

Outstanding Technical Features of Traction System in N700S Shinkansen New Generation Standardized High Speed Train

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This paper overviews a traction system for Tokaido Shinkansen trains and presents a novel silicon carbide (SiC)–applied traction system of the new generation Shinkansen train, “N700S”, which began commercial service in the summer of 2020. To achieve compactness and weight reduction, N700S’s traction system aimed to take advantage of the merits of SiC devices, which have a lower power loss, higher frequency, and a higher current than Si devices, not only in the conversion system but also in the entire traction system. This weight reduction and compactness allowed for flexibility in the design of underfloor equipment of the car body and enabled the realization of a lithium–ion battery self–traction system that could operate catenary–free at low speeds in the event of a power outage. It also contributed toward achieving flexibility by the easy redesign of different configurations of trains such as 8–car or 12–car sets rather than the standard 16–car trains used for the Tokaido Shinkansen, the concept of which is referred to as the “Standardized Shinkansen train”. The continuous introduction of energy–saving Shinkansen trains including N700S has also led to a decrease in Tokaido Shinkansen’s energy consumption. This is the first application of an SiC device and a lithium–ion battery to a high–speed train’s traction system in the world.

Keywords: conversion system, high-speed train, N700S, SiC, traction system, lithium-ion battery

1. Introduction

Since its inauguration in 1964, the year of Tokyo Olympics, the Tokaido Shinkansen has supported Japan’s economic growth as a transportation artery across three largest metropolitan areas, Tokyo, Nagoya and Osaka. Its inter–city transportation capacity is globally unique. Between 1964 and 2019, approximately 6.4 billion people have used the Tokaido Shinkansen, which ensures safety, punctuality, high speed, high frequency, high capacity, environmental feasibility, and comfort⁽¹⁾.

The Tokaido Shinkansen train has significantly evolved since its advent. The engineers of Japanese National Railways (JNR) strategically adopted the distributed traction system, or electric multiple unit (EMU)⁽²⁾, when the first generation of Shinkansen train, or Series 0, was designed in 1960s. They believed that the distributed traction system can efficiently utilize regenerative braking, realize higher acceleration and deceleration performance resulting from effective use of wheel–rail adhesion, and decrease the maximum axle load. They further envisioned that these advantages would continuously enhance the performance of Shinkansen train

by employing new technologies, such as power electronics.

After the privatization of JNR, the philosophy of the Tokaido Shinkansen train was inherited by Central Japan Railway Company (JR Central), one of the six private passenger railway companies. Through effective utilization of power electronics, weight reduction and compactness of the traction system was achieved, thereby enhancing the potential of train performance. Further, it releases the additional space and weight of the underfloor to enhance riding passenger comfort and improve the positive environmental impact.

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, achieving significant weight reduction and compactness of traction systems⁽³⁾. The insulated gate bipolar transistor (IGBT) that was applied to the Series 700 significantly reduced weight and volume. In addition, low–loss IGBTs of the Series N700 allowed for development of a self–cooling system via natural underfloor airflow in the car (called this “blowerless cooling system” or “train–draft cooling system”). Whereas, the forced–ventilation system with cooling blowers was employed as the conventional cooling system in conversion systems in the Shinkansen train⁽⁴⁾. Based on these backgrounds, we developed the silicon carbide (SiC) device applied traction system for the latest type of Shinkansen train, N700S, where “S” is “Supreme”. The train was commercially introduced in July, 2020.

First, this paper presents an overview of the development

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trajectory of traction systems of the Tokaido Shinkansen train. Then, the paper presents the development of the traction system of N700S. The key concept of the N700S traction system is the combination of the SiC applied conversion system with blowerless cooling system and six-pole induction motors to pursue further weight reduction, compactness and higher reliabilities. This compactness and weight reduction expanded the design flexibility of the underfloor layout and realized the concept of “Standardized Shinkansen train”. It further enabled us to install the battery self-traction system for emergency. Finally, the paper introduces the energy conservation achieved by energy-saving Shinkansen trains including N700S.

2. Development Trajectory of Traction System of Tokaido Shinkansen

The traction system of Tokaido Shinkansen train has evolved by adopting power electronics technologies based on the distributed traction system.

2.1 Advantages of Distributed Traction System At the time of its development, the Shinkansen system was to employ the distributed traction system, in which a trainset has several electric units composed of some motor cars. In certain cases, it was equipped with one or more trailers. On the other hand, European high-speed railway like TGV, or a French high-speed train, employed the concentrated traction system represented by the locomotive system, in which one or more locomotives pull or push the trailers⁽⁵⁾. Figure 1 shows an example of those systems. Generally, the distributed traction system has merits:

- (1) Effective use of regenerative brakes
- (2) Higher acceleration and deceleration performance resulting from significant total load on powered axles
- (3) Effective use of space above the floor for passenger cabins
- (4) Reduction in maximum axle load

These merits improved the train performance such as its acceleration and deceleration, energy consumption and less impact on the track. Effective utilization of wheel-rail adhesion was conducted in Shinkansen trains, where less adhesive front car brake efforts are decreased and compensated by the increased brake efforts of middle cars to ensure the total brake of a trainset⁽⁶⁾. The traction system is a primary component of the distributed traction system and has improved by applying power electronics technology. Recently, global high speed have incorporated the distributed traction system, represented by ICE3 in Germany, AGV in Italy, THSR in Taiwan and CRH in China⁽⁷⁾⁻⁽⁹⁾.

