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**Review Paper**

# Energy Saving Technologies for Railway Traction Motors

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It is very important to improve the efficiency of traction motors to save energy in electric trains. In addition, improving the efficiency is also important to realize a totally enclosed traction motor that requires less maintenance. Therefore, the use of high-efficiency motors is expanding. Many of them are induction motors with high-performance materials; e.g. low-loss electrical steel sheets and low-resistivity conductors. Meanwhile, some of them use permanent magnet synchronous motors, which have higher efficiency than induction motors. In this paper, we will review these recent technologies to improve the efficiency of traction motors and give examples of high-efficiency traction motors in use in Japan. © 2010 Institute of Electrical Engineers of Japan. Published by John Wiley & Sons, Inc.

**Keywords:** rail vehicle, traction motor, efficiency, totally enclosed motor, permanent magnet synchronous motor

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## 1. Introduction

Traction motors of rail vehicles are required to be small enough to be housed in a limited space under the vehicle floor and light enough to relieve the impact applied to the track. Therefore, the importance in the design of the traction motor has been attached to reduction of the weight and size rather than losses in the motor. In order to remove the generated heat of the traction motor, a forced ventilation cooling system is usually introduced. However, it requires additional power. The output torque of a traction motor is usually transmitted to the wheel through reduction gears, which generate mechanical loss.

Previous research and development effort on the traction motor mainly concentrated on reduction of maintenance work. AC (induction) traction motors have replaced DC traction motors that require much maintenance work, but the efficiency of the motors has not increased remarkably.

However, the recent rising tide of global ecological concerns is promoting research and development work to increase the efficiency of the traction motors. In particular, the recently developed permanent magnet synchronous motors (PMSMs) have the potential to increase the efficiency of the traction motors and to reduce their weight and size. Accordingly, the introduction of the PMSM to rail vehicle has become active. Higher efficiency traction motor is also being developed to realize a totally enclosed motor that requires less maintenance.

Technologies to improve the efficiency of traction motors and examples of high-efficiency traction motors are reviewed here.

## 2. Structure of the Traction Motor and Classification of the Losses in the Motor

**2.1. Structure of the traction motor** A traction motor is composed of a stator and a rotor. In the case of an AC motor, the stator is composed of a stator iron core and a stator winding (Fig. 1). The stator core is made of stacked electrical steel sheets to reduce the iron loss. The stator winding is composed of form-wound coils, which are made of rectangular copper wire covered with an insulation material. The form-wound coils are suitable for high voltages and have sufficient mechanical strength to bear the vibration stress. The stator slots should be open to install the form-wound coils. Therefore, there are relatively high slot ripples, which generate surface loss in the rotor.

The rotor structure depends on the motor type. In the case of a squirrel-cage induction motor, the rotor is composed of a rotor iron core and a squirrel-cage winding, which is composed of copper alloy bars, short-circuit rings, and retaining rings (Fig. 2). Usually, the sheets for the rotor iron core and the stator iron core are punched from a same magnetic steel sheet at the same time.

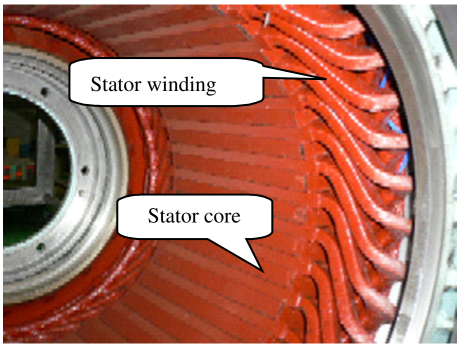


Fig. 1. Stator of a traction motor

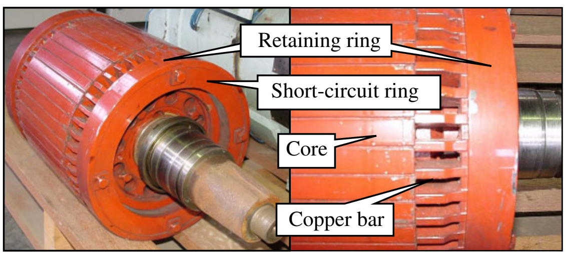


Fig. 2. Rotor of an induction traction motor [1]

