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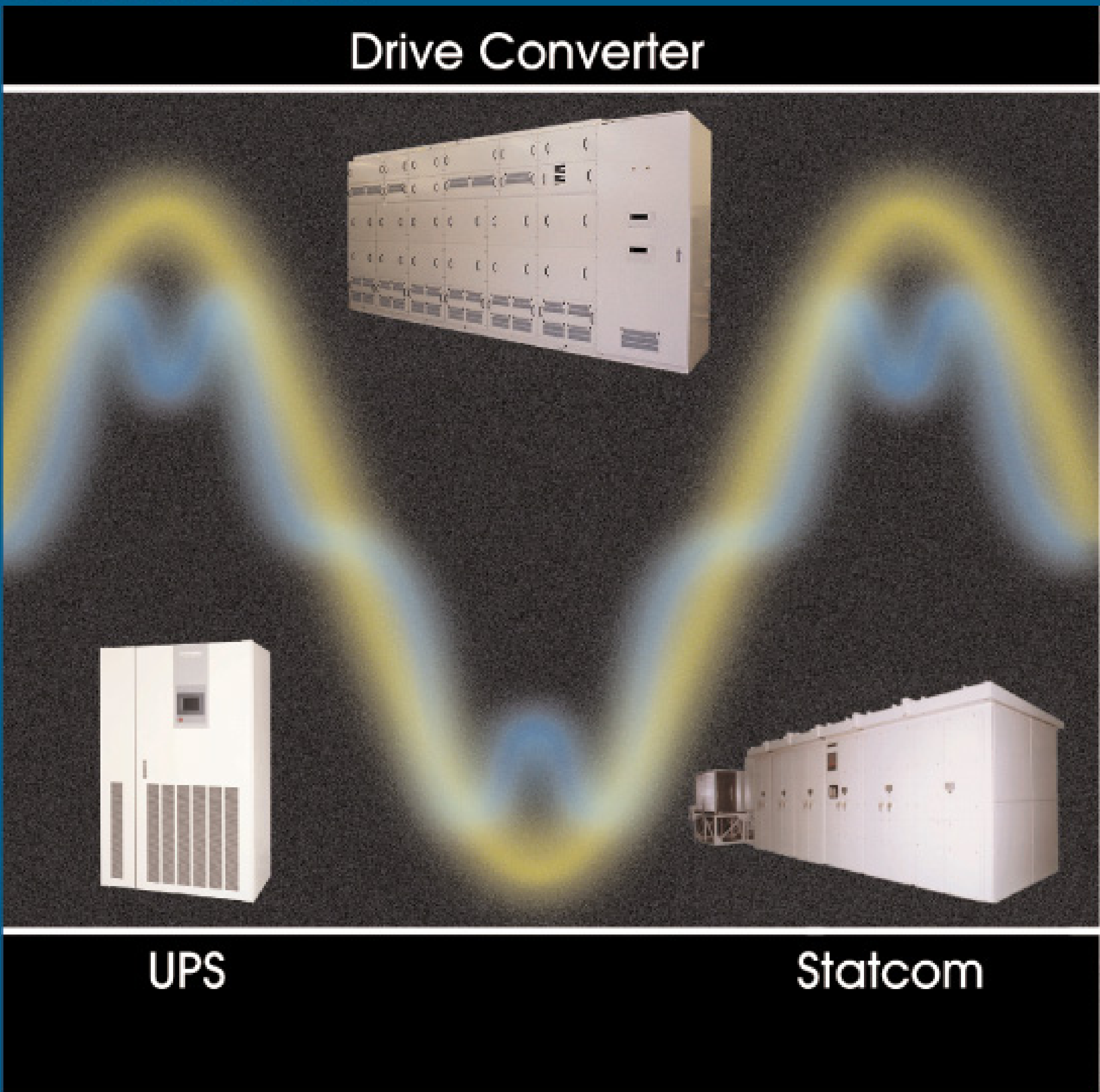
MITSUBISHI ELECTRIC ADVANCE

Power Electronics Edition



MITSUBISHI ELECTRIC

A Quarterly Survey of New Products, Systems, and Technology

●Vol. 89/March 2000 Mitsubishi Electric **ADVANCE**

Power Electronics Edition

CONTENTS

Our cover story illustrates typical power electronics products playing vital roles in electrical power supplies and their control. The UPS is a critically important power supply in the advanced, information-oriented society. Drive inverters improve factory productivity while reducing energy demand, and the STATCOM improves the quality of the electric power supplied.

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Overview

Present State and Future Prospects of Power Electronic Equipment

*by Isamu Matsuyama**

The second half of the 20th century saw the birth of power electronics, which has rapidly taken an important position in the infrastructure supporting all sectors of industry. Uninterruptible power supplies (UPSs) have become indispensable as highly reliable sources of power for the computers and communications equipment on which our increasingly information-oriented society depends. Variable-speed motor drive control has improved factory productivity and made significant contributions to reducing energy demand. Again, traction control for electric trains provides an efficient means of high-speed mass transport, and power electronics equipment such as HVDCs, STATCOMs and active filters plays an important role in improving the efficiency of operation and the quality of service for electric utility transmission and distribution systems.

In the 21st century, if humankind is both to continue economic development and to sustain the environment, high priority must be given to revolutionary developments in the technologies of energy usage. The key lies in the efficient use of electrical power, in which power electronics is expected to play a central role. Mitsubishi Electric's production technology for the world's largest diameter power devices has already established its leadership in increasing the capacity of such devices. The corporation will use these high-capacity power devices in the power electronics equipment vital for the control of large amounts of electrical power. By enabling the fast and flexible control of entire electrical power systems, and the energy-efficient operation of high-power motors, this will offer enormous savings in energy consumption.

We see our mission as a manufacturer in providing power electronics equipment that will combine the very highest performance and reliability in the infrastructure supporting society in the 21st century.

Isamu Matsuyama is General Manager of the Energy & Industrial Systems Center.

Trends in High-Voltage, High-Capacity Power Devices

*by Masanori Yamamoto and Kazufumi Ishii**

While the voltage and power ratings of the largest solid-state power switching devices continue to increase, several new types of power devices have appeared: high-voltage insulated gate bipolar transistor modules (HVIGBTs), high-voltage intelligent power modules (HVIPMs) using MOS technology, and gate-commutated turn-off (GCT) thyristors. This new generation of devices offers higher efficiency and faster switching than its predecessors as well as more compact dimensions. These products are rapidly entering commercial production.

Table 1 shows types and ratings of Mitsubishi power devices, which include diodes, general-use, fast-switching and light-triggered thyristors, gate turn-off (GTO) thyristors, GCT thyristors, HVIGBTs and HVIPMs. Fig. 1 shows how power capacity of these various devices—each made from an entire wafer—has increased by a factor of one hundred as wafer sizes have grown from one to six inches. The increase in wafer diameter has become possible as a result of new technologies ensuring uniform distribution over large areas of the dopant impurities that impart the desired electrical characteristics.

Table 1 Ratings of high-voltage, high-capacity power devices.

Device	Max. rating
General-use diodes	2.8kV, 3.5kA
Fast switching diodes	6.0kV, 3.0kA
General-use electrically triggered thyristors	12.0kV, 1.5kA
Fast-switching electrically triggered thyristors	1.2kV, 1.5kA
Light-triggered thyristors	8.0kV, 3.6kA
GTO thyristors	6.0kV, 6.0kA
GCT thyristors	4.5kV, 4.0kA
HVIGBTs	3.3kV, 1.2kA
HVIPMs	3.3kV, 1.2kA

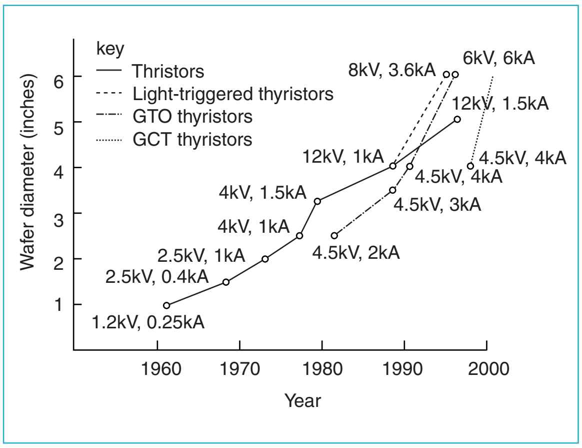


Fig. 1 Evolution of high-capacity power devices.

HVIGBTs and HVIPMs

These devices have been developed to perform the switching functions previously served by GTO thyristor and transistor modules. Fig. 2 shows a 3,300V, 1,200A HVIGBT, Fig. 3 an identically rated HVIPM.

Reliability has been improved as a consequence of several advances: wire-bonding technology with an enlarged contact area, void-free vacuum soldering, X-ray inspection for detecting solder voids, and bubble-free gel-injection systems. The power-cycle lifetime of both types has been increased while higher partial discharge initiation and extinction voltages boost dielectric strength.

IGBTs use a punch-through device structure. This, combined with a proton irradiation process for lifetime control, serves to decrease the collector-emitter saturation voltage while simultaneously lowering the turn-off switching loss.

Advantages of the new devices over those they replace include voltage drive, which reduces the size and weight of the gate-drive circuit, and higher switching speed in the 2~3kHz range. Power modules are smaller and lighter than GTO thyristors, which need separate diodes, because they have IGBTs and diodes in a reverse parallel configuration. Peripheral circuitry is also simpler. Turn off is accomplished without a snubber circuit, and an anode reactor for limiting *di/dt* is unnecessary. The IPMs add sophisticated gate control and protective functions that virtually eliminate typical failure modes. Voltage surges during turn-off are prevented by increasing the gate resistance when *di/dt*, the rate of rise in the collector current, exceeds a specified threshold.

Masanori Yamamoto and Kazufumi Ishii are with Power Device Division.

Fig. 2 Packaged 3,300V, 1,200A HVIGBT.

Fig. 3 Packaged 3,300V, 1,200A HVIPM.

Protective functions for over current (OC), over temperature (OT) and supply circuit under voltage (UV) also activate a fault signal for co-operation with other system equipment. Fig. 4 shows a block diagram of HVIPM control protection circuit.

HVIGBTs and HVIPMs are being used in the inverters and converters that drive electric trains and their auxiliary power supplies, and in steel mill equipment.

Current development objectives for these devices are adapting them to higher-voltage power lines, increasing their operating frequency, and preparing them for operation under higher thermal stresses. Work will focus on increasing the voltage rating of the device and reducing losses, improving package insulating characteristics, and introducing new materials such as AlSiC base plates that can boost reliability.

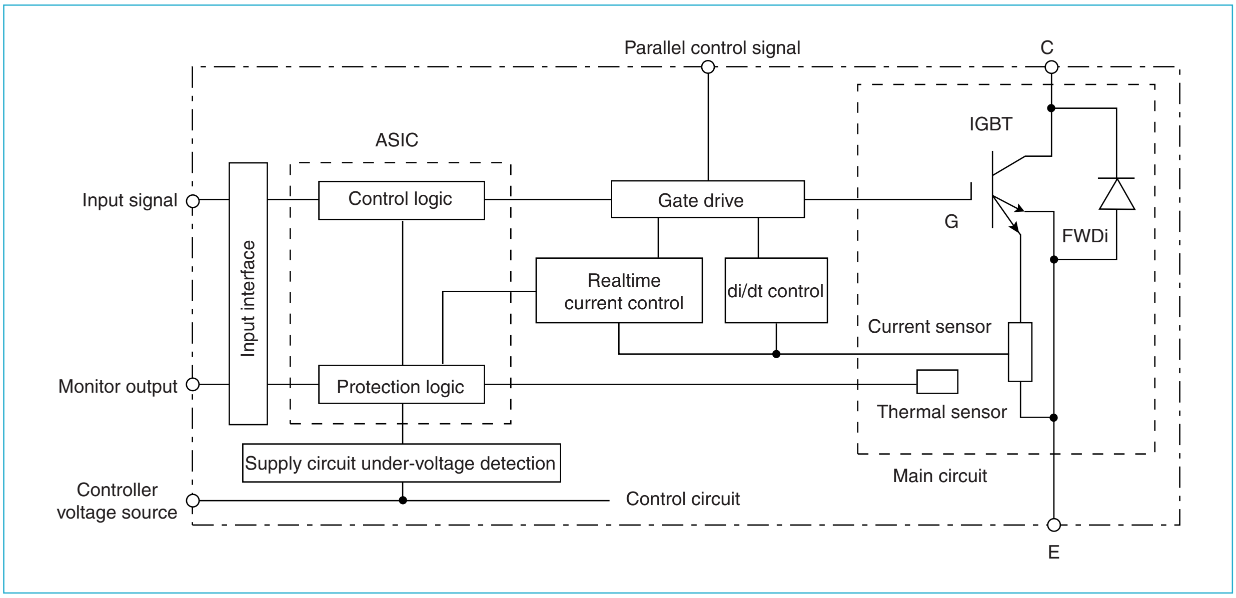
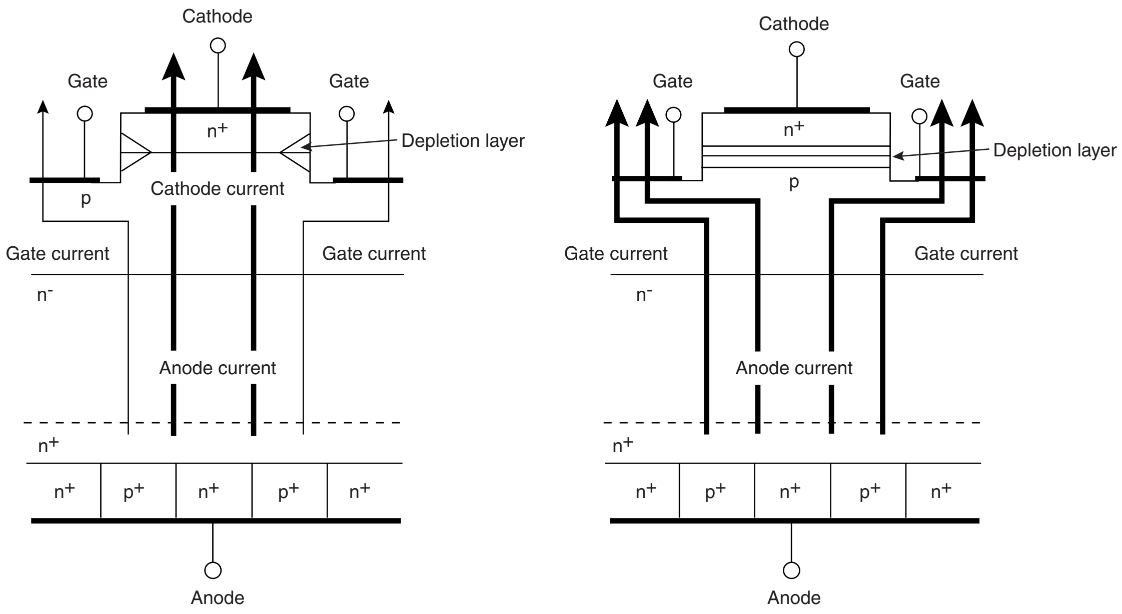


Fig. 4 Block diagram of HVIPM control and protection circuitry.



a) GTO thyristor, turn-off gain 3~5

b) GCT thyristor, turn-off gain unity

Fig. 5 Thyristor operating principles.