The traction system of the Tokaido Shinkansen train consists of main transformers, conversion systems, and traction motors. Figure 2 shows a conventional example of the latest system. A single-phase alternating current (AC) of 25000 V power is supplied to catenary. The pantograph receives electricity from the catenary, and the electricity flows 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 comprises an AC/DC converter and a DC/AC inverter, converts the electricity to direct current (DC) of 3000 V once, and then inverts it to a three phase AC electricity with changing frequencies and voltages to drive

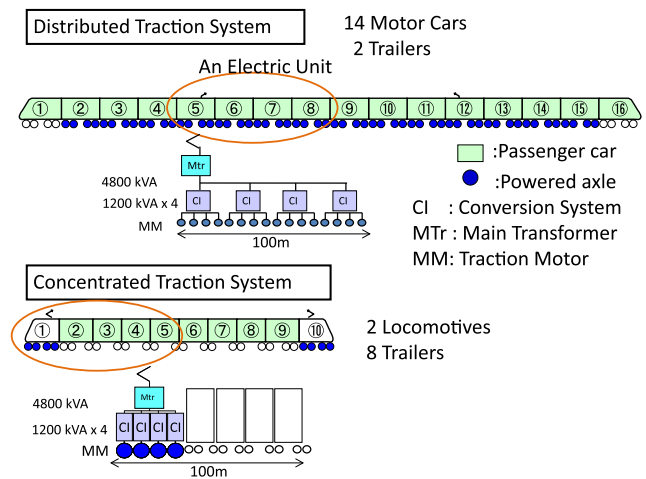


Fig. 1. Example of the distributed traction system and concentrated traction system

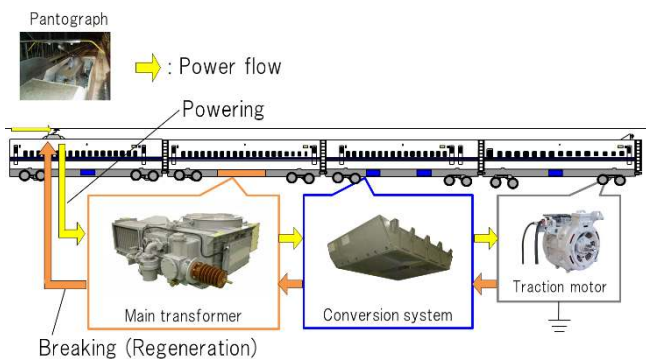


Fig. 2. Traction system of the Shinkansen train

Table 1. Improvement in the traction systems of the Tokaido Shinkansen train

Type							
	Series 0	Series 100	Series 300	Series700	Series N700 N700A	N700S	
Year	1964	1985	1992	1999	2007	2020 (2018)*	
Power device	Diode	Thyristor	GTO thyristor	IGBT	Low-loss IGBT	SiC device	
Control system	Tap changer control	Thyristor – driven phase control	PWM converter and inverter				
Cooling system	Forced ventilation cooling system				Blowerless cooling system (Train draft cooling system)		
Traction motor	DC motor		3-phase induction motor				
			4-pole				6-pole
Electric braking	Rheostatic braking		Regenerative braking				

* N700S validation test train, or the prototype train, started running tests.

the induction motors for traction.

2.2 PWM Converter/Inverter System with Induction Motor Drive and Regenerative Brake Table 1 shows the improvement in the traction systems of the Tokaido Shinkansen train. The first generation train of the Tokaido Shinkansen or Series 0 and second generation or Series 100 used DC motors driven by a rectifier and voltage control, such as the transformer's tap changer or thyristor phase control. This system requires resistors for dissipating the braking energy, which increases weight and wastes the energy as shown in Fig. 3.

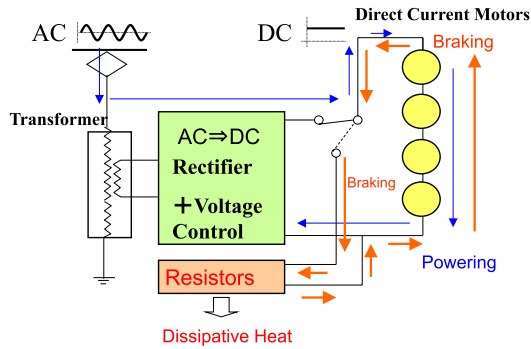


Fig. 3. Direct current motors driven by a rectifier and voltage control

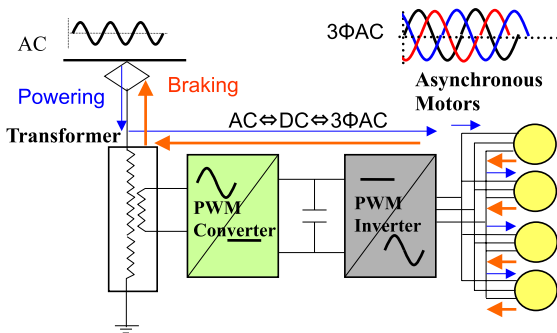


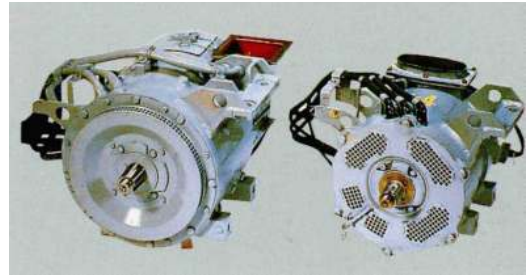
Fig. 4. Pulse-width modulation (PWM) converter/inverter system with AC regenerative brake

In 1992, the Series 300 Shinkansen train adopted the GTO thyristors to realize the PWM converter/inverter system⁽¹⁰⁾ (AC/DC converter and DC/AC inverter) with induction motor drives as shown in Fig. 4. The weight of the traction motor in Series 100 accounts for 40% of total weight of the tractions system. Meanwhile, the rated power output and weight of the DC motor of the Series 100 were 230 kW and 825 kg, respectively, and those of the induction motor of the Series 300 were 300 kW and 390 kg, respectively. This means that the weight per rated power output of the induction motor of the Series 300 was approximately one third of that of DC motor of Series 100. The allocation of lighter induction motors to the traction motors significantly contributed to weight reduction of the traction system as shown in Table 2⁽³⁾ and Fig. 5. The PWM converter/inverter system further realized the AC regenerative brake. This can eliminate the resistor for dissipating braking energy, resulting in compactness and weight reduction. Further, this can return the braking energy to the catenary, resulting in saving energy. Additionally, the power factor of the converter is controlled to be one, which reduces the input current received from the catenary to the pantographs. These developments led to the significant weight reduction and compactness of traction systems. The introduction of PWM converter/inverter system of Series 300 highlighted the advantages of the distribution system. This achievement influenced the development of other Shinkansen trains in Japan and high speed trains abroad⁽¹¹⁾.

