Drive and Power Supply Technology for Solutions in the Transportation Sector

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1. Introduction

Various efforts to reduce the emissions of greenhouse gases are underway worldwide to prevent global warming. The transportation sector accounts for approximately 20% of the total CO_2 emissions for Japan, and of that portion, 90% comes from automobiles. On the other hand, railways and ships are highly energy-efficient, environmentally friendly, large-scale, high-speed, safe and economical modes of transportation. The modal shift toward the use of low-environmental-impact railways and shipping for freight transport is also based upon environmental concerns. As keywords often mentioned in relation to the global environment, "railroads" and "ships" will play even more important roles in the future, and these modes of transportation will develop in a sustainable way.

In response to the strong market needs for energy savings and low environmental impact, Fuji Electric supplies power electronic products and services as drive and power supply technology for use in the rolling stock and ships that provide transportation solutions to customers, and in doing so, benefits the global environment. This paper describes Fuji Electric's drive and power supply technology for rolling stock and ships.

2. Trends of Recent Needs in Transportation Solution Sectors, and Fuji Electric's Approach

2.1 Rolling stock

Responding not only to requests for safety, reliability and economy, but also addressing the demands of the times such as requests for higher speed, greater energy savings, smaller size, lighter weight, easier maintenance, better ride quality and comfort, and harmony with the environment, Fuji Electric has achieved technical innovation in the power electronics used for rolling stock.

In developing products for the rolling stock sector, Fuji Electric is engaged in next-generation technical development for Shinkansen propulsion systems, electrical equipment for electric multiple units (EMU) and diesel multiple units (DMU) and door systems. In particular, Fuji Electric's door systems, having a track record of high reliability and a high level of safety based on international standards, are highly regarded in Japan and overseas.

2.2 Marine

A modal shift is underway from land transportation, which has a high environmental load, to ocean transportation, and in the marine sector, the development of a next-generation coastal ship known as the "Super Eco Ship" having high energy efficiency and low environmental impact is being advanced and promoted as a project of the Japanese Ministry of Land, Infrastructure, Transport and Tourism.

Environmental friendliness has been advanced by equipping ships with electric propulsion systems, which compared to the conventional diesel propulsion systems, are superior with regards to environmental load, economy, operability, maintainability, vibration and noise.

Fuji Electric has delivered ship electric propulsion systems for use in the "Fuji" and "Shirase (1st generation)" ice breakers, and for use in submarines operated by the Japanese Ministry of Defense. In order be able to satisfy future market needs, Fuji Electric is utilizing the technology acquired from these power electronics products to advance technical development aimed at creating an integrated power system that combines an electric propulsion system and an auxiliary machine driving.

3. Rolling Stock

In the transportation sector, which accounts for 20% of the total CO_2 emissions in Japan, railroad transportation systems have large capacity, the highest energy efficiency, safety and stability. Fuji Electric provides transportation solutions that are comfortable, environmentally-friendly and human-friendly, which are based on an electric control system that uses the latest power electronics technologies.

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3.1 Shinkansen propulsion

As a symbol of Japan's advanced railway system, Shinkansen railcars have continuously incorporated state of art technology of the times. Fuji Electric has been delivering propulsion systems (including traction transformers, traction converters and traction motors) for successive generations of Shinkansen trains, from the first-generation series-0 Shinkansen train through the latest series-N700 Shinkansen train (shown in Fig. 1). As a representative example, this chapter describes the traction converter for the series-N700 for the Central Japan Railway Company (JR Tokai).

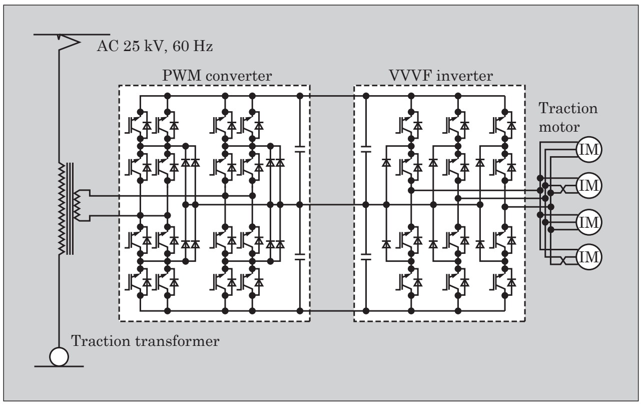
(1) Propulsion system for series-N700 Shinkansen train