GCT Thyristor Development

GCT thyristors feature greatly reduced current concentration during turn-off compared with GTO thyristors as a consequence of instantaneously commutating the main current—rising at several thousand amperes per microsecond—into the gate circuit with unity gain. Fig. 5 contrasts the operating principles of GCT and GTO thyristors. Fig. 6 shows a 4,500V, 4,000A GCT thyristor with gate-drive circuitry. The ring-shaped electrode around the device perimeter reduces the package inductance to one tenth that of GTO thyristors. By making the connection to the gate drive circuit using a multilayer substrate, the total inductance—the inductance of the gate circuit and gate-drive circuit, including the device's gate-to-cathode inductance—is reduced to several nH, about 1/100th that of a GTO thyristor. This low inductance makes it possible to achieve an off-gate current rate-of-rise ($diGQ/dt$) of several thousand amperes per microsecond while keeping the gate voltage at 20V.

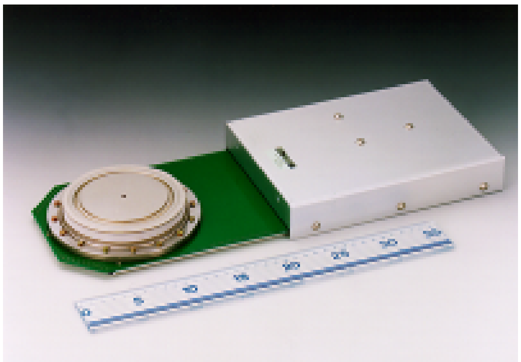


Fig. 6 Packaged 4,500V, 4,000A GCT thyristor with gate driver.

Advantages of GCT thyristors can be summarized as follows: Turn-off is snubberless, reducing total switching losses by 50% during loaded operation and to nearly zero during no-load operation. Switching frequency is boosted to 2~3kHz due to the reduced storage time. More uniform storage times simplify series and paral-

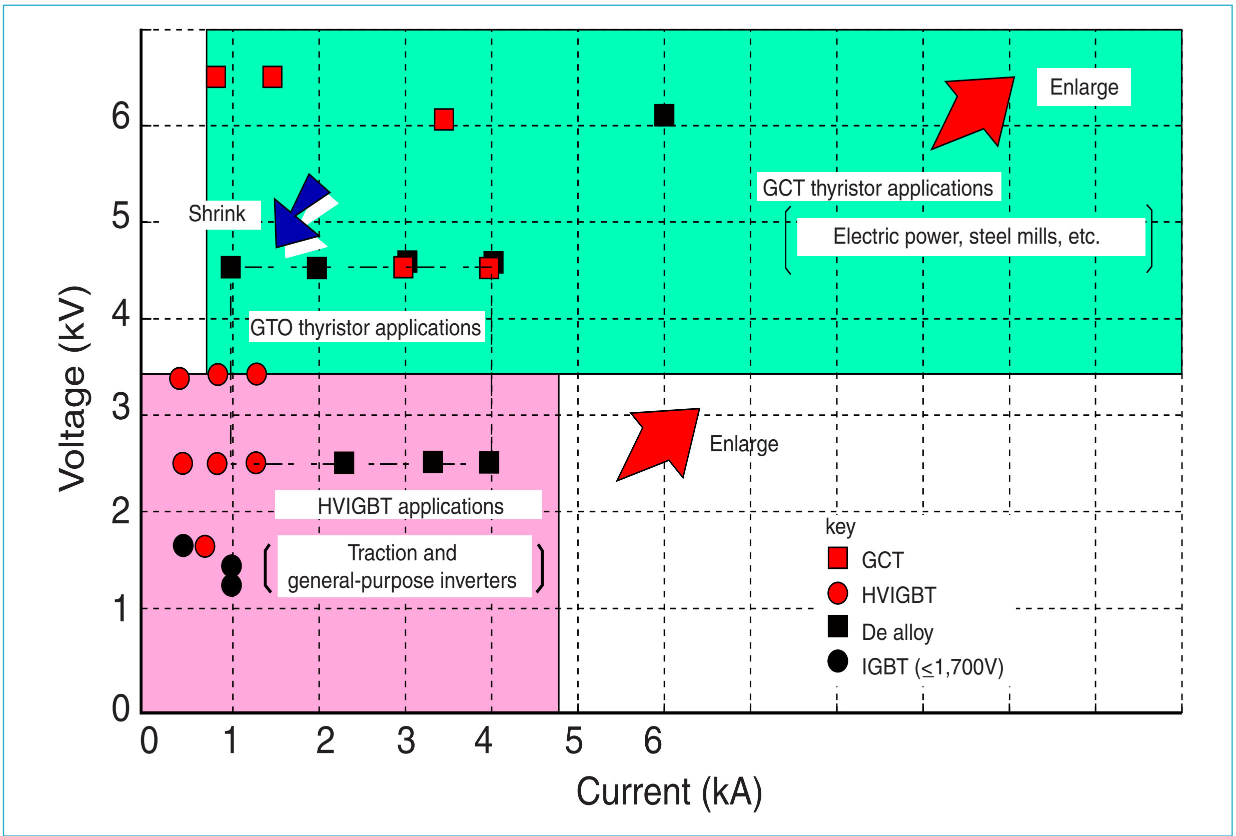


Fig. 7 Application trends in high-voltage high-capacity power devices.

lel configurations. Gate power is 30~40% less than in a GTO thyristor due to the lower gate charge accumulation. The device can withstand more than twice the maximum current rate-of-rise (di/dt) of GTO thyristors, allowing the size of anode reactor that limits di/dt to be halved. Finally, the thyristor construction is characterized by a low on-state voltage, with potential for continued increases in operating voltage and current.

Application Trends

High-voltage high-capacity power devices are primarily used in inverters and converters for traction applications in high-speed electric trains and subways, active filters for power applications, static var generator and static var compensator circuits for managing reactive power, back-to-back (BTB) variable-speed pumped storage, power switching, motor drives for steel and paper mills, and high-voltage power lines.

Fig. 7 illustrates applications for various power devices by voltage and current. GCT thyristors can replace GTO thyristors in applications involving the highest power levels while HVIGBTs are used for lower power levels. Thyristors rated at 12kV serve power network applications with the highest voltages, providing AC switching and SVC functions, with light-triggered thyristors used for DC power transmission.

Faster switching, lower losses, higher voltage and current capacities, and simpler more compact construction continue to expand the application range of solid-state power devices. ❑

Solid-State Power Devices for Electric Power Networks

*by Yasuhiko Hosokawa and Shinji Jochi**

Advances in solid-state power devices have made it possible to implement AC power transmission systems utilizing the superior flexibility of semiconductor power converters to improve network operating characteristics. Mitsubishi Electric has developed a low-loss and highly reliable self-commutated power converter using the industry's largest diameter power devices.

Power networks are beginning to implement flexible AC transmission systems (FACTS) using solid-state power switching devices to improve network flexibility and efficiency. At the heart of these systems are solid-state self-commutated converters that can adapt to various active power and reactive power levels. Mitsubishi Electric pioneered use of solid-state self-commutated converters in power transmission trunks in 1991 with static var generator(*1) (SVG) products for power system stabilization. More recently the company has produced several hundred MVA capacity self-commutated power converter prototypes using the world's first six-inch-diameter gate turn-off (GTO) thyristors under contract to MITI's Natural Resources and Energy Agency as part of a program to develop advanced back-to-back power systems. The company has also worked to reduce the substantial operating losses of self-commutated converters. It now appears feasible to fabricate a snubberless design using gate-commutated turn-off (GCT) thyristors with efficiency comparable to conventional line-commutated designs.

Features of Self-Commutated Converters

In contrast to line-commutated converters using conventional thyristors or diodes, which are restricted to controlling the transition timings between on and off states, self-turn-off devices like GTOs improve control flexibility. This means that they can control AC power network variables independently of voltage phase, serving as a controllable ideal voltage source. The solid-state implementation makes it possible to change voltage phases and amplitudes within microseconds. Faster and more flexible power network control permits equipment to be operated more efficiently. Self-commutated converters permit active power and reactive power to be regulated individually, increasing the degrees of control flexibility in power networks, while the power devices tolerate voltage variations and even power interruptions without failure. A final advantage is that converters' multipulse PWM functions and further multiplexing of converters can minimize the generation of higher harmonics.

Power Network Applications

Mitsubishi Electric first tested self-commutated converters in power networks in 1975, when it developed a 20MVA SVG prototype in a joint research project with Kansai Electric Power Co. In 1980, the companies undertook pioneering field tests of the technology and delivered the world's first products for commercial power networks in 1991. An 80MVA GTO thyristor static var generator was jointly developed and installed at Kansai Electric's Inuyama switching station, where it has remained in service for eight years. In 1993, Mitsubishi Electric delivered a self-commutated converter to the Hokkaido Electric Power Co. for the world's first application as a secondary excitation apparatus for a variable speed pumped-storage system.

Field Tests of a Self-Commutated BTB System

GTO converters were recently tested under the Natural Resources and Energy Agency, Japan's nine domestic power companies, Electric Power Development Co., Ltd. and the Central Research Institute of the Electric Power Industry. Three self-commutated converters using six-inch diameter 6kV, 6kA GTO thyristors were tested in a three-terminal back-to-back field test at Tokyo Electric's Shinshinano Substation. Mitsubishi Electric manufactured a converter for one terminal. Fig. 1 shows the configuration. Each stage of the four-stage multi-connected converter has a three-phase bridge with four series-connected GTO thyristors in each arm. Fig. 2 shows the appearance of one converter stage and Fig. 3 a GTO thyristor unit for the application. These trials have established technology for constructing 100MVA-class converters using large capacity GTOs. The large diameter device reduces the number of components, enhancing reliability to a level adequate for application to trunk-power systems.

**Yasuhiko Hosokawa and Shinji Jochi are with the Energy and Industrial Systems Center.*

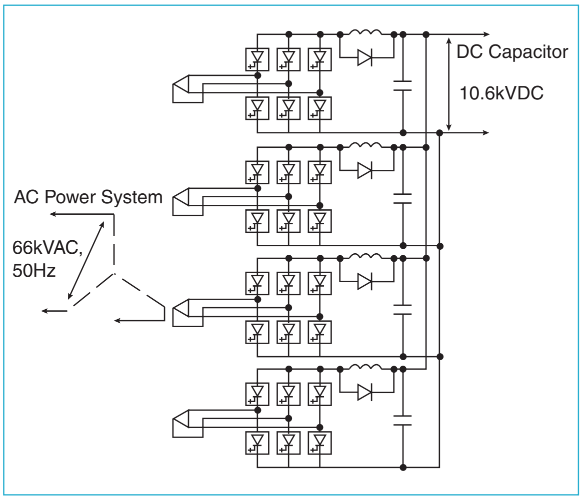


Fig. 1 Circuit configuration of 53MVA GTO thyristor converter.

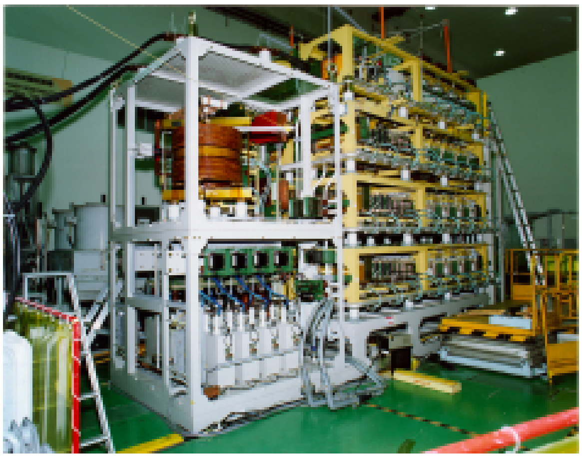


Fig. 2 One of the four stages (1/4 valve) of a 53MVA converter.

