance accompanying increased strain on the motor current occurred. This meant that the switching frequency needed to be increased to align with the 8-pole specification.

However, increasing the switching frequency led to greater loss of the semiconductor devices used inside the inverter, with a bigger cooler and an increase in the number of semiconductor device arrays, leading to fears that the inverter would have to be made larger. Greater loss due to switching also lowered the energy savings.

In order to solve these problems, Hitachi used a compact low-loss all-SiC module for the power device, as described in section 2.1.

Figure 3 — Results of Efficiency Calculation of 6-pole and 8-pole PMSM

A substantial reduction in energy consumption can be expected in operating conditions where low- to medium-speed zones are frequently used.



PMSM: permanent magnet synchronous motor

2. 4 Energy Saving Effect

The energy saving effect was verified by placing the high-efficiency drive system with an all-SiC inverter in Tokyo Metro Tozai Line 07 series rolling stock, with the cooperation of Tokyo Metro Co., Ltd. The effects are described as follows.

The Tozai Line 07 series is a ten-car configuration, equipped with drive systems on the second, fourth, seventh, and ninth cars. In this test, the PMSM drive system was placed only in the seventh car, to compare the energy consumption with the second, fourth, and ninth cars retaining the standard IM drive system.

Table 1 shows the results of the comparison between the existing IM drive system and the PMSM drive system for the measured energy consumption in a day on a track open for traffic. The energy consumption is heavily affected by the passenger load factor, so Hitachi had to use the value of an IM drive system onboard a car with a similar passenger load factor. IM drive systems were installed on the second, fourth, and ninth cars. As the passenger load factor tends to be higher toward the front on the Tozai Line, the company selected the value of the fourth car as having a similar passenger load factor to the seventh car where the PMSM drive system was installed.

Table 1 shows the energy saving effect due to the difference in operation from the results comparing the energy for local (stopping at every station) and rapid-service operation. The PMSM drive system improves efficiency in low-speed zones, with a substantial effect for local operation where the average speed is low. The energy consumption was reduced approximately 30%. For rapid-service operation where the average speed is higher than for local operation, the train mostly operates at speeds where the effect on lowering loss is smaller, so the reduction in energy consumption was approximately 24%.

Table 1 — Results of Measurement of Energy Consumption in One Day on Tracks Open for Traffic

A substantial reduction in energy consumption can be expected in operating conditions where low- to medium-speed zones are frequently used.

Operation at the time of data acquisition	Local operation		Rapid-service operation	
Measured cars	Fourth car IM	Seventh car PMSM	Fourth car IM	Seventh car PMSM
Powering energy consumption (kWh)	638	574	3,126	2,852
Regenerative energy consumption (kWh)	308	342	1,338	1,481
Energy consumption (kWh)	330	232	1,788	1,361
Comparison of energy consumption vs fourth car IM (per unit)	1.00	0.70	1.00	0.76

IM: induction motor

Table 2 — Results of Measurement of Energy Consumption on Tracks Open for Traffic

Energy consumption was reduced by approximately 27%, achieving substantial energy savings.

Number of data acquisition days	172	
Measured cars	Fourth car IM	Seventh car PMSM
Powering energy consumption (kWh)	184,389	163,605
Regenerative energy consumption (kWh)	79,480	87,343
Energy consumption (kWh)	104,909	76,262
Comparison of energy consumption vs fourth car IM (per unit)	1.00	0.73

Table 2 shows the comparative results of the energy amount when operated with the same conditions for 172 days. These are the measurement results for conditions combining both local and rapid-service operation. The PMSM drive system reduced energy consumption by approximately 27% compared to the existing IM drive system, achieving substantial energy savings(3).

3. All-SiC IM System

For commuter and suburban trains, a system combining all-SiC and IM would be better in terms of saving energy and being compact. **Figure 4** shows a typical case of a drive system incorporating an all-SiC module that Hitachi recently delivered. Specifically, drive systems with all-SiC modules for inverters delivered to East Japan Railway Company and West Japan Railway Company and for main converters delivered to Metropolitan Intercity Railway Company achieved more compact and lightweight electrical parts.

4. Conclusions

Responding to the demand for more compact, lightweight, and efficient electrical parts in rolling stock, Hitachi developed and commercialized both the main parts and drive

Figure 4 — Example Applications of All-SiC Module

A more compact and lightweight inverter was achieved by using an all-Sic module in East Japan Railway Company's E261 (left) and West Japan Railway Company's 271 (center). A more compact and lightweight main converter was also achieved through its use in Metropolitan Intercity Railway Company's TX-3000 (right).

East Japan Railway Company E261 rolling stock | West Japan Railway Company 271 rolling stock | Metropolitan Intercity Railway Company Tsukuba Express TX-3000 rolling stock

systems including a state-of-the-art SiC power device and drive system with all SiC inverter, as well as a highly efficient PMSM, PMSM drive system.

Hitachi will continue to meet the needs of rail companies and further expand globally, providing railway systems that excel in safety, environmental performance, and comfort.

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