(a) Traction converter

The traction converter, as can be seen in Fig. 2, is configured from a PWM (Pulse Width Modulation) converter and a VVVF (Variable Voltage Variable Frequency) inverter, and a single VVVF inverter collectively drives 4 traction motors connected in parallel. Two types of traction converters using different methods for cooling power devices have been delivered, a TCI3-model traction converter that uses a combination of boiling cooling (with a coolant) and forced cooling with a blower, and as shown in Fig. 3, a blower-less TCI100-model traction converter that uses a simple aluminum radiating fin and a natural ventilation method of self-cooling without the use of a blower or coolant.

Fig.1 Series-N700 Shinkansen train (photo courtesy of Central Japan Railway Co.)

Fig.2 Configuration of traction converter for series-N700 cars



The main circuit of a traction converter is configured from a converter unit, a filter capacitor unit and an inverter unit. Three-level converters and inverters are used. High efficiency and light weight are achieved by utilizing a low-loss snuberless circuit that includes a high-voltage, high-power, low-loss IGBT (Insulated Gate Bipolar Transistor) module (3,300 V, 1,200 A).

(b) Small size and light weight

The TCI3-model traction converter eliminates the snubber circuit and has an optimized structure to realize approximately 3% smaller volume and approximately 15% less mass than the previous TCI2-model while increasing the output by approximately 10%.

Moreover, the blower-less TCI100-model traction converter is 12% lighter than the TCI3-model.

(2) Control unit for traction converter

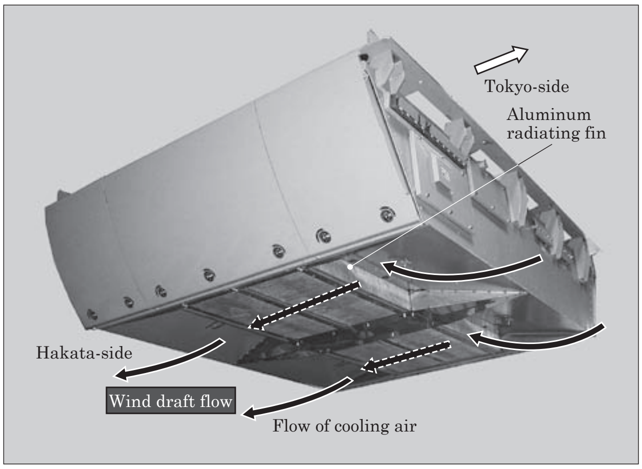
(a) Control unit for traction converter

The controller has a multi-processor configuration based on a 64-bit CPU core. The controller performs diverse control computations at high speed and with high accuracy, and for the purpose of advanced train control, also exchanges operating commands and transmits operating status monitor data. The latest microelectronics technology, data communications technology and the like are used to realize multi-functionality and high reliability while reducing the part count.

(b) 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 power devices. Focusing on the behavior of the potential voltage of the neutral point during periods in which power device switching is idle in a traction

Fig.3 Appearance of blower-less traction converter and cooling mechanism (wind draft flow)



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.

(c) Motor control

In the control of a rolling stock propulsion system, the acceleration and braking torque of the traction motor control must be highly responsive and highly accurate.

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 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.

3.2 Auxiliary power unit

An essential device for modern rolling stock, the auxiliary power unit, not only supplies stable power to the air-conditioning and lighting equipment necessary for maintaining comfortable conditions inside a railcar, but also functions to supply control power for devices such as the traction converter, and as a power supply for various IT devices such as the train control unit, display indicators inside a railcar, and the like.

The configuration of the auxiliary power unit will vary greatly according to the type of power source installed in the rolling stock.

(1) Auxiliary power unit for DC EMU

Feeding voltages in DC feeding systems are DC 1,500 V, DC 750 V or DC 600 V, and according to the output capacity and specifications required of the feeding voltage and equipment, an optimal voltage and current of IGBT are selected for configuring the circuitry or for application to the power circuit.

Usually, an IGBT having a withstand voltage capability that corresponds to the feeding voltage is used to configure a 2-level inverter, thereby simplifying the circuit, reducing the part count and increasing the reliability. On the other hand, for DC 1,500 V feeding, a product is commercialized in which the DC input sides of 2 inverter units that use 1,700 V-class IGBTs are connected in series, and the output of each inverter unit is combined with an output transformer, so as to increase the carrier frequency of the inverter and reduce noise. Figure 4 shows the configuration of the power unit for a DC electric railcar in a DC feeding system.