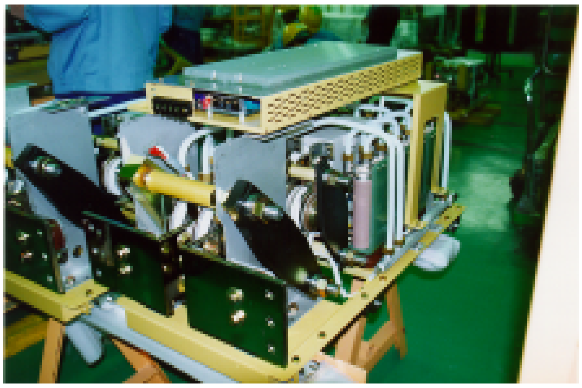


Fig. 3 The GTO thyristor unit for the 53MVA converter.

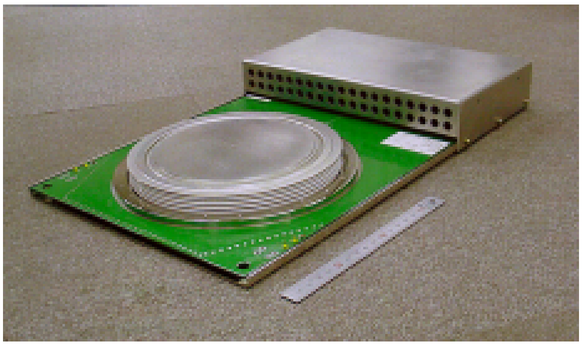


Fig. 4 A 6kV, 6kA GCT thyristor unit.

Loss Reduction

Despite the many advantages of self-commutated converters, applications have lagged due to higher operating losses. Mitsubishi Electric has recently developed a new power device, a gate commutated turn-off thyristor (GCT) that dramatically reduces switching losses. Fig. 4 shows a GCT thyristor unit with drive circuitry. GCT thyristors have an improved gate structure that allows fast switching with all of the principal current commutated through the gate. No snubber circuit is required to stabilize operation as in previous devices. Eliminating the snubber circuit halves the loss compared to previous GTO thyristor-based converters. Fewer external components also means reduced equipment size with improved reliability. Low losses are especially important in large-capacity converters used in power transmission trunks. Large-diameter high-voltage high-current GCT thyristors in a single-serial single-parallel configuration with a choice of five or less harmonics has proven optimal. Harmonics can be reduced by multiplex voltage conversion. This configuration eliminates AC filter and phase-compensation circuits, achieving efficiency comparable to line-commutated equipment while occupying about half the floor space.

Application to Distribution Networks

Self-commutated converters provide a powerful tool to compensate for power quality problems such as voltage fluctuations, harmonic components, and voltage sag that occur in power distribution systems. Mitsubishi Electric's Compact STATCOM is solid-state self-commutated static var compensator using IGBTs and four-inch GTO or GCT thyristors. The compensators provide high-speed control of reactive power, making them suitable for flicker suppression for arc furnaces, compensating voltage sag during traction-motor starts, and compensating imbalances when three-phase AC power systems are used to drive large single-phase loads such as electric trains. Compact STATCOM employs high-performance GTO thyristors in a new circuit that maximizes device performance and dramatically reduces equipment volume and floor space compared to previous products. The smaller, lighter equipment has fewer installation constraints and may be relocated with relative ease. Fig. 5 shows a 20MVA Compact STATCOM that occupies about 70m^2. The converter uses a four-stage multi-connected configuration with five-pulse PWM. Arc furnace flicker is reduced by 60%, a much higher value than is practical using a line-commutated converter. Fig. 6 shows a GTO inverter unit, the main component of the converter.

Fig. 5 A 20MVA Compact STATCOM installation.

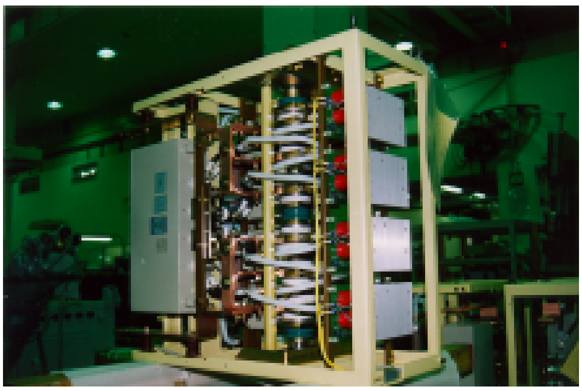


Fig. 6 A GTO thyristor inverter unit for the 20MVA Compact STATCOM.

The power-handling capacity and the operating characteristics of solid-state power switching devices continues to improve. With lower loss and fewer operating constraints, the latest generation of devices is ready for commercial applications in power networks and distribution systems. ❑

Variable-Speed Drive Systems for Steel Mills

*by Yasuhito Shimomura and Haruki Ogawa**

Mitsubishi Electric has developed voltage-source inverters for AC motor drive systems with IGBT based inverters serving applications under 3,600kVA and GTO thyristor inverters for higher power levels.

Because steel manufacturing lines use so many variable-speed motors, size reductions in the motor drive units can contribute to substantial savings in factory floor space that reduce investment costs. High-power-factor converters are another focus of technology development since these converters produce less reactive power and introduce lower levels of power line harmonics.

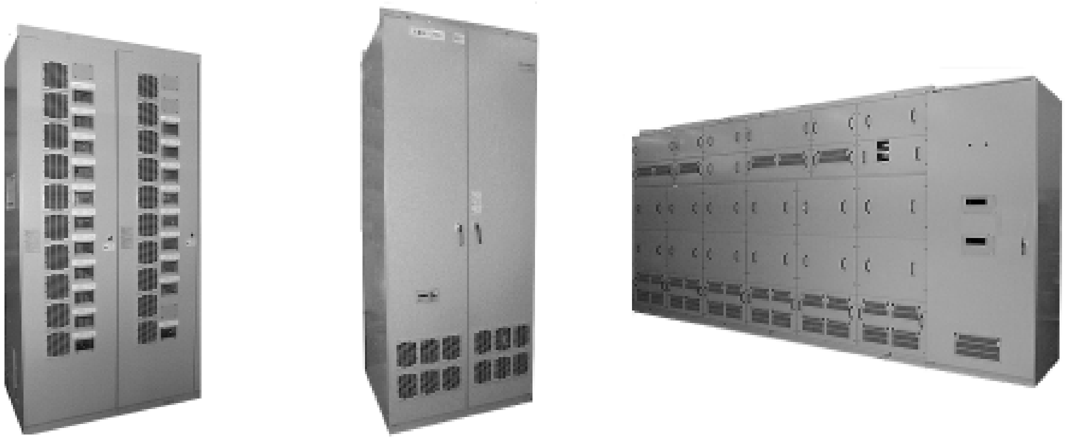
The company is meeting these objectives in AC motor drive systems for the largest applications using three-level gate turn-off (GTO) thyristor inverters. Insulated-gate bipolar transistors (IGBTs) are used in medium- and small-scale inverters with capacities under 3,600kVA. Fig. 1 shows the appearance of these drive units. Two-level IGBT inverters meet applications up to 1,200kVA, three-level IGBT inverters up to 3,600kVA, and GTO thyristor inverters up to 20,000kVA. All are voltage-source power converters that can withstand brief power interruptions and employ a common converter configuration conducive to compact dimensions and high efficiency. A maximum motor speed of 1,800rpm is supported.

Table 1 lists specifications of these inverters. The input voltage specifications assume a thyristor converter used with IGBT thyristor inverters, and GTO thyristor converters with GTO thyristor inverters. Water cooling used for GTO thyristor inverters allows a smaller enclosure to be used for the main circuit board.

Diode converters are available for GTO thyristor inverters. High-efficiency IGBT converters are also available to support a variety of configurations and inverter capacities. Both employ a common converter configuration.

GTO Thyristor Inverters

These inverters drive high-capacity variable-speed AC motors for rolling mills. The company has delivered over a hundred of these units since they were first launched in 1994. Two products are available, a single inverter unit with a 10,000kVA capacity and a dual inverter with a 20,000kVA capacity and a shared reactor. The MELVEC-3000A series, the company's most recently developed product, incorporates advances that improve efficiency while reducing equipment dimensions.



a) MELVEC-1200 for lower capacity motors
b) MELVEC-2000N for medium capacity motors
c) MELVEC-3000A for high-capacity motors

Fig. 1 Variable-speed AC drive systems and their application ranges.

**Yasuhito Shimomura and Haruki Ogawa are with the Energy and Industrial Systems Center*

The early models were large. All main circuit components were on a single board and repair involved replacing all of these components at the same time. Today the main circuits are smaller and lighter due to use of smaller snubber capacitors and other components. The weight of new-model MELVEC-3000A inverters is 44% less than the company's earliest products, while the footprint of the inverter cabinet has been halved, see Fig. 2.

A second benefit of the smaller main circuit dimensions is a lower inductance. This low inductance reduces the snubber capacitance by 40%, enabling new-model inverters to deliver the same 6,000A switching capacity with a lower loss. Use of IGBTs in a snubber energy regenerating circuit reduces these losses still further.

Inverters

Table 2 lists the products in the Mitsubishi IGBT inverter series.

The compact MELVEC-1200NS series employs two-level IGBT inverters to deliver capacities under 36kVA. MELVEC-1200N series inverters, also with two-level IGBT inverters, meet requirements up to 1,200kVA. MELVEC-2000N series three-level IGBT inverters are used for capacities up to 3,600A.

MELVEC-1200N two-level inverters have flexible configuration options allowing them to deliver a range of capacities up to 36kVA. Water cooling and extensive use of ASICs allow the control control board to accommodate up to eight units with a maximum capacity of 75kVa within an 800mm-wide enclosure.

MELVEC-1200NS inverters achieve small dimensions by integrating the main circuit and gate drive circuit on the same printed wiring board and by using a specially designed controller board. Up to twelve inverter units with a maximum capacity of 18kVA can be accommodated in a 600mm-wide enclosure.

For larger capacity IGBT inverter applications, equipment is supplied in one-panel units with peripheral control circuits that are individually replaceable.

Optimized component layout in MELVEC-2000N inverters has made it possible to reduce

Table 1 Inverters Specifications

Parameter	2-level IGBT	3-level IGBT	3-level GTO thyristor
Input voltage	300/600V	1,220V	3,300V
Output voltage	210/420V	840V	3,300V
Max. output frequency	90Hz	60Hz	60Hz
Speed control accuracy	0.01%	0.01%	0.01%
Current control response	500 rad/s	500 rad/s	600 rad/s
Speed control response	60 rad/s	60 rad/s	60 rad/s
Field down control range	1:5	1:5	1:5
Max. torque ripple	1%	0.5%	0.5%
Cooling medium	Air	Air	Water

Table 2 IGBT Inverter Panel Construction

<table>
<tr><td colspan="6">MELVEC-1200NS</td></tr>
<tr><td>Capacity</td><td colspan="2">Up to 18kVA</td><td colspan="3">36kVA</td></tr>
<tr><td>Panel outline (WxDxH)</td><td colspan="2">600 x 650 x 2,300mm</td><td colspan="3">600 x 650 x 2,300mm</td></tr>
<tr><td>Configuration</td><td colspan="2">12 units/panel</td><td colspan="3">6 units/panel</td></tr>
<tr><td colspan="6">MELVEC-1200N</td></tr>
<tr><td>Capacity</td><td>Up to 75kVA</td><td>150kVA</td><td>300kVA</td><td>600kVA</td><td>1,200kVA</td></tr>
<tr><td>Panel outline (WxDxH)</td><td colspan="4">800 x 650 x 2,300mm</td><td>1,600 x 650 x 2,300mm</td></tr>
<tr><td>Configuration</td><td>8 units/panel</td><td>4 units/panel</td><td>2 units/panel</td><td>1 panel</td><td>2 panels</td></tr>
<tr><td colspan="6">MELVEC-2000N</td></tr>
<tr><td>Capacity</td><td colspan="2">Up to 1,800kVa</td><td colspan="3">Up to 3,600kVA</td></tr>
<tr><td>Panel outline (WxDxH)</td><td colspan="2">1,200 x 1,000 x 2,300mm</td><td colspan="3">2,400 x 1,000 x 2,300mm</td></tr>
<tr><td>Configuration</td><td colspan="2">1 panel</td><td colspan="3">2 panels</td></tr>
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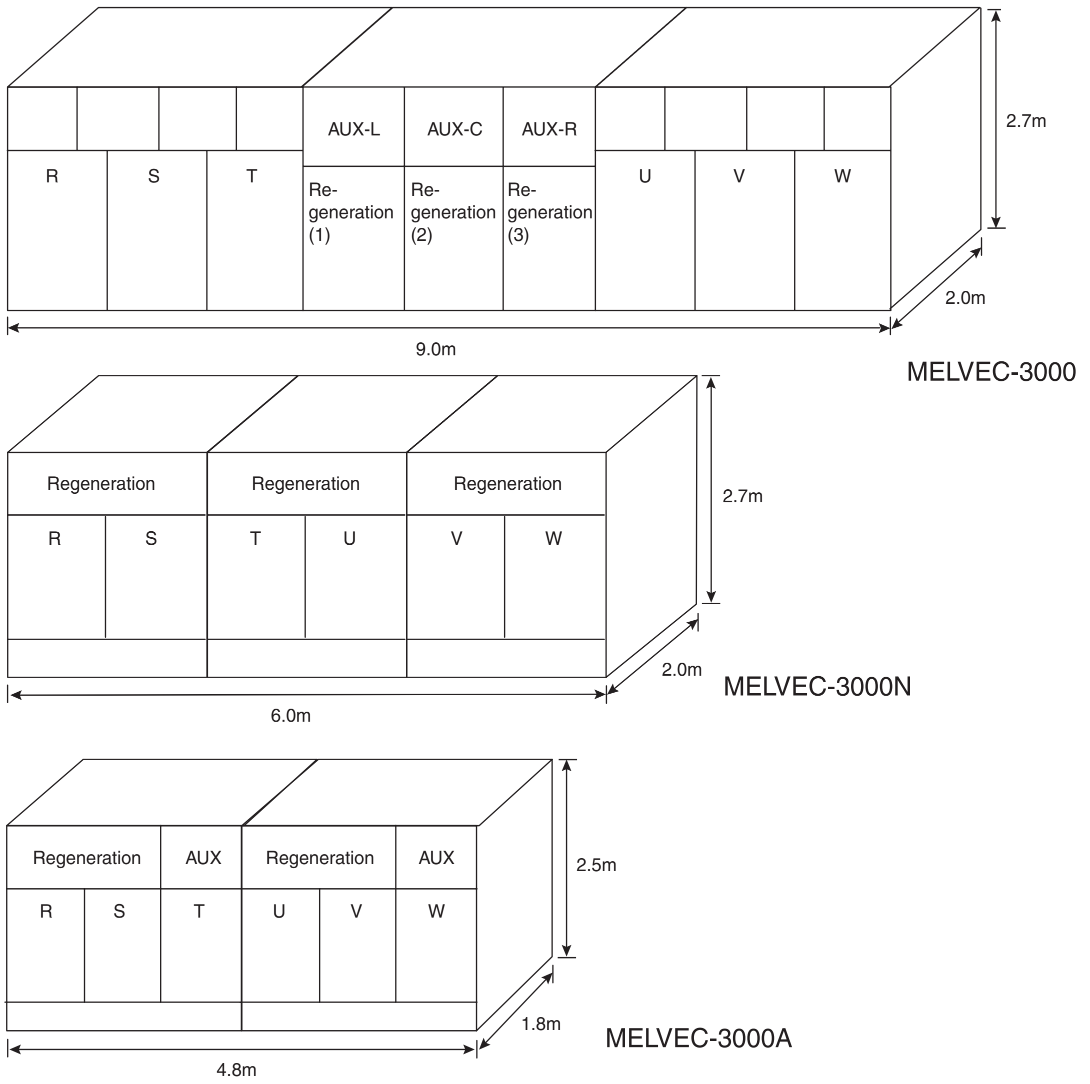


