

Evolution of Devices Supporting Power Electronics and Expansion of Technologies for Mounting, Circuits, and Application to Products

■ MOCHIKAWA Hiroshi

With the ongoing introduction of renewable energy systems including photovoltaic power generation systems, whose output tends to vary according to the weather conditions, power generation systems with high efficiency over a wide output range are required. Power transmission systems must also offer high efficiency, in order to minimize energy losses while transmitting electricity from widely distributed power systems to distant power-consuming areas. Furthermore, there is a growing need for energy storage systems to balance supply and demand. On the other hand, to avoid wastage of precious energy, it is also important to make greater efforts to enhance energy conservation.

To fulfill these diverse requirements, Toshiba has been continuously engaged in the development of state-of-the-art power electronics technologies for optimal efficiency of electricity operation in each process from electricity generation through to transmission, storage, and consumption, aimed at the construction of smart communities.

Increase in power density

The performance of power electronics equipment is often represented by its power density, which is defined as the output per unit volume of equipment. Power density therefore increases as the volume of equipment is reduced. **Figure 1** shows the trends in power density of power electronics equipment. Since 1970, power density has been doubling every four years. This means that the volume of equipment has been reduced by half every four years for the same amount of output. Power density has been increasing at a rate that approaches the increase in circuit density predicted by Moore's law^{*1}. This trend is expected to continue, driven by changes in the social situation such as the accelerating uptake of renewable power generation, the building

(*1) Observation made by G. Moore in 1965 that the transistor density in a semiconductor integrated circuit doubles every 18 to 24 months

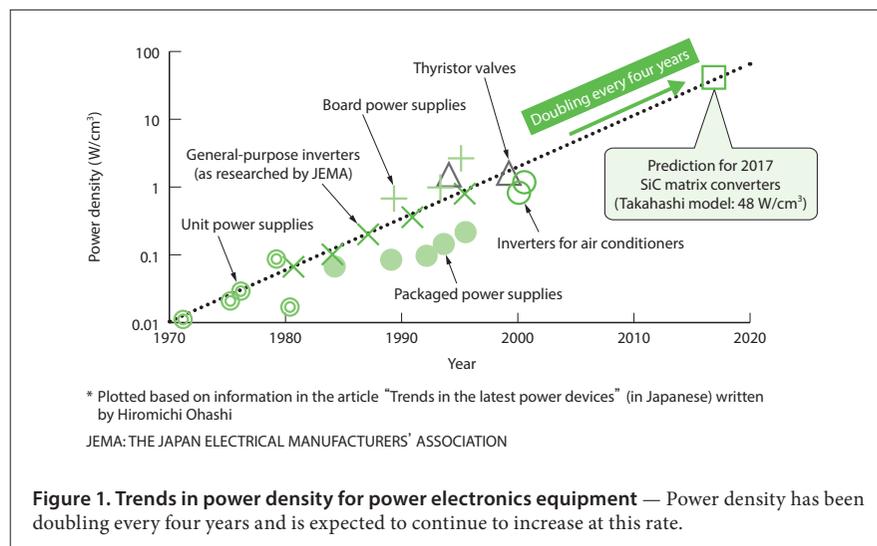


Figure 1. Trends in power density for power electronics equipment — Power density has been doubling every four years and is expected to continue to increase at this rate.

of smart communities, the prevalence of electric vehicles (EVs), and demand for further reduction in carbon dioxide (CO₂) emissions.

Multiple technologies have supported the high growth rate of power density, including a reduction in equipment losses, an improvement in cooling performance, a rise in heat resistance and

an increase in assembly density. Toshiba has been continually developing the technologies necessary to improve the power density of power electronics equipment.

Evolution of power devices

The performance of power devices contributes most to the reduction of

losses of power electronics equipment.

Major technologies we have been working on to improve the performance of power devices are described below.