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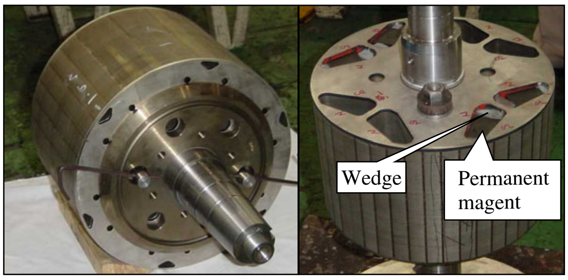



Fig. 3. Rotor of a permanent magnet synchronous traction motor [1]

In the case of a PMSM, the rotor is composed of a rotor iron core and permanent magnets. The structures of PMSMs can be classified into interior permanent magnet structures and surface permanent magnet structures. In the case of an interior permanent magnet structure, the permanent magnets are inside the rotor iron core (Fig. 3), and often have magnetic saliency, which can produce reluctance torque. In contrast, in surface permanent magnet structures, the permanent magnets are on the rotor surface, held against centrifugal force by a retaining structure made of nonmagnetic material.

**2.2. Losses in the traction motor** The losses in traction motors can be classified according to the location and origin of the loss.

The major stator losses are stator copper loss and stator iron loss. In the case of an induction motor, the major rotor loss is the rotor copper loss. Because the fundamental frequency of the magnetic field in the rotor is very low, the rotor iron loss due to the fundamental component is relatively small and usually neglected in the conventional loss calculation. In the case of a PMSM, there is no major loss in the rotor. This is one of the advantages of the PMSM. However, the surface loss in the permanent magnet is not negligible, especially in the case of the surface permanent magnet motors. The surface loss is induced on the surface of a rotor mainly by the stator slot ripples. The surface loss is also generated in the rotor core of an interior permanent magnet motor or an induction motor. In the case of an induction motor, the loss due to the slot ripples is also generated in the copper bars. This loss is a major component of the harmonic secondary copper loss, which is a relatively large loss according to a recent study [2]. These are the major electromagnetic losses in traction motors.

Another major loss is mechanical loss. In the case of a self-ventilated motor, a ventilation fan is attached directly on the shaft of the traction motor. Therefore, the ventilation fan rotates at the same speed as the traction motor, which rotates at a speed proportional to the train speed. In general, the airflow rate increases proportional to the rotational speed of the fan, and the power to rotate the fan increases proportional to the third power of the rotational speed. Consequently, the mechanical loss, which is composed of draft loss of the ventilation fan, bearing loss, and other friction losses, increases proportional to the second to the third power of the train speed. In addition, unlike the electromagnetic losses, the mechanical loss is generated while not only powering but also coasting. Therefore, even if the mechanical loss is relatively small at the rated point, the total mechanical loss in a train operation sometimes becomes large.

There is still another loss called stray load loss. As the name implies, the origin of the stray load loss is uncertain. Although some recent studies [3,4] have revealed the origin of the stray load loss in some industrial induction motors, few studies deal with the stray load loss in railway traction motors and this loss merits further research.

## 3. Technologies to Improve the Efficiency of Traction Motors

**3.1. Low-loss materials** The choice of materials has a great effect on the efficiency of traction motors.

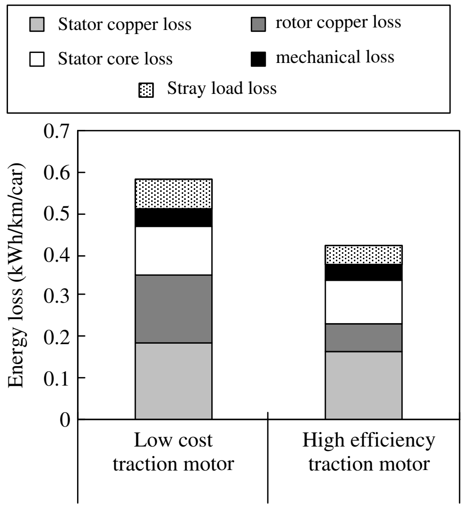
Firstly, the insulation material of the electric wire used for the stator windings affects the stator copper loss. If the thickness of the insulation is small, the space factor can be improved, and thereby the stator copper loss can be reduced. The general choice of wire for a traction motor for 1500 V DC feeding is a double-glass-fiber-covered wire. On the other hand, another possible choice is a polyimide covering. The thickness of the polyimide covering is smaller than that of glass fiber insulation. However, it is more expensive. Therefore, it is often used for high-performance traction motors for high-speed trains and seldom used for conventional commuter trains.

