Development of SiC Applied Traction System for Next-Generation Shinkansen High-Speed Trains

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This paper presents the development of a traction system for high-speed trains by adopting SiC power devices to pursue weight reduction and compactness of the system. We found that the combination of the SiC applied conversion system with a blower-less cooling system and 6-pole induction motors is a suitable approach to highlight the merits of SiC devices. The running tests of a prototype were conducted to confirm its sound performances. The developed traction system is installed in the latest type of Shinkansen train, or the Series N700S, which debuted in March 2018 and will enter commercial service in the summer of 2020. This SiC application to the high-speed train’s traction system is the first in the world.

Keywords: conversion system, high-speed train, SiC, traction system

1. Introduction

The traction system of Tokaido Shinkansen train consists of main transformers, conversion systems and traction motors. Figure 1 shows a typical example of the latest system. The AC 25000 V power is supplied on catenary. The pantograph receives the electricity from the catenary and sends it to the main transformer. The transformer steps down its voltage to AC 1500 V and sends it to the conversion system. The conversion system, which comprise a converter and an inverter, converts the electricity to DC 3000 V once, and then inverts it to three phase AC electricity with changing frequencies and voltages in order to drive induction motors for traction.

By applying the power electronics technology, the traction system for the Shinkansen high-speed train has been improved since its inauguration in 1964 as shown in Table 1. In 1992, the Series 300 Shinkansen train adopted the gate turn-off (GTO) thyristors to realize the pulse-width modulation (PWM) converter/inverter system with the induction motor drives, which achieved the significant weight reduction and compactness of traction systems a). The insulated gate bipolar transistor (IGBT) that was applied to the Series 700 increasingly reduced weight and volume. In addition, low-loss IGBTs of the Series N700 allowed us to develop self-cooling system by natural underfloor airflow on the car (we call this “blower-less cooling system” or “train-draft cooling system”), while the conventional cooling system of Shinkansen train’s conversion systems is the forced-ventilation system with cooling blowers as shown in Fig. 2 a). Since the conversion system with blower-less cooling abolished the cooling blowers, it realized the further weight reduction, compactness and higher reliability.

Based on these backgrounds, we developed the silicon carbide (SiC) device applied traction system for the latest type of Shinkansen train, whose prototype train for experiments debuted in March, 2018. The key concept of the system is the combination of the SiC applied conversion system with blower-less cooling system and 6-pole induction motors to pursue additional weight reduction, compactness and higher reliabilities. We conducted running tests of the prototype of the developed traction system and confirmed its sound performances.
performances. This SiC application to high speed trains is the first time in the world.

2. Key Concept of SiC Applied Traction System

The power devices used in Shinkansen traction system has been the silicon device (Si device) from diodes of the Series 0 in 1964 to low-loss IGBTs of the Series N700 in 2007. Though the performance of IGBTs has been improved in terms of switching frequency and current capacity, the Si device seems to reach its theoretical limitation because of its indigenous characteristics. On the other hand, the wide-bandgap devices such as a silicon carbide device (SiC device), which is expected to have lower loss and to be resistant to higher temperatures, recently appeared on the market (3) (4). Considering that the SiC device of 3.3 kV–1500 A was ready for commercial applications, we decided to adopt the SiC device to the Shinkansen traction system and started developments in 2012(5) (6).

Through the developments, we thought that our key concept is to take advantage of the merits of the SiC device, which enables lower loss, higher frequency and larger current, in not only the conversion system but also in whole traction system as shown in Fig. 3.

After the preliminary study, we found that the merits of the SiC device can be utilized in the most effective way by combining the conversion system with blower-less cooling system and 6-pole induction motors. The weight portion of cooling fins in the blower-less cooling system is larger than that of the conventional forced ventilation system. Thus, we found that the application of SiC devices to the conversion system with blower-less cooling system could be quite effective because cooling fins can be downsized due to lower switching losses. The larger current capacity enables us to introduce 6-pole induction motors instead of conventional 4-pole induction motors, resulting in drastic weight reduction because of volume reduction of iron cores by increasing poles.

3. Development of Prototype

3.1 Conversion System

The conversion system of Shinkansen trains consists of a PWM converter and a PWM inverter as shown in Fig. 4. In our study, we tried to apply SiC devices to both of the converter and the inverter, and also to consider the application of two types of SiC devices, which are the IGBT with SiC-Schottky Barrier Diode (Hybrid SiC) and the SiC-MOSFET with SiC-SBD (Full SiC). Figures 5 and 6 show the schematics of our developed conversion system. We study two types of conversion systems using two different types of SiC devises respectively: Hybrid-SiC and Full-SiC. These are designed to be compatible in terms of basic structural configurations and electrical specifications. Through the bench tests and the running experiments, we compared two types and learned their own characteristics.

