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What Drives Electric Multiple Units?

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Evolution to AC Motors

Direct current (DC) traction motors were used for a long time after the development of electric railways. However, since the 1980s, they have been replaced by alternating current (AC) motors, one type of which commonly used in Japan is inverter controlled. This article discusses the basic traction systems used in today's electric multiple units (EMUs) in Japan, with emphasis on the inverter control system.

From Current Collection to Driving

Almost everybody knows that EMUs are driven by electric motors powered by current collected through pantographs on the top of the car. The entire mechanism can be explained from the viewpoint of how current flows and drives the motors. Figure 1 shows a concept of the main equipment installed on an inverter-controlled EMU and a circuit diagram of the propulsion circuit. The current collected by the pantograph is fed to a high-speed circuit breaker designed to protect the propulsion circuit from ground faults by isolating large fault currents. The current then passes through a filter reactor to an inverter where it is converted to AC that drives the AC traction motors mounted on the trucks. The motors generate torque that is transmitted via gear wheels to the driving wheels. The motor speed is reduced and torque is increased by engaging the gears at ratios of 1:5 to 1:7 (commuter EMUs), to power the wheels. The above description is for a DC EMU, but the AC EMU has an additional step-down transformer to convert the high voltage from the overhead line to a level for controlling the motors, and an AC to DC rectifier. In Japan, both the rectifier and inverter are often housed in a single box called the main converter (Fig. 2).

A common question is, 'Why is AC from

the overhead wire converted to DC when the motor is powered by AC?' It is because current from the overhead wire is single phase at a constant voltage and frequency, while the motor current is three phase with voltages and frequencies that vary according to speed (explained later); there is no power converter able to convert voltage and frequency from single to

three phase in one step.

Clearly, it is confusing to use AC and DC, for the electrification system on one side and the traction motor on the other and this requires a clear explanation. Viewed from the pantograph as the 'gateway' to the EMU, DC was used first in Japan starting at the end of the 19th century. The AC electrification system was developed

Figure 1 Main Equipment on Inverter-controlled DC EMU and Circuit Diagram of Propulsion Circuit

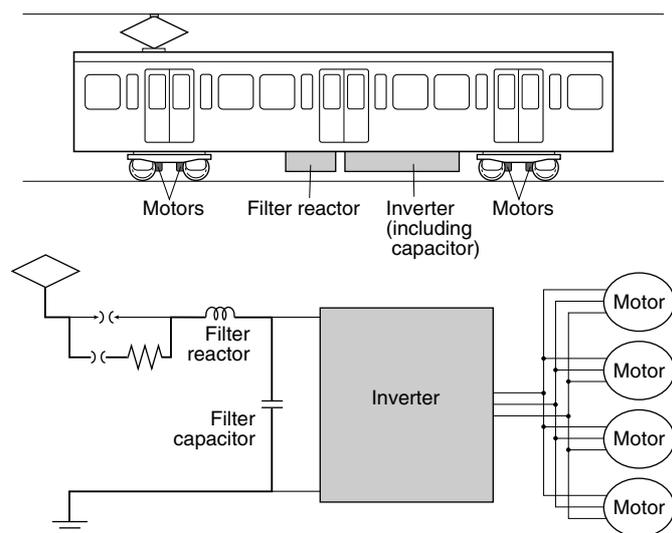
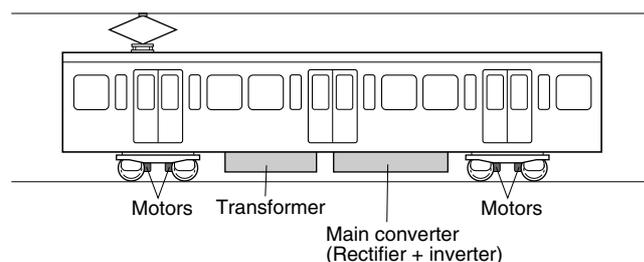
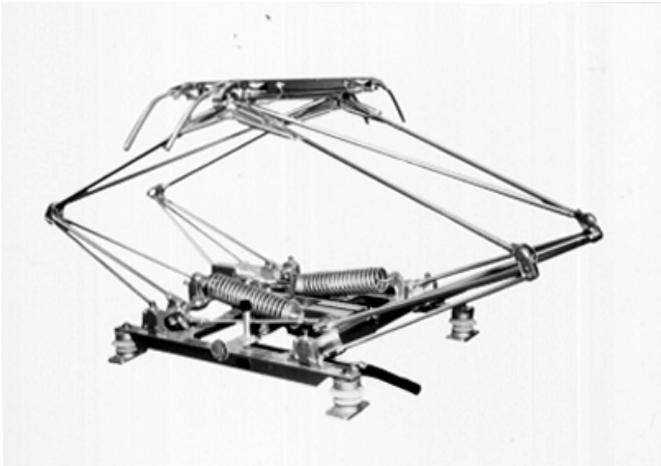