(2) Auxiliary power unit for AC EMU

In an AC electric railcar, power to large loads such as the cooling system is typically supplied directly from the traction transformer. The auxiliary power unit is limited to relatively small capacity loads such as indicator lamps, interior lights, control power, etc. These are critically important loads, and a high level of reliability is required of the auxiliary power unit.

As an example of an auxiliary power unit for an AC EMU, Fig. 5 shows the power unit configuration in the 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, and 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.

(3) Auxiliary power unit for diesel multiple unit (DMU)

A DMU is unable to receive power externally and so the installed diesel engine drives a generator that produces electric power. Fuji Electric has a history of numerous successes in manufacturing and delivering auxiliary power units for DMUs to various Japan Railway companies.

Figure 6 shows an example configuration of the main circuit of an auxiliary power unit for a DMU. The rotational speed of the diesel engine for driving the main shaft, which is the power source of the auxiliary power unit, will vary according to the operating conditions. Constant-frequency AC power obtained by a 3-phase AC power generator with the constant speed shaft by a constant speed unit is supplied directly to a load such as the air-conditioning system. The power control unit controls the excitation of the generator so

Fig.4 Example configuration of main circuit of auxiliary power unit for DC EMU

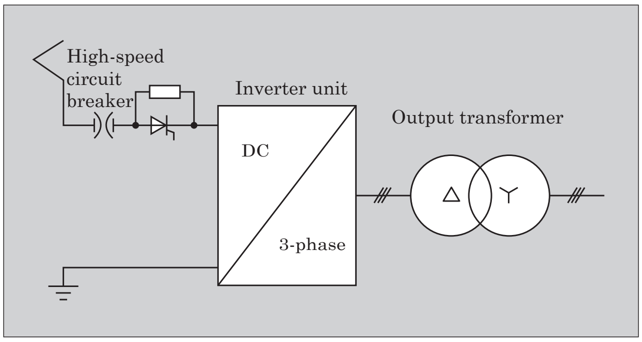


Fig.5 Example configuration of main circuit of auxiliary power unit for AC EMU

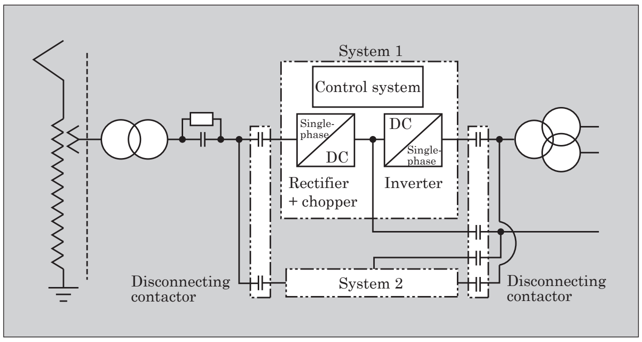
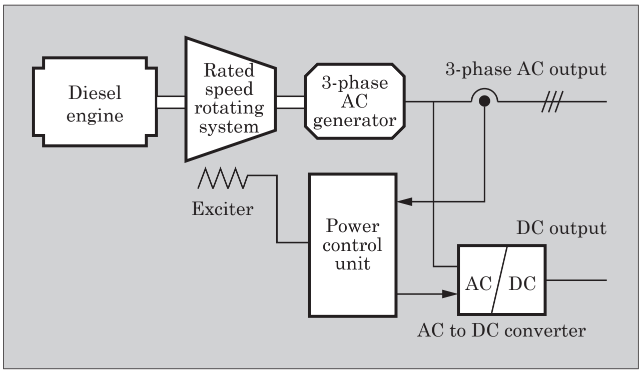


Fig.6 Example configuration of the main circuit of an auxiliary power unit for DMU



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 and the like.

(4) Features of Fuji Electric's auxiliary power unit

(a) High-performing control

The auxiliary power unit is required to provide a stable supply of electric power with little waveform distortion or voltage fluctuation even in the case of sudden changes in the feeding voltage, in the load current when a compressor or the like is turned-on or shut-off, or in an unbalanced 3-phase load such as a single-phase load. 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 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, and 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 ±1% or less and waveform distortion of approximately 1%.

(b) Higher reliability

Generally, a long rake of rolling stock 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 result in a suspension of the rolling stock operation.

