Innovative lightweight traction system technologies employing power electronics on the Shinkansen high-speed EMUs
- Environmentally-friendly aspect and innovative traction systems -

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Abstract

In 1964, the Tokaido Shinkansen marked the start of the world’s first commercial service high-speed railway that operates at over 200km/h. Since then, the Tokaido Shinkansen has demonstrated itself as a successful business and technological advancement. In the event of speed-up of the Shinkansen, wayside environmental matters such as noise and vibration have been critical. Countermeasures against wayside noise and vibration, such as weight reduction and aerodynamics, also effect on global environmental measures to reduce energy consumption and CO₂ emission. After the Series 300, system change of applying AC drive system and lightweight body realized performance improvement from the Series 0.

The high-speed EMUs readily take advantage of technological innovation such as electronics technology. Particularly, an innovative AC drive system comprising a power converter with a GTO thyristor and asynchronous motors realized a high-performance and lightweight traction system for high-speed EMUs in the 1990s. Furthermore, recent innovations in electronics technology, such as low switching loss power devices and high-power permanent magnets, have improved the AC drive systems of the high-speed EMUs of the 21st century.

This paper starts out by introducing environmentally friendliness of the Shinkansen in terms of low energy consumption by means of traction system change of innovative Shinkansen trains, and then continues on by introducing recent technological innovations that have given birth to lightweight traction systems, such as the Permanent Magnet Synchronous traction Motor (PMSM) and power converters with train-draft-cooling systems. The paper concludes by introducing environmentally-friendly aspects of the Tokaido Shinkansen.

1. Introduction

Because of recent environmental friendly consciousness, transport sector has tried to save energy consumption and reduce CO₂ emission. Railway system takes advantages in environmental friendliness. In general, energy consumption of railway per person per kilometer is only 1/6 of automobile and 1/4 of airplane. In addition, CO₂ emission of railway is only 1/9 of automobile and 1/6 of airplane[9]. Moreover, to use innovation of power electronics, further energy saving measures are advancing.

In 1992, Central Japan Railway Company started revenue service of the series 300 Shinkansen train to increase maximum speed to 270km/h by 50km/h more than ever, and connected Tokyo and Shin-Osaka in 2.5hours. The series 300 has applied innovative AC drive system, AC regenerative brake system, extruded aluminum alloy body structure, bolster-less bogie, to realize thoroughly weight reduction as anti-vibration measure, and flush surface, optimization of nose shape, improvement of current collection system to realize aerodynamics as noise reduction and anti-micro-pressure wave measure. These measurers also contribute to save energy and CO₂ emission. In case of the series 700, CO₂ emission per seat per kilometer is only 1/10 of airplane. This figure indicates that Tokaido Shinkansen is the best mass transportation supporting for global environment[10].

Because these energy saving trains contribute to lower load on environment, Central Japan Railway Company proposed introducing further energy saving trains as voluntary plan for global
environment. In fact, after 15 years of introduction of the series 300, its energy saving effect was realized as electricity consumption saving.

Electronics technology has played an important role since the conception of the Shinkansen in the 1960s in improving the speed and power, of the Shinkansen high-speed EMU as well as making it lighter in weight. Power devices for power converters have evolved from the thyristor, to the Gate Turn-Off (GTO) thyristor to the Insulated Gate Bipolar Transistor (IGBT). And, traction systems have evolved from the DC motor drive to the AC motor drive, all of which has consequently improved the total performance of the traction system. For example, the power/weight ratio of the latest N700 Shinkansen train as a train-set is twice that of the Series 0 Shinkansen train, and the maximum operational speed has increased from 210km/h to 300km/h over the last 40 years. Particularly, in the 1990s, power electronics technologies, such as the power converter with GTO thyristor, the asynchronous motor drive system, and the AC regenerative brake system, were applied to innovative high-speed EMUs in Japan. As a result, the energy saving effect of lightweight trains, maximum axle load reduction, good running performance with high adhesion force, high-speed running on steep gradient routes, efficient transport capacity and train configuration flexibility and optimum traction performance of the EMU were reevaluated and put to use. Thus, high-speed EMUs readily take advantage of technological innovations, such as in the field of electronics technology, and develop according to the advancement of power devices [2], [12], [13].