Product	External dimensions H x W x D (m)	Weight (kg)
MELVEC-3000	9.0 x 2.7 x 2.0	28,000
MELVEC-3000N	6.0 x 2.7 x 2.0	16,500
MELVEC-3000A	4.8 x 2.5 x 1.8	12,100

Fig. 2 MELVEC-3000 series panel dimensions.

enclosure external dimensions, decreasing the floor space to 38%—less than half that of earliest models. An original three-level pulse-wave modulation scheme reduces torque ripple.

Mitsubishi Electric has a strong record delivering compact efficient solid-state variable-speed AC drive systems using original voltage-source inverter technology. In future we expect to see continued reductions in equipment dimensions alongside improvements in efficiency, drive capacity and reliability. ❑

Inverter Control for Electric Trains Based on High-Voltage Intelligent Power Modules

*by Takeshi Tanaka and Yuuji Ooyama**

Mitsubishi Electric has developed compact, lightweight two-level inverters for rail applications based on a new generation of high-voltage intelligent power modules (HVIPMs) with internal drive circuits and protective functions.

Drive systems for electric trains are being developed for higher speeds, better energy efficiency, improved passenger comfort and reduced maintenance. Key to achieving these goals is use of insulated-gate bipolar transistors (IGBTs) that offer fast switching, low loss, and a low-power voltage-driven control circuits. IGBT based inverters offer smaller dimensions and weight, higher efficiency, faster control and lower noise. Mitsubishi Electric is deploying still smaller, lighter and more reliable inverters using next-generation high-voltage intelligent power modules (HVIPMs) consisting of IGBTs with integrated gate drive and protection circuits. This article introduces an inverter for electric train applications based on 3.3kV HVIPMs.

Two-Level VVVF Inverter for Traction Motor Drive

Mitsubishi Electric has developed a prototype inverter for future electric trains aiming at reduced size and weight, greater reliability, reduced maintenance and lower environment impact. Fig. 1 illustrates the main technical challenges and their solutions.One train has two bogies, each withe two motors. The diamond represents the pantograph. Table 1 lists basic specifications.

The power devices are 3.3kV 1.2kA HVIPMs. Main circuit inductance is reduced by using an ultralow-inductance oil-filled filter capacitor and a low-inductance laminated busbar in a snubberless design. The reduced component count contributes to higher reliability and to smaller, lighter equipment.

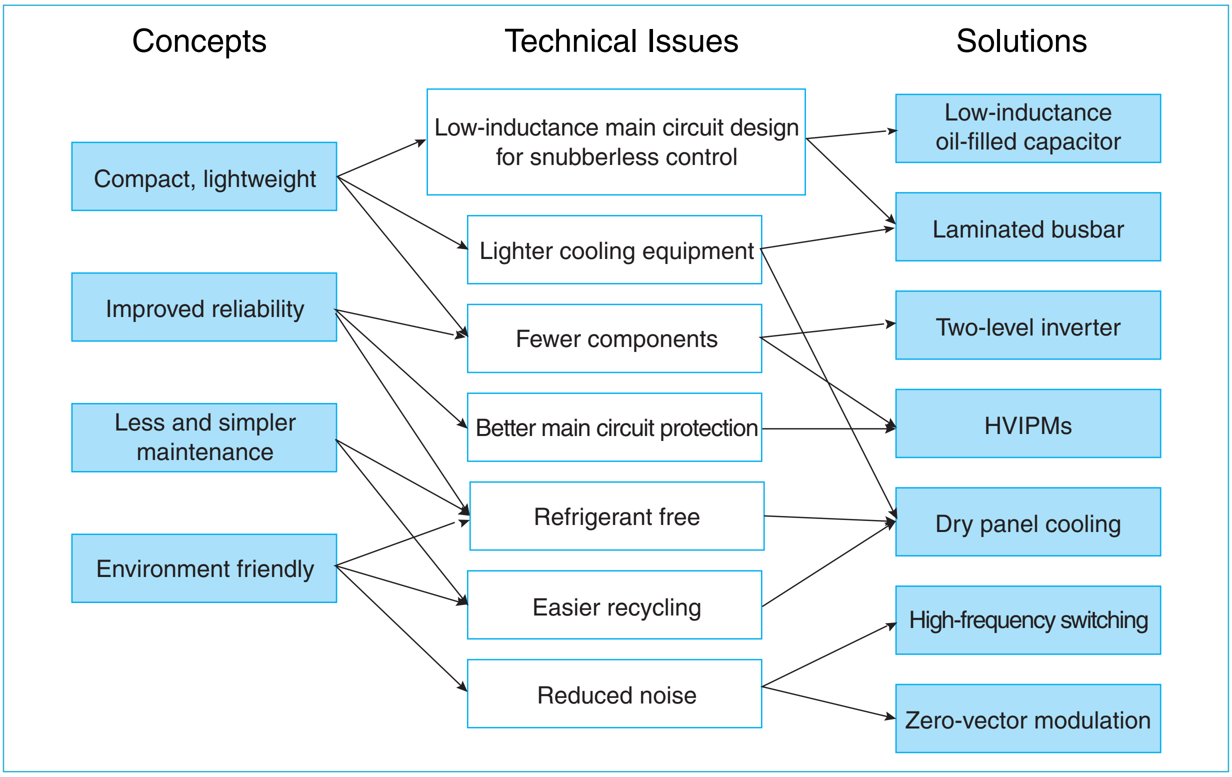


Fig. 1 Concept, technical issues and solutions.

**Takeshi Tanaka is with Transmission & Distribution, Transportation Systems Center, and Yuuji Ooyama is with Energy & Industrial Systems Center.*

Table 1 Inverter Specifications

Power supply	1,500VDC
Control capacity	1,640kW
Configuration	Four 410kW power units each driving a pair of 205kW motors
Main circuit	2-level inverter
Power device	3.3kV, 1.2kA IPMs in a 6-arm 1S1P configuration (one series, one parallel)
Cooling	Air-cooling using winds generated by train velocity
Control system	Variable-voltage variable-frequency control; rapid-response torque control using vector control; noise reduction using zero-vector control
Output frequency	0~200Hz (asynchronous overmodulated range one-pulse mode)
Output voltage range	0~1,400VAC

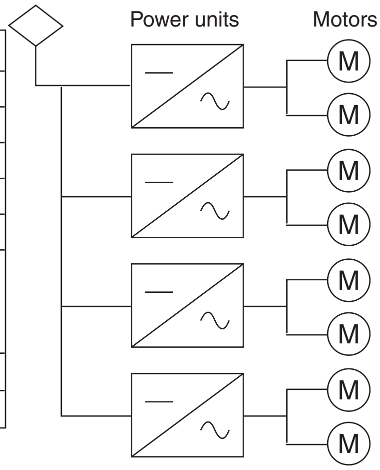


Fig. 2 shows the appearance of an HVIPM. In addition to its IGBT power device, the module contains an integrated gate-drive circuit along with circuitry for detecting and preventing damage from overcurrent, excessive temperature and insufficient gate-drive voltage conditions.

Low-Noise Design

Noise is an important environmental consideration in the design of railway inverter equipment. Mitsubishi Electric has introduced a high carrier frequency and zero-vector modulation to hold the noise level of the new two-level inverter equipment to the same low level the company achieved in its three-level inverters.

The carrier frequency band of 800~1,200Hz reduces both noise and loss, while the zero-vector modulation scheme avoids exciting the mechanical resonance frequencies of the bogie and car body.

Zero-vector modulation distributes characteristic noise frequencies by varying the frequency components of the current over time while preventing voltages from developing across any pairs of the three phases over the entire cycle with upper and lower arms energized. Spectral analysis of the motor current in Fig. 3 shows the distribution of frequencies using this approach. A 65dBA noise level was measured 1.5m above the bogie while powering at 30km/h, comparable to the noise performance of three-level inverters. Further noise reductions are expected.

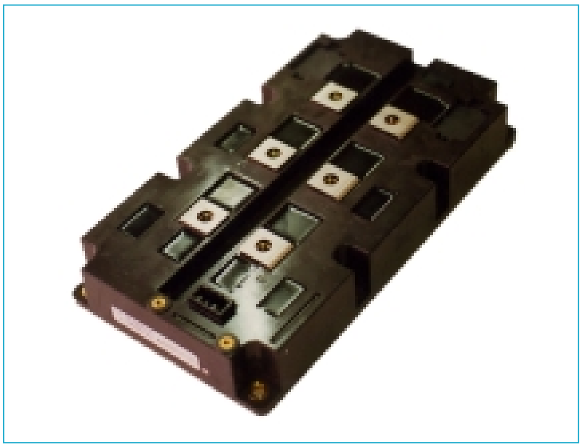
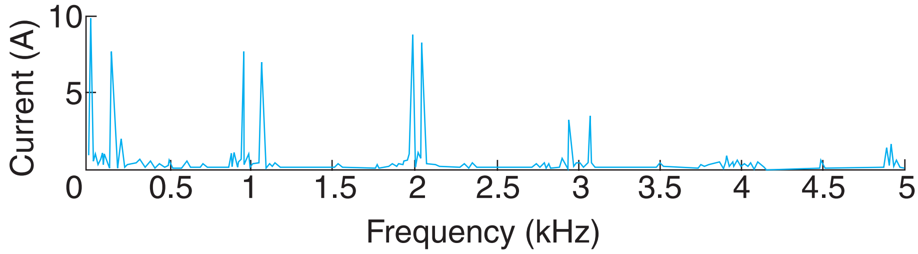


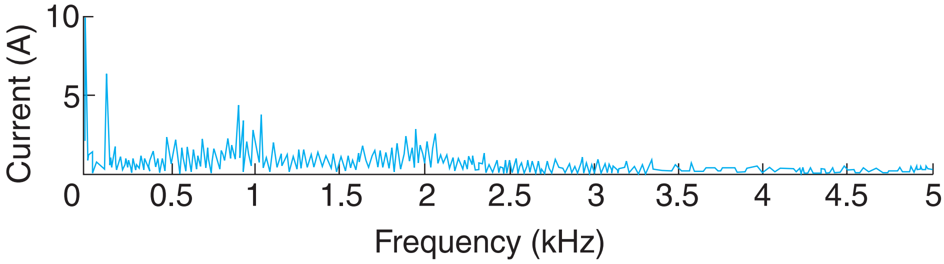
Fig. 2 HVIPM.

Air Cooling System

The new inverter uses winds generated by train travel to cool the fins of its aluminum heat sinks. It is the first domestically produced refrigerant-free inverter for this application. Eliminating refrigerants lowers potential environmental impact and reduces size and weight of the inverter and power unit. Compared with our previous GTO thyristor-based inverter equipment,



a) Without zero-vector modulation



b) With zero-vector modulation

Fig. 3 Frequency analysis of main motor current.

the new inverter enclosure has 64% of the volume and half the weight, while the power unit occupies 47% of the volume with 43% of the weight. Fig. 4a shows a side view of the filter capacitor of the inverter power unit and Fig. 4b a similar view of its heat sink.

a) Side view of filter capacitor

b) Side view of head sink

Fig. 4 Inverter power unit.