Figure 7 shows the developed SiC-applied conversion system with blower-less cooling system for running experiments. The SiC devices are placed on upper side of cooling fins, whereas the lower side of fins faces the underfloor.
and is cooled down by the train-draft airflows. Since the airflow speeds affect cooling capabilities, we had collected the field data in commercial operations which show the relations among train speeds, underfloor airflow and temperature raises of devices.

Figure 8 shows the simulation results of the device energy loss per phase based on data of running experiments, comparing the converter in the conversion system with the IGBT and with the Hybrid-SiC. The results show that not only the loss of the freewheeling diodes (FWD) and the clamp diodes (CDd), or the SiC-SBD, in Hybrid-SiC is reduced mainly because of the decrease of recovery loss, but also the loss of IGBTs in Hybrid-SiC is reduced mainly because of the decrease of the currents derived by recovery currents of SiC-SBD. This yields an approximate 30% decrease of total device energy loss per phase of the converter. Given those data, we decided the size of fins and positions of devices on the fins to avoid heat spots. This enables us to streamline the cooling fins themselves and then also power unit including cooling fins, components and switching drive circuits as shown in Fig. 9. Both simulations and running experimental results show that the conversion system with Hybrid-SiC can achieve our original goal for compactness and lightweight. We also found that the Full-SiC has the potential to explore further weight reduction in the future by optimizing structures of cooling fins and surrounding parts of them, while its cost effectiveness is supposed to be carefully considered in its application. The research bought us to decide that both the Hybrid-SiC and the Full-SiC are to be adopted to our systems to meet the different purposes, depending on the extent of the expected and prospective weight reduction and compactness.

3.2 Traction Motor Figure 10 shows our concept in developing the 6-pole traction motor driven by the SiC applied conversion system. First of all in the design process, assuming that the required train performance and the interface (gear ratio, wheel diameter, etc.) with other devices including the bogie are the same as those of N700A, we designed the relationship between the voltages and the trains speed to align with that of the 4 pole motor. Thus, we started to consider that the total number of primary windings of the 6 pole is equal to that of the 4 pole motor. On the condition that the total magnetomotive force is kept constant, the increase of poles makes each magnetic circuit smaller and the excitation inductance is decreased, which leads to decrease of the power factor and need of larger motor currents. The SiC applied conversion system can supply larger current and therefore realize the increase of the number of poles from 4 poles to 6 poles. This enables the volume reduction of the core, subject to keeping the same magnetic flux density in the core. The
6-pole traction motor also reduces overhangs of the primary coils, resulting in downsizing in the axial direction as shown in Fig. 11.

In addition, we developed a novel structure of secondary core, or rotor, based on the magnetic field analysis. The secondary cores of conventional traction motors of Shinkansen trains have round holes for cooling because the traction motors are more highly power densified for high-speed running. While the core around the rotor bars contributes to the magnetic circuit, the core surrounding the axis, where the magnetic fields don’t go through, can be reduced. We conducted magnetic field simulations as shown in Fig. 12, and thus we reached a spoke shape as an optimized secondary core instead of the conventional shape with round holes as shown in Fig. 13.

Thanks to larger current capacity of the SiC applied conversion system, we also changed the motor characteristics from the magnetic-loaded to the electric-loaded. The gap magnetic field is proportional to ratio of the motor input voltage to the motor input frequency ($V/f$) as in (1), which decides the motor characteristics.

$$V/f \propto \phi$$ \hspace{1cm} (1)

where $\phi$ is gap magnetic field. If $V/f$ is raised, the input voltage will increase and motor current will decrease. On contrary, if $V/f$ is lowered, the input voltage will decrease and motor current will increased, which lead to changing the motor characteristic to more electric-loaded type. The electric-loaded type motor has an advantage of weight reduction of the motor because it can decrease the volume of iron core which dominates total weight of the motor. However, the margin of stalling torque varies with the square of the $V/f$ as described in (2).

$$T_m \propto \frac{(V/f)^2}{l}$$ \hspace{1cm} (2)

where $T_m$ is a stalling torque and $l$ is a leakage inductance. Therefore, we studied the optimum $V/f$ to reduce total weight and motor currents with ensuring the same stalling torque margin as that of Series N700 as shown in Fig. 14. The study leads us to decide that the $V/f$ constant terminal speed is set at a certain speed between 200 km/h and 210 km/h so that its weight reduction effect can meet our expectations. Figure 15 shows the motor input voltages and the motor currents comparing the 4-pole motor for Series N700A and the 6-pole motor for Series N700S.

4. Running Test Results

We conducted running tests of the developed SiC applied traction system (conversion systems and 6-pole traction
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Fig. 16. Summary of weight reduction effect by comparing weight/power of conventional 4-pole motors and the 6-pole motor for Series N700S

Fig. 17. Running test results of the 6-pole motor by using the N700 Shinkansen train.