Secondly, the characteristics of electrical steel sheets used for the magnetic core directly affect the iron loss in the stator core as well as the rotor core. The most commonly used core material is M800-50A5, which is a standardized material [5,6]. The numbers in this symbol express the guaranteed iron loss, normal thickness, and test frequency, respectively. Thus, the iron loss in this steel sheet is less than 0.8 W/kg at 1.5 T and 50 Hz and the thickness is 0.5 mm. Although there are lower loss materials in the standard, the designers prefer M800-50A5 because of commercial availability and workability. However, low-loss materials are sometimes used for high-performance motors. For example, the traction motors of the gauge-change trains [7] use M300-35A5.

Figure 4 shows the calculation result [8] of energy loss in two traction motors in commuter train operation. One is a typical traction motor designed aiming at product cost reduction. The other is a high-efficiency motor that uses the low-loss materials previously described. The use of low-loss materials effectively reduces the energy loss. The use of polyimide wire insulation reduces the stator copper loss by about 12%. The use of low-loss steel sheet reduces the iron loss by 14%. However, the effect of the iron loss reduction is smaller than expected from the guaranteed value. This is because the building factor; i.e. the deterioration of the steel sheet due to manufacturing process, is larger in low-loss materials. The stray load loss is also reduced in the high-efficiency motor, because the loss is assumed to be 30% of the sum of stator copper loss and rotor copper loss in this calculation.

There is a high-performance core material called permendur, which is a kind of iron–cobalt alloy. It has high magnetic permeability and low loss characteristics, and therefore it is suitable for a high-power-density motor. A prototype motor for high-speed train that uses permendur core was manufactured and tested [9]. The test result demonstrates that the use of permendur increases the power density by 20% and reduces the core loss by 15%. However, permendur is a very expensive material and not used for mass-produced motors.

**3.2. High-efficiency induction motors** An inherent loss in induction motors is the rotor copper loss. Railway traction motors often use relatively low conductivity material, for example brass, as rotor conductor material. In most traction systems, one inverter drives multiple motors. In those systems, the slip in the induction motors should be kept at a relatively large value to allow for the difference in wheel diameters driven in parallel by a single inverter. That is the reason why low-conductivity material is used as rotor conductor material, although their use is not good in respect of the motor efficiency. However, if we postulate the use of individual inverter drive, we can choose a material that has higher conductivity. Silver-bearing copper is one of the possible materials with higher conductivity, because it has sufficient mechanical strength and high conductivity, which is almost the same as that of

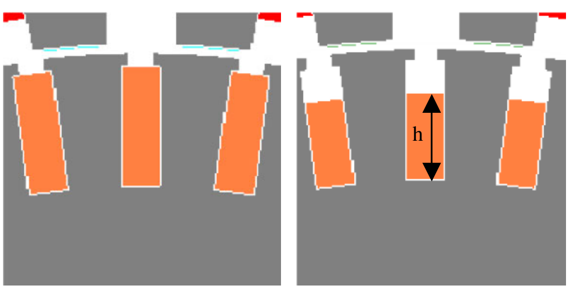



| | Low cost motor | High efficiency motor |
|---|---|---|
| Stator wire insulation | Glass fiber | Polyimide |
| Core | M800-50A5 | M300-35A5 |
| Rotor conductor | Brass | Silver bearing copper |
| Efficiency | 90.1% | 92.6% |

Fig. 4. Effect of materials on energy loss in traction motors in commuter train operation [8]

copper. Figure 4 shows the comparison between brass and silver-bearing copper. The rotor copper loss of a high-efficiency motor is about one-third of that of the low-cost motor.