In 1997, the Series 700 became the first high-speed train globally to use innovative IGBT technology. In addition to improving train performance and introducing lighter and more compact traction system, these technological innovations have reduced the high harmonics and noise emitted

Table 2. Power density comparison between direct current motors (Series 0, Series 100) and induction motor (Series 300)

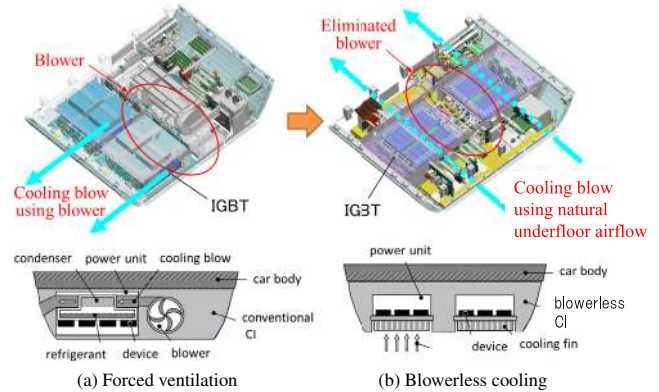
	Series 0	Series 100	Series 300
	DC Motor		Induction Motor
Power (kW)	185	230 (124%)	300 (162%)
Weight (kg)	876	825 (94%)	390 (45%)
Weight/Power (kg/kW)	4.74	3.59 (76%)	1.30 (27%)



(a) DC motor

(b) Induction motor

Fig. 5. Direct current motor of Series 100 and induction motor (prototype) of Series 300



(a) Forced ventilation

(b) Blowerless cooling

Fig. 6. Conversion system with blowerless cooling

from the traction system via the higher switching frequency of IGBT and a three-level control method.

2.3 Conversion System with Blowerless Cooling System In 2007, low-loss IGBTs of the Series N700 allowed us to develop self-cooling system by natural underfloor airflow on the car (we call this “blowerless 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. 6. The blowerless cooling conversion system is advantageous in that they are lighter in weight since cooling blower motors, fans and liquid cooling mediums are not required. Moreover, their simple structure, which does not comprise the cooling medium and cooling components, contributes to easier maintenance, higher reliability, cost-reduction, and eco-harmony such as reduction in green-house effect gases. The blowerless cooling conversion system realized the further weight reduction, compactness and higher reliability.

3. Development of Traction System of N700S

3.1 Development Concept The power devices used in the Shinkansen traction systems were the silicon devices (Si devices) ranging from diodes of the Series 0, in 1964, to low-loss IGBT of the Series N700 in 2007. Although the

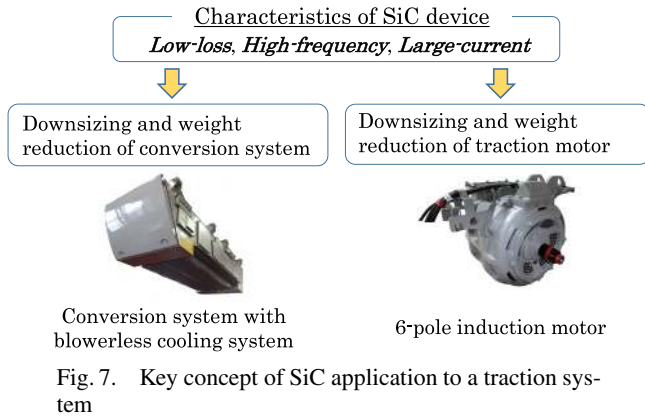


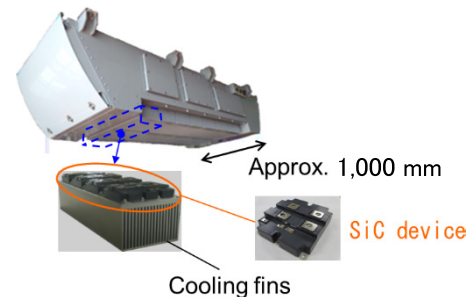
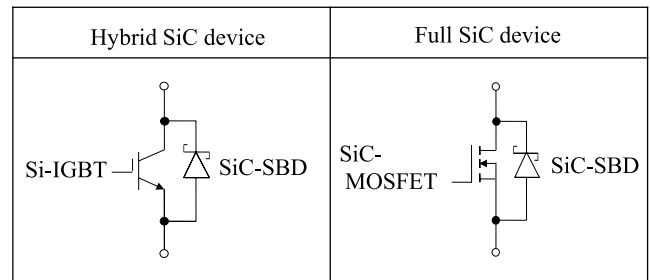
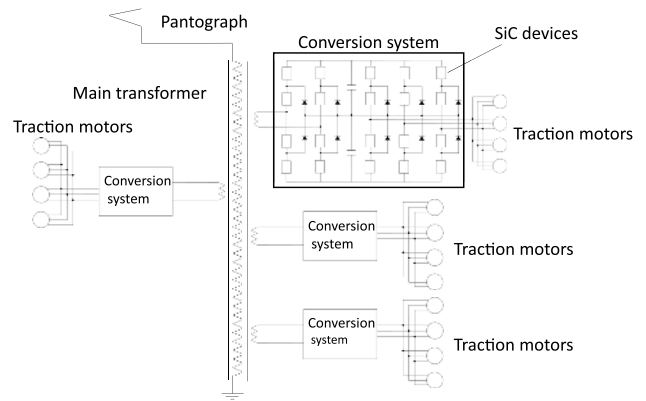
Table 3. Specifications of N700S traction system

	Main Transformer	Conversion System	Traction Motor
Capacity or Power	Primary: 5090 (kVA) Secondary: 4640 (kVA) Auxiliary: 450 (kVA)	1220 (kW) (Nominal Output)	305 (kW)

performance of the IGBTs improved in terms of switching frequency and current capacity, the Si device appears to have reached its theoretical limitation because of its indigenous characteristics⁽¹²⁾. Wide-bandgap devices, such as a SiC device, have lower loss and resistance to higher temperatures and are available for commercial applications⁽¹³⁾⁽¹⁴⁾. Therefore, the 3.3 kV–1500 A SiC device was adopted in the Shinkansen traction system, and developments had begun in 2012⁽¹⁵⁾⁽¹⁶⁾.

