Development of Main Circuit System using Direct Drive Motor (DDM)

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JR EAST is making efforts to develop the AC Train (Advanced Commuter Train) with the aim of making it the suburban commuter train meeting 21st-century requirements, and is engaged in conducting running tests. One of the development concepts of the AC train is to achieve cost reduction by innovative system changes. We have developed a main circuit system using the DDM (Direct Drive Motor) as a new drive system independent of the conventional method, and have conducted a running test on the existing car. This test has demonstrated that the basic performances are satisfactory.

● Keyword : Direct drive system, Synchronous motor, Permanent magnet, Buffer coupling, Adhesion, Wheel slip, Sliding control

1 Introduction

Thanks to the progress in power electronics and advanced control technologies, the rolling stock drive motor system has changed from the DC motor system to the induction motor system. This has brought about a compact size, light weight and maintenance-free configuration, and there has been a growing need for further advance in this direction. However, the conventional main circuit system has almost reached the stage of maturity, and it is difficult to expect further improvement from the conventional system. To solve this problem, we have abolished the current drive system (reduction gear unit), and have been committed to achieving a technological innovation through radical system change where the wheel is driven directly by a traction motor. Regarding this direct-drive motor system, we have developed a drive system for AC Train, where a major objective is to reduce the total cost as well as the initial cost, and to ensure 13-year maintenance-free operations.

2 Development concept

To reduce the life cycle cost of the drive system, we are determined to achieve the following two points:

(1) Elimination of the need for maintenance and loss in power transmission by abolishing use of the conventional reduction gear unit

(2) Improvement of motor efficiency by application of a permanent magnet type synchronous motor, maintenance-free operation by a totally enclosed cooling system, reduced noise and decreased manufacturing man-hours

For the AC train, efforts have been made to develop an articulated bogie system to reduce the number of bogies. For the DDM, it has been determined to reduce the number of drive axles through effective use of the adhesion between the rail and wheel per axle obtained from this articulated system.

3 How to set the performances

3.1 Underlying car specifications

Table 1 shows the underlying car specifications that provided the basis for setting the performances. Fig. 1 shows the trainset configuration. The maximum speed, startup acceleration and deceleration conform to those of the Series E2 as a standard suburban commuter train.

The number of drive axles is twelve in terms of the 10-car trainset of Series E2 (a trainset length of 200 meters). This is a reduction of 25 percent as compared to the current sixteen.

Table 1 Underlying car specifications

Item	Specifications
Trainset	5 cars
Trainset length	74m
Trainset weight (under max. load)	85ton(165ton)
Number of drive axles	4
Max. speed	120km/h
Startup acceleration	0.694m/s^2(2.5km/h/s)
Max. deceleration of service braking	1.17m/s^2(4.2km/h/s)

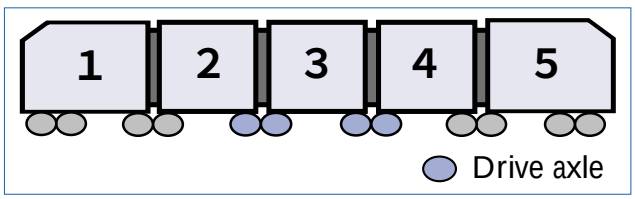

Fig. 1 Test car trainset (AC train)

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3.2 Redundancy

In the conventional induction motor system, multiple traction motors can be controlled by one inverter. Four axles are the standard unit for controlling the traction motor. The permanent magnet synchronous motor is designed according to an independent control scheme where one traction motor is controlled by one inverter.

This characteristic is effectively utilized to improve the redundancy. Namely, one unit (one motor), which is the same as the control unit, is used as the traction motor cut-out unit when a problem arises in a device in the main circuit.

4 System

4.1 Main motor

4.1.1 Main specifications

Table 2 shows the major specifications of the traction motor.

Table 2 Major specifications of the traction motor

Item	Specifications
Method	Synchronous motor with embedded magnet structure
Structure	Inner rotor elastic support system
Cooling method	Totally closed self-cooling
Rated cooling	160 kW (continuous) 200 kW (one hour)
Rated rotation speed	360 rpm
Torque	4244 Nm (for rated rotation) 11800 Nm (at the time of startup)
Efficiency	95 %

As a result of running a simulation, the output has been determined in such a way that the continuous rated output is 160 kW and the one-hour rated output is 200 kW. A totally enclosed self-cooling system has been adopted in order to eliminate the need of maintenance including air blowing.

