

Power Electronic Devices for Railway Vehicles

UMEZAWA Kotaro [†]

ABSTRACT

As effects on the global environment are becoming a problem, the world is focusing on railway vehicles for their better energy efficiency so they can be a means of transport that is environmentally friendly, high capacity, fast, safe, and economical. Fuji Electric has anticipated market needs related to energy efficiency and the environment and used the latest power electronics technology to provide environmentally-friendly electric equipment with increased consideration for the user comfort for railway vehicles such as vehicle propulsion (driving) system for Shinkansen etc., auxiliary power supply and door system in the Japanese and world markets. In addition, we are proactively expanding into markets around the world such as North America and Asia, as well as working to support international standards and localized production.

1. Introduction

As the effects to the global environment are becoming a problem due to the emissions of greenhouse gases such as CO₂, the world is focusing on railway vehicles since they exhibit high energy efficiency while providing a means of transport that is environmentally friendly, high capacity, fast, safe and economical.

In light of this situation, the demand for railway vehicles has been showing steady growth in Japan. Overseas markets such as China, Taiwan, South Korea and Southeast Asian countries have been constructing new lines as well as electrifying existing lines in order to strengthen transportation volume. Furthermore, the demand for railway vehicles in these countries has been increasing significantly, being bolstered by the economic growth that they have experienced in recent years. Likewise, the U.S. is facing the need to upgrade old and dilapidated railway vehicles, and demand there has also been expanding.

Fuji Electric has been helping to meet this growing need by providing its state-of-the-art power electronics equipment for railway vehicles as an eco-friendly means of transportation in order to contribute to the protection of the global environment by energy savings and conservation.

In this paper, current status of Fuji's power electronics equipment for railway vehicles and future trends will be presented.

2. Current Demand for Electronic Equipment for Railway Vehicles and Fuji Electric's Response

Items in demand among power electronics equipment for railway vehicles include technologies that fa-

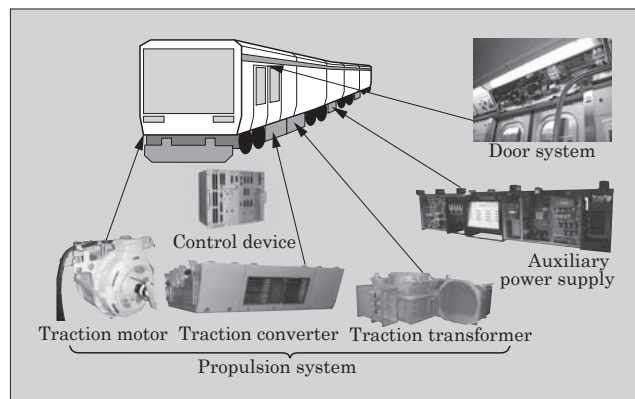


Fig.1 Electronic equipment for railway vehicles

cilitate energy-savings and harmonization with the environment as well as provide the needed levels of safety and reliability demanded from public transportation systems. In addition to these demands, the market is requiring a diversity of enhancements in economic efficiency, speed, size and weight savings, maintainability, and ride quality and comfort.

Fuji Electric has been dedicated to the development of next-generation technologies such as a vehicle propulsion (driving) system for the Shinkansen etc., auxiliary power supply and door system (see Fig. 1). In particular, our door system has been highly evaluated both in the Japanese and overseas markets as a highly safe product with a highly reliable performance record that conforms to international standards.

3. Propulsion System for the Shinkansen

The Shinkansen has attracted world-wide attention as a symbol of Japan's advanced railway technology. Shinkansen railcars have continuously incorporated the state-of-the-art technology of the times. Fuji

[†] Fuji Electric Co., Ltd.



Fig.2 Series N700 Shinkansen (Photo courtesy of JR Central)

Electric has delivered its propulsion system (including traction motors, traction converters, and traction transformers) for successive generations of Shinkansen trains from the first-generation series 0 Shinkansen train through the latest series N700 Shinkansen train. In this paper, we will present an outline of the traction converter of the series N700 (see Fig. 2) operated by the Central Japan Railway Company (JR Central) as a representative example.