Figure 2 Location of Transformer and Main Converter on AC EMU





Traditional diamond-shaped pantograph

(JR East)



Single-arm pantograph

(JR East)

in the 1950s and has been adopted on various conventional lines (Hokkaido and Kyushu, etc.) as well as on shinkansen (JRTR 16, pp. 48 to 58). DC traction motors, which have been in use for a long time, are being replaced by AC motors.

Types of Pantographs and Principal Mechanism

The pantograph is an integral part of the EMU used to collect current from the over-

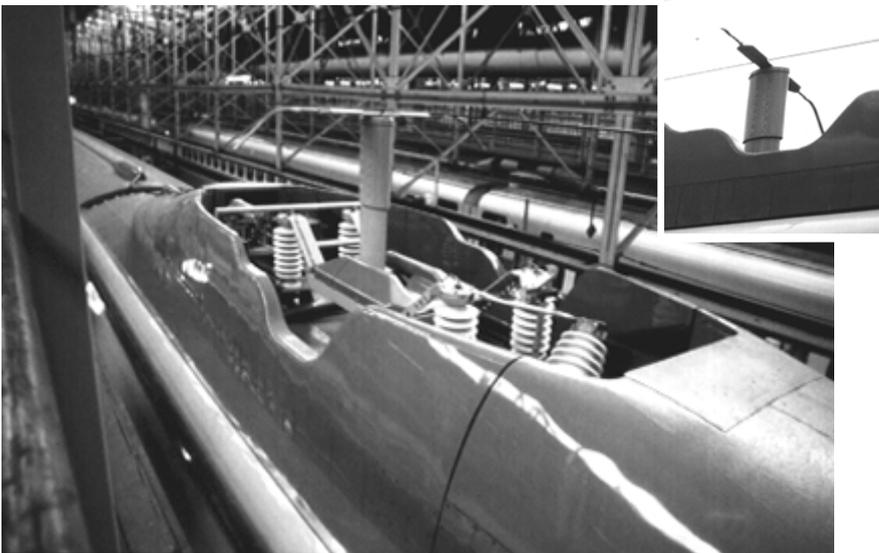
head line. It has the following characteristics:

- It must remain in continuous contact with the overhead wire while the EMU is running.
- It must not abrade the overhead wire, and neither must it be subject to excessive wear.
- It must have low aerodynamic resistance.

Japanese railways have long used a diamond-shaped pantograph. It has a re-

placeable contact strip that touches the overhead wire and is replaced when it becomes worn by the running abrasion. This strip must also be able to withstand arcing current that sometimes occurs between the overhead wire and the contact strip if the two become separated during running. The strip is fixed to the base called the collector shoe, mounted on a frame.

In Europe, a single-arm pantograph has been used traditionally and it is being used increasingly in Japan. A third type of pantograph is called the wing pantograph which was developed to reduce wind noise generated by high-speed trains, it is now used on some of the latest shinkansen.