■ IEGT

At present, many insulated-gate bipolar transistors (IGBTs) are used in power electronics equipment. Toshiba developed a new type of device with a unique structure called an injection-enhanced gate transistor (IEGT) in order to reduce the on-state voltage of IGBTs. IEGTs are now available for practical applications. While gate turn-off thyristors (GTOs) and other power devices have a cylindrical wafer structure, IEGTs consist of a few tens of square IEGT chips housed in a cylindrical casing.

It has been theoretically elucidated that the performance of IEGTs can be further improved by reducing process geometries. There is a possibility that, at above 2 kV, even silicon (Si) devices will exhibit on-resistance lower than silicon carbide (SiC) field-effect transistors (FETs).

■ SJ-MOSFET

In recent years, there has been a significant improvement in the performance of metal-oxide-semiconductor field-effect transistors with a superjunction structure (SJ-MOSFET). The losses of an SJ-MOSFET are primarily attributable to its specific on-resistance. In recent years, the specific on-resistance of the SJ-MOSFET has been reduced at a very rapid rate of 10 % per year. It is expected that the specific on-resistance of a 600-V SJ-MOSFET device will shortly fall below 10 mΩ·cm². This improvement is due to shrinking process geometries, as was previously achieved for semiconductor memory devices. The reduction in specific on-resistance means that the chip area can be reduced without increasing on-resistance. The resulting reduction in chip cost will fuel increased demand for SJ-MOSFET devices. Once the demand begins to increase, power devices might be improved at a faster rate, as reflected

in Moore's law for integrated circuits. In the future, SJ-MOSFET devices will be more widely used in power conditioning systems (PCS) for photovoltaic (PV) power generation applications as well as in energy-saving equipment.

■ SiC and GaN devices

SiC and gallium nitride (GaN) power devices tolerate electric fields an order of magnitude higher than Si power devices. This means that the thickness of SiC and GaN devices can be reduced to one-tenth that of Si power devices at the same breakdown voltage. It is considered that, as a result, the conduction resistance of SiC and GaN devices can theoretically be reduced to 1/300th. Therefore, SiC and GaN devices are expected as next-generation devices.

Of SiC power devices, Schottky barrier diodes (SBDs) have already been commercialized and used in practical applications. This is because an SiC SBD helps to significantly reduce the losses of a switching device during turn-on (reverse recovery loss and turn-on loss), even if it is a Si device (IGBT or SJ-MOSFET). Furthermore, while Si SBDs are available with a breakdown voltage of only up to 200 V or so, SiC SBDs exhibit excellent performance at up to around 3 kV. Toshiba conducted a detailed verification of loss characteristics for a combination of a Si IGBT and a SiC SBD. As a result, it was found that the combination of a Si IGBT and a SiC SBD reduces not only turn-on loss as had previously been postulated but also turn-off loss since the SiC SBD has no forward recovery voltage.

In contrast, although SiC switching devices, particularly SiC MOSFETs that have recently been attracting much attention, are finding applications in end-use products, they have yet to be commonly used in power electronics equipment. This is presumably because the crystal quality of SiC wafers has yet to reach the level of Si wafers. The carrier mobility through the channel of SiC MOSFETs is still lower than desired, causing their on-resistance to be much higher than

is theoretically possible. Moreover, semiconductor fabs are still working to improve their gate oxide reliability to a level necessary for mass production. Although SiC MOSFETs will gradually be adopted in applications where high efficiency is critical, it will take a while until all Si power devices are replaced by SiC devices.

In order to reduce wafer cost, semiconductor fabs developed lateral GaN devices that are fabricated by growing a thin layer of GaN on a low-cost Si wafer in which the main current flows laterally through a thin GaN layer. GaN devices are about to enter mass production. However, GaN devices still have reliability issues such as an abrupt increase in resistance during active operation. These reliability issues are considered to be primarily attributable to the inadequate crystal quality of the GaN layer and electric field concentration in a device. Semiconductor fabs are now working to resolve these issues.

Device cooling and assembly technologies

As described above, R&D efforts are underway to improve power devices. However, improving the performance of power devices is not enough. Let's perform a simple calculation to see why.