3.1 Traction converter of series N700 Shinkansen railcars

(1) Configuration

The traction converter shown in Fig. 3 is configured from a 3-level pulse width modulation (PWM) converter and a variable voltage variable frequency (VVVF) control system inverter, where a single 3-level VVVF inverter collectively drives 4 traction motors connected in parallel. In order to increase efficiency and reduce weight, a low-loss snubber-less system has been employed, where insulated gate bipolar transistor (IGBT) modules (3,300 V, 1,200 A) that have a high blocking voltage, high capacity, and low loss are used. Two types of cooling systems are employed in the traction converter. The two types of systems include: (a) TCI3 model traction converter that employs a combination of ebullient cooling using a coolant, and forced cooling with a blower; (b) TCI100 model traction converter that uses a simple aluminum radiating fin, and a natu-

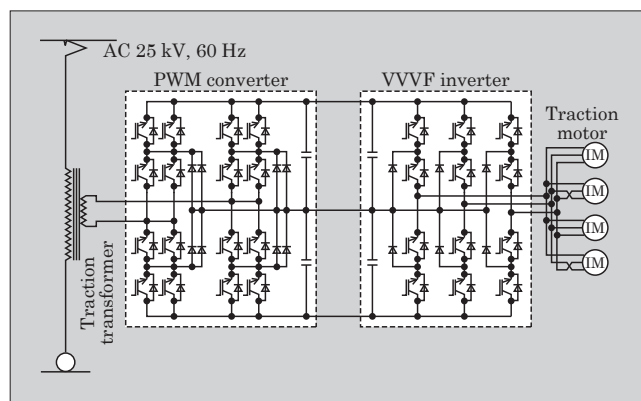


Fig.3 Configuration of series N700 traction converter

ral ventilation method of self-cooling without using coolant or blower.

(2) Reduced size and weight

The TCI3 model traction converter has achieved a reduced size by omitting a snubber circuit, optimizing its structure, etc. Compared to the series 700 TCI-2 model, the TCI-3 model aims to improve output by approximately 10% and realized to reduce volume by about 3% and unit mass by about 15%.

In addition, the blower-less TCI100 model traction converter has achieved a reduced weight of 12% compared to the TCI3 model.

We are also scheduled to provide traction converters in the series N700A, which is to make its debut in 2012.

3.2 Control of the traction converter for series N700 Shinkansen railcars

(1) Non-contact control equipment

The controller has a multi-processor configuration composed of 64-bit CPUs. The controller performs diverse control computations at high speed and with high accuracy, and for the purpose of advanced train control, also transfers operating commands and transmits operating status monitoring data. By utilizing the latest microelectronics, data transmission technology and the like, multi-functionality and high reliability have been achieved aiming at reducing part count and achieving.

(2) Converter and inverter control

Depending on the operating condition, a 3-level converter may cause a voltage imbalance at the positive and negative sides of the filter capacitor with respect to the DC neutral point, and there is a risk that an excessive voltage may be applied to certain components. While focusing on the behavior of the potential voltage of the neutral point during periods in which power device switching is idle in a traction converter, Fuji Electric developed neutral point potential control that does not depend on the polarity of power or current, and has applied this control to practical applications.

(3) Motor control

In the control of a railway vehicles propulsion system, the motoring^{*1} and braking torque of traction motor must be controlled responsively and accurately. In the industrial sector, vector control is typically employed as a means to realize this type of control, but the vector control of a single inverter connected to a parallel configuration of 4 motors, as in the case of Shinkansen trains, is difficult to implement in principle. However, by using the phase angle of primary flux, which is considered to be a common state variable

^{*1}: Motoring: With regards to railways, this term refers to speed increases by transmitting the dynamic force to the wheels from a motor or engine of an electric train car or locomotive engine.

unrelated to the number of motors connected in parallel, as a basis for the vector control, Fuji Electric has used vector control in practical applications and has achieved good results.

4. Auxiliary Power supply

The auxiliary power supply supplies stable power to the air-conditioning and lighting equipment necessary for maintaining comfortable conditions inside a railcar. It is an essential device for modern railway vehicles; it functions to supply control power for devices such as the traction converter and power supply for various IT devices such as the train control unit and display indicators inside a railcar.

Configuration of auxiliary power supplies varies greatly depending on the various types of power supply installed for the railway vehicle.

4.1 Auxiliary power supply for DC electric railcars

Figure 4 shows an example of the configuration of the power circuit of the auxiliary power supply for DC electric railcars

The feeding voltage for a DC feeding system is 1,500 V DC, 750 V DC or 600 V DC. In accordance with the output capacity and specifications required of the feeding voltage and equipment, an optimal voltage and current are selected for a semi-conductor insulated gate bipolar transistor (IGBT) configuring the circuitry or applying to the power circuit.