This paper describes factors and effects of energy saving of Shinkansen trains, in terms of system change from former Series 0 and 100 to innovative Series 300, 700, and N700. In addition, innovative lightweight technologies, such as Permanent Magnet Synchronous traction Motor (PMSM) and power converters with train-draft-cooling, will be introduced by focusing on power electronics technologies for high-speed EMUs. Furthermore, the low energy consumption and environmentally-friendly aspect of the Tokaido Shinkansen will be examined from the standpoint of being a result of these innovative technologies.

2. Factors to effect on energy consumption in running
Countermeasures against wayside noise and vibration, such as weight reduction and aerodynamics, also effect on global environmental measures to reduce energy consumption and CO₂ emission. After the Series 300, system change of applying AC drive system and lightweight body realized performance improvement from the Series 0. From train system's point of view, major factors to reduce energy consumption are as follows.

1) Reduction of running resistance (mechanical resistance and aerodynamic resistance)
2) Weight reduction of train
3) Use of regenerative brake
4) Improvement of power factor
5) Reduction of loss of electrical equipment
These factors to reduce running energy consumption are considered below [3].

2.1 Reduction of running resistance
Generally, figures of running resistance of railway vehicles are shown as below [11].

\[
R = (a + b \cdot V) \cdot M + (c \cdot F + d \cdot L \cdot l) \cdot V^2
\]

Mechanical resistance: \(R1 = (a + b \cdot V) \cdot M\)
Aerodynamic resistance: \(R2 = (c \cdot F + d \cdot L \cdot l) \cdot V^2\)

\(R\):Running resistance, \(R1\):Mechanical resistance, \(R2\):Aerodynamic resistance, \(V\):Velocity, \(M\):Mass of train set, \(F\):Cross section of car body, \(L\):Train Length, \(l\):Outside length of cross section of car body, \(a, b, c, d\):Constant

Running resistance is composed of mechanical resistance and aerodynamic resistance. As mechanical resistance increases in proportion to train weight \((M)\), reduction of train weight,
friction between wheel and rail, and rotating friction of bearing, contribute to reduce mechanical resistance. As aerodynamic resistance increases in proportion to square of velocity \(V^2\), small cross section, nose shape, and flush surface contribute to reduce aerodynamic resistance.

Figure 1 shows comparison of running resistance of Series 0, 300, 700 and N700 Shinkansen trains. The newer the train is, the lower running resistance becomes. In case of the series 700, aerodynamic resistance and mechanical resistance are almost equal at 185\(\text{km/h}\). While, in high-speed region, aerodynamic resistance is dominated and aerodynamic resistance becomes 175% of mechanical resistance at 285\(\text{km/h}\). In comparison with running resistance of series 0 and 700, running resistance of series 700 is 62%, mechanical resistance is 56%, and aerodynamic resistance is 69% of those of the series 0.

![Figure 1: Comparison of running resistance (as a train-set with 16cars)](image)

2.2 Weight reduction of train
In addition to reduction of mechanical resistance, weight reduction has effect on reduction of gradient resistance and traction force in acceleration and deceleration. Table 1 shows technological trajectory of traction system from series 0 to N700. The series 300 has applied lightweight technologies, such as AC drive system, aluminum alloy body, bolster-less bogie, then thoroughly weight reduction realized. The series 700 and N700 achieved further weight reduction by application of IGBT device. IGBT does not need snapper circuit and reduces heat loss, in contrast with GTO thyristor. In addition, higher switching frequency of the IGBT reduces higher harmonics and loss from traction transformer. Consequently, application of the IGBT realized compact and lightweight traction system.