Just suppose that we have successfully developed an epoch-making device with half the on-resistance per unit area of the conventional device. Now, suppose that we pass twice the current through the new device as we did before. Then, the resulting voltage drop that occurs in the new device is the same as for the conventional device. This means that where it was previously necessary to connect two chips in parallel in a system, only one new chip can now conduct the same amount of current. Indeed, it seems fine. However, the heat generated in a chip due to conduction loss is $R \cdot I^2$ (where R is resistance and I is current). Even if R is reduced by half, the generated heat becomes twice as much if twice the

amount of current, I , is passed. Moreover, since the new chip has a current density twice as high as the previous chip, it is also necessary to double the current-carrying capacity of on-chip wires.

Therefore, we need a technology for efficiently dissipating heat that concentrates in the chip. We also need a wiring technology for conducting an electric current through a small chip without a loss. In order to get the best performance from a chip, it is also necessary to improve the device cooling and assembly technologies at the same time.

Toshiba developed an assembly structure in which both sides of a chip are cooled inside an IGBT module and put it into practical use. As a result, the new IGBT module has 60 % less thermal resistance and one half the volume of the previous module. The new IGBT module was mounted on a hybrid electric vehicle (HEV) to demonstrate that it exhibits excellent heat dissipation performance and high reliability when the vehicle is accelerating and driving at a constant speed.

Evolution of circuit technology

■ NPC circuit

PCS and other PV grid connection systems need to shape the pulse-width modulated (PWM) output from an inverter to sine-wave voltage with minimal harmonic distortions. Grid connection systems have a sine-wave filter at the output stage for this purpose. However, the use of a sine-wave filter is a bottleneck in improving the efficiency and reducing the size of a grid connection system. One way to overcome this bottleneck is by increasing the switching frequency of an inverter, but this, in turn, causes its switching loss to increase. The switching operation of the inverter must be completed in a short period of time to reduce its switching loss. However, high-speed switching causes abrupt changes in voltage and current, as well as an increase in the number of switching operations.

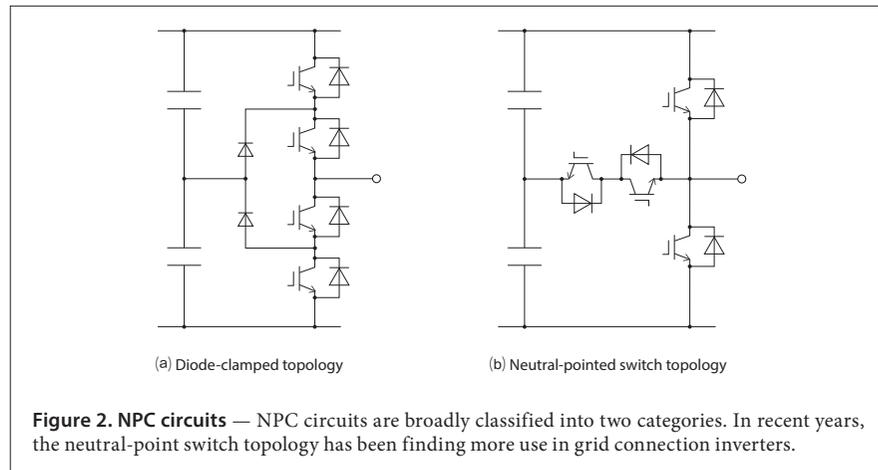


Figure 2. NPC circuits — NPC circuits are broadly classified into two categories. In recent years, the neutral-point switch topology has been finding more use in grid connection inverters.

Consequently, electromagnetic noise increases. In order to solve this problem, Toshiba developed an effective circuit technology for damping electromagnetic noise.

We developed a small electromagnetic interference (EMI) filter with excellent noise suppression performance suitable for high-frequency switching applications. The new EMI filter has intra-phase capacitors at both the input and output. Connecting the phases at the neutral point helps to significantly reduce common-mode noise (i.e., noise caused by a current that flows through an earth line to the earth).