Wing pantograph on JR West Series 500 shinkansen

(JR West)

From Rheostatic to Inverter Control

The propulsion system has undergone considerable change in the history of electric railways. Up until 10 years ago, the traction motor was DC. For the EMU to accelerate as it starts, the voltage applied to the DC motor must be increased as the EMU picks up speed. This is accomplished by inserting a variable resistor between the pantograph and motors. The voltage applied to the motor is controlled

Figure 3 Principle of Rheostatic Control

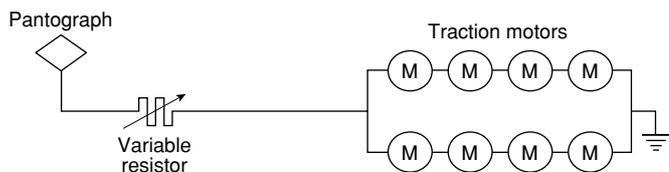
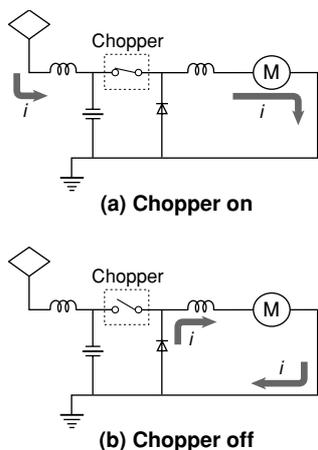


Figure 4 Chopper Control Circuit



by varying the resistance. This is called rheostatic control (Fig. 3). In this system, the resistance consumes most of the voltage supplied when the EMU is running slowly and the motor is operating at a low voltage, presenting various problems, such as low energy efficiency and a fire risk if the resistor overheats.

To overcome these problems, chopper control was developed in the 1970s. As shown in Fig. 4, instead of a resistor, a switch is inserted between the pantograph and motor and the average voltage applied to the motor is varied by changing the switch on/off time (Fig. 5). On/off switching must be performed several hundred times per second, and a semiconductor thyristor is used. In fact, commercialization of the chopper control system was enabled by development of a large-capacity thyristor, which also triggered a revolution in EMU control—

replacement of the DC motor by the AC motor.

The principle of the AC motor is quite complex and is discussed below, focusing on the differences between AC and DC motors.

There are several types of AC motors, and the cage asynchronous motor used widely in Japan as the traction motor, is described. Figure 6 shows a DC motor; Figure 7 shows the stator and rotor of an asynchronous motor. The DC motor has a commutator to supply current to the armature windings during rotation via carbon brushes. In contrast, the asynchronous motor uses windings on the stator side to feed three-phase current. A major feature is the cage-like construction of the rotor (Fig. 8), which does not exchange current with the stator.

What are the major advantages of the asynchronous motor of this type? They come from the absence of the commutator and brushes. First, the asynchronous motor is smaller and lighter. Second, it is free from the danger of ground faults occurring when the commutator turns at high speed and supplies a large current (several hundred amps) to brushes that may cause sparking to the motor frame or sparking between brushes. In fact, ground faults account for the major number of traction motor failures. Third, brushes require regular inspection and replacement, and the commutator requires over-

Figure 5 On/Off Chopper Timing Control

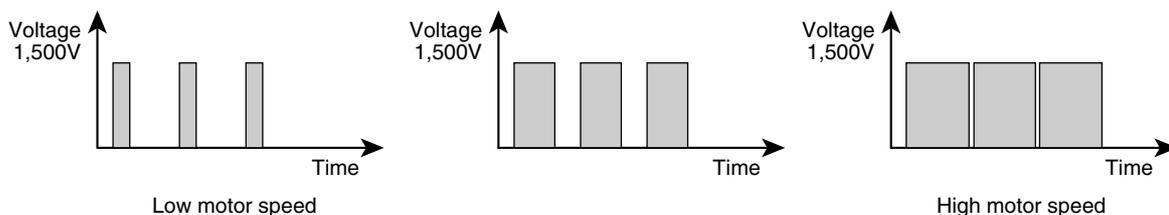


Figure 6 DC Motor



(Mitsubishi Electric Co., Ltd.)