Weight reduction is also effective on reduction of kinetic energy, which increases in proportion of mass and square of velocity. When velocity increases from 220\(\text{km/h}\) to 270\(\text{km/h}\), kinetic energy becomes 150% more. However, 30% of weight reduction realized, like the series 300, kinetic energy increases only 5%.
2.3 Use of regenerative brake
Regenerative brake system converts kinetic energy to electric energy, and then returns it to catenaries. If regenerative energy is effectively used, energy saving is possible. In case of former externally commuted regenerative brake system of conventional railway vehicles, if distance between substations is long, enough brake power is not available because of large commutation reactance. In this circumstance, to provide enough brake power and to realize power factor 1 control, self-commuted power converter was developed for the series 300. In the regenerative brake system, a resistor, which converts brake energy to thermal energy, is eliminated, as a result, weight reduction, speed-up, operation in long steep line, and energy saving realized. In addition, as Shinkansen applies power-distributed system, i.e. EMUs, many traction axles with electrical dynamic brake, such as a rheostatic brake and regenerative brake, absorb most of braking energy, and large regenerative brake power generated in case of regenerative brake.

2.4 Improvement of power factor
AC drive system of the series 300 carries out power factor 1 control at a point of pantograph with self-commuted PWM power converter. Power factor of DC motor drive system with thyristor phase control was 0.8, so loss from catenaries and power supply system was reduced by 20%. In spite of power up for speed up, power factor control saved increase of electric ground facilities.

2.5 Reduction of loss of electrical equipment
High-efficient traction system reduces loss from input of a traction transformer to output of a traction motor. For ground facilities, high-efficiency of equipment directly improves total efficiency. Whereas, as on board electric equipment has to be mounted under floor, which requires compactness and lightweight. Therefore, small and light equipment contributes to total energy saving, rather than efficiency improvement of on board equipment.

3. Effects of traction system changes on the Shinkansen high-speed EMU made in accordance with advances in power electronics
EMU systems readily take advantage of innovations in electronics technology, and develop according to the advancement of power devices. For example, the Series 300 Shinkansen train utilized a GTO thyristor to realize an AC drive system in 1990, and in 1997 the Series 700 Shinkansen train became the first high-speed train in the world to use innovative IGBT technology. In addition to improving train performance and giving birth to a lighter and more compact traction system, these technological innovations have reduced the high harmonics and

### Table 1: Technological trajectory of traction system of Shinkansen trains

<table>
<thead>
<tr>
<th></th>
<th>Series 0</th>
<th>Series 100</th>
<th>Series 300</th>
<th>Series 700</th>
<th>Series N700</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Composition of traction unit</strong></td>
<td>2cars unit/MM</td>
<td>2cars unit/MM</td>
<td>3cars unit/MTM</td>
<td>4cars unit/TTMMM</td>
<td>4cars unit/TTMMM and MMMM</td>
</tr>
<tr>
<td><strong>Motored cars and Trailers</strong></td>
<td>16M</td>
<td>12M4T</td>
<td>10M6T</td>
<td>12M4T</td>
<td>14M2T</td>
</tr>
<tr>
<td><strong>Traction control system</strong></td>
<td>Low voltage tap changer</td>
<td>Thyristor phase control</td>
<td>PWM control (with GTO thyristor)</td>
<td>PWM control (with IGBT)</td>
<td>PWM control (with IGBT)</td>
</tr>
<tr>
<td><strong>Electrical brake system</strong></td>
<td>Rheostatic brake</td>
<td>Rheostatic brake</td>
<td>Regenerative brake</td>
<td>Regenerative brake</td>
<td>Regenerative brake</td>
</tr>
<tr>
<td><strong>Type of traction motor</strong></td>
<td>DC motor 185kW 64 motors</td>
<td>DC motor 230kW 48 motors</td>
<td>Asynchronous motor 300kw 40 motors</td>
<td>Asynchronous motor 275kw 48 motors</td>
<td>Asynchronous motor 305kw 56 motors</td>
</tr>
<tr>
<td><strong>Rated power</strong></td>
<td>11840kw</td>
<td>11040kw</td>
<td>12000kw</td>
<td>13200kw</td>
<td>17080kw</td>
</tr>
<tr>
<td><strong>Maximum operating speed</strong></td>
<td>220km/h</td>
<td>220km/h</td>
<td>270km/h</td>
<td>285km/h</td>
<td>300km/h</td>
</tr>
<tr>
<td><strong>Rated power per train</strong></td>
<td>11840kw</td>
<td>11040kw</td>
<td>12000kw</td>
<td>13200kw</td>
<td>17080kw</td>
</tr>
</tbody>
</table>

Notes) M: Motored car, T: Trailer car
noise emitting from the traction system by means of the higher switching frequency of IGBT and a three-level control method.