Another solution for improving the efficiency and reducing the size of a sine-wave filter is the use of a multilevel inverter that provides multiple levels of output voltage. It is true that a multilevel inverter is more complex and consists of a larger number of components, but the benefit of even the simplest three-level inverter is equivalent to quadrupling the switching frequency of a two-level inverter. Moreover, a three-level inverter has one-half the voltage step of a two-step inverter and therefore reduces EMI noise by half. **Figure 2** shows two typical examples of a three-level inverter called a neutral-point-clamped (NPC) circuit that has been proposed in the semiconductor industry.

The currently proposed NPC circuits are broadly classified into two types shown in Figure 2: diode-clamped invert-

ers (a) and neutral-point switch inverters (b). In a diode-clamped inverter, two vertically adjacent diodes are connected in series. Since a voltage is applied across the ends of the series-connected diodes, diodes with a lower breakdown voltage can be used. Although device utilization is high, a voltage drop occurs across two diodes, causing a significant conduction loss. In contrast, two vertically adjacent diodes are not series-connected in the neutral-point switch. Although diodes with twice the breakdown voltage are needed, this topology causes a voltage drop across only one diode and thus a lower conduction loss. In the late 1970s, Toshiba led the world in R&D of NPC inverters and proposed original circuit topologies that subsequently led to the circuits shown in Figure 2. In recent years, the neutral-point switch topology has frequently been used for grid connection inverters and other applications, vindicating our foresight.

■ Recovery-assist and A-SRB circuits

A parasitic diode is formed inside the SJ-MOSFET. The slow recovery of the parasitic diode causes a switching loss. This switching loss can be reduced by adding an external circuit called a recovery-assist circuit. **Figure 3** shows an example of a recovery-assist circuit.

In 2003, Toshiba used a recovery-assist circuit for the first time in the compressor drive inverter of the GDR series of

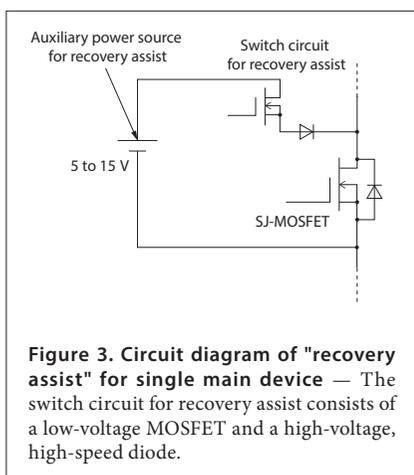


Figure 3. Circuit diagram of "recovery assist" for single main device — The switch circuit for recovery assist consists of a low-voltage MOSFET and a high-voltage, high-speed diode.

air conditioners for residential use. Since then, roughly 600,000 units of the GDR series have been shipped. It has been proven that the recovery-assist circuit is

effective in reducing the switching loss of even high-voltage IEGTs and IGBTs that contain a flywheel diode with slow reverse recovery. For IEGTs and IGBTs, a high-speed, high-voltage diode must be incorporated into a recovery-assist circuit. An SiC diode is suitable for this application. Since the SiC diode conducts only briefly, a small-capacity diode suffices. We also found a solution for reducing the turn-off loss, which had been a challenge for SJ-MOSFETs. As a result, we developed an innovative advanced synchronous reverse blocking (A-SRB) circuit (see Column).

Since the main current needs to be applied to the recovery-assist circuit for each switching operation, power must be supplied from an auxiliary power

source. In this respect, the A-SRB circuit is more beneficial for applications with a relatively high switching frequency such as grid connection. On the other hand, the recovery-assist circuit may be more advantageous for applications with a relatively low switching frequency such as motor drive. There are high expectations of its evolution and applications.