Figure 8 Rotor Cage of AC Asynchronous Motor

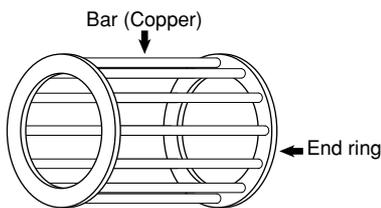


Figure 7 AC Asynchronous Motor



Stator of asynchronous motor. The stator is composed of a steel frame covered by coils inside. The coils are divided into three blocks: the U, V, and W phases, forming a rotating field using three-phase current from the inverter.



Rotor of asynchronous motor. The lack of commutator allows a larger space for torque-generating coils.

(Mitsubishi Electric Co., Ltd.)

haul. Elimination of this work halves motor maintenance time and costs.

Operating Principles of Inverter Control System

To understand the inverter control system, the following three points are important:

- How is torque generated?
- How is the rotating field created by applying three-phase AC to the asynchronous motor?
- How does the inverter create three-phase AC from DC with varying frequency and voltage?

These points are explained below.

How is torque generated?

We should start from Fleming's left- and right-hand rules (Fig. 9). Fleming's left-hand rule explains the force applied to a

conductor in a magnetic field when current is applied to the conductor. Under the rule, the direction of the magnetic field is denoted by the index finger, the direction of current is denoted by the middle finger and direction of the force applied to the conductor is denoted by the thumb, when each is held at 90° to the other. The strength of the force applied to the conductor is proportional to the product of the field strength and power of the current.

Fleming's right-hand rule describes the direction and strength of voltage generated on the conductor moving through the magnetic field. When the same three fingers are held at 90° to each other, the index finger denotes the lines of the magnetic force, the thumb denotes the motion of the conductor, and the middle finger denotes the direction of the gener-

ated voltage (positive at finger tip and negative at base). Again, the level of the voltage is proportional to the product of the strength of the field and the velocity of the conductor.

The torque generation mechanism in the asynchronous motor is explained below based on Fleming's rules.

In the asynchronous motor, a rotating magnetic field is generated when AC is applied to the stator windings. Figure 10 demonstrates this point by showing a magnet turning around the rotor. In relative terms, the magnet is static and the rotor bars move. Based on the right-hand rule, this generates voltage at both ends of each bar. Since the two ends of the bar are connected to an end ring (conductor), a current flows through the bar, end ring, other bar, other end ring. Unlike the DC motor, this means current flows

Figure 9 Fleming's Rules

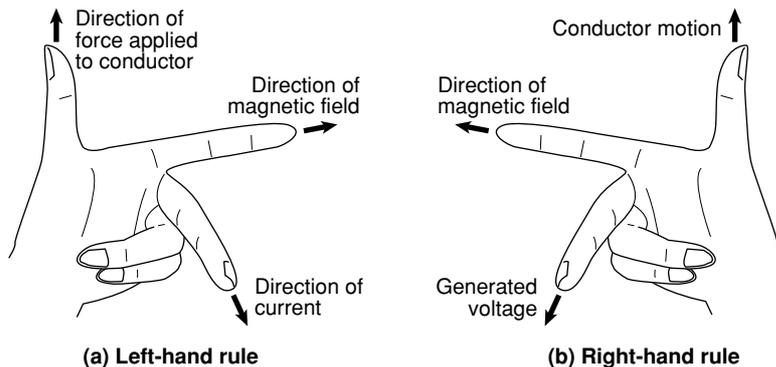
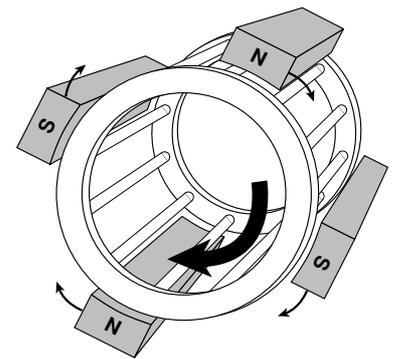


Figure 10 Rotating Magnetic Field



in the rotor without the need to supply it from the stator. Once current is flowing through the rotor which is in a magnetic field, based on the left-hand rule, force is applied to the bars and rotor rotates. In other words, the motor runs and drives the EMU.