Fuji Electric has commercialized an auxiliary power unit 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 site of the failure and the site of suspended operation are switched over so that operation will continue. During the system design phase, sites for redundancy are selected

Fig.7 Control block diagram of Fuji Electric's high performance auxiliary power supply

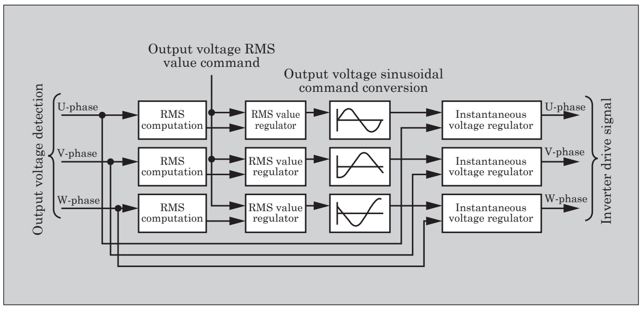
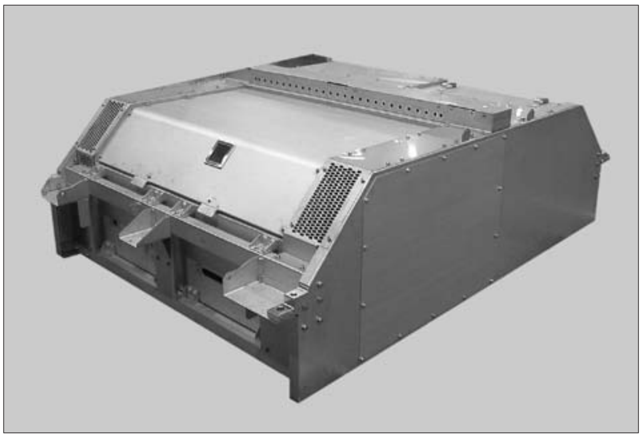


Fig.8 Roof-mount type auxiliary power system



based upon computed values of the failure rate and upon historical data to create the most appropriate system from rolling stock-use electric products for which small size and light weight are strongly requested. This method is being used in the general-type AC EMU series E721 trains operated by the East Japan Railway Company (JR East).

(c) Enhanced functionality

IT is being incorporated into equipment for rolling stock to achieve advanced rolling stock operation and to improve the ease of maintenance. The auxiliary power unit usually employs a data transmission system with an RS485 for physical layer and a transmission procedure based on polling/selecting for the necessary data transmission function of IT equipment. To further advance the functionality of a data transmission system for rolling stock, Fuji Electric was early to commercialize a transmission system for rolling stock based on the highly-versatile MODBUS on TCP/IP protocol, and has shipped an auxiliary power unit for double-decker rolling stock to Australia. Figure 8 shows the appearance of the roof-mount model of the power supply unit.

3.3 Side door system for rolling stock

Among the types of equipment used in rolling stock, a side door system is the most familiar to passengers. During rush-hour, the failure of even a single door among the many installed on a commuter train may immediately cause a serious effect on the operation of the train. Therefore, among the many electric products used in rolling stock, train doors have particularly strong requirements for safety and reliability. Electrically-driven doors are able to achieve higher-speed control response and higher functionality than pneumatic doors, and are rapidly achieving popularity primarily in the Tokyo metropolitan area and in overseas markets.

(1) Features of electrically-driven doors and linear doors

(a) Advantages of electrically-driven doors

An electrically-driven door not only eliminates the air piping that had been required with a pneumatic door, but also has the advantages of being less susceptible to the effects of aging and of providing highly reproducible electric control, and consequently, results in lower initial costs and maintenance costs of the rolling stock system. Additionally, the flexibility of the controller has been leveraged and data transmission technology applied to simplify the pre-operation inspection work, increase the level of intelligence, and enhance the door self-diagnosis function.

(b) Power transmission mechanism

With conventional electrically-driven doors, a ball screw has been widely used as a mechanism for converting the torque of the rotating motor into linear operation of the door. This method, however, has the problems of requiring frequent lubrication of the sliding part, a decreased sensitivity to door obstruction (to be described later), and difficulty in ensuring the reproducibility of the preset detection sensitivity.

By employing a linear motor to directly drive a linear motion door, Fuji Electric has simplified the door driving mechanism and commercialized a linear door that uses servo technology to realize high-performing control.