The harmonic electromagnetic field in an induction motor produces an additional loss in the rotor. This loss is called harmonic secondary loss. A recent study [2] focuses on reducing the harmonic secondary copper loss in a traction motor. In the study, the harmonic secondary loss in a 135-kW traction motor was studied by conducting a finite element method (FEM) analysis and no-load test. The result shows that the copper loss makes up the majority of the harmonic secondary loss [2]. Therefore, reducing the harmonic secondary copper loss is important to improve the efficiency of the traction motors. A new rotor design was proposed to reduce the secondary copper loss [2]. Figure 5 shows the proposed rotor structure and the conventional one. In the proposed rotor, the height of the conductor bar is lower than the slot height, and there is some space near the rotor surface in the rotor slot. From the FEM analysis result, it was found out that the harmonic secondary current exists only in the area near the surface in the conductor bar [2]. Therefore, it is expected that simply removing the conductor in the area could reduce the loss. Figure 6 shows the calculation result of harmonic secondary losses in the proposed rotor. According to the result, the proposed design can reduce the harmonic secondary copper loss by half [2].




(Left: conventional rotor, right proposed rotor)

Fig. 5. Cross-sectional diagram of the rotors [2]

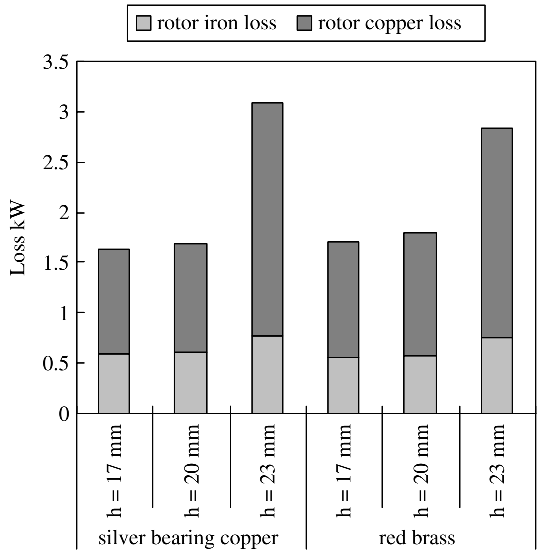



Fig. 6. Calculation result of harmonic secondary losses in the proposed rotor and the conventional rotor in a no-load synchronous test [2]

### 3.3. Permanent magnet synchronous motors

The invention of high-performance magnet materials has enabled the application of PMSMs to various fields including railway traction. A number of high-performance PMSMs have been developed for railway traction. One major merit of the PMSM is its high efficiency. To estimate the energy saving effect of PMSMs with high efficiency, a comparative study [10] was carried out using running simulation and equivalent circuit calculation based on performance test results of a prototype PMSM for commuter train [9,10]. The simulation results show that the total loss of the PMSM becomes about 60% of that of the induction motor when used as a traction motor for a typical commuter train (Fig. 7).

A prototype 300-kW PMSM for high-speed trains was also manufactured and performance tests were carried out to demonstrate the superiority of a PMSM to a conventional induction motor [1]. The prototype motor was manufactured by replacing the rotor of a conventional induction motor. From the test results, the loss characteristics were demonstrated in comparison with those of the induction motor (Fig. 8). The loss of the PMSM is 45–60% of that of the induction motor. Therefore, energy saving is also possible in high-speed trains with PMSM.

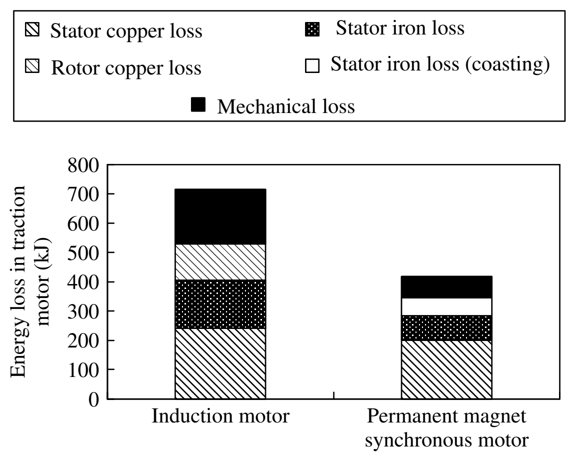



Fig. 7. Calculated energy loss in traction motors on a commuter train in operation [10]