Based on the developments, we believed that our key concept is to leverage the merits of the SiC device as shown in Fig. 7⁽¹⁷⁾. The weight proportion of cooling fins in the blowerless cooling system is larger than that of the conventional forced ventilation system. The application of SiC devices to the conversion system with a blowerless cooling system is effective because cooling fins can be downsized owing to lower switching losses. The larger current capacity enables us to introduce six-pole induction motors instead of conventional four-pole induction motors, resulting in a drastic weight reduction because of volume reduction of iron cores by increasing poles. Therefore, we found that the merits of the SiC device can be utilized effectively by combining the conversion system with blowerless cooling system and six-pole induction motors. For the first time, in 2020, N700S featuring the developed traction system using SiC devices was made available for commercial operations. Table 3 lists the specifications of the traction system.

3.2 SiC-applied Conversion System The conversion system of the Shinkansen trains consists of PWM converter and a PWM inverter. We employed SiC devices in both of the 3-level converter and 3-level inverter and further used two types of SiC devices, the silicon IGBT with SiC-Schottky Barrier Diode (Hybrid SiC) and SiC-MOSFET with SiC-SBD (Full SiC). The device rated voltage and current are 3.3 kV and 1500 A, respectively. Figures 8 and 9 show the schematics of our developed conversion system. Figure 10 shows the developed SiC-applied conversion system with blowerless cooling system for conducting train running tests. The SiC devices are placed on the upper side of



cooling fins, whereas the lower side of the fins faces the underfloor and is cooled down by the train-draft airflows. As the airflow speeds effect cooling capabilities, we collected the field data in commercial operations; the data revealed the relationships between train speeds, underfloor airflow, and temperature raises of the devices.

We simulated the device energy loss per phase based on the data obtained from train running tests by comparing the converter in the conversion system with the IGBT and Hybrid-SiC. The results show an approximate 30% decrease of total device energy loss per phase of the converter. From those data, we selected the size of the fins and positions of the devices on the fins to avoid heat spots. Further, the power unit including cooling fins, components, and switching drive circuits, could be streamlined.

We conducted running tests of the developed SiC-applied traction system (conversion systems and six-pole traction motors) using the N700 Shinkansen train and N700S validation test train, or a prototype train from 2015 to 2019. Figure 11 shows an example of the running test results between

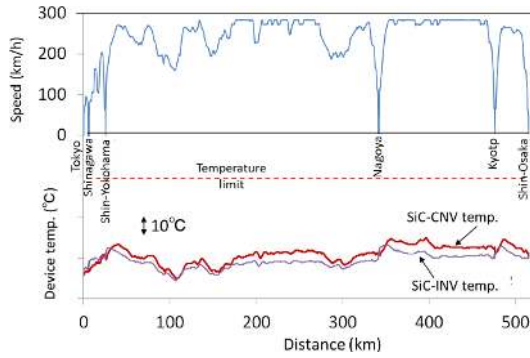


Fig. 11. Running test results of the conversion system

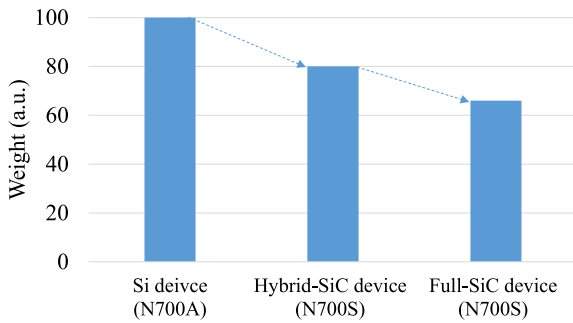


Fig. 12. Weight comparison of the conversion system among N700A with Si device, N700S with Hybrid-SiC and N700S with Full-SiC

Tokyo and Shin-Osaka (distance = 515 km); the results indicate the estimated junction temperatures of an SiC device (Hybrid-SiC) placed at an extreme position on the cooling fin. The results show that temperature rises are sufficiently below the limit values, and the performance of the traction system is satisfactory. We further found that the Full-SiC has the potential to achieve further weight reduction by optimizing structures of cooling fins and their surrounding parts, while its cost effectiveness should be carefully considered in its application. Thus, we inferred that both the Hybrid-SiC and Full-SiC should be adopted in our systems for different purposes, depending on the extent of the expected and prospective weight reduction and compactness. In series-production N700S trains, the conversion systems comprising Full-SiC devices are installed in cars equipped with a main transformer. This is because such a car requires more weight reduction than other cars, and thereby effectively utilizing the advantage of Full-SiC.

Figure 12 shows the weight comparison of the conversion system among N700A with Si device, N700S with Hybrid-SiC and N700S with Full-SiC. The weight is reduced by 20% in the Hybrid-SiC device and 30% in Full-SiC device of N700S, compared with that of Si device of N700A.

3.3 Compact and Lightweight Traction Motor (Six-pole Induction Motor)⁽¹⁷⁾ The SiC-applied conversion system can supply higher current and, thereby realizing an increase in the number of poles from four poles to six poles. This enables volume reduction of the core, subject to maintaining the magnetic flux density in the core. Figure 13 shows our concept implemented to develop the six-pole traction motor driven by the SiC-applied conversion system.