■ MMC circuit

For the long-haul bulk transmission of electrical power, using alternating current (AC) at a mains frequency (50 Hz or 60 Hz) is disadvantageous because of a significant voltage drop due to the inductance of long power lines and the skin effect of an AC current (i.e., the tendency of an AC current to flow near the outer

Output capacitance of the SJ-MOSFET and reduction of output capacitance through application of auxiliary voltage

The output capacitance of SJ-MOSFETs exhibits markedly non-linear characteristics. Their output capacitance is very high in the low output voltage region. This is due to the structure of the SJ-MOSFET in which alternating p and n pillars form a drift region to achieve a high breakdown voltage.

Immediately after turn-off, a depletion region is formed in the p-n junction. This causes output capacitance to increase. Due to the alternating p and n pillars, a depletion region is formed across a wide area. The depletion region is thin at low terminal voltage, causing output capaci-

tance to become very high (Figures A and B). If the adjacent element is turned on in this state, a short-circuit current flows, charging the output capacitance.

This phenomenon occurs immediately after the adjacent element is turned on. As a result, a voltage close to the main voltage is applied to the terminal of the adjacent element, causing a significant turn-on loss.

To resolve this issue, Toshiba developed the A-SRB topology (Figure C).

When an SJ-MOSFET is turned off, the A-SRB circuit turns off a reverse blocking FET simultaneously and then activates an

auxiliary voltage application circuit to apply 20 to 30 V to the SJ-MOSFET. Consequently, a voltage is applied across terminals of the SJ-MOSFET while the gate is off (i.e., during the reverse blocking period). This causes the entire drift region in the SJ-MOSFET to become a depletion region instantaneously, reducing output capacitance by two orders of magnitude. This, in turn, reduces the current that charges output capacitance and eliminates a turn-on loss caused by the turn-on of the adjacent element.

Even in the off state, when the applied voltage is low, a wide depletion layer forms, causing a large output capacitance.