The structure is designed to allow the wheel to be replaced in the same way as before. The inner rotor elastic support structure has been adopted, with consideration given to influence upon the running performances and track. The rotor shaft is made in a hollow structure, and a resilient rubber is placed between the rotor and axle passing through its interior so that the axle is elastically supported. Fig. 2 shows the elastic support structure, and Fig. 3 shows the installation on the AC train.

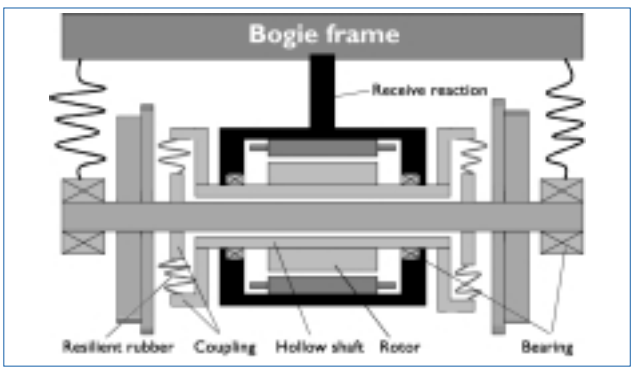

Fig. 2 Inner rotor elastic support structure

Fig. 3 External view of a traction motor

4.1.2 Studying the possibility for more compact configuration

The required torque is about nine times that of the MT73 traction motor used in the Series E231. In order to permit installation in a limited space using the intended totally enclosed cooling system, it is important to develop a more compact configuration through improvement of the cooling performances of the traction motor. In this development, we used the following items to allow installation inside the bogie:

(1) Magnet

We used the neodymium-based magnet characterized by a high density of magnetic flux density, great resistance to demagnetization and excellent heat resistance.

(2) Use of reluctance torque

To ensure that the rotor having a limited size generates greater

torque, the rotor has been designed in a built-in magnet structure to obtain a reluctance torque. Fig. 4 shows the rotor structure, and Fig. 5 shows the reluctance torque generating principle. Motor torques is given in Equations (1) to (3).

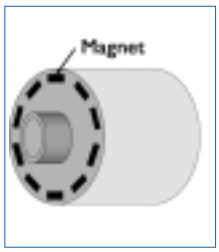

Fig. 4 Rotor structure

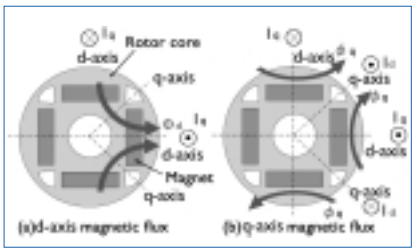

Fig. 5 Reluctance torque generating principle

$$T_{\phi} = k \cdot \phi_f \cdot I_q \quad (1)$$

$$T_L = k \cdot (L_d - L_q) \cdot I_d \cdot I_q \quad (2)$$

$$T_q = T_{\phi} + T_L \quad (3)$$

T_{ϕ} : Magnet torque (Nm) T_L : Reluctance torque (Nm)

T_q : Motor torque (Nm) ϕ_f : Effective magnet flux (Wb)

I_q : q-axis current (A) I_d : d-axis current (A)

L_q : q-axis inductance (H) L_d : d-axis inductance (H)

k : Constant

(3) Improved cooling performances

The stator core as a heat generating source has been designed in a frameless structure that allows direct cooling. At the same time, a circulation duct system has been adopted to cool the air heated in the mortor. Further, to improve the effect of releasing heat from the motor proper, a cooling fin is provided on the outside. Fig. 6 shows the overview of the cooling structure.