To demonstrate the effect of the lighter weight and higher efficiency of high-speed EMUs, the traction systems of high-speed Shinkansen trains are compared in terms of their systematic weight and power. In this case study, the Series 100 Shinkansen train represents the DC motor traction system; the Series 300 represents the GTO thyristor-applied AC drive system; and the Series 700 represents the IGBT-applied AC drive system. [6], [7]

Since the Series 100 uses a DC motor driven system, it requires a number of components, such as a resistor, a phase controlled rectifier and a smoothing reactor, for the power conversion system which results in a total system weight of 92 tons. The Series 300 employs the first AC drive system to have a GTO thyristor which resulted in a traction system that is lighter and is high-powered. The total weight is 72 tons, 20% less than the Series 100. The Series 300 also employs total weight reduction technologies, such as an extruded aluminum alloy body and bolster-less bogies. Consequently, total train-set weight was reduced by 25% thereby realizing service operation at 270km/h. The Series 700 succeeded in reducing the weight of traction systems, and the total weight is 55 tons. As a result, a 40% weight reduction and 200% power/weight ratio are achieved as compared to the traction system of the Series 100. Figure 2 shows trends in the weight/power ratio of the traction systems of Shinkansen trains, from the Series 0 to the Series N700. Thus, systematic change of the traction system has contributed to realizing a powerful, lightweight and efficient traction system for high speed EMUs.

![Figure 2: Weight/Power ratio of traction systems](attachment:image.png)

### 4. Recent examples of innovative lightweight technologies in the traction systems of the Shinkansen EMU

#### 4.1 Power converter with train-draft-cooling system

In the 1990s, the first AC drive system with a power converter and asynchronous traction motors were developed for the Shinkansen high-speed train in Japan. The AC drive system realized an AC regenerative braking system, power factor control and a lightweight traction system, and greatly contributed to increasing the speed of the Shinkansen.

In case of the Shinkansen EMUs, traction equipment has to be mounted under the floor in the limited space between bogies under each vehicle. Therefore, traction equipment must be light and compact. In general, forced-ventilation cooling systems minimize traction equipment such as traction transformers, traction motors, and power converters, and traction equipment in turn have their own blower motors and fans for cooling. In particular, the large amount of traction power needed as the Shinkansen runs at high speeds means that an extraordinary amount of heat produced by traction equipment must be absorbed somehow. Therefore, until recently it was thought that the use of power converters that employ train-draft-cooling, i.e., self-cooling,
was impossible for the Shinkansen high-speed train, even though self-cooling inverters are quite practical for commuter trains or auxiliary power supplies. However, around 2003, the use of power converters with train-draft-cooling systems on Shinkansen trains entered the realm of possibility as new IGBT with lower switching loss becomes available.

The train-draft-cooling power converters are advantageous in that they are lighter in weight since cooling blower motors, fans and liquid cooling mediums are not required. Moreover, their simple structure that doesn’t comprise a cooling medium and cooling system will be easy to maintain and highly reliable. [8]

4.1.1 Improvement in switching loss of the IGBT
In 1996, powerful 2500V-1800A IGBTs became available which enabled the start of IGBTs application to the power converters of the Shinkansen trains together with Neutral Point Clamp (NPC) systems. Currently, IGBTs are the standard power devices of power converters and inverters on all new trains in Japan.

Low-loss IGBT with NPC was necessary for realizing the train-draft-cooling power converters. After 2000, switching loss of the IGBT was improved, and IGBT switching loss was reduced by 30% in 2003. The low switching loss IGBT was the key to the self-cooling power converter.