(c) 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.

(d) Safety function

In recent years, accidents in which a passenger gets caught in a closing door of a building or train have occurred frequently, and door safety has become an important issue. Fuji Electric's linear door uses microprocessor-based electronic control to implement highly sensitive door obstruction sensing based on the door speed and other control information. Additionally, after sensing a door obstruction, the safety operation is implemented with detailed control based upon various different requirements according to the railway company.

(2) Example of linear door product

(a) One motor per door opening type

A biparting type or single-leaf type train door is driven by a single linear motor. This implementation is used in JR East's series E231, E233 and E531, and Seibu Railway's series 30000, and a total of approximately 14,000 of these doors were being used in commercial operations at the end of 2008.

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 mechani-

Fig.9 Configuration of side door system

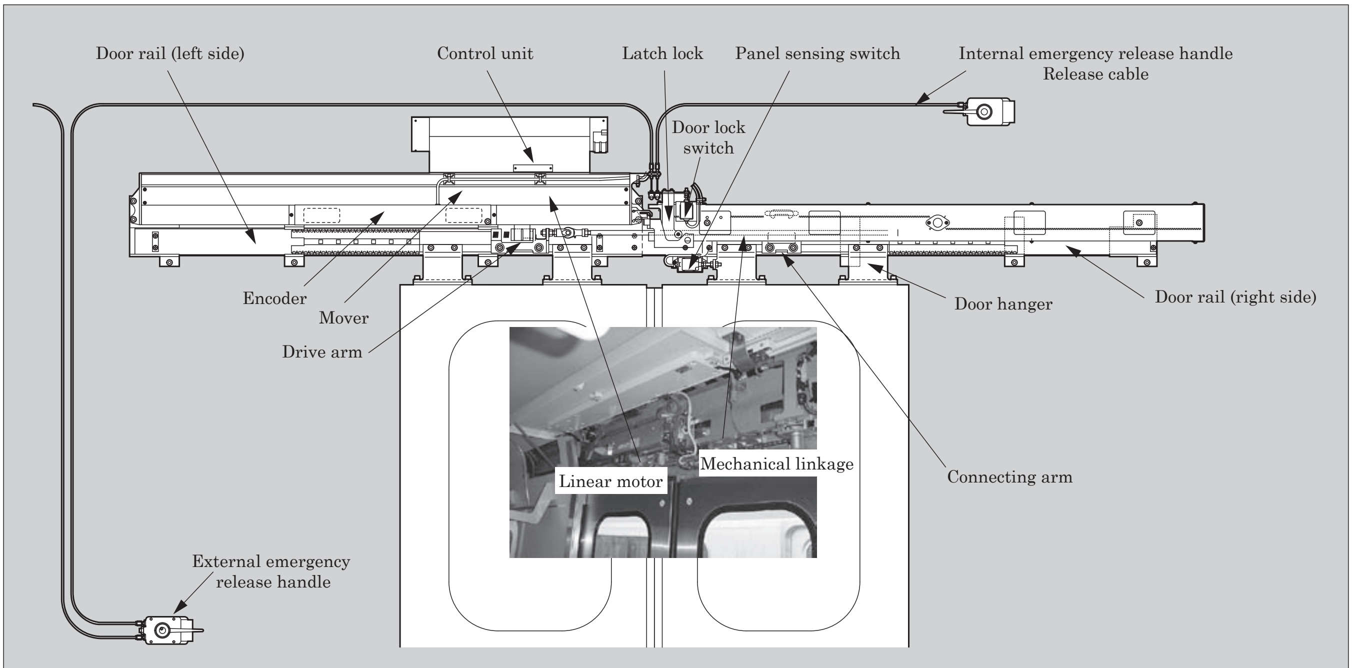


Fig.10 NYCT R160 train and door system

cal 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 linkage). 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. Figure 9 shows the door system configuration.

The series E231 and subsequent models of rolling stock of the Tokaido Line use a standby redundancy system that features dual-redundant signal I/O interface circuits, control circuits and VVVF inverters. Even if a failure were to occur, operation is able to continue without any decrease in functionality.

(b) 2 motors per door opening type

In this implementation, each door leaf is driven by a linear motor. This implementation is used in the R160 subway cars operated by the New York City Transit (NYCT) Authority. By the end of 2008, 4,320 of these doors had been delivered and more than 2,000 were in operation. Figure 10 shows the external appearance of the NYCT R160 car and door system. To ensure stable operation despite voltage fluctuations in the DC37.5 V power supply, the supplied power is boosted to a constant voltage and stabilized by a chopper circuit, and then input to an inverter.