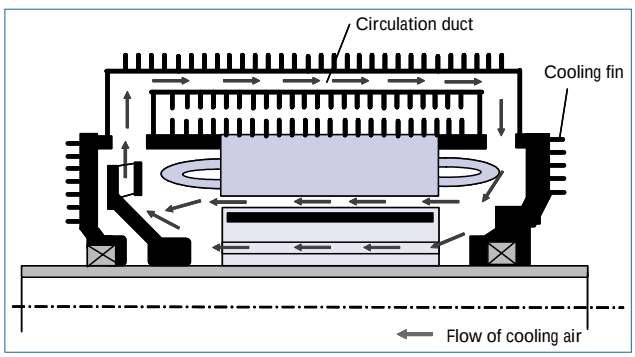

Fig. 6 Cooling structure

(4) Studying the V/f

If the terminal speed of the constant V/f (V: voltage and f: frequency) to make constant the acceleration (motor torque) at the time of startup is set to the low-speed side, there will be an increase in the area requiring the weak flux control. This will cause an increase of the reactive power. It also becomes necessary to increase the weight of the magnet and number of turns of the coil, with the result that the weight of the traction motor will be increased. On the other hand, if it is set to the high-speed side, there will be an increase in the current for delivering the torque in the amount that corresponds to the voltage drop. This requires the quality of the inverter element to be raised or the mass to be increased. With consideration given to these factors, the terminal speed of constant V/f has been set to a higher value than that of the conventional inductor motor.

4.2 Coupling rubber

(1) Concept of buffer

The motor of this model is suspended on the axle through the spring called a coupling rubber (Fig. 7). Thus, the natural period T when the displacement of vibration in the vertical direction is applied is expressed by the Equation (4) of the vibration determined by the mass of the motor and the spring constant of the coupling rubber.

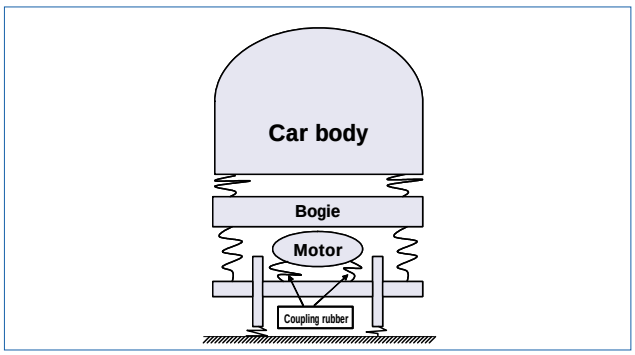

Fig. 7 Spring model

$$T = 2\pi\sqrt{W / (G \cdot K)} \quad (4)$$

T : Natural period (s)

W: Motor mass ($kg \cdot s^2/m$)

G : Gravitational acceleration 9.8 (m/s^2)

K : Coupling rubber spring constant (kg/m)

The load (amplitude) variation according to the motor mass is gradually attenuated, and is one fourth of the natural period T when the maximum load occurs, as shown in Fig. 8. Then superimposition of two loads can be avoided by t < T/4, where "t" is assumed to represent the time when impact load is given by the wheel set at the time of running on the rail joints.

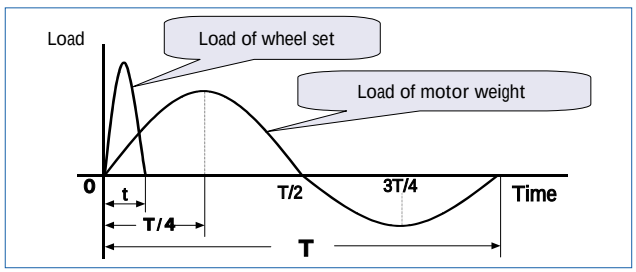

Fig. 8 Vibration load

(2) Studying the spring constant

When setting the spring constant of the coupling, we simulated the impact upon the track, using a spring mass model including a bogie, car body and track. In this simulation, consideration was given to meet the following requirements:

(1) Must have the same effect of alleviating impact on the rail as that in the conventional parallel cardan method.

(2) No superimposition is allowed when passing through rail joints.

(3) No resonance with the car body, whirling of the traction motor proper or torsional resonance shall occur in the working speed range of the traction motor.

(4) The above-mentioned requirements shall be met even when the rubber is subjected to aged deterioration.

4.3 Inverter

4.3.1 Major specifications

Table 3 shows the major inverter specifications, and Fig. 9 shows the external view:

Table 3 Major inverter specifications

Item	Specifications
Control unit	Control by one motor for one inverter
Structure	(Main motor capacity 160 kW x 2) x 2 boxes
Operating method	2-level, 3-phase voltage PWM
Elemental device	IGBT3300V-1200A (module)
Cooling method	Natural cooling of heat pipe

Fig. 9 External view of inverter

4.3.2 Main circuit connection

Fig. 10 is a schematic diagram showing the main circuit connection. Since the traction motor is a type of synchronous motor, control is effected according to the separate control system of one inverter for each motor specific to the synchronous motor. Further, in order to protect the induced voltage caused by the permanent magnet inside the traction motor at the time of short-circuiting of the inverter arm, an open circuit breaker was installed between the inverter and traction motor.