4.1.2 Analyzing airflow under the floor during high-speed running
To utilize airflow under the floor as cooling air for power converters, characteristics of under-floor airflow such as airspeed, air direction and fluctuation, had to be grasped. To analyze the airflow, computer analysis, experiments with small models, and running experiments with actual...
sized models, were carried out. As a result, it was discovered that at suitable angles of wind slope, airflow traveling at speeds of more than 20% of the train’s running speed can be utilized as cooling air.

4.1.3 Running test on the Series N700 Shinkansen train
The prototype of the train-draft-cooling power converter was mounted on the Series N700 and running tests were carried out. The prototype power converter is shown in Figure 3.

Figure 4 shows the running test result of the train-draft-cooling power converter on the Series N700. Even though air speed varies, it was assured that on average cooling air flow traveling at speeds of more than 22% of the running speed is available. As a result of the running test, it is assured that the temperature increase seen in each part of the power converter is well below temperature limits.

![Figure 4: Running test result of the power converter with train-draft-cooling system](image)

4.1.4 Considerations
The results of the running tests on power converters confirmed that train-draft-cooling for the Shinkansen high-speed train can be practical. In addition, the simple power converter structure will contribute to higher reliability and easier maintenance.

In terms of the weight reduction effect, the weight/power ratio of the innovative train-draft-cooling power converter is half that of the power converter of the Series 300 in 1990.

4.2 Permanent Magnet Synchronous traction Motor (PMSM)
DC motors have been used for traction motors on railway vehicles for a long time because of the ease of drive control and traction characteristics. After the 1990s, however, in accordance with innovation of power electronics and computer control technologies, AC drive systems with inverters and asynchronous motors became the standard traction drive system for railway vehicles since they are easily maintained and high-performing asynchronous motors.

AC motors drastically reduced the weight of traction motors. For example, the weight/power ratio of the asynchronous motor of the Series 300 Shinkansen train is almost 1/4 that of the DC
motor of the Series 0 Shinkansen train. Asynchronous motors are advantageous in that one inverter drives multiple traction motors, so the system is very suitable for EMUs. However, after the Series 300, lightweight traction motor technologies matured, and further weight reduction of the asynchronous motor seemed impossible. System changes are needed to make further improvements. A Permanent Magnet Synchronous traction Motor (PMSM) has been developed to utilize the innovation of high-performance permanent magnets and electronics technology in pursuit of further traction motor weight reduction.

4.2.1 Technological background in developing lightweight PMSM
(1) Improvement permanent magnet performance
Permanent magnets have been used for small DC motors, but industrial application has been weak due to their small power output. Since the 1980s, the performance of Ne-Fe-B permanent magnets has been thoroughly improved, and the price of the magnet became reasonable after the year 2000.

(2) Industrial applications of PMSM
Industrial application of PMSM has expanded rapidly due to improvements in its performance and a reduction in its cost. Compared to the asynchronous motor, the PMSM has advantages of being highly efficient, low energy consuming, lightweight and compact. Therefore, the PMSM has become a standard over the asynchronous motor in electric car, elevator and air conditioner applications as a one-inverter-fed-motor system.

(3) Improvement of power electronics
Development of the IGBT from the GTO thyristor in the 1990s has promoted high-power, high-voltage, high switching frequency and low-loss power devices. The 3.3kV-1.2kA IGBT is a standard device for the power converters of Shinkansen high-speed trains and high-voltage 4.5kV IGBT has also been developed for use.

(4) Improvement of control technology
In accordance with improvements in power electronics, inverter control technology has also improved. Vector control has become mainstream and sensor-less control is being practically applied to railway vehicles. Output frequency of the traction inverter increases in proportion to the polarity of the traction motor. In other words, high inverter control frequency has enabled an increase in the polarity of the traction motor. It is standard for railway vehicles to employ AC motors with 4 poles. The new lightweight PMSM employs 6 poles for further weight reduction. As a traction motor with 6 poles realizes a short stator coil end and thin core back, consequently, it is advantageous to lightweight and compactness of a traction motor.