Auxiliary Power Supply

Mitsubishi Electric test manufactured a prototype 180kVA auxiliary power supply based on a two-level inverter using 3.3kV 400A IPMs. The snubberless main circuit with integrated protective functions and low-inductance busbars achieves size and weight reductions and reliability improvement over previous equipment. Each module package houses two IPMs, one for each polarity. Three modules are used to control three phases, contrasting the 18 separate devices—12 IGBTs and six clamp diodes—previously required.

Fig. 5 shows this auxiliary power supply. Cooling of the HVIPMs was accomplished using pure water heat pipe cooling that reduces equipment size and weight. The IPMs are mounted in front of the heat pipes for easy accessibility.

Inductance was reduced by making the busbars short (accomplished by positioning the filter capacitors below the IPMs) and by using copper laminate busbars with two layers for each polarity. Overall component count has been reduced from 170 to about 80. Volume is 20% less than previous equipment; weight is 10% lower.

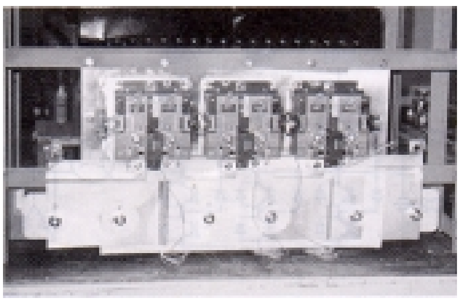


Fig. 5 Auxiliary power unit.

These improvements in power devices and smaller, more efficient control equipment will contribute to the next generation of electric trains.❏

Energy-Saving High-Voltage Inverter MELTRAC-F500HV Series

*by Naohide Tsuchimoto and Shoji Isoda**

A multiphase input transformer feeding single-phase series-connected IGBT inverters enables this equipment to achieve 98% conversion efficiency and 95% power factor, sufficient to satisfy regulatory guidelines for harmonic energy generation without external components. The series-connected PWM multiplex control system suppresses power surges, permitting application to existing motor systems.

Table 1 Specifications of MELTRAC F500HV Series Inverters

3,000/3,300V Inverters		
Capacity (kVA)	Current (A)	Motor capacity (kW)
500/550	97	375/400
750/825	145	550/600
1,100/1,200	212	825/900
1,600/1,800	315	1,200/1,350
2,250/2,500	438	1,675/1,875
6,000/6,600V Inverters		
Capacity (kVA)	Current (A)	Motor capacity (kW)
500/550	49	375/400
750/825	73	550/600
1,000/1,100	97	750/800
1,500/1,650	145	1,100/1,200
2,200/2,400	212	1,650/1,800
3,200/3,600	315	2,400/2,700
4,500/5,000	438	3,350/3,750

Input transformer	Dry 18/36 phase
Converter	Three-phase full-wave diode rectifier
Inverter	Single-phase full-bridge 3/6 series connected
Switching devices	1,700V IGBTs
Control system	7/13 level multiplex PWM
Output voltage	3,000/3,300/6,000/6,600V
Output frequency	0.5~120Hz
Input voltage	3,000/3,300/6,000/6,600V +/-10%
Input frequency	50/60Hz +/-5%
Overload capacity	120% of rated output for 60s (Option: 150% for 60s)
Efficiency	Approx. 98%
Power factor	95%
Cooling	Forced air

Table 1 lists the specifications. Twelve models are available with capacities of 500~2,500kVA at 3kV and 500~5,000kVA for 6kV equipment. A naturally air-cooled input transformer and three-phase diode converter feed single-phase 3/6 serial-connected high-voltage multiplex inverters that employ 7 or 13 level PWM control. The inverter is implemented by 1,700V IGBTs with 150 ~300A capacities. A variable-frequency control system with newly developed 3/6 serial connected multiplex PWM control minimizes switching surges. The equipment tolerates overloads to 120% of rated capacity for 60s, and can optionally be configured to withstand 150% capacity for 60s. Conversion efficiency is about 98%, dropping to 95% if an I/O transformer is used. Power factor is 95%, eliminating requirement for an output capacitor for power factor improvement. Use of an 18/36 phase input transformer meets regulatory guidelines for harmonic emissions without external filter. Open-standard network capabilities are provided to support various connectivity options while a variety of maintenance tools are provided to facilitate equipment setup and maintenance.

Fig. 1 shows the circuit configuration of Model F533HV for 3.3kV operation. The input transformer is an naturally air-cooled type that is accommodated in the input panel. A phase shift

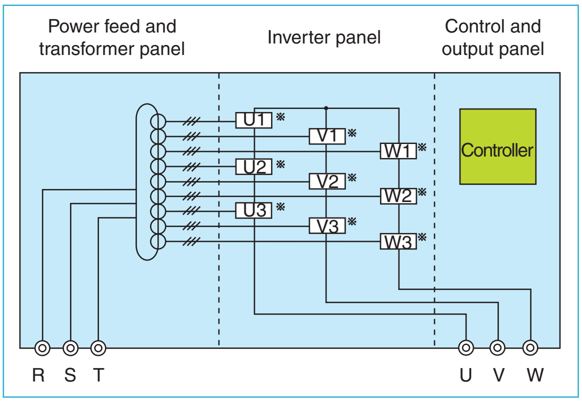


Fig. 1 Circuit configuration.

*Naohide Tsuchimoto and Shoji Isoda are with Energy & Industrial Systems Center.

built into the secondary windings reduces the level of harmonic current components returned to the power supply. Each of the blocks U1, U2, U3, V1, V2, V3, W1, W2, W3 consists of the single-phase inverter unit shown in Fig. 2.

Each phase employs three single-phase inverters with a three-phase diode converter connected in series. A newly developed serial connected multiple PWM control system prevents simultaneous switching of the single-phase inverters, reducing switching transients, which facilitates applications with existing motor equipment. The control panel is similar to the company's FREQROL A500L/F500L series controller, sharing parts and design for high reliability.

Fig. 3 shows the output voltage and current waveforms. Fig. 4 shows the inverter configuration. Three series-connected IGBTs for each phase provide a 1,905V rated capacity per phase, yielding a rated phase-to-phase voltage output of 3,300V. The series connected multiplex configuration provides an almost perfect sinewave current output.

Fig. 5 shows the conversion efficiency. The output transformerless design achieves 98% conversion efficiency including losses of the input transformer, a 3% improvement over previous designs where an output transformer was used.

Fig. 6 shows the input voltage and input current waveforms. An 18-phase input transformer that minimizes waveform distortion combined with the diode converter achieves 95% power factor, eliminating the requirement for an output capacitor to improve power factor. Table 2 and Fig. 7 compare the harmonic energy introduced by the inverter into the power supply with regulatory guidelines. Phase shifts of -20°, 0° and +20° in the 18-phase input transformer secondaries satisfy regulatory guidelines for harmonic

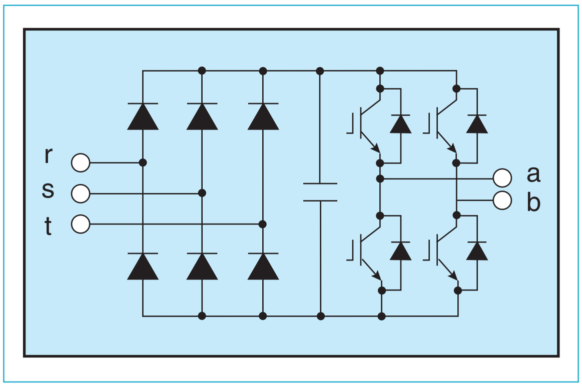


Fig. 2 Single phase inverter unit.

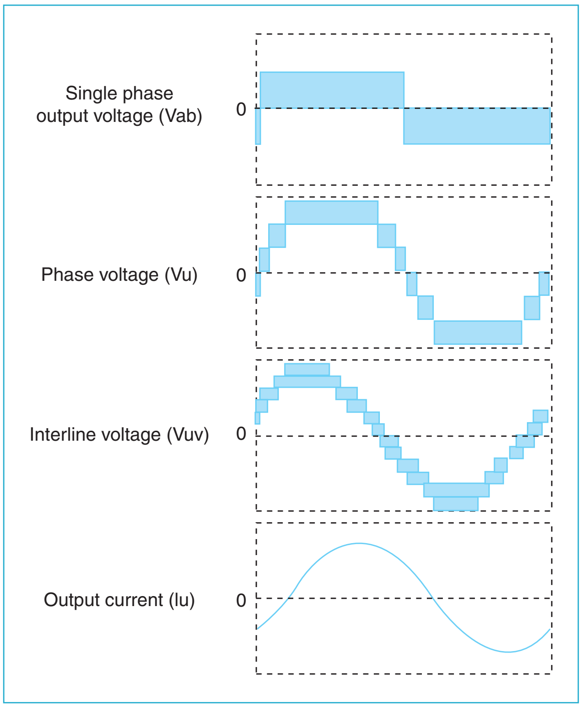


Fig. 3 Output voltage/current waveform.

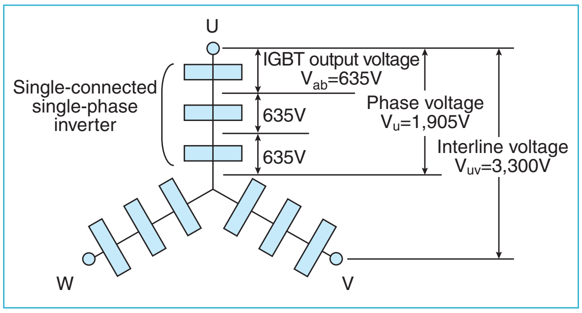


Fig. 4 Inverter stacking configuration.

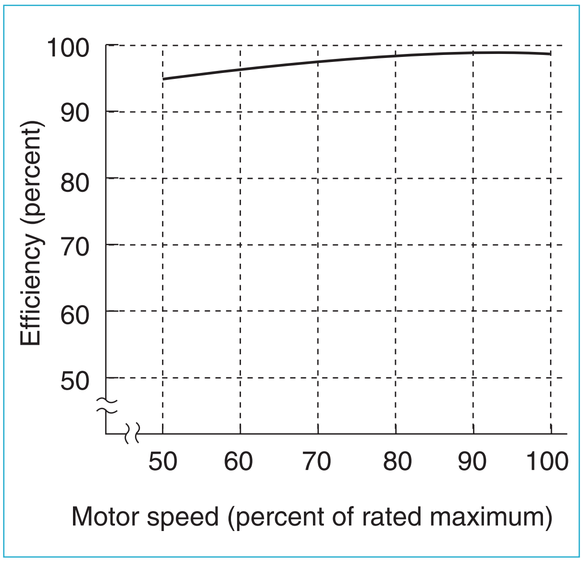


Fig. 5 Inverter efficiency with second-order torque load. (Includes input transformer losses.)

Table 2 Harmonic Current in Power Feed (Percent)

Order	5th	7th	11th	13th	17th	19th	23rd	Higher
Regulatory guidelines 6.6kV power feed	4.00	2.80	1.80	1.50	1.10	1.00	0.87	0.80
22kV power feed and above	6.70	4.80	3.10	2.60	1.90	1.80	1.50	1.40
MELTRAC PMT-F500HV (calculated)	2.00	1.40	0.11	0.09	1.10	0.86	0.05	0.29

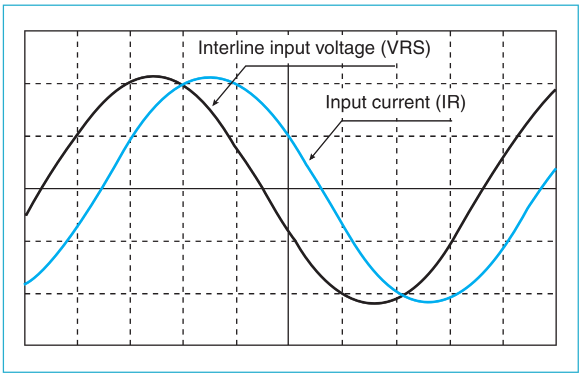


Fig. 6 Input voltage and current waveforms.

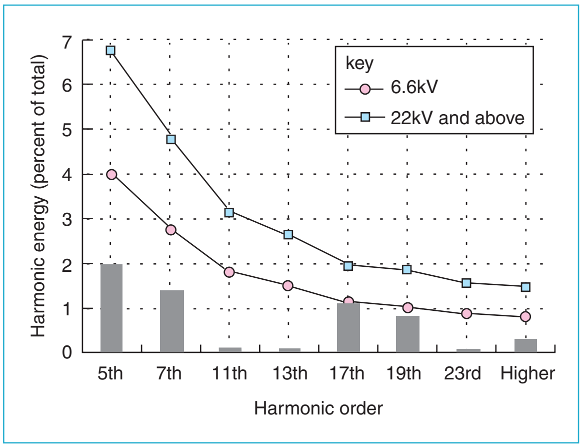


Fig. 7 Regulatory guidelines for harmonic current in power feed.