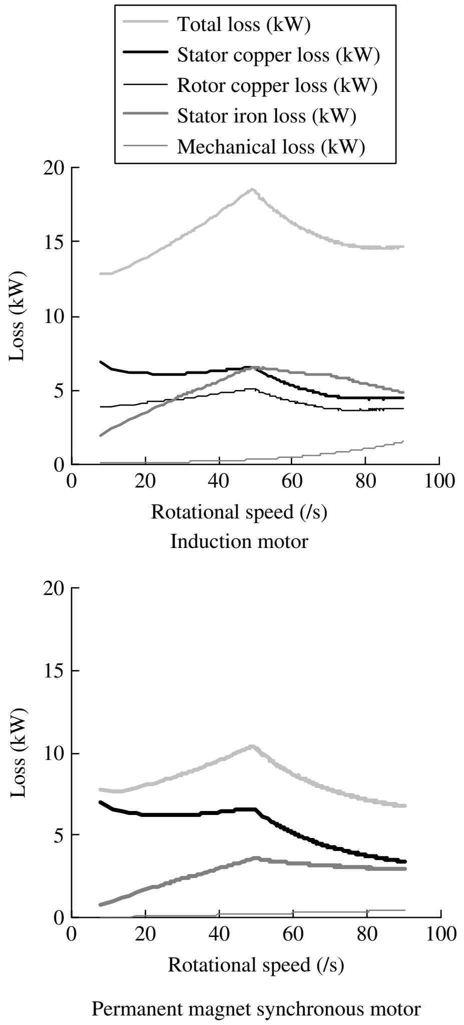



Fig. 8. Loss characteristics in two different types of traction motors for a high-speed train [1]

In these calculations, the stator iron loss and the mechanical loss are calculated from the no-load test result. The stray load loss is neglected.

Although many development projects demonstrated the high performance of PMSM, there are very few commercial uses for them. The major disadvantage of the PMSMs is that they require individual inverter drives, and therefore the initial cost of the traction system tends to be high. However, as the demand for saving energy increases, high-efficiency PMSMs are likely to be used in more trains in the future.

## 4. Development Examples of High-Efficiency Traction Motors

### 4.1. Totally enclosed induction traction motors

Traction motors for rail vehicles usually have ventilation cooling system in order to get high output with small size machine. However, they require regular maintenance work of overhaul and cleaning to remove the accumulated dust that is contained in the ventilation air and may clog the ventilation holes to cause temperature rise of the motor. In addition, the cooling fan connected to the shaft of the motor produces large noise, especially at high speed. In order to solve these problems, totally enclosed traction motors have been developed. However, the cooling capacity of the totally enclosed type is inferior to that of the ventilation cooling type. Therefore, the totally enclosed motor must be of low-loss type.

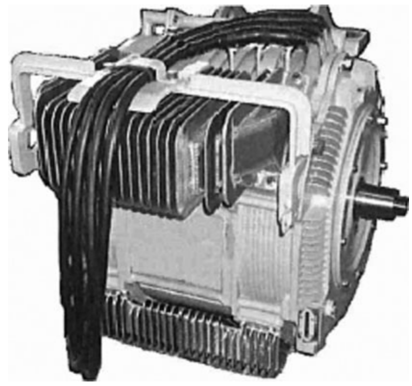


Fig. 9. Totally enclosed self-cooled induction traction motor for narrow gage EMU (1-h rated output 170 kW, oil lubrication) [11]

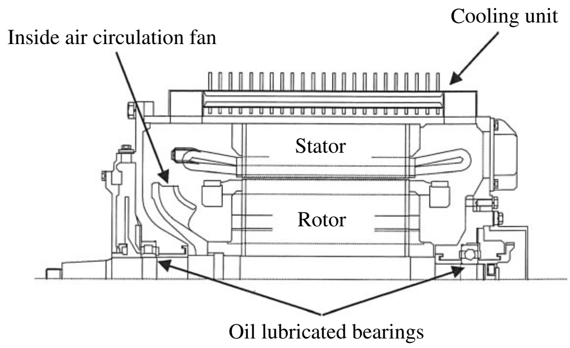



Fig. 10. Longitudinal section of the totally enclosed self-cooled induction traction motor [11]