In addition, we developed a novel structure of secondary

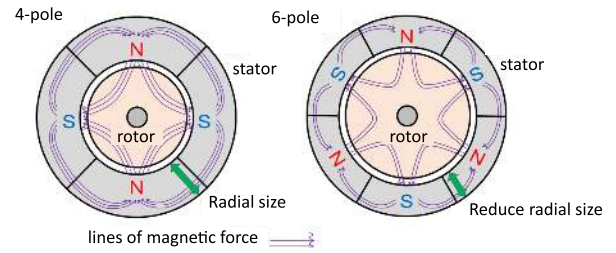


Fig. 13. Concept of developing six-pole motor instead of 4-pole motor

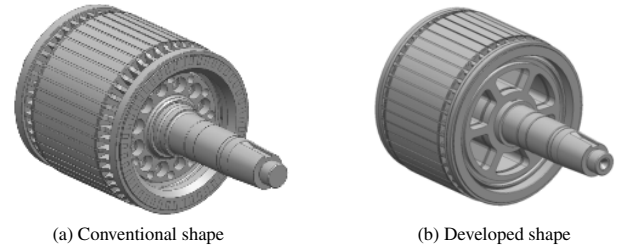


Fig. 14. Secondary core shapes

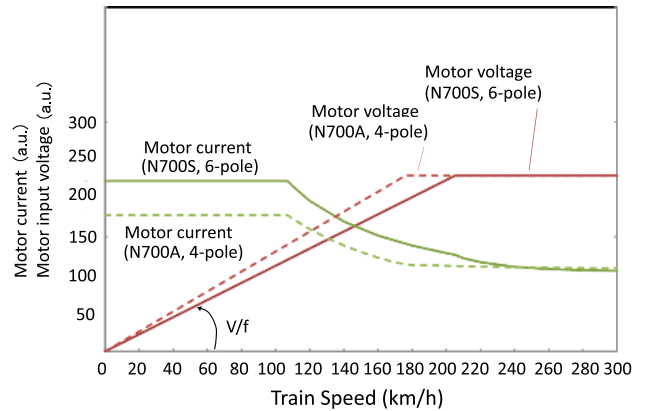


Fig. 15. Comparison of the input voltage and motor current between the four-pole motor for N700A and six-pole motor for N700S

core, or rotor, based on magnetic field analysis. The secondary cores of conventional traction motors of the Shinkansen trains have round holes for cooling because the traction motors are more highly power densified for high-speed operation. While the core around the rotor bars contributes to the magnetic circuit, the core surrounding the axis, where the magnetic field does not pass through, can be reduced⁽¹⁸⁾. We conducted magnetic field simulations and thus we attained a “spoke” shape as an optimized secondary core instead of the conventional shape with round holes as shown in Fig. 14.

Because of the higher current capacity of the SiC-applied conversion system, we further changed the motor characteristics from magnetic-load to electric-load. The electric-load type motor has an advantage of weight reduction of the motor because it can decrease the volume of iron core, which dominates the total weight of the motor. Figure 15 shows the motor input voltages and motor currents by comparing the four-pole motor for Series N700 and six-pole motor for N700S. The ratio of motor input voltage (V) and frequency (f), V/f , decreased by 15%, and the motor current of N700S increased. These designing changes, such as six-poles and electric-load

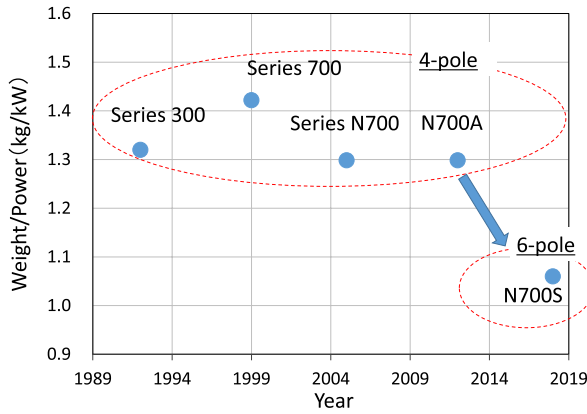


Fig. 16. Summary of weight reduction effect by comparing weight/power of conventional four-pole motors and six-pole motor for N700S

characteristics combined with the SiC-applied conversion system can achieve significant weight reduction. Figure 16 summarizes the effects of weight reduction by comparing weight/power of motors of Series 300, Series 700, Series N700, and Series N700A, which are conventional four-pole motors, and N700S, which is the developed six-pole motor. The weight/power of the N700S is reduced by 20%, which significantly contributes to weight reduction of the tractions system of the N700S.

4. Weight Reduction and Downsizing Effects

Figure 17 summarizes the weight reduction and downsizing effects. The width of the SiC-applied conversion system of the N700S is reduced to half of that for the Series N700. The axial length of the six-pole traction motor for N700S is reduced by 10%. The weight of main transformer is reduced by employing a newly developed cooling system rather than SiC. The weight of the developed traction system for N700S is reduced by 20% when compared with that of N700. These results show that our approach to leverage the SiC for weight reduction and compactness is successfully effective.

4.1 Design Flexibility of Train Underfloor Layout⁽¹⁷⁾

The weight reduction and compactness can expand the flexibilities of designing the layout of underfloor equipment as shown in Fig. 18. Because the conversion system used in Series N700 or N700A is not sufficiently small to be installed with a main transformer in the same car, the conversion system has to be installed on a different car, which requires additional connections between cars from the main transformer via the conversion system to the traction motors. Such separate installation of a main transformer and a conversion system on different cars restricts the flexibilities of designing the underfloor layout. This could be a challenging issue for the distributed traction system.