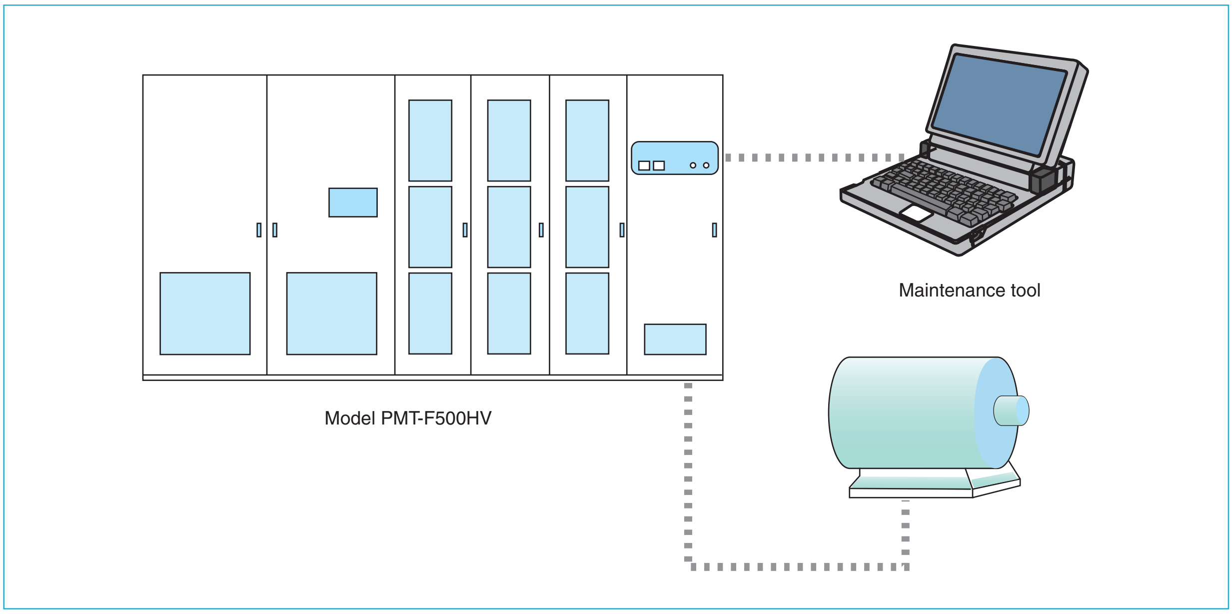


Fig. 8 Maintenance options.

emissions without filter capacitors. A network interface card and maintenance tools illustrated in Fig. 8 are available to simplify equipment setup and maintenance.

A 3% efficiency improvement with low harmonic emissions gives MELTRAC F500HV series inverters a substantial performance improvement over previous high-voltage inverter equipment. ❑

Elevator Drive Control Systems

*by Shigeki Yamakawa and Hiroshi Gokan**

Mitsubishi Electric has developed a new elevator-control ASIC that is more highly integrated with better control performance than the company's first elevator control LSIs released in 1995. The company's first car control system employed two microprocessors, one for sequencing and speed control, the other to generate PWM current control signals for the converter and inverter.

All major functional blocks—the elevator current-control processor, PWM generator and the 8-bit speed feedback processor—have been integrated into a monolithic device, reducing the size and complexity of the peripheral circuits. Better arithmetic processing performance provide improved current-control response, implementing short-circuit protection and controlling torque ripple without the voltage feedback circuit previously used for this purpose.

Engineering the device required development of tools for design and verifying system behavior. Development time was reduced by developing hardware and software concurrently.

Control System

Fig. 1 shows the control system configuration for a high-speed elevator. Fig. 2 shows the functional blocks of the elevator control ASIC, which we call AML for "associated management logic." Most of the logic functions for controlling the elevator and its traction motor are contained in this single device. The few external components include the car control processor (CCP) and ADCs.

The motor control processor (MCP) is an original RISC processor core developed to generate current-control commands for the inverter and converter. The PWM unit generates pulse-width modulated signals corresponding to the MCP current commands. The encoder counting unit (ECU) tallies pulses from encoders and generates phase data for the MCP and speed and position data for the CCP. The CCP is an external 32-bit processor that performs car equipment sequencing and processes user commands to implement the highest level of elevator control. The CCP exchanges data with the MCP via

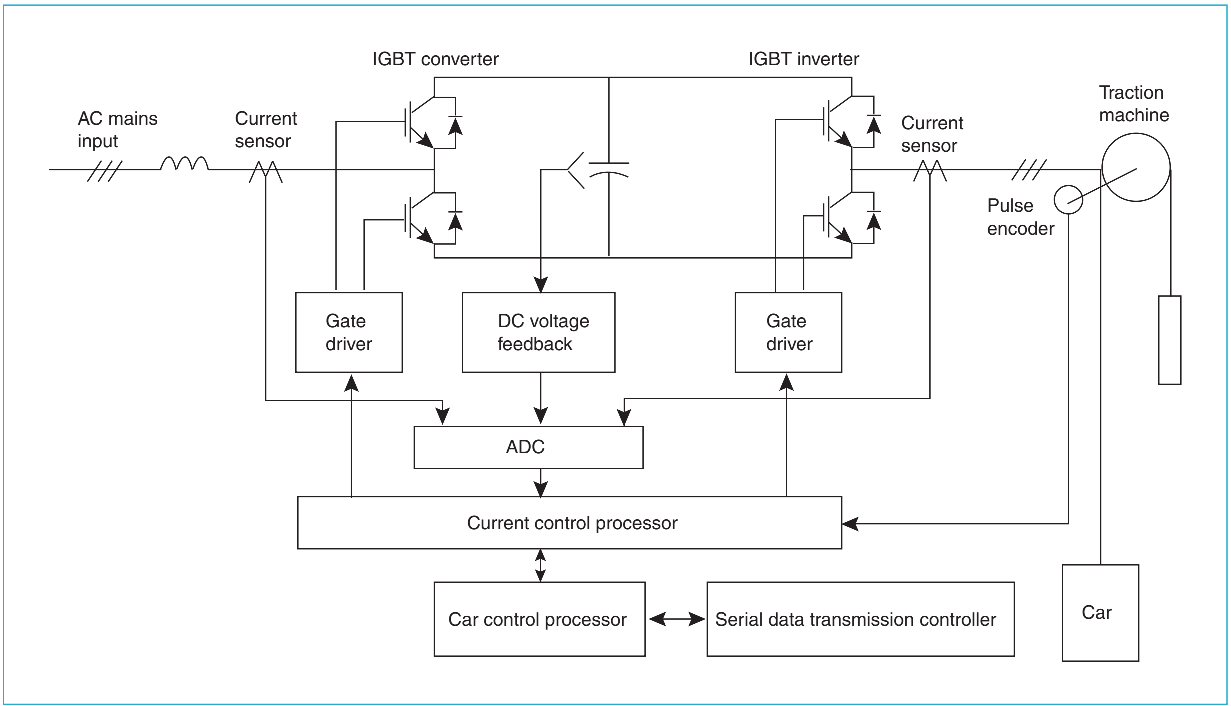


Fig. 1 Configuration of high-speed elevator control system.

**Shigeki Yamakawa is with the Inazawa Works and Hiroshi Gokan is with the Design Systems Engineering Center.*

dual-port memory on the AML chip using bus control logic also contained on the AML chip.

MCP Calculation Performance

The 6μs inverter dead time (Td) in previous systems would result in error in the output-current zero-cross point, requiring addition of a voltage feedback circuit. The faster current calculations of the new MCP permit the current feedback loop to respond more quickly, reducing distortion in the output current waveforms so that motor control is more accurate. Tests on an actual elevator were used to verify that the intended current control response would be fast enough to eliminate these error sources and with them, the need for a voltage feedback circuit. Fig. 3 shows car vibration for various crossover current angular frequencies in a high-speed elevator operating at low speed. The data in Fig. 3a is for a conventional control system with a voltage-feedback circuit to compensate for Td. The system in Fig. 3d shows comparable performance without a compensation circuit for ωc = 5,000 radians/s. This capability was achieved by reducing the time required for the MCP to complete a current calculation cycle to under 50μs.

MCP Data Transfer System

On initialization, the CCP reads the MCP control program from external flash memory and loads it into synchronous SRAM located directly on the AML chip. This allows the software to be easily updated to accommodate increases in processor speed and other improvements. The SRAM's fast access allows one instruction to be executed per clock cycle at speeds up to 40MHz. Following initialization in the normal operating mode, the CCP transfers torque command values to the MCP at 5ms intervals. The MCP uses these commands to calculate corresponding converter and inverter current values at 50us intervals. Independent data registers on both devices allow data transfers despite the different device operating speeds.

MCP Core Configuration

An original RISC core was designed to perform

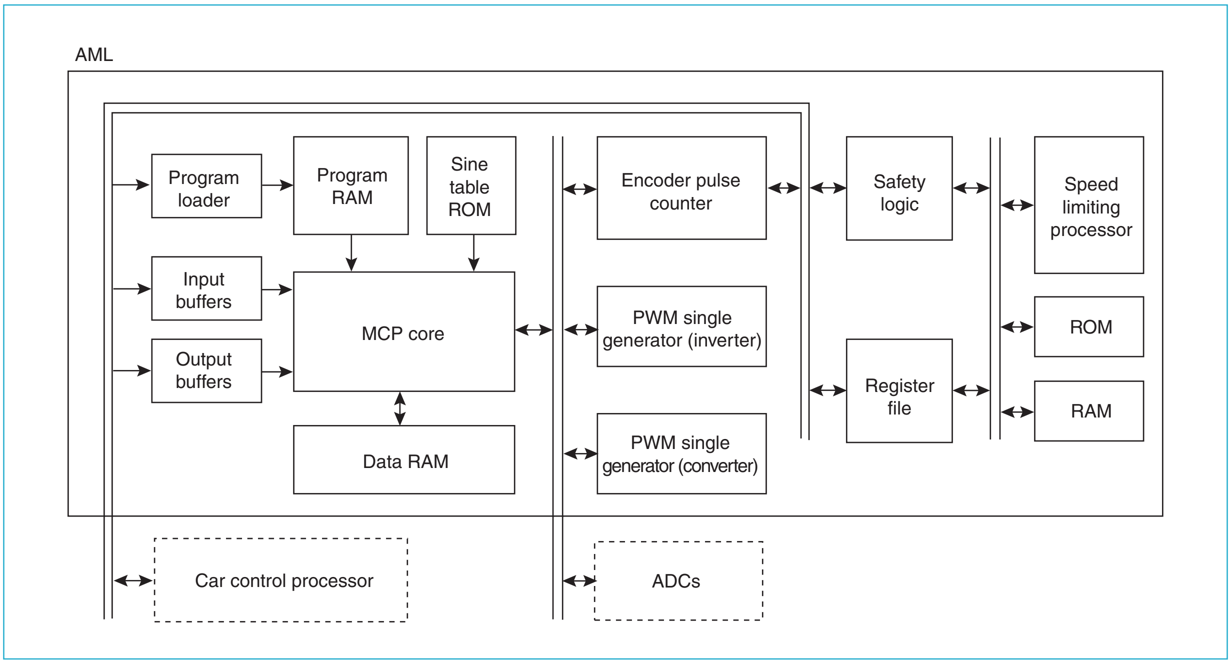


Fig. 2 AML chip configuration.

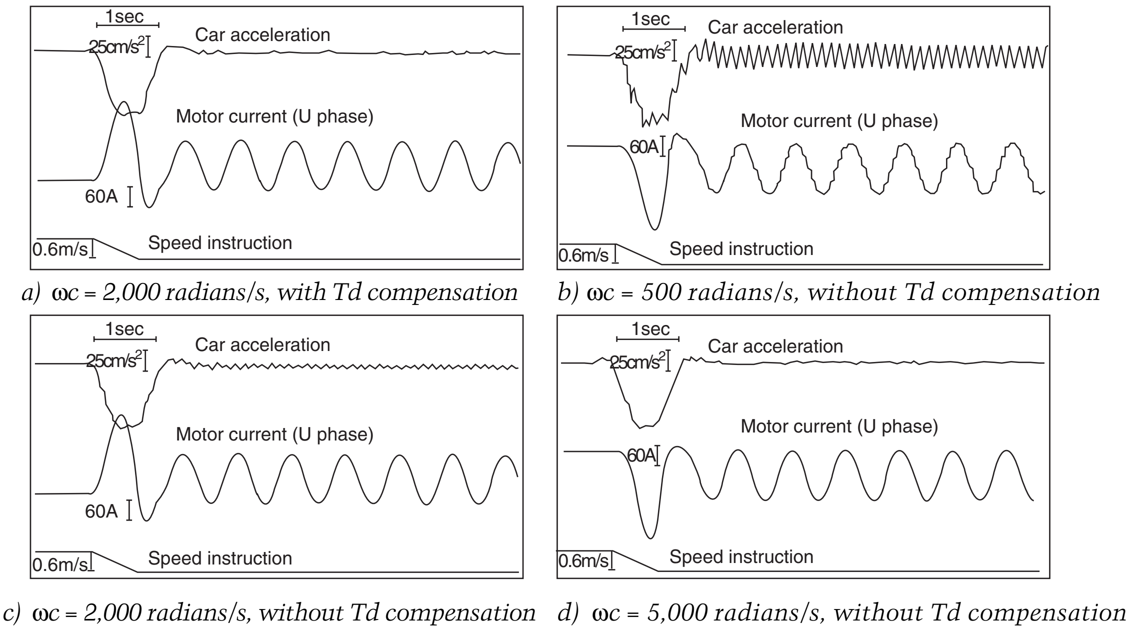


Fig. 3 Relationship between crossover angular frequency wc and car acceleration for Td = 6μs and a balanced load.