Figure 9 shows an example of the totally enclosed self-cooled induction traction motor that was manufactured by Toshiba and applied to series 3300 EMU of the Nagoya Railways [11]. One-hour rated output of the motor was 170 kW and the total mass was 660 kg; Fig. 10 shows the cross section [11]. Cooling units are attached on top and at the bottom of the motor, and cooling air is circulated within the motor. Bearings are lubricated by oil, which can be replaced without dismantling the motor. The measured noise level was more than 20 dB lower than that of the conventional ventilation cooling traction motor [11]. Low-loss electrical sheets and high-conductivity rotor bar material were introduced to improve the efficiency. The consumed energy of the onboard traction circuit was 9% lower than that of the conventional ventilation cooling traction motor [11].

In order to get higher output than the totally enclosed self-cooled motor, the totally enclosed fan-cooled type motor was also developed; however, the noise level is higher than that of the self-cooled type. Figure 11 shows an example of the totally enclosed fan-cooled induction traction motor that was manufactured by Mitsubishi and applied to series 40 000 and 6000 EMUs of the Odakyu Electric Railways [12]. One-hour rated output of the motor was 190 kW and the total mass was 760 kg. Figure 12 shows the cross section [12]. It has both inside and outside fans. In addition to circulating the internal air, external fresh air is taken in the ventilation holes around the motor (Fig. 12). High-conductivity chromium–copper alloy was applied to the rotor bar to improve the efficiency [12].

### 4.2. Totally enclosed permanent magnet synchronous traction motors

The high-efficiency, low-loss PMSM is suitable for the totally enclosed motor. We started the development of a totally enclosed traction motor for a commuter train using the PMSM in 1998 [13,14] and manufactured an experimental

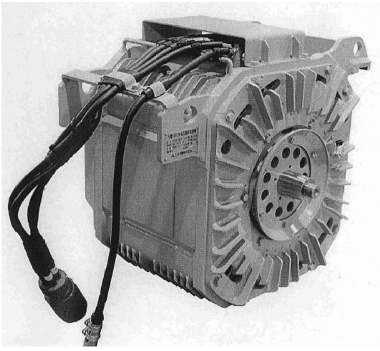


Fig. 11. Totally enclosed fan-cooled induction traction motor for narrow gage EMU (1-h rated output 190 kW, grease lubrication) [12]

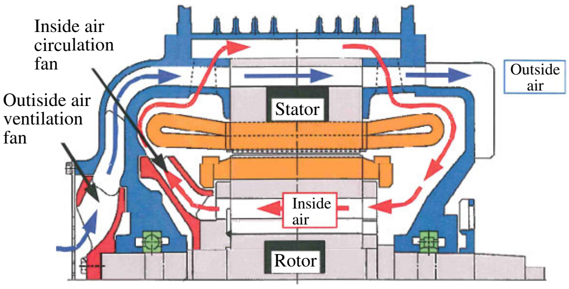



Fig. 12. Longitudinal section of the totally enclosed fan-cooled induction traction motor [12]

traction motor type RMT19 as shown in Fig. 13 [13,14]. One-hour rated output of the motor was 200 kW. The table in Fig. 13 shows the specifications of the experimental motor compared with

| | | Protype motor | | Conventional motor |
|---|---|---|---|---|
| Motor type | | Permanent magnet synchronous motor | | Induction motor |
| Cooling system | | Totally-enclosed | | Self-ventilated |
| Rating | Class | Continuous | 1 hour | 1 hour |
| | Output | 140 kW | 200 kW | 200 kW |
| | Voltage | 1000 V | 1100 V | 1100 V |
| | Current | 108 A | 148 A | 130 A |
| | Rotational speed | 2550 $\text{min}^{-1}$ | 2550 $\text{min}^{-1}$ | 2535 $\text{min}^{-1}$ |
| Efficiency | | 97% | 97% | 92% |
| Lubricant | | Grease | | Grease |
| Mass 57 | | 0 kg | | 595 kg |