As the EMU accelerates, the rotor speed eventually catches up with the rotating speed of the magnetic field. At this point, there is no relative motion between the rotor bar and the rotating magnetic field, so no voltage is generated and no current flows, resulting in loss of torque and meaning that the motor stops when the above state is reached. To keep the motor (and EMU) running, the speed of the rotating magnetic field is increased steadily to keep it above the rotor speed, thereby maintaining torque. As discussed later, this is accomplished by raising the frequency of the AC applied to the motor. In other words, the motor requires continuous output frequency control using the inverter.

How is the rotating field created by applying three-phase AC to the asynchronous motor?

So how is the rotating magnetic field generated by applying AC to the asynchro-

nous motor windings? To understand the mechanism, the principles of electromagnetism must be explained. Based on the screw law, the direction of the magnetic field generated by an electric current is clockwise to the current direction.

Figure 11 shows the simplified asynchronous motor stator windings, which are connected alternately at four points.

Figure 12 shows the change in the current flowing in the stator windings, and the change in the magnetic field generated by the current. There are two points that look like the north pole of a magnet where the magnetic flux originates and two points that look like the south pole where the magnetic flux ends. Furthermore, these north and south poles appear to rotate with time. The relationship between the current waveform and the stator shown in the figure indicates that the shorter the current cycle (or the higher the frequency), the faster the magnetic field rotates. In other words, the motor torque can be maintained at a constant level by controlling the frequency generated in the inverter and applied to the motor.

How does the inverter convert DC to three-phase AC with varying frequency and voltage?

The mechanism for converting DC to AC using an inverter is explained below.

As shown in Fig. 13, when switches S1 and S4 are ON, and S2 and S3 are OFF, +E (V) is applied to the motor windings. On the other hand, when S1 and S4 are OFF and S2 and S3 are ON, -E (V) is applied. No voltage is applied when all the switches are off. Each switch can be turned on or off at any timing. For example, on/off switching at the timing shown in Fig. 13 (a), produces a voltage waveform that can be called AC. The average voltages are shown by the dotted line. The voltage is decreased by controlling the on/off switching as shown in (b), and the frequency is increased by controlling the on/off switching as shown in (c). For simplicity, the figure illustrates a single phase, but a three-phase circuit is actually used. The switches have evolved first from a thyristor to a smaller and lighter gate turn-off thyristor (GTO) that can be turned off without external voltage, and then to the insulated gate bipolar transistor (IGBT) capable of high-speed switching. In Japan, this inverter control system is often called VVVF

Figure 11 Simplified Stator Winding

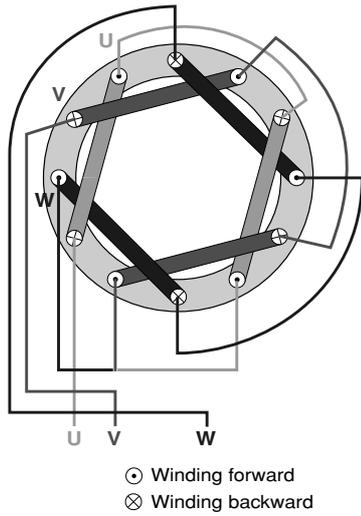


Figure 13 Inverter Operating Principle (Single Phase)