Usually, IGBTs having a withstand voltage capability that corresponds to the feeding voltage is used to configure a 2-level inverter, thereby streamlining the circuit, reducing the part count, and increasing the reliability.

4.2 Auxiliary power supply for AC electric railcars

The loads connected to the auxiliary power of AC electric railcars are indicator lamps, interior lighting, control power and the like, and are comparatively small in capacity. However, since these loads are critically important, a high level of reliability is required of the auxiliary power supply.

Figure 5 shows an example of a configuration of the power circuit of the auxiliary power supply for AC

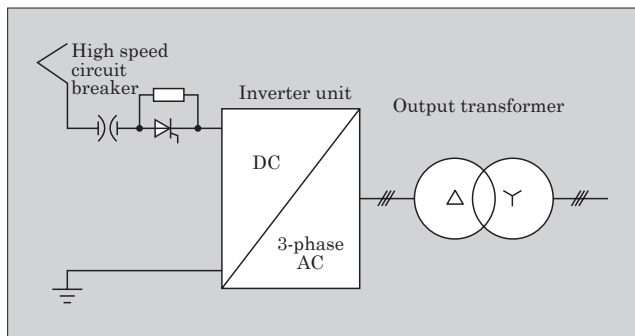


Fig.4 Example of the configuration of the power circuit of the auxiliary power supply for DC electric railcars

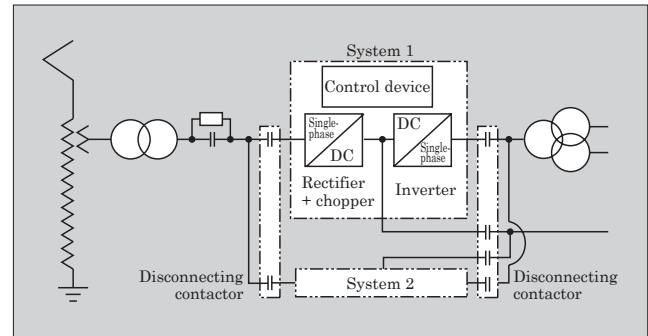


Fig.5 Example of power circuit configuration in auxiliary power supply for AC electric railcars

electric railcars. This is a case where the single-phase AC power of the tertiary winding of the traction transformer is rectified using a diode rectifier and an IGBT chopper, and then is supplied as DC power to a DC load. As for an AC load, that DC power is converted by an IGBT inverter unit and an output transformer into single-phase AC power and then supplied to the AC load.

4.3 Electric power supply for diesel-powered railcars

Diesel-powered railcars are unable to receive power externally, and therefore the installed diesel engine drives a generator to produce electric power. Fuji Electric has a history of manufacturing and supplying numerous electric power supplies for diesel-powered railcars to train companies, mostly including Japan Railway companies.

Figure 6 shows an example of configuration of the power circuit of the electric power supply for diesel-powered railcars. The rotational speed of the diesel engine for driving the main shaft, which is the power source of the power supply, will vary depending on the operating conditions. Constant-frequency AC power is supplied directly to a load such as the air-conditioning system by obtaining from a 3-phase AC power generator which is made run at a constant speed. The power control unit controls the excitation of the generator so that the generator output voltage is maintained at a constant level, and AC to DC conversion is performed to supply DC power to the controller, etc.

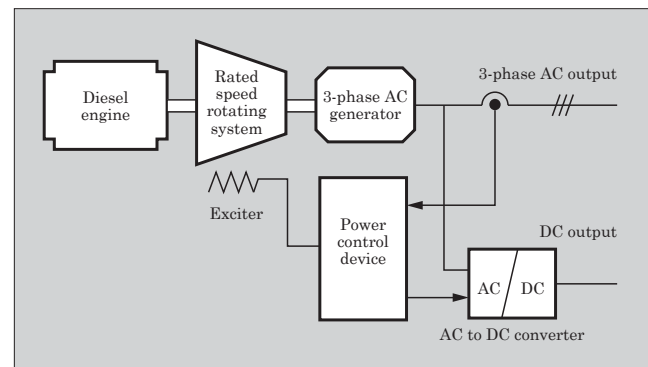


Fig.6 Example of power circuit configuration in electric power supply for diesel-powered railcars