Figure 17 shows estimated junction temperatures of an SiC device (Hybrid-SiC) placed at the most severe position which were measured in running tests of 515 km between Tokyo and Shin-Osaka. To suppress the motor noise at lower speeds caused by electromagnetic force vibrations of harmonic components in motor currents, the pulse mode of the inverter at a lower speed range is set to be an asynchronous mode with higher switching frequency. The devise temperature of the inverter raised steeply in train starting because of smaller air flow at lower speed and higher switching pulse modes at a low speed range. At high speed ranges, the device temperature of the inverter due to larger current with the constant switching pulse mode. Figure 18 shows temperature rises of the stator coil and rotor bar of 6-pole traction motors related to the running time. The temperature limit of stator comes from the insulation class and that of rotor is a target value considering the stator’s temperature limit. The experimental results agreed with what we calculated by considering root-mean-square currents and time constant of heat capacities. They also show that temperature rises are sufficiently blow the limit values and the performances of traction system are satisfactory as we expected. Based on the experimental results, we conducted severe-condition simulations assuming that multiple conversion systems in the train would fail and then start running on a steep slope. We confirmed that these results are sound enough as well.

5. Weight Reduction and Downsizing Effects

The weight reduction and downsizing effects are shown in Fig. 19. The width of developed conversion system for the Series N700S is reduced to a half of conventional one for the Series N700. The axial length of the 6-pole traction motor for N700S is reduced by 10%. The main transformer is lightened by applying a newly developed cooling system rather than SiC applications. In terms of weight, the developed traction system for N700S is lightened by 20%, compared with N700. These results allow us to confirm that our approach to take advantage of SiC merits for weight reduction and compactness is successfully effective.

5.1 Design Flexibility of Train Underfloor Layout

This weight reduction and compactness can expand the flexibilities of designing the layout of underfloor equipment as shown in Fig. 20. Since a conversion system of Series N700A is not smaller enough to be installed with a main transformer at the same car, the conversion system should be installed at a different car aside, which requires the additional connections from the main transformer via conversion systems to motors between cars. Such separate installation of a main transformer and a conversion system at different cars restricts the flexibilities of designing the underfloor layout.

The SiC-applied traction system solves this issue because a main transformer and a conversion system can be installed at...
5.2 Battery Self-Traction System

We developed a novel lithium-ion battery self-traction system for emergency such as power failures of the catenary. The system is installed in spaces released by adopting the compact and lightweight traction system as shown in Fig. 21. The purpose is to enable the train to propel itself at low speed when an earthquake strikes or other long-hour supply interruptions occur. The system will also be utilized for shunting trains at the rolling stock depots in night-work maintenance.

Figure 22 shows the simplified circuit diagram of battery self-traction system. The self-traction battery unit mainly consists of a lithium-ion battery unit, contactors and a control unit. In normal mode, the batteries are charged by the auxiliary power unit. In self-traction mode, the batteries with the voltage of DC750 V get connected to the DC link of the conversion system, which is DC 3000 V in its normal mode, by changing the connection of the contactors. The system itself is also designed to be compact and lightweight enough to be mounted on released underfloor space.

We conducted running tests by using the Series N700S prototype train to confirm the basic performances of the system. For the confirmation tests, we installed four battery self-traction units in the 16-car train for experiments, whereas series-production of N700S will have eight of the units. Figure 23 shows the results of the running tests up to a speed of nearly 30 km/h. The battery output current was controlled to be larger at startup in considering of steep gradients and then to be constant to keep output power constant. We also confirmed that the decrease in the state of charge (SOC) was sound enough as we expected. The Series N700S is successfully equipped with the first battery-powered self-traction system using a lithium-ion battery in the world high-speed rail.

6. Conclusions

The traction system of Tokaido Shinkansen train has been improved by applying the power electronics. Based on accumulated technologies through the improvements, we developed the SiC applied traction system to pursue further weight reduction and compactness. In the development, we found that the merits of SiC device can be the most effective by combining the conversion system with blower-less cooling system and 6-pole induction motors.

We developed a prototype of the traction system, and conducted running tests. The test results showed the sound performance as we expected. In terms of weight reduction and compactness, the width of the conversion system is reduced to a half, and the axial length of the 6-pole traction motor is reduced by 10%, compared with conventional ones of the Series N700. The total weight of the traction system is lightened by 20%. Additionally, we can have a prospect on the possibilities of further weight reduction in future research.

This weight reduction and compactness expands the flexibilities of designing the layout of underfloor equipment of the Shinkansen train in that a main transformer and a conversion system can be installed at the same car. These flexibilities enable us to easily redesign different configurations of trains (ex. 8-car train or 12-car train) from the original 16-car train.
which can be called as “Standardized Shinkansen train.” Utilizing underfloor spaces released by the lightweight and compactness traction system, we also developed and introduced a novel lithium-ion battery self-traction system for emergency such as power failures of the catenary.

The developed traction system is installed in the latest type of Shinkansen train, or the Series N700S, which debuted in March 2018 and will enter commercial service in the summer of 2020, and this traction system is the first application of SiC devices to high-speed trains’ traction systems in the world. We hope that our development will pave the way for SiC applications in railway both at home and abroad.

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