The SiC-applied traction system solves this issue because a main transformer and a conversion system can be installed on the same car owing to their compactness and lightweight. The Full-SiC employed conversion systems are installed in cars equipped with a main transformer because its lightness is completely utilized for solving the issue. These flexibilities enable us to easily redesign different configurations of trains (e.g. an 8-car train or a 12-car train) from the original 16-

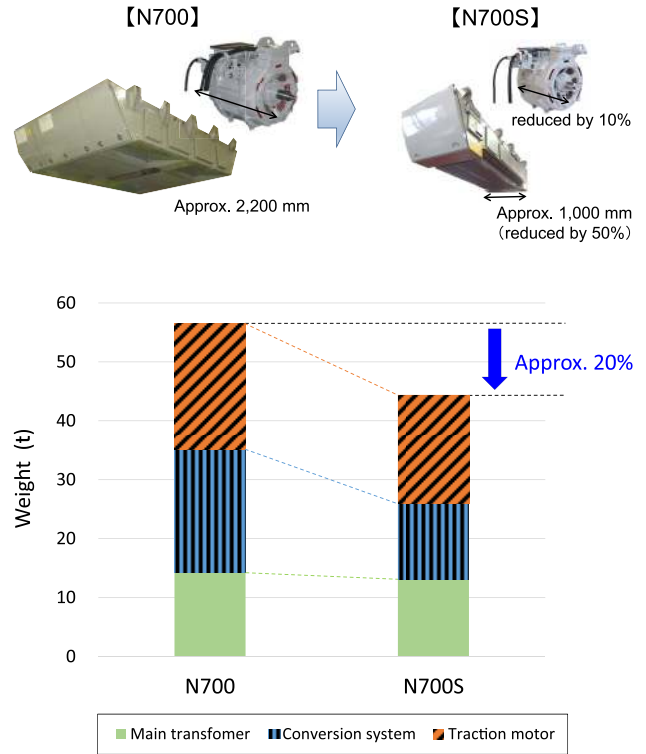


Fig. 17. Weight reduction and downsizing results

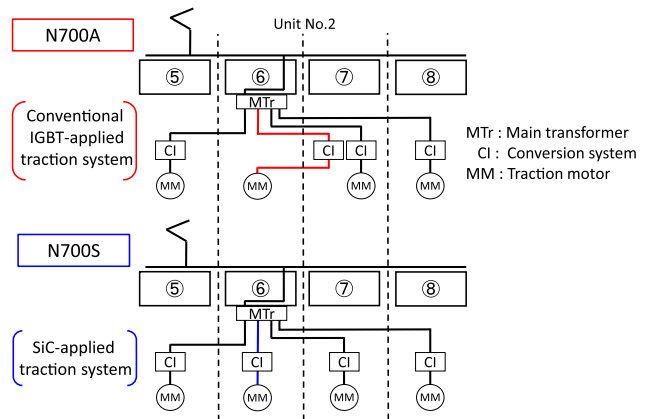


Fig. 18. Flexibilities of designing the layout of underfloor equipment owing to compactness and weight reduction of SiC-applied traction system

car train. This concept is called as “Standardized Shinkansen train”, which highlights the advantages of distribution traction systems. It was thoroughly and strategically decided when the Tokaido Shinkansen train was designed over 50 years ago. The concept is expected to be pervaded at home and abroad. Recently, it was announced that the six-car set N700S train will be introduced to West-Kyushu (Nagasaki) Route of Kyushu Shinkansen.

4.2 Battery Self-Traction System We developed a novel lithium-ion battery self-traction system for emergency such as power failures of the catenary⁽¹⁹⁾. The system is installed in spaces released by adopting the compact and lightweight traction system as shown in Fig. 19. The purpose is to enable the train to self-propel at a low speed when long-hour power supply outages occur. The system will further be utilized for shunting trains at the rolling stock depots during

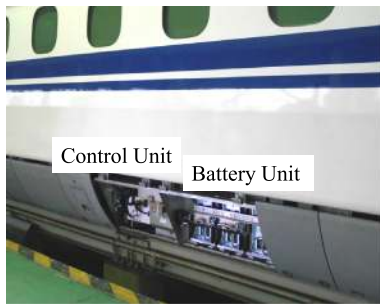


Fig. 19. Self-traction battery unit mounted on N700S prototype train

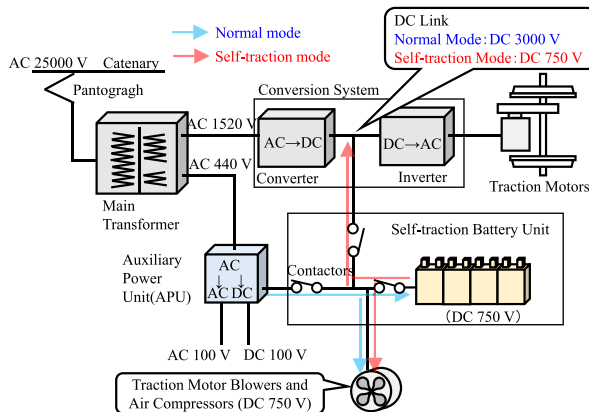


Fig. 20. Circuit diagram of battery self-traction system

night-time maintenance.

As for conventional trains and subway trains, the battery self-traction systems have already been used for practical purpose⁽²⁰⁾. However, these systems were not suitable for Shinkansen trains in terms of compactness, lightweight and compatibility with the functions for high-speed running performance. Therefore, we developed the novel system using the following concepts:

- (1) The original traction performance and basic configuration of traction system that are optimally designed for high-speed running remain unchanged;
- (2) Battery type, protective detections, and protective functions are meticulously selected to ensure safety and reliability;
- (3) Compactness and lightweight to be accommodated at the released space on underfloor of car body are pursued;
- (4) The energy of battery is effectively utilized in the usual condition in addition to the emergency condition.