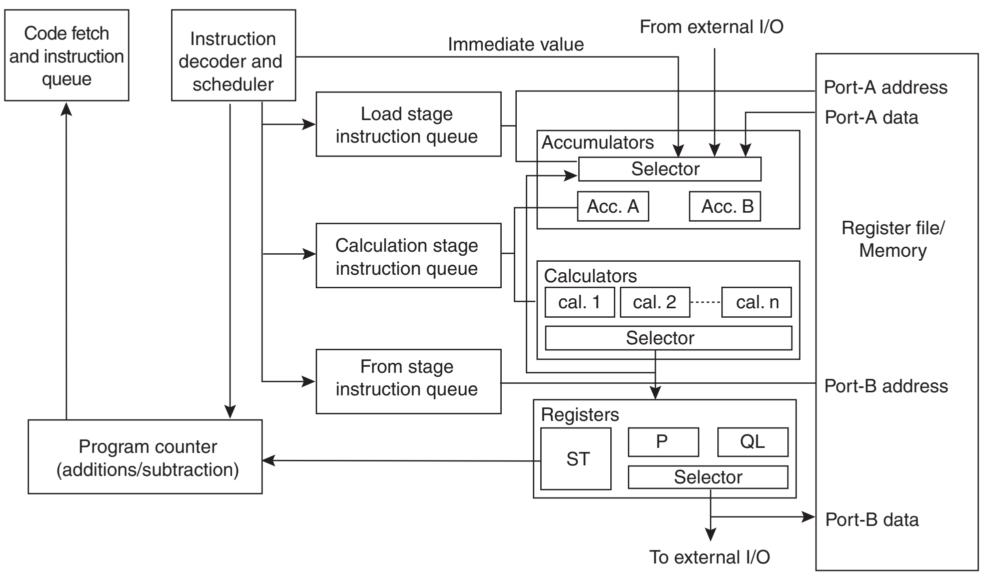


Fig. 4 Configuration of MCP core.

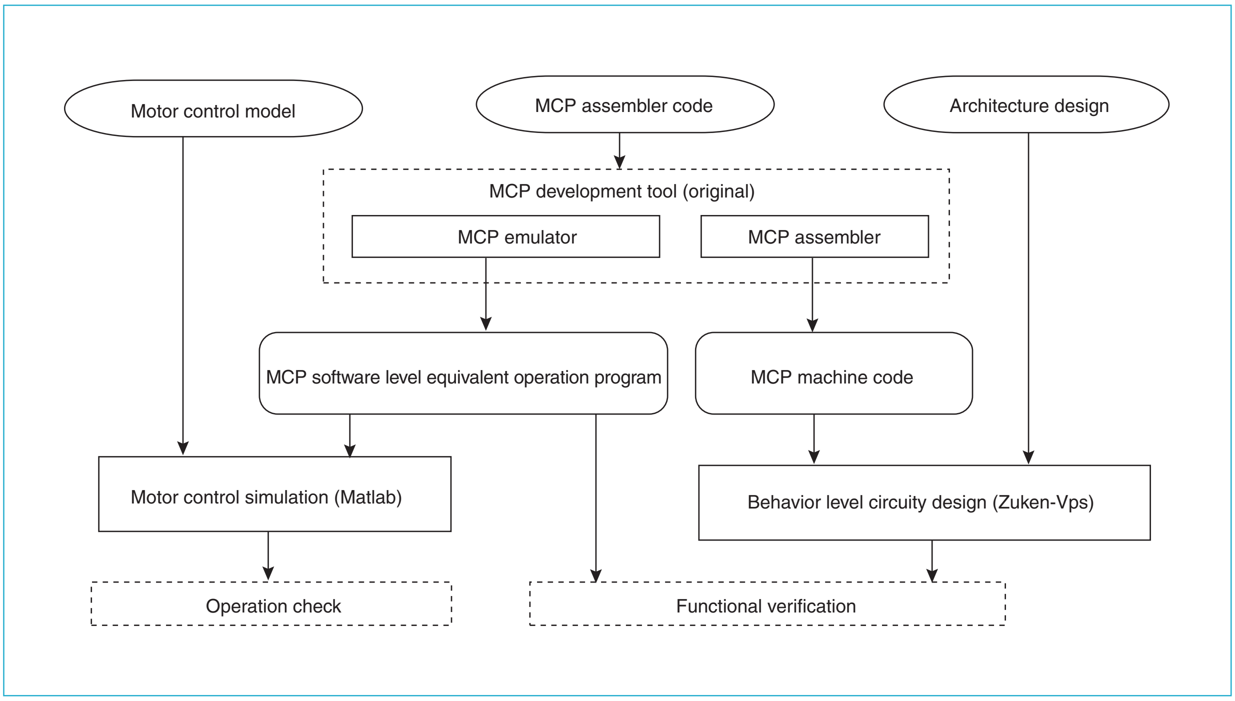


Fig. 5 MCP debugging flow.

current control calculations while permitting integration on the AML chip. We analyzed the motor control software instructions and adopted a 16-bit fixed-length word instruction set with 48 instructions. Fig. 4 shows the core configuration. Arithmetic, specifically 32-bit addition and 16-bit multiplication, is performed by a 32-bit fixed-point processor. A three-stage load-calculate-store pipeline with parallel execution permits one instruction to be executed per clock cycle. An original assembler was written to support operating software development.

Top-Down Design Methodology

Fig. 5 shows the flow of the process used to design and verify the AML chip's functionality. We used the best available development tools to design and verify each functional block. Designs for the high-level circuits of the MCP core were entered and their functions simulated using the Zuken-Vps virtual prototyping tool. Design entry for the rest of the circuit blocks was conducted using Verilog's Hardware Description Language (HDL) with functional simulation performed using Verilog-XL from Cadence Design Systems. Logic synthesis was conducted using Design Compiler from Synopsys Inc. Static timing analysis tools supplied by the ASIC vendor were used to reduce the time required for delay simulations. Scan path design automatic test pattern generation was used to support a fully concurrent design process.

AML Chip Debugging

Fig. 6 shows the debugging process flow. We used a virtual debugging method in which the MCP operation is expressed in C and linked with the Matlab control system analysis tool from The Mathworks, Inc. to analyze the converter and inverter operation. Meanwhile, machine code compiled using the MCP assembler is loaded onto the MCP logic circuits designed on Zuken-Vps and operation is simulated. The register contents of the two simulations are com-

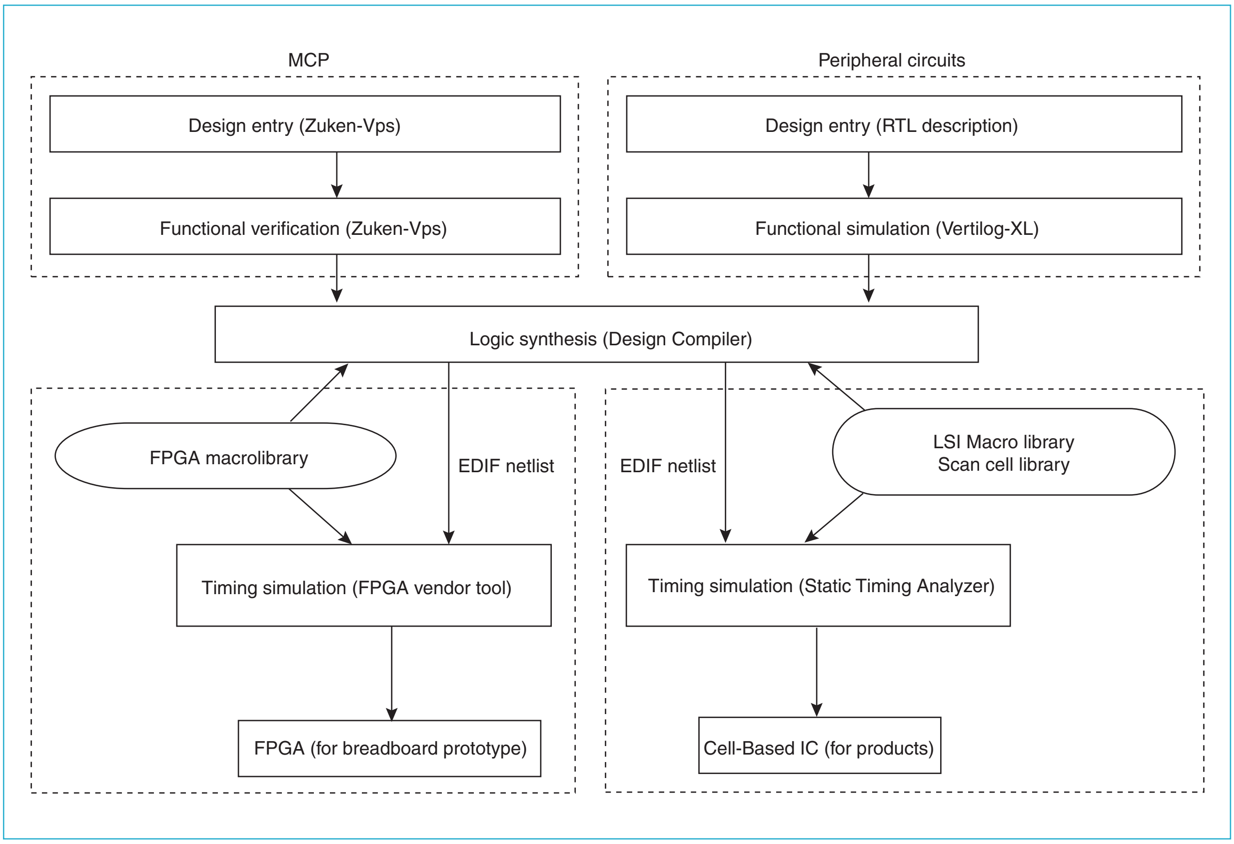


Fig. 6 AML design flow.

pared with identical register contents taken as an acceptance criteria.

Breadboard Qualification

Prior to fabricating the AML chip, we constructed an equivalent logic prototype controller using six field-programmable gate arrays (FPGAs) and one masked gate array device. Hardware and software debugging was performed using this controller to operate an actual elevator in a test building.

The AML elevator control ASIC cuts the size and cost of elevator control units. Development of the 250,000 gate device was completed in ten months, and methods to support larger device scales were established. ❑

Compact High-Efficiency UPS Systems

*by Yuushin Yamamoto and Kenji Honjo**

Mitsubishi Electric has developed UPS systems that use an IGBT based pulse-width modulation (PWM) converter and inverter and digital control to achieve compact dimensions, high efficiency, sophisticated functionality and high reliability. Model 2033C is rated at 208V and 7.5~20kVA capacity with internal batteries. Model 2233B is rated at 380, 400 or 415V and 7.5~30kVA capacity and applies external batteries. Both have three-phase four-wire input and output.

Features

The outputs of these UPS systems are suited to computer equipment loads that typically utilize switching power supplies generating large harmonic components. An instantaneous waveform-control system maintains sinusoidal voltage waveforms even under the peak currents with large harmonic components. Output voltage distortion 4% or less under a 100% rectifier load with crest factor 3.

The PWM converter maintains an input power factor very near unity, with input apparent power lower than the output nominal kVA power. High-frequency PWM in the converter suppresses input current harmonic components, achieving a sinusoidal current waveform with less than 3% distortion at 100% load.

The UPS systems are compact to fit in the restricted spaces of offices and computer rooms. Model 2033C with 20kVA capacity, internal batteries and a maintenance bypass functions is housed in single unit occupying 23% of the floor space of equivalent previous products. Table 1 lists the specifications of both types of systems.

Table 1 Specifications

Item		Specifications													Notes
UPS type		2033C				2233B									
Rated output kVA		7.5	10	15	20	7.5	10	15	20	30	40	50	60	80	
Rated output kW		6	8	12	16	6	8	12	16	24	32	40	48	64	
AC input	Configuration	3-phase, 4-wire													
	Voltage	208V –25~+15%				380/400/415V –55~+15%									
	Frequency	60Hz ±5%				50Hz ±5%									
Battery	Type	VRLA													
	Nominal voltage	360V				576V									
	Ride through	8min (internal)	5min (internal)	11min (internal)	7min (internal)	External battery									At 25℃, 100% load.
AC output	Configuration	3-phase, 4-wire													
	Voltage	208V				380/400/415V									
	Voltage regulation	±1%				±1%									
	Frequency	60Hz				50Hz									
	Frequency accuracy	±0.01%				±0.01%									In free running mode
	Power factor	0.8 (lagging)													
	Power factor range	0.8~1.0 (lagging)													
	Voltage THD	2% typical (at 100% linear load)													4% typical (at 100% non-linear load)
	Transient voltage fluctuation	±3% or less (at 100% load step) ±1% or less (at loss/return of AC input) ±3% or less (at transfer from bypass to inverter)													
	Transient recovery	16.7ms				20ms									
	Voltage unbalance	±2% or less (at 100% unbalanced load)													
	Inverter overload	150% for one minute													
	Bypass overload	1000% for one cycle													

**Yuushin Yamamoto and Kenji Honjo are with the Energy & Industrial Systems Center*

Configuration

MAIN CIRCUIT. Fig. 1 shows single-line diagrams of the main circuits of both systems.

In Model 2033C, the converter input and bypass are both fed by the same three-phase power supply. Under normal operation, the converter supplies power to the inverter while simultaneously charging the batteries and rendering the input current sinusoidal. The inverter utilizes PWM technology to generate AC voltage output for the load. The AC output voltage is synchronized with the bypass input voltage when the latter is within the specified frequency range. Under overload or inverter failure conditions, the static transfer switch smoothly transits from bypass supply mode.

Model 2233B offers comparable operating characteristics with I/O voltages extending to 380, 400 or 415VAC. The bypass input is separate from the AC input, facilitating alternative system applications such as a standby redundant system, and batteries are external to provide for customer-specified battery applications.

POWER DEVICES. Fourth-generation trench-gate IGBTs (shown in Fig. 2) are used as the power switching devices in both the converter and inverter. These devices feature low drive power with high current and high-speed switching capabilities. High-frequency switching enables greatly enhanced control performace, noise reduction, and miniaturization of the output filter for a more compact UPS..