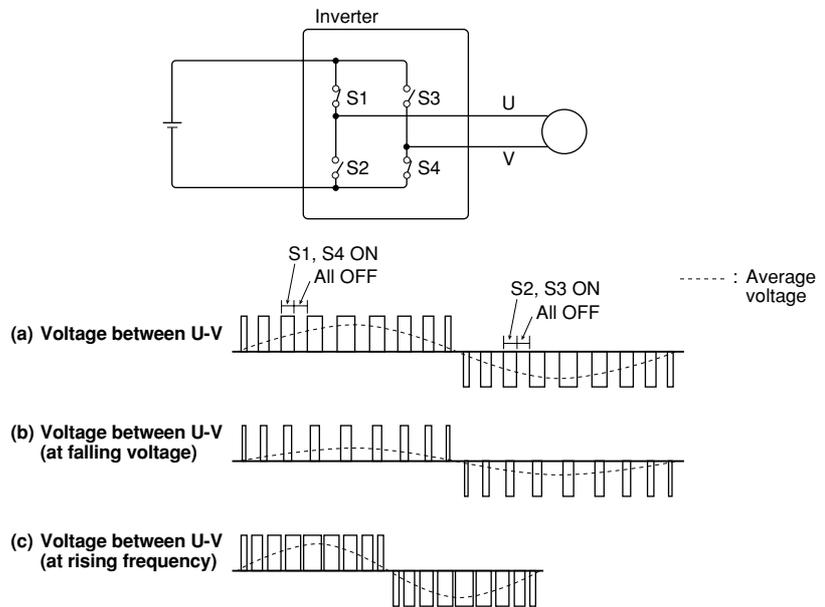


Figure 12 Generation of Rotating Field by Flowing Three-phase Current

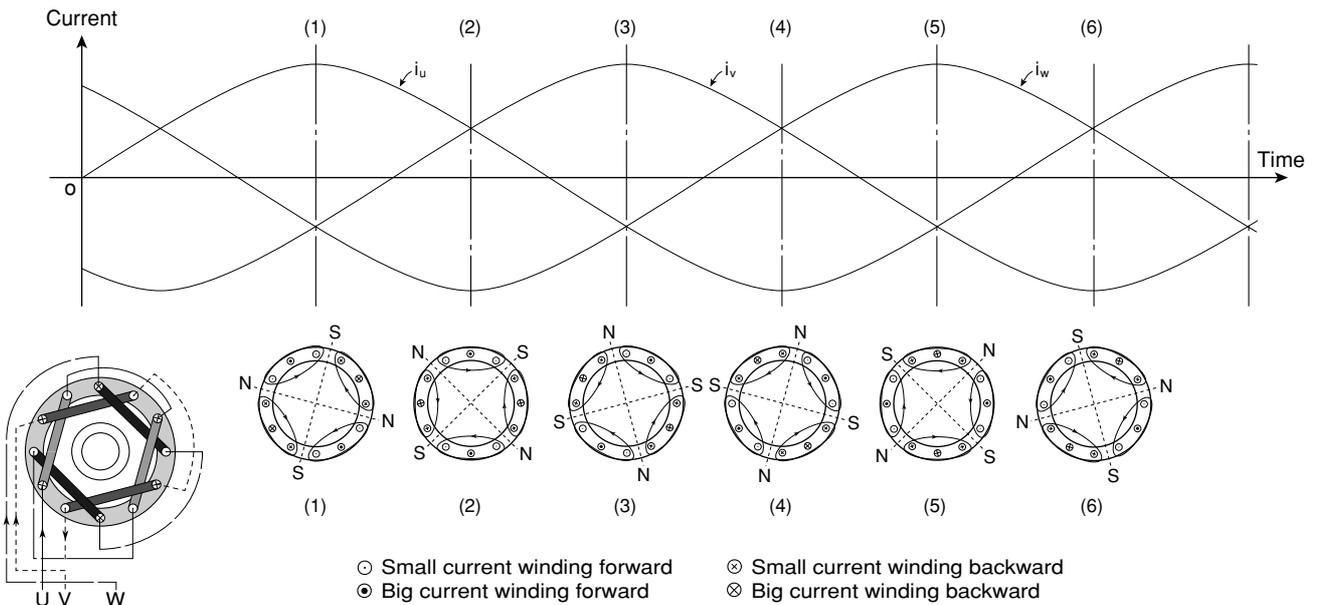
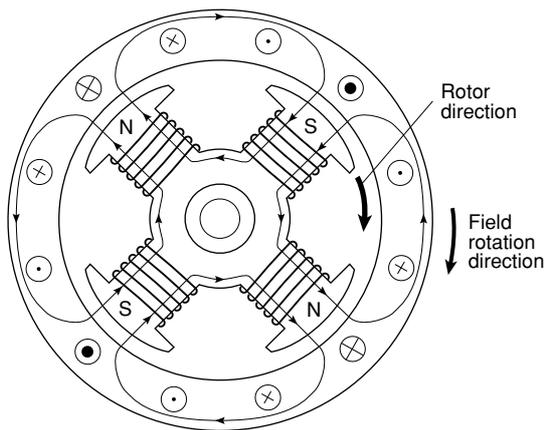