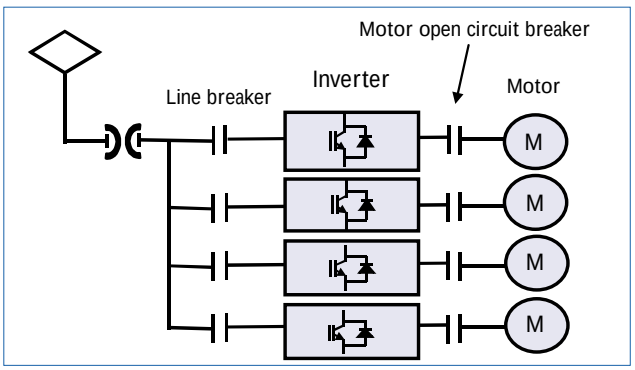

Fig. 10 Schematic diagram of main circuit connection

4.3.3 Control

We adopted a method of using the resolver (rotary angle detector) to measure the position (rotary angle) of the rotor with respect to the stator, as a vector control means for stable and accurate control of the output torque of the traction motor.

Fig. 11 shows the control block. From the above-mentioned equation (1), it can be seen that the output torque Tq of the traction motor is changed if there is a discrepancy in the ratio between the d-axis

current and q-axis current, even if the effective current is the same. In the vector control operation part in the control block diagram, the d-axis current command Id and q-axis current command Iq that are capable of outputting the minimum effective current value as the torque in conformity to the given torque command pattern are output according to the preset function. In the voltage command operation part, output voltage is controlled through the current feedback in such a way that the currents id and iq flowing to the traction motor conform to the current command value, and the instantaneous value of the current is controlled.

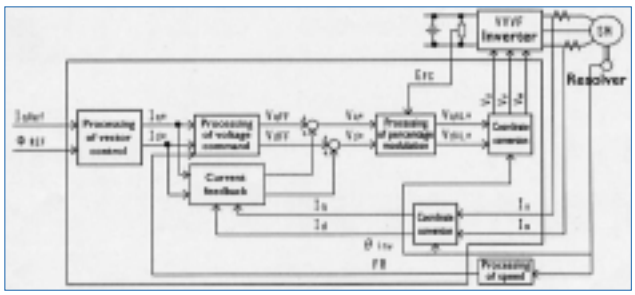

Fig. 11 Control block diagram

In the permanent magnet synchronous motor, induced voltage proportional to the speed occurs to the traction motor due to the magnetic flux of the permanent magnet. So, by feeding the weak flux current to the high-speed range, control is made in such a way that the induced voltage is kept within the voltage that can be controlled by the inverter at the time of power running, and the regenerative mode is prevented at the time of coasting.

Table 4 Control mode

Mode	Speed range	Control mode	Current control
Power running / regenerative running	Intermediate speed	Torque current control	q-axis current in amounts equivalent to torque d-axis current in amounts equivalent to reluctance torque
	High-speed	Weak flux control	q-axis current in amounts equivalent to torque d-axis current in amounts equivalent to weak flux
Coasting	Intermediate speed	Gate off	———
	High-speed	Weak flux control (power running)	q-axis current = 0 d-axis current in amounts equivalent to weak flux

5 Test

5.1 Stationary test

In the stationary test, a test stand simulating the bogie was connected with the motor by means of a reaction receiving rod, and various evaluations were made in combination with an inverter. Fig. 12 shows the external view of the test.

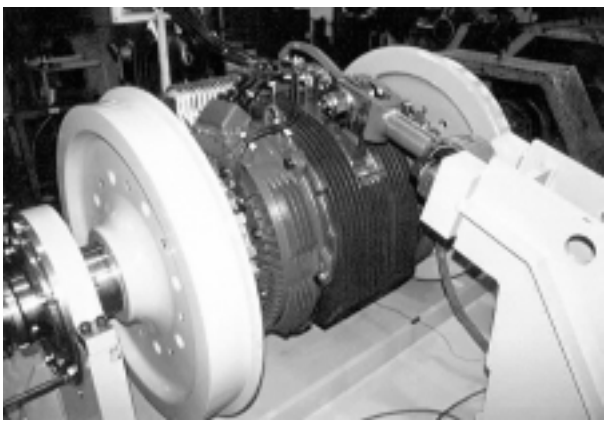

Fig. 12 External View of the Test

5.1.1 Main motor

(1) Characteristics

Table 5 shows the result of the rated load characteristic test. The test result indicates that the characteristics approximately conforming to the specification values have been attained. The efficiency has been improved about 4 % over the level of the conventional induced motor of about 92 %. When elimination of the power transmission loss in the gear drive unit is taken into account, power saving of about 5 to 6 % is expected to be attained in terms of power consumption.