Also, an unlocking mechanism that uses a solenoid is applied to support customer specifications based on a safety concept that emphasizes functional independence.

4. Marine

In the domestic transportation sector, coastal shipping ranks second, after railways, as a highly energy efficient, environmentally friendly, large-scale, safe and economical mode of transportation. The volume of cargo transported via coastal shipping (in terms of ton-miles) accounts for approximately 40% of Japanese domestic cargo transport.

On the other hand, the shipping industry faces various challenges, such as the aging of seafaring workers, difficulty of securing young seafarers, a harsh work environment, delayed implementation of energy-saving measures, and so on. With the goals of conserving the global environment, increasing the efficiency of distribution and increasing the vitality of the marine transportation business, the Japanese Ministry of Land, Infrastructure, Transport and Tourism has, since 2005, been promoting coastal ships that use an electric propulsion system.

In addition, the Japanese “Law Concerning the Rational Use of Energy” (abbreviated as the Energy Saving Law), revised in 2008 and put into force on April 2009, obliges shipping service operators with a transport capacity exceeding 20,000 gross tons to report their status of compliance with criteria based upon this law. These criteria include the “Super Eco Ship” (electrical propulsion ship) and “inverter controlled electrical equipment” as examples of the “use of superior transportation machinery and tools.”

According to Lloyd’s statistics for overseas electrical propulsion ships in 2007, European ship builders have a considerable backlog of orders for global cruise ships, and similar backlogs exist for LNG carriers in Korea and for offshore supply vessels in China, suggesting a growing trend of applying electrical propulsion to ship types that effectively utilize the features of electrical propulsion systems, i.e., operational flexibility, increased maneuverability, high efficiency, flexibility of installation, and so on.

Fuji Electric has delivered various systems such as electric propulsion systems, shaft generator and booster systems, various types of hoists, and data acquisition and analysis equipment for use in the “Fuji” and “Shirase (1st generation)” ice breakers and for use in submarines operated by the Japanese Ministry of Defense, and also has delivered various component devices such as inverters for variable-speed driving, electric motors, high-voltage molded transformers, vacuum circuit breakers, electromagnetic contactors and programmable controllers.

4.1 Simulation of electrical propulsion ship

Recently, there is a high state of anticipation regarding the application of various types of electrical propulsion systems to the aforementioned coastal ships and to other types of ships. Effective simulation techniques when planning to design a ship with an electric propulsion system are described below.

Figures 11 to 13 show example simulations of an electric propulsion ship that comprehensively model the power generating equipment including the prime motor, generator, electrical propulsion system, onboard load, propeller and hull. Data, such as the ship stopping distance, time, power supply voltage, frequency fluctuation, and back power for braking of the propeller, at the time of a crash-astern maneuver can be