Figure 14 Synchronous Motor Structure



control, an abbreviation of variable voltage, variable frequency, suggesting the ability to adjust the three-phase AC voltage and frequency supplied from the inverter to the motor according to the changing train speed.

Synchronous and Asynchronous Motors

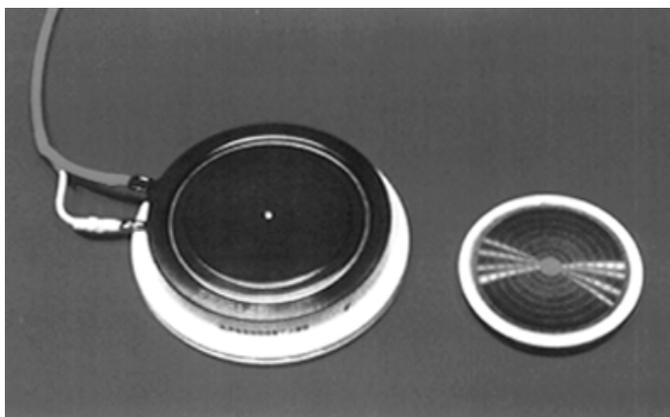
Another type of AC motor, called the synchronous motor, is in use, especially on most French TGVs including Thalys, and Spanish AVEs. Figure 14 shows its struc-

ture. Like the asynchronous motor, the synchronous motor also has three-phase AC windings, but the rotor is energized by DC from an external source to create magnets. Three-phase current on the stator windings produces a rotating field. The rotor becomes an electric magnet due to the DC. Attraction and repulsion between the field and rotor magnet turn the rotor. Since the rotor speed is the same as that of the rotating magnetic field, the motor is synchronous. Unlike the asynchronous motor, the synchronous motor requires a slip ring to supply current to the rotor.

Brushes are used for this purpose and require some maintenance, although it is not as frequent nor as costly as that required for DC motors. Why is the synchronous motor used by TGVs and other rolling stock? The answer is in the level of technology available when the TGV-A was designed. Since a large-capacity GTO had not been developed, supplying voltage to turn off the thyristor was a major problem. However, the rotor in a synchronous motor is a magnet so it produces the required voltage between the terminals of the stator windings. In fact, the voltage is generated at the exact timing to turn off the thyristor, eliminating the need for a turn-off circuit and resulting in reduced inverter weight. Conversely, the asynchronous motor does not use the above mechanism and the inverter (at that time) needed turn-off circuits, which added weight. In France, the TGV axle weight was limited to 17 tonnes, and the synchronous motor was the only available choice meeting this requirement.

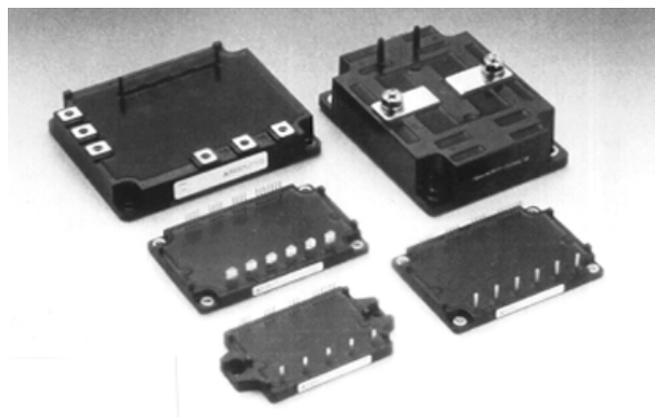
Concentrated and Distributed Traction Systems