Fig. 13. Photo and specifications of the totally enclosed permanent magnet synchronous traction motor type RMT19 [13,14]

Fig. 14. Totally enclosed, self-cooled permanent magnet synchronous traction motor for narrow gauge EMU (1-h rated output 270 kW, grease lubrication) [16]

the conventional traction motor of the same output ratings. We confirmed that a totally enclosed traction motor of the same output and same size as the conventional ventilation-cooling induction traction motor could be realized by using the PMSM. In addition, it was less noisy (the acoustic noise level was more than 10 dB lower at high speed) and efficient (approximately 5% higher) than the conventional motor [13].

Based on this achievement, a higher output, 270 kW (1 h) totally enclosed traction motor for suburban trains was developed [15–17]. Figure 14 shows the appearance of the motor [16]. The rated efficiency of the motor was 97%. It was mounted on the conventional line technical experimental train U@tech of JR West (West Japan Railway Company) [17]. Around 10% reduction of energy consumption was measured in the experimental train [16].

**4.3. Direct drive traction motors** The Railway Technical Research Institute (RTRI) started research and development

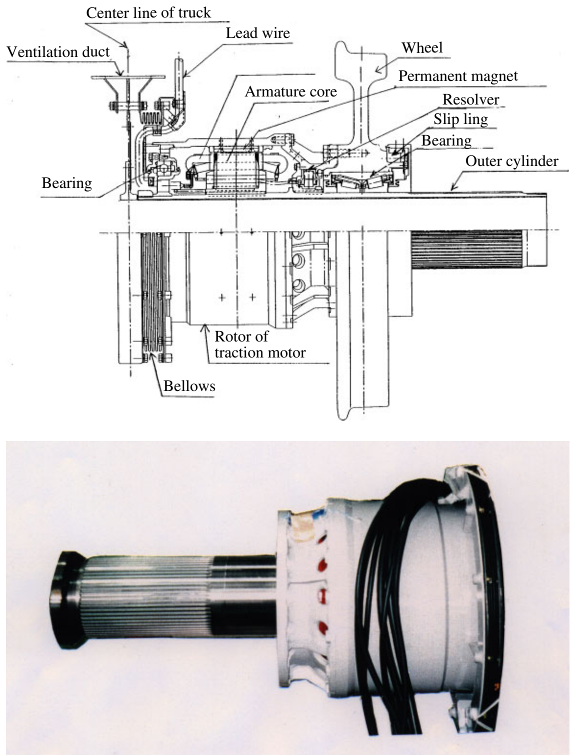



Fig. 15. Photo and cross section of the traction motor type RMT17 for the gauge adjustable EMU [7]

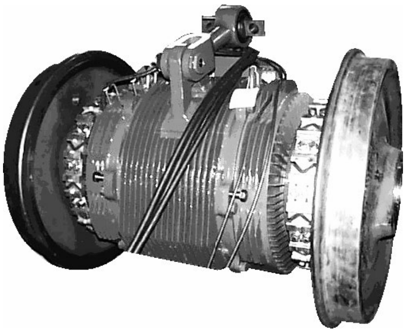


Fig. 16. Direct-drive traction motor for the AC train [22]

work on the direct drive system to eliminate the usual reduction gear system by introducing a wheel-mounted traction motor around 1990 [18,19]. Traction motor for the direct drive system is required to be light-weight and have high torque. The PMSM fits these requirements. The direct drive system permits a simple truck structure without reduction gear, so that it suits well with low-floor light rail vehicle (LRV), gauge-adjustable trains, and so on. Application to the next generation commuter train was also examined because of the elimination of power loss and acoustic noise associated with the reduction gear [20,21].

Figure 15 shows the appearance and structure of the wheel-mounted direct drive traction motor developed for the gauge-adjustable EMU [7]. Two wheel units integral with the traction motors slide on a fixed axle to adjust the distance between two wheels in order to enable through operation between different gauge track sections like standard gauge Shinkansen line and narrow gauge conventional line. The rated continuous output was 95 kW, the measured efficiency was 95.4%, and mass of the motor was 275 kg [7].