Figure 20 shows a simplified circuit diagram of the battery-powered self-traction system. The self-traction battery unit majorly consists of a lithium-ion battery unit, contactors and a control unit. In normal mode, the batteries are charged by an auxiliary power unit. In self-traction mode, the batteries with the voltage of DC 750 V is 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 is designed to be sufficiently compact and lightweight to be mounted on released underfloor space.

The N700S have eight battery-powered self-traction units

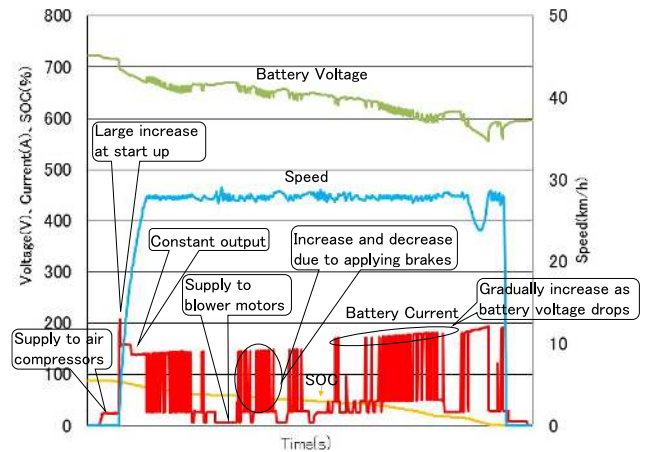


Fig. 21. Running test results of battery self-traction system

in a 16-car train. It enables the train to pass through tunnels and bridges in the Tokaido Shinkansen line from Tokyo to Shin-Osaka.

Figure 21 shows running test results conducted by using the N700S prototype train up to a speed of nearly 30 km/h. For the confirmation tests, we installed four battery self-traction units in the 16-car train for experiments. The battery output current was controlled to be larger at the start by considering steep gradients and then to be constant to maintain output power constant. The battery further supplies current to air compressors and blower motors for traction motors. We confirmed that the decrease in the state of charge (SOC) was satisfactory. The N700S pioneers the battery-powered self-traction system using a lithium-ion battery for the first time in the global high-speed rail.

5. Energy Conservation achieved by introducing Energy-Saving Shinkansen Trains

In Tokaido Shinkansen, further reduction in the energy consumption has been actively achieved by developing and introducing energy-conserving trains⁽¹⁾. The N700S improved its energy saving performance by running resistance reduction, train weight reduction and improved efficiency owing to SiC application. The compactness and weight reduction of traction system ensures the additional space and weight for introducing appropriate measures for the running resistance reduction owing to streamlining car body such as bogie covers.

Figure 22 shows the comparison of electricity consumption. The N700S will reduce energy consumption by additional 6% when compared with the N700A owing to its SiC-applied traction system, lighter car body, reduced air resistance, etc.

When operating between Tokyo and Shin-Osaka at a maximum speed of 285 km/h, N700A consumes 23% less energy than Series 300 and 16% less energy than Series 700 when they are running at the maximum speed of 270 km/h. This means that N700A is faster and much more energy efficient. Consequently, the energy consumption unit at the end of fiscal year 2018 (from April 1 2018 to March 31 2019) decreased approximately by 34% compared to that in fiscal 1990 as shown in Fig. 23. Further reduction in energy

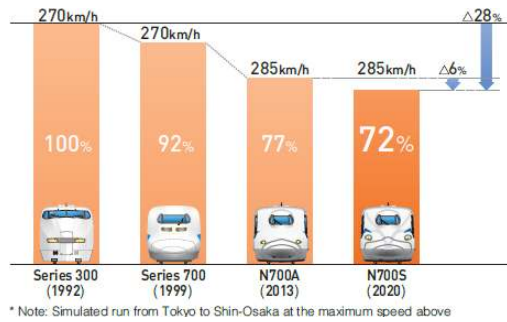


Fig. 22. Comparison of electricity consumption by Tokaido Shinkansen train type

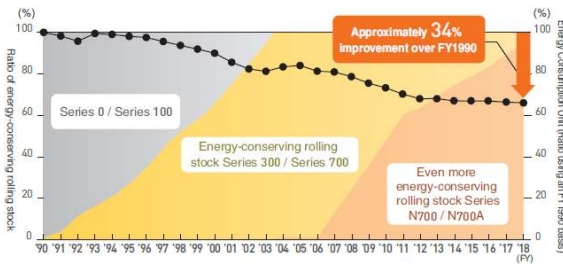


Fig. 23. Shifts in the ratio of the Tokaido Shinkansen energy-conserving trains and energy consumption unit

consumption unit is expected to be achieved by increasing the number of N700S trains.

6. Conclusions

The Tokaido Shinkansen train was strategically designed as a distributed traction system over 50 years ago. The engineers at the time envisioned that new technologies, such as the power electronics can enhance the performance of the train. Following their prospects, the Tokaido Shinkansen train has been evolving by adopting the latest technologies to meet its mission which is the mass transportation artery in Japan.

The PWM converter/inverter system with induction motor drive and regenerative brake in Series 300 was an epoch-making technology, which influenced the high-speed trains in Japan and overseas. The conversion system with blowerless cooling introduced in Series N700 expanded the design potential for further compactness and weight reduction.

Based on these accumulated technologies, the SiC-applied traction system was developed to pursue further weight reduction and compactness. The merits of the SiC device were effectively utilized by combining the conversion system with blowerless cooling system and six-pole induction motors. The width of the conversion system of N700S was reduced to a half, and the axial length of the six-pole traction motor was reduced by 10%, when compared with the conventional values of the Series N700. The total weight of the traction system was reduced by 20%.

This weight reduction and compactness expanded the flexibilities of designing the layout of underfloor equipment of the Shinkansen train where a main transformer and conversion system can be installed in the same car. We deployed the Full-SiC applied conversion system, which achieved a more significant reduction, in the car equipped with the transformer.