4.4 Features of Fuji Electric's auxiliary power supply

(1) High performance control

The auxiliary power supply is required to provide a stable electric power supply with little waveform distortion or voltage fluctuation even in the case of sudden changes in the feeding voltage, the load current when a compressor or the like is turned-on or shut-off, or an unbalanced 3-phase load such as a single-phase load operation. Responding to this requirement, Fuji Electric uses individual 3-phase waveform control, as shown in the control block diagram of Fig. 7, in the output voltage control. Individual 3-phase root mean square (RMS) value control is implemented, based on detected values of the 3-phase output voltages, so that the RMS voltage value of each phase becomes constant. Furthermore, by combining with individual 3-phase instantaneous control, transient fluctuations in the output voltage due to load changes and so on can be suppressed. As a result, even in the case of sudden changes in the feeding voltage or load, stable voltage control performance is realized with a high-accuracy sinusoidal voltage having an output voltage deviation of $\pm 1\%$ or less and waveform distortion of approximately 1%.

(2) Higher reliability

Generally, a long rake of railway vehicles is equipped with 2 to 3 auxiliary power supply units, while a short rake is often only provided with a single unit. Consequently, failure of the auxiliary power supply directly leads to a deterioration in service, and may

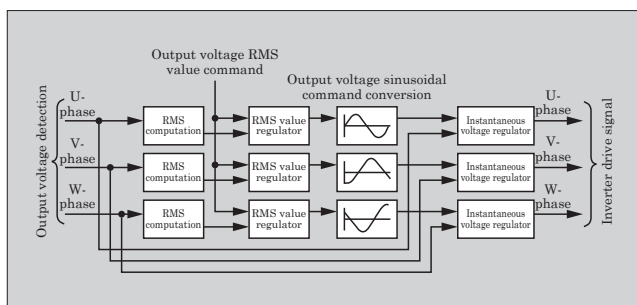


Fig.7 Control block diagram of high performance auxiliary power supply

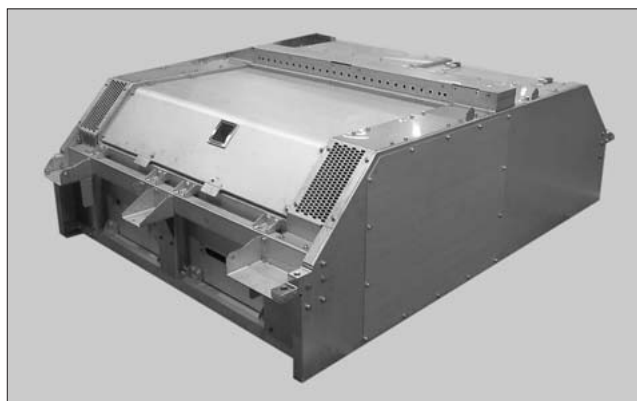


Fig.8 Roof-mount type auxiliary power supply

even result in a suspension of the railway vehicle operation. Fuji Electric has commercialized an auxiliary power supply equipped with dual-redundant inverters and controllers, and the unit itself has a standby redundancy system configuration for improved redundancy. When a failure occurs, the failed unit and standby unit are switched over so that operation will continue. During the system design phase, parts to be redundant are selected based upon computed values of the failure rate and upon historical data to create the most appropriate system as railway vehicle-use electric products for which small size and light weight are strongly requested. This method is being used as the auxiliary power supply for AC electric railcars in Japan.

(3) Enhanced functionality

IT is being incorporated into equipment for railway vehicles to achieve advanced railway vehicle operation and to improve the ease of maintenance. IT equipment with a data transmission function has become indispensable. The auxiliary power supply usually employs a data transmission system with an RS-485 for the physical layer and a transmission procedure based on polling/selecting. To advance further the functionality of a data transmission system for railway vehicles, Fuji Electric was early to commercialize a transmission system for railway vehicles based on the highly-versatile MODBUS on TCP/IP protocol, and has shipped auxiliary power supplies for railway vehicles overseas. Figure 8 shows the appearance of the roof-mount model of an auxiliary power supply unit.

We will study our auxiliary power supply to include a revised structure and new circuitry since we often receive requests from overseas to reduce the size and weight of the auxiliary power supply.

5. Door System

Among the types of equipment used in railway vehicles, a door system is the most familiar to passengers. Many systems are installed in a railway vehicle, each of them operating independently. Therefore, train doors have particularly strong requirements for safety, reliability, high functionality and low maintenance. Electric door systems have been long in use overseas. On the other hand, air-operated door systems have often been used in Japan. However, in recent years, the popularity of electric door systems have been quickly increasing as a result of reduced maintenance owing to self-diagnostic functions as well as improved safety through the use of high-speed control response systems in situations where a passenger or a passenger's luggage gets caught in a door.