(5) Accumulated know-how of weight reduction techniques for traction motors
In the 1990s, lightweight asynchronous traction motor technology was thoroughly improved. This asynchronous motor engineering design can be applied to PMSM, but not to rotors.

(6) Improvement of method for analyzing magnetic fields
Sophisticated magnetic field analyzing methods helps in precise PMSM engineering design.

### Table 2: Comparison of weight and power of traction motors on high-speed trains [11], [12], [13]

<table>
<thead>
<tr>
<th>Motor type</th>
<th>Series 0 (JNR, Japan)</th>
<th>Series 300 (JRC, Japan)</th>
<th>Series N700 (JRC, Japan)</th>
<th>ICE1 (Germany)</th>
<th>TGV-A (France)</th>
<th>AGV (France)</th>
<th>Lightweight PMSM (JRC, Japan)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor power output [kW]</td>
<td>185</td>
<td>300</td>
<td>305</td>
<td>1200</td>
<td>1100</td>
<td>770</td>
<td>305</td>
</tr>
<tr>
<td>Motor weight [kg]</td>
<td>876</td>
<td>390</td>
<td>394</td>
<td>1980</td>
<td>1450</td>
<td>740</td>
<td>276</td>
</tr>
<tr>
<td>Weight/Power [kg/kW]</td>
<td>4.74</td>
<td>1.30</td>
<td>1.29</td>
<td>1.65</td>
<td>1.32</td>
<td>0.96</td>
<td>0.90</td>
</tr>
</tbody>
</table>

4.2.2 Technological development of lightweight PMSM

(1) Design concept
The engineering design concept concerning innovative lightweight PMSM is:

1) To pursue optimal performance by choosing a permanent magnet with the highest BH max
2) To alleviate increases in temperature by setting the polarity of the traction motor set at 6 poles
3) To pursue lighter weights by employing forced-ventilation to cool motors

(2) Test results for the lightweight PMSM
Test results for the overall characteristics of the lightweight PMSM indicate that required torque and power are obtained, and measured terminal voltage and phase current almost match those of designed values.

(3) Considerations
To evaluate the weight reduction effect, the weight/power ratios of traction motors on high-speed trains are compared in Table 2. Around 1.30kg/kW is the standard value of traction motors on recent high-speed trains worldwide. The lightweight PMSM (Figure 5) marks 0.90kg/kW, which seems to be the world's lightest traction motor in terms of application to high-speed trains.

In the event of actual application of the PMSM traction systems for high-speed trains, disadvantages of the PMSM system, such as 1-motor-1-inverter system of PMSM rather than 4-motors-1-inverter system of asynchronous motor and additional contactors between inverter and traction motor, have to be considered. A power converter of the PMSM tends to become more complicated compared to the asynchronous motor drive system. However, technological innovation of power electronics such as Silicon Carbide (SiC) power device will contribute to realize a compact and lightweight power converter, and relief the disadvantage of the PMSM traction system.

![Figure 5: Comparison of traction motors of Shinkansen EMU](image)
(From left: DC motor, Asynchronous motor, PMSM)
CONCLUSION

As power-distributed high-speed train system (EMU), the Shinkansen train has many advantages such as low axle loads, good adhesion, and efficient braking. Weight reduction also contributes to low energy consumption, low braking energy, and good train performance. The Shinkansen high-speed EMUs readily use and employ innovative power electronics, such as new power devices and PMSMs. Lightweight technology firmly contributes to energy conservation and the global warming.

In conclusion, as a good total effect of the innovation and lightweight technology, comparison of the energy consumption of Shinkansen trains is shown in Figure 6. The latest Shinkansen train, the Series N700, consumes only 68% of the energy of that of the Series 0, even though speed has been increased from 220km/h to 270km/h. As a result, the total energy efficiency of the Tokaido Shinkansen was 19% better in 2006 compared to the level in 1990. We hope that new technologies applied to the Tokaido Shinkansen will contribute to a better global environment.

References