Fig.11 Example of electric propulsion ship simulation model

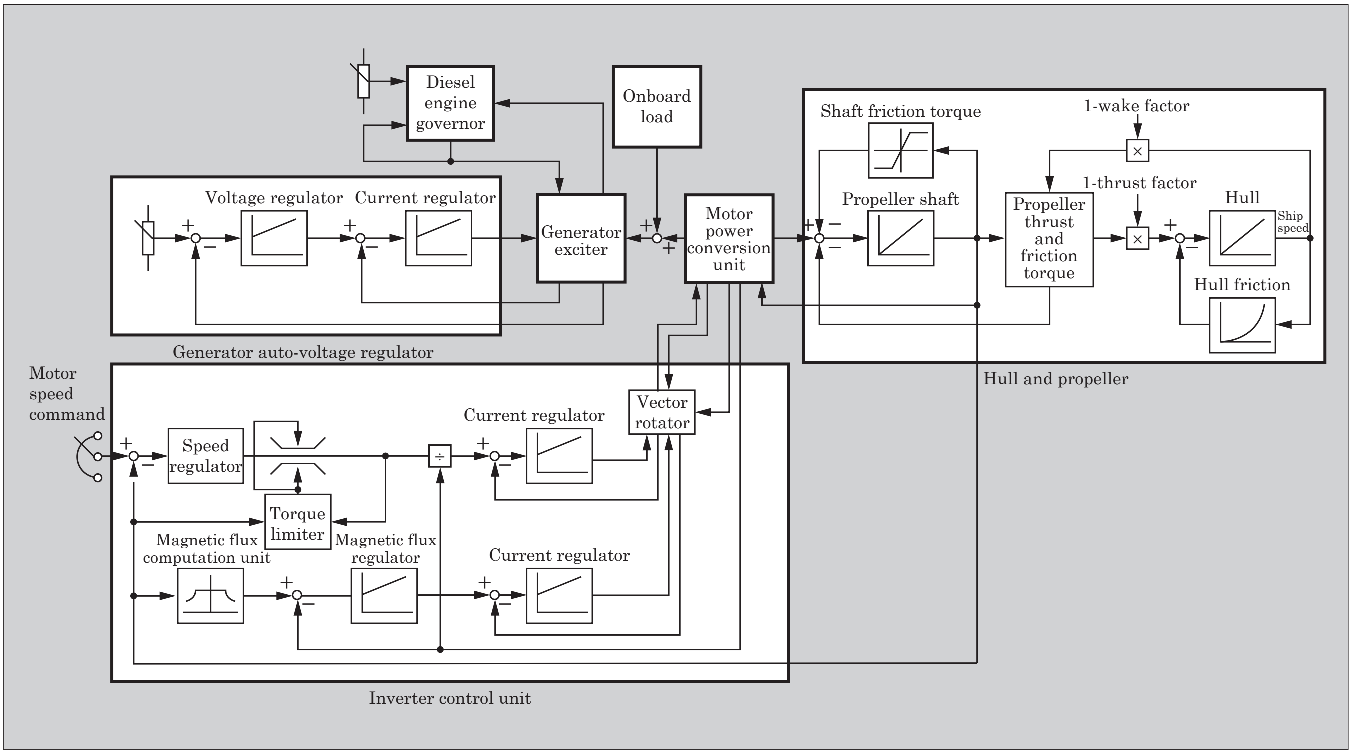


Fig.12 Simulation results (crash-astern) *1

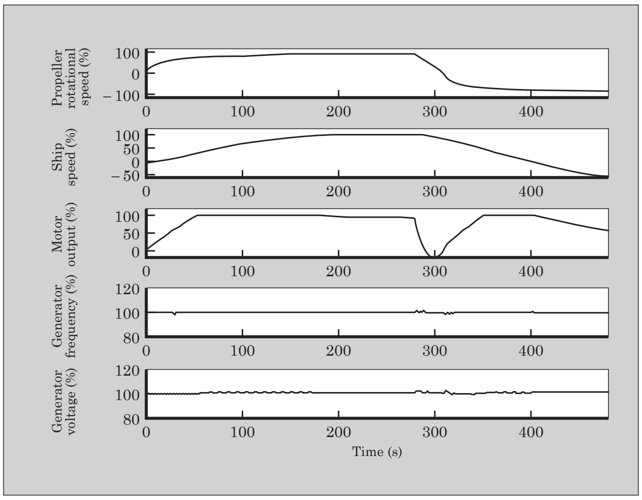
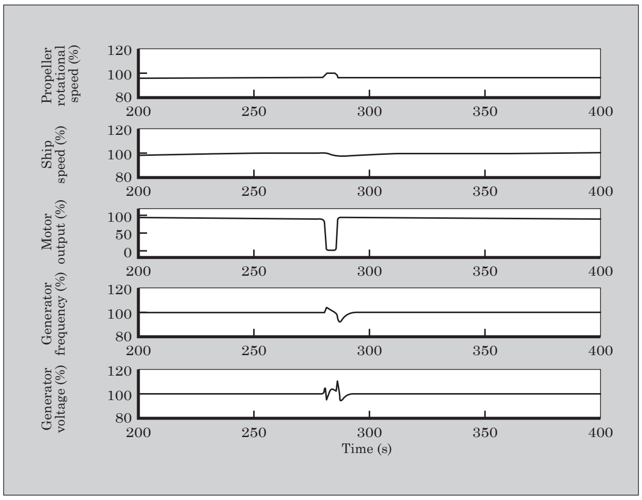