CONTROL CIRCUIT. The inverter control circuit performs instantaneous waveform control with current minor loop control for each of the three power phases, achieving low-distortion output voltage control and output overcurrent protection. This allows the UPS to be used without excessive concern for load characteristics or load inrush currents. Converter control capabilities include both a soft-start "walk-in" function to manage powering up and a power-demand function that controls the input power within specified limits when recharging batteries. Together, these functions ensure stable, well-matched operation of both the UPS and the generator when a generator is used to supply the UPS input power.

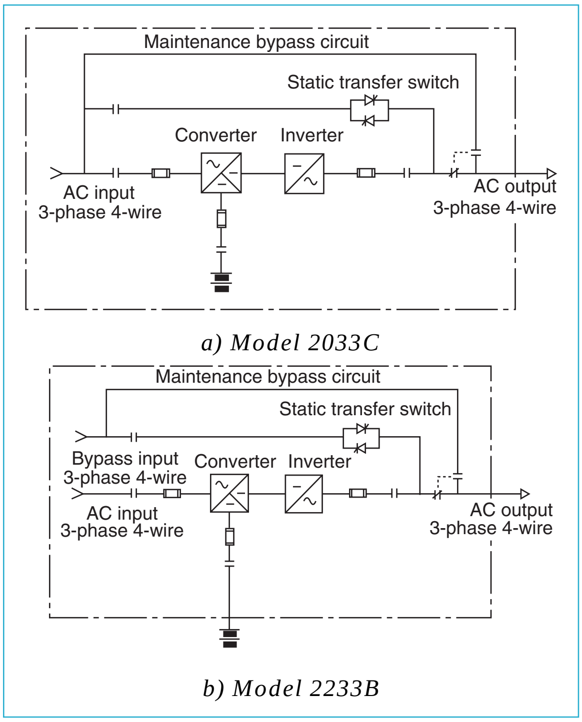


Fig. 1 Main circuit configuration.

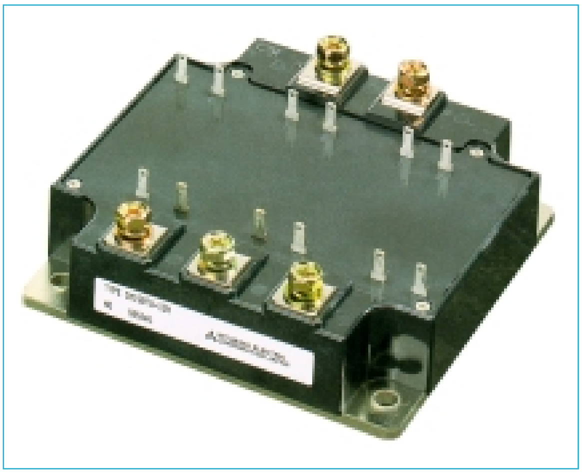
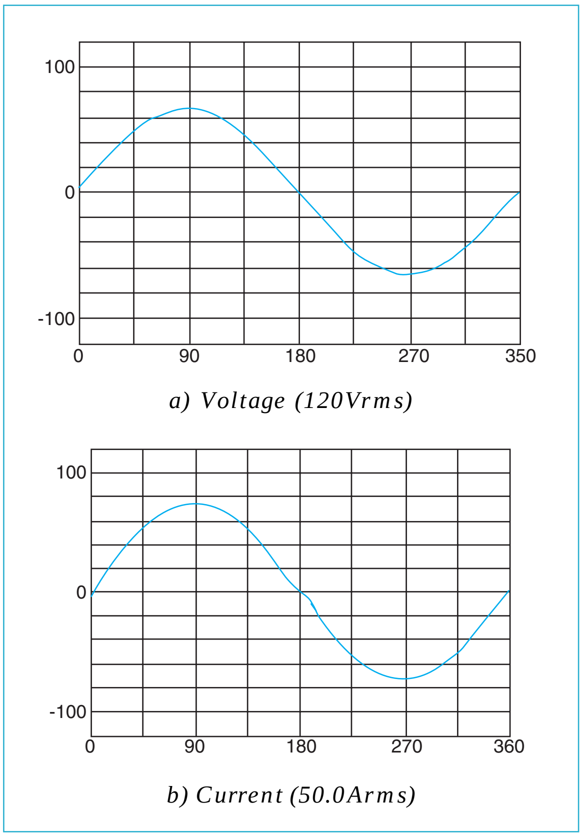


Fig. 2 Fourth-generation IGBT module.

Fig. 3 Appearance of 20kVA Model 2033C.



a) Voltage (120Vrms)

b) Current (50.0Arms)

Fig. 4 AC input waveforms.

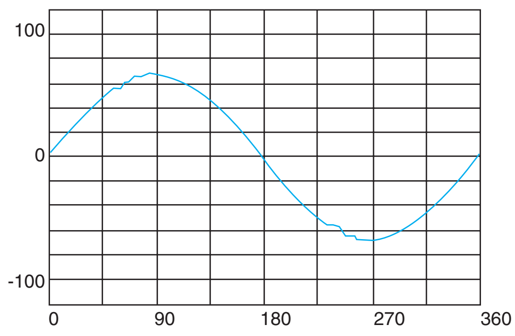
The control circuitry is implemented using DSP and ASIC devices that achieve fine-grained control with high reliability. The UPS includes self-diagnostic functions to monitor battery degradation.

MECHANICAL DESIGN. Fig. 3 shows the appearance of a 20kVA Model 2033C. Table 2 lists dimensions and weight of the two systems. Both are designed for easy installation, operation and maintenance in confined office or computer room spaces with compact single enclosures, built-in bypass circuits for maintenance, simple control and monitor panel, and casters for moving over the floor. The power I/O terminal is located at the front of the cabinet. Maintenance requires only front and top access. Model 2033C allows access from the front for battery maintenance.

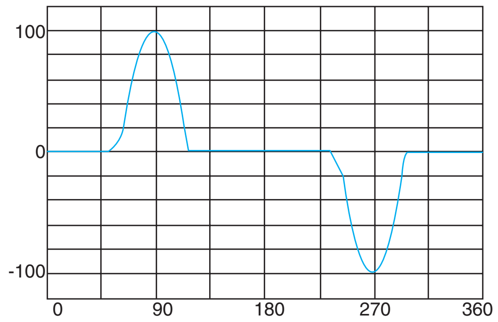
POWER MONITORING. A hardware contact interface and proprietary Diamondlink software allow power monitoring and logging of UPS activity by a workstation or personal computer.

Table 2 Dimensions and weight

Rated output	7.5kVA	10kVA	15kVA	20kVA	30kVA	40kVA	50kVA	60kVA	80kVA
Model 2033C (internal batteries)									
Dimensions(WxDxH)		450 x 800 x 1,100mm							
Weight	255kg	255kg	370kg	370kg	—				
Model 2233B (external batteries)									
Dimensions (WxDxH)		500 x 800 x 1,000mm					800 x 800 x 1,500mm		
Weight	160kg	160kg	175kg	175kg	200kg	460kg	460kg	500kg	550kg



a) Voltage (120Vrms)



b) Current (53.7Arms)

Fig. 5 AC output waveforms for rectifier load.

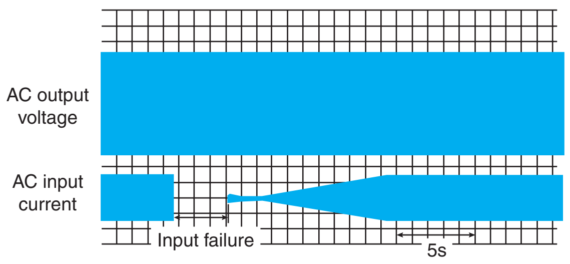


Fig. 6 UPS operation during input power failure.

Operating Characteristics

This section describes equipment test results.

AC INPUT CHARACTERISTICS. Fig. 4 shows AC input voltage and current waveforms for a 20kVA Model 2033C operating at rated load. Input current distortion is 2.2% regardless of load characteristics, well below the specified 3% value. This indicates that the UPS maintains sinusoidal current waveforms, successfully eliminating harmonic current that would otherwise affect the commercial power system. The power factor is a high 0.99, so that the input apparent power is only 18kVA with a rated UPS load of 20kVA/18kW This high input power factor allows a UPS to be introduced between the commercial power supply and target equipment without need to increase power cable or breaker ratings.

AC OUTPUT CHARACTERISTICS. Fig. 5 shows AC output voltage and current waveforms for a 20kVA Model 2033C operating at 100% rectifier load. Instantaneous waveform control holds voltage distortion to 1.7% and maintains stable operation even under loads with large harmonic components such as the switching power supplies of computers and instrumentation.

AC I/O CHARACTERISTICS DURING POWER INTERRUPTIONS AND RECOVERY. Fig. 6 shows voltage and current waveforms during power interruption and recovery. The UPS AC output shows no disturbance when the mains power is interrupted and battery operation is switched in. The UPS absorbs the effects of power outages and attenuates voltage fluctuations, permitting easy integration with a backup generator and ensuring stable operation when the generator is in use.

EFFICIENCY. Use of advanced IGBTs raises efficiency to 89~93%, reducing the power loss or cost for the UPS operation and lowering air conditioning operating cost.

Improving the efficiency and performance of UPS systems has made it simpler to integrate protective functions into mission-critical information systems with battery backup and an emergency generator supplementing the commercial power supply. ❑

A Solid-State Transfer Switch Based on 12kV Thyristors

Mitsubishi Electric has launched solid-state transfer switch (SSTS) thyristor-based switching devices that can respond to undervoltage conditions within one half of a cycle (approximately 0.01s). The SSTS can transfer from preferred source to alternate source during an interruption in time to prevent damage to sensitive electrical equipment such as the large electric motors and inverter control systems used in manufacturing lines, elevators and HVAC systems, as well as computers, communications equipment and lighting systems. Mechanical interrupters and switches generally take several cycles to reestablish a stable power supply—too slow to prevent damage. Fig. 1 shows the configuration and Fig. 2 the control characteristics of these switching devices, illustrating a response sufficiently fast to avoid disturbances to computer equipment. ❑

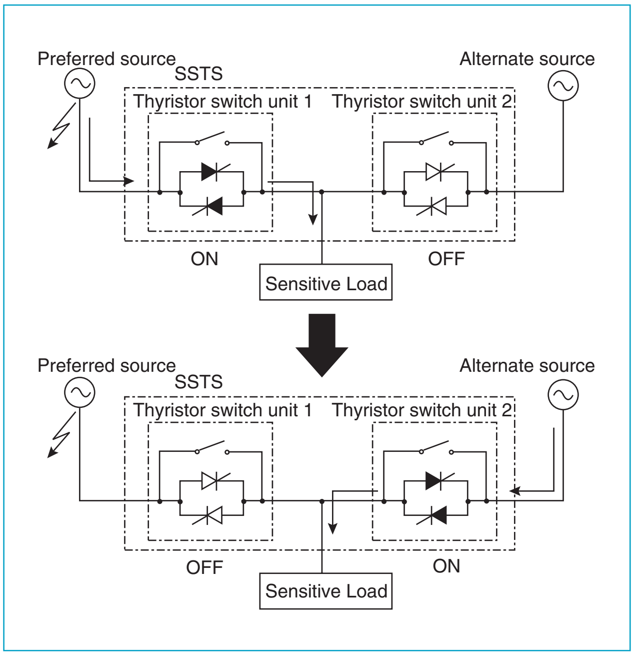


Fig. 1 An SSTS system (single line diagram).

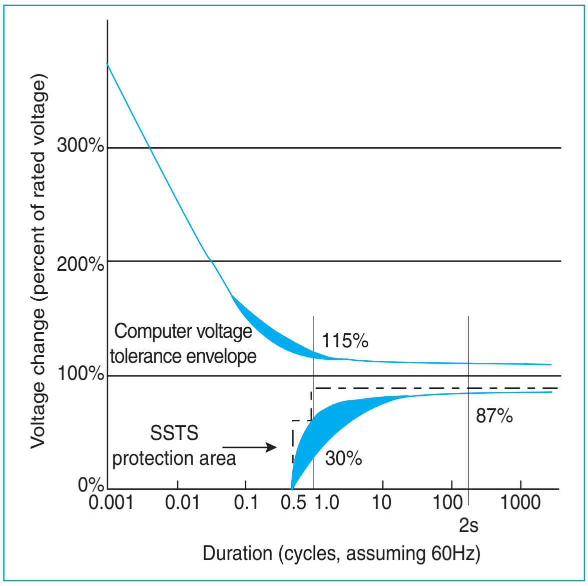


Fig. 2 Control characteristics. [From "Typical Design Goals of Power-Conscious Computer Manufacturers (ANSI/IEEE Std. 446-1987)]

9800A Series High-Capacity UPS

9800A Series UPS with 225kVA capacity

Mitsubishi Electric has developed a series of online three-phase UPS systems with 480 and 600V input/output and capacities from 100kVA ~375kVA. IGBTs are used in the inverter and rectifier/charger with combined advantages of high performance and compact dimensions.

Instantaneous voltage control and the inverter's fast-switching IGBTs reduce output voltage transients and voltage waveform distortion. Output voltage transient response is within ±2% during a 100% load step, while total harmonic distortion (THD) in the output voltage is within 2% with a 100% linear load and 5% with a 100% nonlinear load.

The rectifier/charger uses diode rectifiers and IGBTs that reduce current harmonics while achieving high power factor and low input capacitance. Input current THD is 6% at 100% load, 9% at 50% load.

An LCD monitor with touch-panel input provides a centralized high-level user interface. Standard functions include a mimic flow diagram, voltage, current and power monitoring, and event history management.

The new UPS also reduces the footprint to half that of the previous 480V model.❑

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	Mitsubishi Electronics Manufacturing Singapore Pte. Ltd.	3000, Marsiling Road, Singapore 739108	269-9711
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