Table 5 Load characteristics test (when heated)

	Specification value	Measurement
Voltage (V) / current (A)	730 / 140	733 / 140
Speed (rpm)	360	360
Output (kW)	160	164.9
Torque (Nm)	4244	4374.3
Efficiency (%)	95.0	96.0
Power factor (%)	95.0	96.6

(2) Temperature

Table 6 shows the result of the temperature rise test.

Fig. 6 Result of the temperature rise test

		Specification value	Measurement
Cooling method		Totally enclosed self-cooling (without wind caused by running)	
Time rating / power supply		Continuous rating / inverter drive	
Voltage (V) / Current (A)		730 / 140	728 / 140
Rise in temperature (K)	Primary winding	163	139
	Permanent magnet	130	129
	Bearing	65	59

It has been verified that the temperature rise in each section can be kept within the specified value.

Especially, in the primary winding the loss is below the specified value, and due to the direct cooling of the frameless structure, the specified value is cut by 15%.

(3) Noise

The noise of the traction motor as a single unit (1 meter in circumference under no load) at the maximum speed of 120 km per hour has been reduced by about 15 dB (A) from the level of the conventional cardan drive type induction motor. Further effects can be anticipated when consideration is given to the fact that the noise of the cardan drive unit disappears in actual running mode.

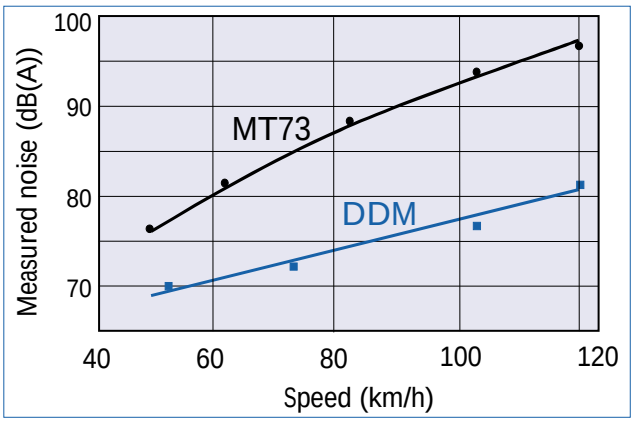

Fig. 13 Noise of motor as a single unit

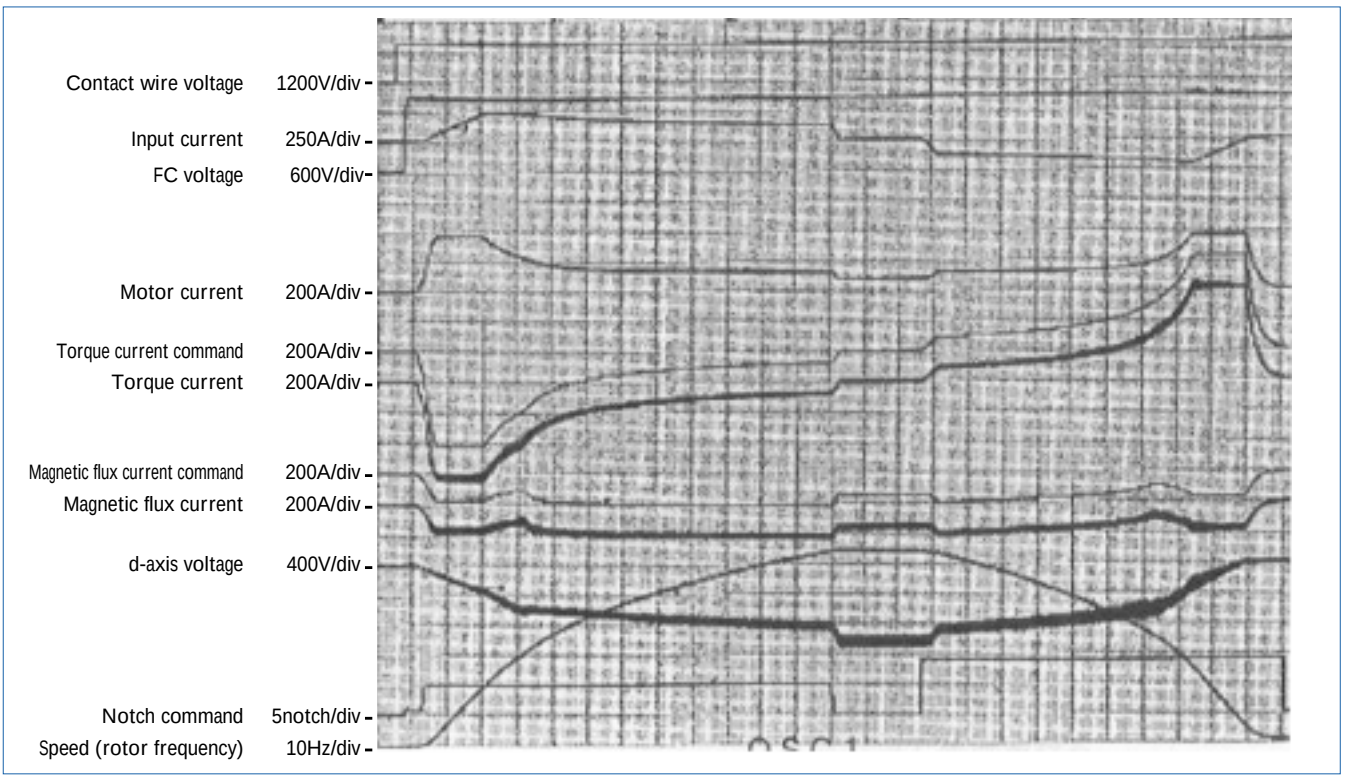

Fig. 14 Test chart

5.1.2 Control

Induced voltage proportional to the speed occurs to the traction motor due to use of the permanent magnet. This makes it possible to perform specific control such as weak flux control that is not found in the induction motor. The following discusses the result of testing this specific control:

(1) Weak flux control: coasting control

It has been verified in both the power running mode and regenerative mode that the weak flux control is performed correctly according to the contact wire voltage in the high-speed range. By way of an example, Fig. 14 shows the test chart in the power running, coasting and regenerative modes at the speed of up to 120 km per hour. It can be confirmed that, when notch-off operation has been made at the speed higher than 80 km per hour, the weak flux current is fed with the gate kept turned on, and coasting control is performed without any torque produced.

(2) Transient response test