5.1 Linear motor door system

Fuji Electric has commercialized and delivered door systems that use linear motors that simplify the door driving mechanism through utilization of the mo-

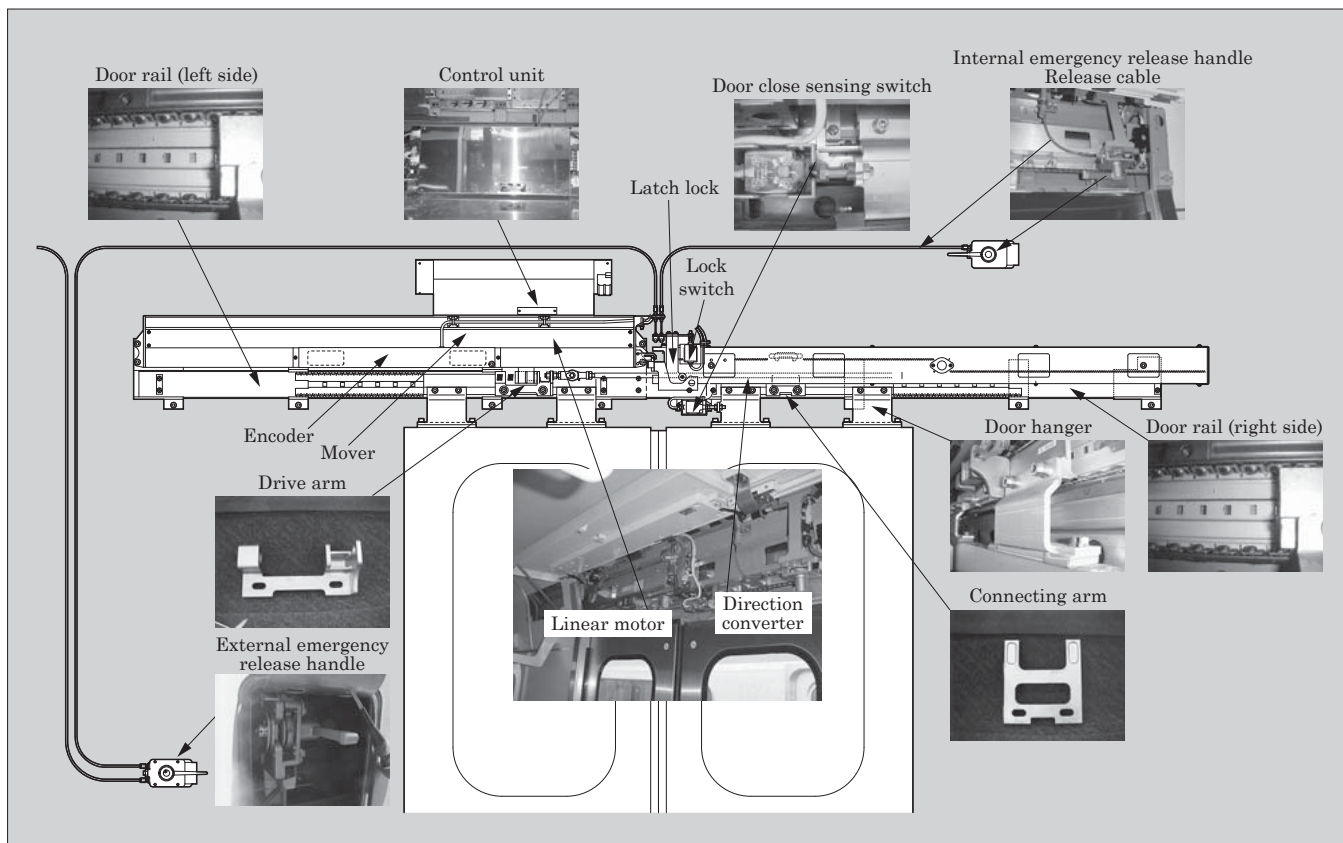


Fig.9 Configuration of door system

tion of motor itself.

In biparting type side doors, two motors drive the right and left doors respectively, pulling them apart from each other. In another type of system, both doors are driven by a single motor, using a mechanism to connect and interlock the doors. Decision regarding which system to employ depends on the needs (redundancy, economic efficiency, etc.) of each railroad company. Fuji Electric is producing door systems so as to meet each and every customer's need.