Japanese shinkansen use electrical multiple units, sometimes called a distributed traction system. On the other hand, high-speed railways in Europe mostly use the concentrated traction system (similar to



Gate turn-off thyristor (GTO)

(Mitsubishi Electric Co., Ltd.)



Insulated gate bipolar transistor (IGBT)

(Mitsubishi Electric Co., Ltd.)

conventional loco-hauled system), where the train consists of one or two power cars and several passenger cars. For example, the Series E2 shinkansen has six powered passenger cars and two non-powered passenger cars (trailers), while the TGV-Réseau has one power car at each end of eight passenger cars. The TGV-Réseau power cars carry no passengers. The relative merits of the two systems are compared below:

Concentrated traction system

- Relatively small amount of electrical equipment per train resulting in lower manufacturing and maintenance costs
- Lower noise and vibration in passenger cars due to physical isolation of passenger cars from power units

Distributed traction system

- Electrical braking on multiple axles resulting in: (a) less maintenance requirements for pneumatic brake parts such as brake shoes, (b) good braking performance for a variety of performance conditions, (c) better energy efficiency through use of regenerative braking
- Reduced maximum axle load, resulting in: (a) simplified tracks and structures which reduce maintenance cost, (b) lowered maximum ground vibration
- Low adhesion coefficient required for driving axles
- Lower performance loss if propulsion unit fails in powered car
- High seating capacity

The final choice depends upon which factors are emphasized. In Europe, high-speed trains have traditionally been hauled by locomotives which have been superseded by the TGV and ICE. In Japan, the distributed traction system was selected to reduce maximum axle load thereby minimizing impact on track and other structures and reducing construction costs, as well as to reduce mechanical braking requirements by using electric braking on all axles.

A second reason reflects a major difference in railway conditions between Japan

and Europe—the braking frequency as a result of distances between stations. On the 515-km Tokaido Shinkansen connecting Tokyo and Osaka, originally there were ten intermediate stations separated by an average of 47 km (currently there are 14 intermediate stations). On the other hand, on the 389-km TGV Southeast Line between Paris and Lyon, there are only two intermediate stations where most TGVs do not stop. Electric brakes offer a large advantage when braking is frequent. Overall, European railways selected the concentrated traction system based on the initial cost and ride comfort, while the distributed traction system was selected in Japan in consideration of the impact on track and maintenance cost.

With the recent technological advances, electrical maintenance requirements have declined, a factor favouring the distributed traction system. Also, stricter environmental regulation, including public demand for reduced wayside vibration, serves as a tail wind for the distributed traction system.

However, there are already high-speed European trains using the distributed traction system—the Italian ETR450, 460 and 470, and the future German ICE3. Italy selected the distributed system to implement pendulum EMUs (pendulum locomotives are not technically feasible at present). The German ICE3 chose the distributed

system to minimize the required adhesion coefficient, to increase passenger capacity and, perhaps more importantly, to lower the maximum axle load.

Future Challenges

What are the major challenges facing future propulsion systems?

First, development of more compact lighter on-board equipment is an issue to pursue. Although the shift from DC to AC motors has permitted major progress in these fields, there is still plenty of room for improvement. Second, energy efficiency is an important challenge. Recent concern about environmental issues is prompting railways to step up energy saving efforts, although they already offer a clear advantage over other transport modes. In particular, railways are expected to develop hardware and controllers to improve inverter and motor operating efficiency, while fully leveraging regenerative braking.

On the negative side, inverter control produces high-harmonic noise affecting signalling and communication systems. Research is required to solve this problem. Some other technical hurdles, including noise reduction and optimized control for wheel slip remain to be cleared. ■

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