These flexibilities enabled us to easily redesign different configurations of trains (e.g. 8-car or 12-car trains) from the original 16-car train, which is called as “Standardized Shinkansen train”. By utilizing underfloor spaces released by the lightweight and compactness of the traction system, we further developed and introduced a novel lithium-ion battery self-traction system for emergency such as power outages of the catenary.

Furthermore, the weight reduction and compactness of the traction system, which yielded the additional space and weight, improve its positive environmental impacts, such as energy saving. The continuous introduction of energy-saving Shinkansen trains including N700S has promoted the decrease in energy consumption of the Tokaido Shinkansen train.

This innovative traction system installed in the N700S next-generation Tokaido Shinkansen train entered commercial service in the summer of 2020, and it is the first global application of SiC devices and lithium-ion batteries to high-speed trains’ traction systems. We hope that our development will pave the way for applications of the latest power electronics both at home and abroad.

References

- (1) Central Japan Railway Company Annual Report 2019, p.18, 33 (2019)
- (2) Collection of posthumous writings of Hideo Shima, Japan Railway Engineer’s Association (JREA), pp.126–130 (2003) (in Japanese)
- (3) S. Ishikawa: “A Success of Advanced AC Drive System for NOZOMI”, *Transactions on Industry Applications*, Vol.114, No.6, pp.604–607 (1994) (in Japanese)
- (4) K. Sato, M. Yoshizawa, and T. Fukushima: “Traction systems using power electronics for Shinkansen high-speed electric multiple units”, *Proc. of the 2010 International Power Electronics Conference (IPEC-Sapporo)*, pp.2859–2866 (2010)
- (5) K. Ishizu: “Special Issue on ‘New Electric Railway Technology’, 1. The Latest Technologies of Electric Rolling Stock on Europe and Japan”, *Transactions on Industry Applications*, Vol.119, No.11, pp.1286–1288 (1999) (in Japanese)
- (6) M. Ueno and S. Kikuno: “Adhesion Technology of Braking in Tokaido Shinkansen Train”, *JREA Magazine*, Vol.46, No.5, pp.30069–30074 (2019) (in Japanese)
- (7) M. Hara, S. Oomata, O. Kawakami, and K. Asano: “The Concept of Experimental Platform on Next-Generation Shinkansen Development—Type E956 Shinkansen Test Train named ALFA-X—”, *Proc. of 12th World Congress on Railway Research (WCRR 2019 Tokyo)*, OP.13 (2019)
- (8) M. Kopp: “Velaro Novo—Improving Life Cycle Cost by reduction of aerodynamic resistance”, *Proc. of 12th World Congress on Railway Research (WCRR 2019 Tokyo)*, OP.13 (2019)
- (9) J. Hartill: “Italy joins the premier speed league”, *Railway Gazette International* July 2017, pp.28–31 (2017)
- (10) S. Ishikawa, S. Tanaka, S. Tadakuma, and E. Takahara: “Consideration on High Quality AC Traction Motor Drives using PWM Converters”, *Transactions on Industry Applications*, Vol.107, No.3, pp.304–311 (1987) (in Japanese)
- (11) T. Numano, E. Okitsu, and M. Kimata: “III Development of Shinkansen at the Next Generation”, *Transactions on Industry Applications*, Vol.114, No.6, pp.608–611 (1994) (in Japanese)
- (12) H. Shimoyama, H. Kato, G. Kobayashi, and K. Sakanoue: “Advancement of Shinkansen rolling stock by downsizing and weight reduction of propulsion system”, *Proc. of The International Symposium on Speed-up and Sustainable Technology for Railway and Maglev Systems (STECH 2015)*, No.2D23, pp.1–6 (2015) (in Japanese)
- (13) K. Ishikawa, K. Ogawa, and M. Nagasu: “Traction Inverter that Applies Hybrid Module Using 3 kV SiC-SBDs and High-Speed Drive Circuit”, *IEEE Transactions on Industry Applications*, Vol.135, No.5, pp.531–537 (2015) (in Japanese)
- (14) T. Mineyoshi, R. Ikeda, K. Koiki, K. Natori, K. Kondo, K. Fujimoto, and S.

Makishima: "Characteristics Analysis of Traction Inverter Loss in the Case of Current Increase by Using a SiC Switching Device for Energy Saving Railway Vehicles", *IEEE Transactions on Industry Applications*, Vol.139, No.3, pp.258–265 (2019) (in Japanese)

- (15) G. Kobayashi, H. Shimoyama, H. Tanaka, and N. Suyama: "Downsizing and weight reduction of the SiC applied traction system for Shinkansen high speed trains", *Rolling stock & machinery (R&M)*, Vol.23, No.10, pp.38–41 (2015) (in Japanese)
- (16) K. Sato, T. Fukushima, N. Suyama, K. Oda, and M. Kasahara: "Development of the SiC applied traction system for Shinkansen high speed trains", *Proc. of IEE-Japan Industry Applications Society Conference 2016*, pp.307–308 (2016) (in Japanese)
- (17) K. Sato, H. Kato, and T. Fukushima: "Development of SiC Applied Traction System for Next-Generation Shinkansen High-Speed Train", *IEEE Journal of Industry Applications*, Vol.9, No.4, pp.453–459 (2020)
- (18) K. Sato, T. Onuki, S. Wakao, and M. Tokuhisa: "A Novel Structure of Induction Motors for Weight Reduction", *Proc. of International Symposium on Theoretical Electrical Engineering (ISTET'99)*, pp.589–593 (1999)
- (19) H. Kato and K. Sato: "Battery Self-Traction System for High Speed Train", *IEEE Transactions on Industry Applications*, Vol.140, No.5, pp.349–355 (2020) (in Japanese)
- (20) Y. Taguchi, K. Hatakeda, T. Kaneko, and T. Kimura: "Development of Traction Circuit for Converting AC EMU into Battery-Powered Dual Source EMU", *IEEE Trans. IA.*, Vol.135-D, No.4, pp.403–410 (2015) (in Japanese)



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