Figure 16 shows the appearance of a direct-drive traction motor manufactured by Toshiba and applied to the AC Train (Advanced Commuter Train), which is an experimental train for the next-generation commuter EMU of JR East (East Japan Railway Company) [21]. It was a totally enclosed, self-cooled inner-rotor type PMSM. The efficiency of the motor was 96%, which is 4% higher than that of the conventional induction motor [21].

### 4.4. Traction motors for high-speed trains

The need of the PMSM for the Shinkansen EMU was relatively low, because the forced ventilation traction motor for Shinkansen was small enough. However, further speedup of Shinkansen and the recent increased apprehension about global environment has encouraged the application of PMSM to Shinkansen EMU.

For example, series E954 Shinkansen high-speed experimental train of JR East aiming at a commercial operation speed of 360 km/h employs a self-ventilated PMSM [23]. Figure 17 shows the appearance of the motor [23]. Continuous rated output of the motor was 355 kW, and the rated efficiency was 97%, which is about 3% higher than that of the conventional induction traction motor [24]. By making use of the high-efficiency feature of the PMSM, the self-ventilated traction motor achieved the same size and mass as the conventional forced ventilation traction motor. The self-ventilated motor does not require the blower, and space for it is unnecessary.

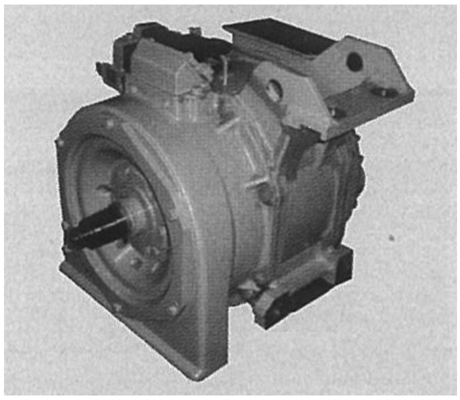


Fig. 17. Permanent magnet synchronous traction motor for the high-speed experimental Shinkansen train of the JR East [23]

Since the opening of the Tokaido Shinkansen in 1964, traction motors have progressed from DC motors to induction motors, and more recently to PMSMs under development to reduce the weight and improve the efficiency. Table I shows the output and weight of traction motors for the Tokaido Shinkansen EMUs and overseas high-speed trains for comparison [25]. The rated continuous output of the trial PMSM was 305 kW, which is same as that of the latest series N700 Shinkansen EMU, whereas the mass was reduced from 394 to 276 kg [25]. The efficiency was 5% higher compared to the conventional induction traction motor, and around 7% reduction of energy consumption is expected when operated on the Shinkansen line between Tokyo and Osaka [26].

## 5. Conclusions

Technologies to improve the efficiency of traction motors can be summarized as follows:

1. application of thinner insulation films such as polyimide;
2. application of higher grade iron core materials such M-360-35-A electrical steel sheet or permendur;
3. application of higher conductivity rotor bar materials such as silver-bearing copper;
4. reduction of the harmonic secondary loss of induction motor by shortening of the rotor bar height;
5. introduction of the PMSM.

We presented the effects of these technologies and examples utilizing these technologies. Introduction of these technologies may be expensive, though recent increased apprehension about global environment will compensate for the expense, and traction motors

Table I. Output and mass of traction motors for Shinkansen and overseas high-speed trains [25]

| | Tokaido Shinkansen train | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Train type | Series 0 | Series 100 | Series 300 | Series N700 | Trial machine | ICE1 (Germany) | TGV-A (France) | AGV (France) |
| Motor type | DC motor | DC motor | Induction motor | Induction motor | PMSM | Induction motor | Synchronous motor | PMSM |
| Rated output (kW) | 185 | 230 | 300 | 305 | 305 | 1200 | 1100 | 770 |
| Mass (kg) | 876 | 825 | 390 | 394 | 276 | 1980 | 1450 | 740 |
| Mass to power ratio (kg/kW) | 4.74 | 3.59 | 1.30 | 1.29 | 0.90 | 1.65 | 1.32 | 0.96 |

utilizing these technologies are increasing in number. The totally enclosed traction motor is a typical example of the high-efficiency motor.

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