(1) One motor per one door opening type

This implementation is used in JR East's series E231, E233 and E531, and Seibu Railway's series 30000, and a total of more than 17,000 of these doors were being used in commercial operations at the end of 2011.

Figure 9 shows the configuration of a door system. One door leaf of a biparting type door is driven directly by the mover of a linear motor via a universal joint that isolates the motor from mechanical shocks from the door, and the other door leaf is driven in the opposite direction by a mover via a rack-and-pinion mechanism (mechanical direction converter). When a door is about to open, an unlocking operation is performed using a self-unlocking mechanism of which drive force is supplied by the linear motor.

The series E231 and subsequent models of railway vehicles of the Tokaido Line use a standby redundancy system that features dual-redundant signal I/O inter-



Fig.10 New York City Transit (NYCT) R160 train car

face circuits, control circuits and VVVF inverters so that even if a failure were to occur, operation is able to continue without any decrease in functionality.

Also, we have delivered our door systems overseas for use in Taipei on the Xinyi and Songshan Lines. We are currently waiting for the operation of the doors system to begin.

(2) Two motors per one door opening type

This implementation is used in the R160 subway cars operated by the New York City Transit (NYCT) Authority. By the end of 2011, more than 5,000 of these doors were in operation (see Fig. 10).

To ensure stable operation despite voltage fluctuations in the 37.5 V DC power supply, the supplied

power is boosted to a constant voltage and stabilized by a chopper circuit, and then input to inverters. In addition, an unlocking mechanism that uses a solenoid is applied to support customer specifications based on a safety concept that emphasizes functional independence. This door system greatly increases reliability over other door systems that have been previously used by NYCT, and has been well-received by the customer.

5.2 FCPM type door system

This is a system that drives side doors, by rotating (via a rotary motor) the pinions of a rack and pinion mechanism, which were applied in one motor per one door opening type of linear motor. In order to provide storage in the narrow space inside the head jamb, the motor has made use of a flattened flat cup permanent magnet motor (FCPM). This system realizes a weight that is lighter than linear motor type systems, while having the ability to change the movement of the side doors in the same manner as a linear motor. We are starting to make deliveries of the FCPM system as it is beginning to be employed in several railway vehicle projects both in Japan and overseas.

5.3 Features of electrical driven door and Fuji Electric's door system

(1) Advantages of electrical driven door

In comparison with air-operated systems, electrical driven door systems do not need pneumatic piping, and as such, they suffer aging effect scarcely and there is no need for on-site adjustment as pneumatic piping. These features reduce both the initial cost and maintenance cost associated with railway vehicle systems. In addition, our door system employs data transmission technology and controller functions that flexibly respond to changes in opening-and-closing operations, and achieves streamlining of pre-operation checks, increased intelligence, and a complete self-diagnostic function for individual door unit.

(2) Power transmission mechanism

In conventional electrical door systems, ball screw type system had been widely employed. The ball screw type is a system in which a nut moves when a screw is turned by a driver. It is a mechanism for opening and closing doors that are connected to parts that touch nuts via rotating the shaft that cut the screw thread by a rotary motor. This system requires many parts, since a mechanism is needed for converting the motor's rotational movements to linear door motion. This method has problems of requiring frequent lubrication in the sliding part and a decreased sensibility of door obstructions as described later.

Fuji Electric is employing both FCPM system and linear motor system to directly drive door system by using the motor's direction of motion directly. This has streamlined the door driving mechanism and improved the sensibility to obstruction. Figure 11 shows a com-