Fig.13 Simulation results (propeller racing) *1



obtained. An optimal system can be constructed for an entire ship in which the hull, propeller and electrical propulsion system including the power supply have matched characteristics. An electrical propulsion ship supplies both the propulsion power source, required for driving the propeller and propelling the hull, and the onboard power source required for using various devices and electric products onboard, from the same power generating equipment. For this reason, in addition to ensuring the required ship maneuverability, the maintenance of a certain level of power source quality (i.e., frequency, voltage, and the like) is also required. The performance of an electrical propulsion ship cannot be evaluated adequately from a simulation of only the hull and propeller system by themselves (i.e., a simulation of the changes in ship speed, propeller rotational speed and the like without consideration of the power source) or from a simulation of the electrical system by itself (i.e., a simulation of changes in the electric power, voltage and current with respect to simple load fluctuations). Simulations must be performed using a comprehensive model of the ship, from the power generating equipment to the propeller and hull.

Consequently, evaluating the relevance of analytical data obtained from a simulation becomes an issue. The relevance of simulations of the harmonics and

*1: See the "Glossary" on page 172.

short-circuit failure is already acknowledged. A simulation of the total system, including the hull, is evaluated for relevance based on comparisons with data acquired from an actual ship or with data acquired experimentally using a reduced-scale model. The popularization of electrical propulsion ships in the future will result in an accumulation of measured data from actual ships, and Fuji Electric plans to use this data to improve the accuracy of the simulation models.

4.2 Example of maritime solution

Figure 14 shows the "f(s) NISDAS" as an example of a data acquisition system for ships. The system is configured from an electric propulsion system, an on-board load, a PLC for acquiring GPS and other data, and a personal computer. The sampling time is 1ms at the fastest. The number of inputs is limited by the storage capacity and the sampling time. Figure 15 shows examples of the acquired data. The ship operation, from the stopped state to the accelerating state, can be verified. The capability to observe the energy flow is said to be important for realizing energy savings, and detailed data acquisition facilitates the planning of energy saving measures.

In the future, Fuji Electric intends to propose additional solutions based on such needs as "smoke and soot countermeasures for engines and boilers", "motorization of the hydraulic system to improve maintainability" and so on, and to apply new technologies and products, such as electric dust collecting technology, IH (induction heating) boilers and small-size large-performance inverters, to ships. While receiving guidance from ship owners, ship builders and manufacturers of marine equipment, Fuji Electric plans to continue to commercialize new products in the future.

Fig.14 Example of data acquisition system for ships

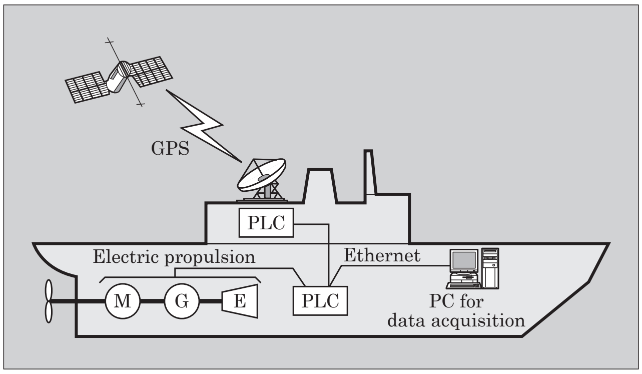
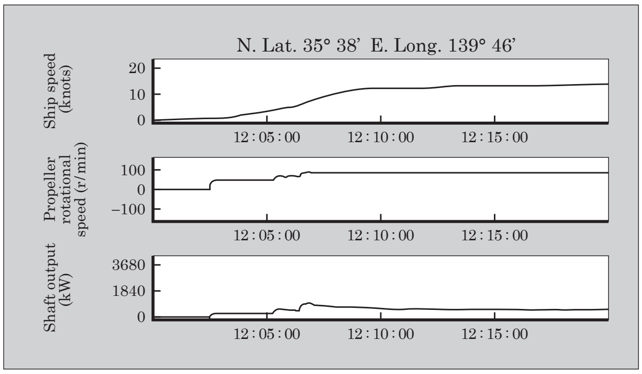


Fig.15 Examples of acquired data



5. Postscript

Power electronics technology for rolling stock and ships has been presented as a transportation solution. In these market sectors, requests for smaller size and lighter weight, higher performance, higher functionality, reduced maintenance, greater comfort and environmental friendliness are expected to continue to be driven by advances in power electronics technology and microelectronics technology. Fuji Electric is actively advancing research and development that anticipates market needs for energy savings and environmental friendliness, and intends to continue to provide products that benefit society.