[1] It has been verified that, despite an abrupt change and cutoff of regenerative load during weak flux control and coasting control, MMOCD operation (traction motor overcurrent) or OVD operation (filter capacitor overvoltage) does not take place, and satisfactory torque control continues.

[2] It has been verified that, despite an abrupt change of the contact wire voltage in the power running, coasting and regenerative modes, MMOCD operation (traction motor overcurrent) or OVD operation (filter capacitor overvoltage) does not take place, and satisfactory torque control continues.

(3) Protection coordination test

It has been confirmed in the inverter arm short-circuiting test (CFD), motor overcurrent test (MMOCD) and overcurrent test (OVD) that the inverter can be protected by opening the traction motor cut-out switch simultaneously when the gate is turned off.

(4) Re-closing test for traction motor cut-out switch

It has been confirmed that, when the traction motor cut-out switch is re-closed at the maximum speed of 120 km per hour, protective operation of the MMOCD or the like does not take place, and there is no problem.

5.2 Running test

Various performance tests have been conducted in the running test conducted on the Saikyo, Kawagoe and Chuo Lines. The following is the overview of the items that have been verified so far:

(1) It has been verified that basic operations are satisfactory, including weak flux control and coasting control in the high-speed range specific to the synchronous motor based on a permanent magnet.

(2) It has been confirmed that the motor current is stable even at a speed of about 0 km per hour in gradient startup and backward startup, and satisfactory operation is performed.

(3) We have verified the running stability at a speed of up to 120 km per hour. It has also been confirmed that vibration of the traction motor is reduced by the coupling.

(4) It has been verified in the power running and braking test with sprinkled water that re-adhesion is satisfactory without wheel slip or slide.

(5) It has been confirmed that noise outside the car (at 120 km per hour) is reduced about 5 dB (A) below that of the Series 205 train (at 100 km per hour) running through this section.

6 Conclusion and program for subsequent research

In the running tests conducted so far, we have confirmed that the planned functions and performances are excellent. We are planning to conduct a running test to make an overall assessment centering on durability evaluation.

References:

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