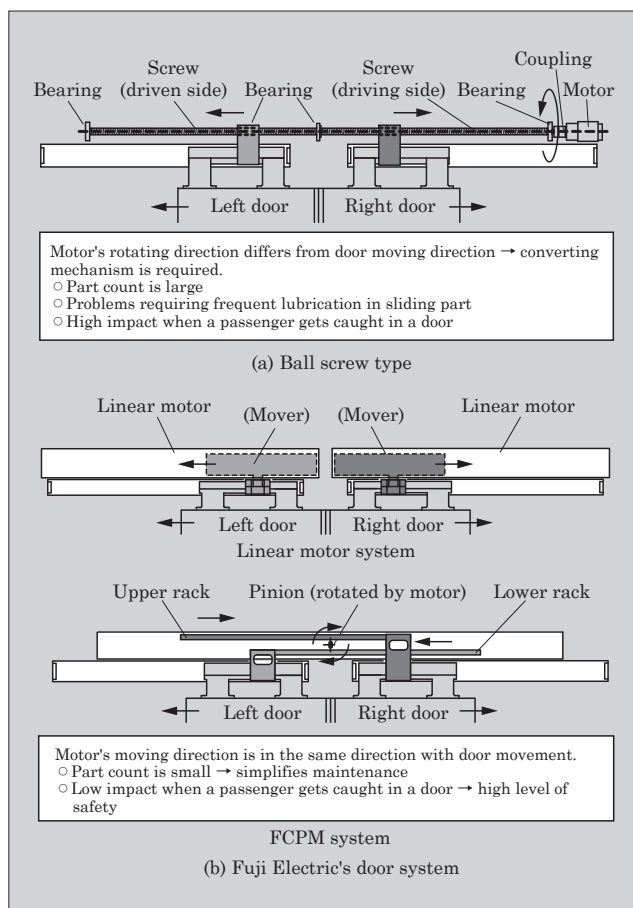


Fig.11 Comparison of door driving systems

parison of door driving systems.

(3) Locking/unlocking mechanism

In order to assure the door closed position and secure the safety, a locking mechanism with a lock pin is used. An unlocking mechanism is also provided for releasing the locked state when the door is about to open.

(4) Safety function

In recent years, accidents in which a passenger gets caught in a closing door have occurred frequently, and door safety has become an important issue. Fuji Electric's linear door employs highly sensitive door obstruction sensing based on the door speed and other control information. Additionally, after sensing a door obstruction, the safety operation is achieved with detailed control action based on various different requirements of railway companies.

6. Overseas Development

The demand for railway vehicles has been expanding in overseas markets, mostly owing to new rail line construction in Asia and renovation of existing lines in North America. To meet this demand, Fuji Electric has been actively advancing in its development overseas.

In order to do this, it is necessary to comply with overseas regulations and meet requests for local pro-

duction.

6.1 Implementation of SIL, SSIL

In Asian markets, SIL certification is required sometimes as a measure of safety according to IEC 61508 regulations stipulating functional safety. Electrical products destined for the Singapore subway system were required to implement SIL (SSIL) for software, and we acquired SSIL certification through gradual evaluation at each development stage.

Furthermore, we have been actively working to obtain this SIL certification since the door system itself also requires compliance to SIL in the Asian countries that we are currently advancing into.

6.2 Implementation of CMM, CMMI in North America

Doors for the NYCT-R160 require implementation of CMM^{*2}, and we have acquired certification based on a public assessment (assessed by a certified assessor) for CMM.

In addition, since we are currently involved in new auxiliary power supply and door projects to be carried out in North America, we have been actively pursuing CMMI^{*3} certification, which expands on CMM. Many projects in North America require implementation of CMMI, and as such, acquiring certification will be a big key to obtaining future orders.

*2: Capability Maturity Model (CMM): A model for appraising the software development maturity of an organization. CMM was developed by the Software Engineering Institute (SEI) at Carnegie Mellon University on the request of the U.S. Department of Defense.

*3: Capability Maturity Model Integration (CMMI): Guideline for integrating the capability evaluation model to help improve processes for organizations that perform system developments.

6.3 Response to request for local production

We have been finding it increasingly necessary to set up local production facilities in the overseas markets where we do business so that we can reduce costs associated with transportation, expenses required in mitigating foreign exchange risk as well as meet the demands of our overseas partner countries. In the U.S., it is required by law (as set forth by the “Buy American Act”) that at least 60% of the cost spent on production content and components be of the U.S. origin. In order to continue receiving North American projects in the future, we have been making efforts to comply with this law by setting up cooperative work projects and alliances with our affiliated American factories and parts makers.

7. Postscript

In this paper, we presented information on our power electronics equipment that are currently being used in railway vehicles and introduced some future trends. We are utilizing our state-of-the-art power electronics technology as a base for our developments in the railway vehicle industry in order to provide products that have reduced size and weight, high performance, high functionality, low maintenance, and a high level of comfort. In addition, we are committed to develop products that help conserve the global environment, as we believe that this will become a critical issue. We have been actively promoting our research and development anticipating the market needs of energy conservation and eco-friendly products, and we will strive continually to provide products that contribute to reducing the environmental burden of society as a whole.





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