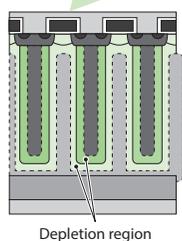


Figure A. Depletion layer immediately after turn-off of SJ-MOSFET

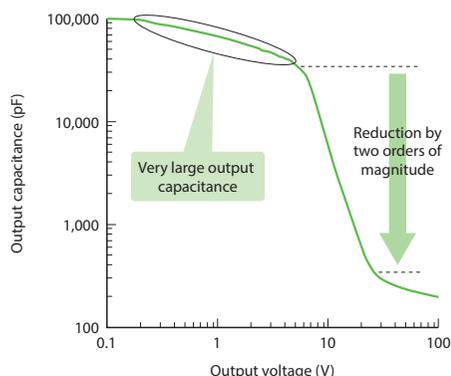


Figure B. Example of output capacitance characteristics of SJ-MOSFET

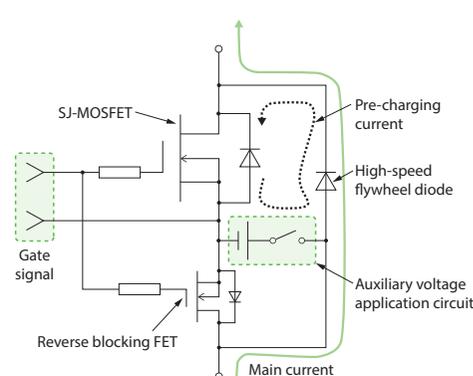


Figure C. A-SRB circuit

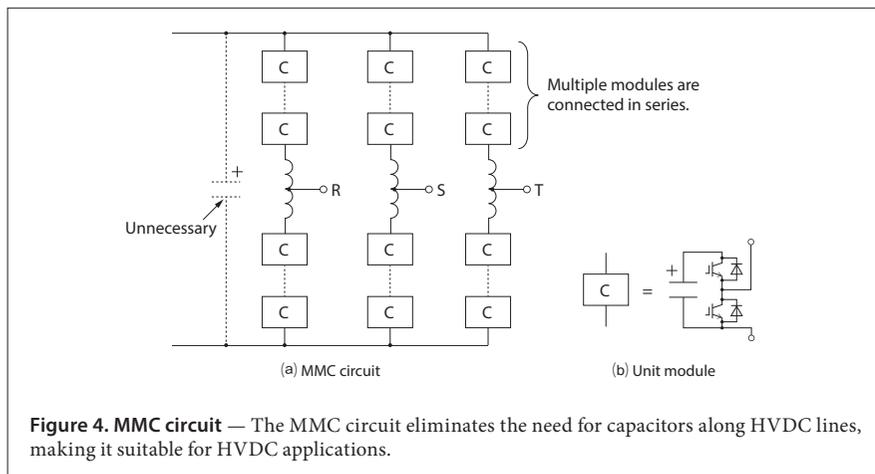


Figure 4. MMC circuit — The MMC circuit eliminates the need for capacitors along HVDC lines, making it suitable for HVDC applications.

surface of the conductor). High-voltage direct current (HVDC) transmission provides effective solutions for these issues. For HVDC transmission, power converters are required at the interface of HVDC and AC systems in order to convert electricity from AC to DC and from DC to AC. For full conversion of power between AC and DC, very high-capacity converters are needed. Conventionally, a high-voltage, high-current thyristor was commonly used in line-commutated converters for HVDC. In recent years, self-commutated converters that do not require a harmonic filter or a phase adjuster have been attracting much attention. Self-commutated converters can be operated without any AC voltage. For example, even when the AC system at the receiving end has stopped due to a power failure, self-commutated converters can keep transmitting electric power and can be started under power failure conditions.

Toshiba has been focusing on the modular multilevel converter (MMC) shown in **Figure 4** that is suitable for self-commutated HVDC systems. The MMC consists of multiple series-connected modules that comprise a capacitor and a half-bridge circuit. Each module can be configured to provide either the capacitor voltage or a zero voltage. The MMC combines voltages from individual modules to produce multiple voltage levels. Since voltage processing is completed in each module during switching, simple and

reliable power converters can be realized without using a snubber circuit. Furthermore, the MMC does not require any capacitors along the HVDC lines, eliminating the need for ultrahigh-voltage capacitor banks. Therefore, the MMC is suitable for HVDC applications.

We have been working on R&D to achieve practical applications of the MMC to self-commutated HVDC. We have developed a unique three-winding transformer MMC by applying basic principles of the MMC. The new AC-DC converter reduces the number of passive components required. It helps reduce the transformer footprint area and cost and eliminates the need for provisions for harmonic filtering.

Technologies for power electronics applications

■ Energy storage systems using rechargeable batteries

Toshiba offers the SCiB™ rechargeable battery, an improvement over lithium-ion batteries. SCiB™ features rapid charging/discharging and has many other outstanding characteristics compared to lithium-ion batteries, including enhanced safety, long life and low-temperature operation. Because of these features, SCiB™ has been widely used for hybrid electric vehicles (HEVs) and other vehicles. In addition, due to long life and low operating temperature, SCiB™ is now utilized in stationary equip-

ment as well as backup power supplies used to ensure uninterrupted power in the event of a power failure.

The voltage across the terminals of a rechargeable battery varies with the state of charge (SOC). In addition, since a voltage drop also occurs due to the internal resistance of a battery, the battery voltage changes during charging and discharging. In order to use rechargeable batteries effectively, it is necessary to convert the constantly changing voltage to an appropriate voltage. For power conversion, high efficiency is required for power electronics equipment. The conventional power electronics equipment has low efficiency in the low output voltage region. When a rechargeable battery is charged and then used to operate power electronics equipment that is frequently operated at low output voltage, almost half of the charged energy is lost. This loss occurs mainly because the efficiency of power electronics equipment decreases at low power. Efficiency in the low output region is therefore important for systems with a rechargeable battery. Toshiba is committed to the development of equipment that delivers high efficiency even in the low output region.

Toshiba Elevator and Building Systems Corporation developed a battery energy storage system using SCiB™ and applied it to an elevator. SCiB™ recovers regenerative energy during braking and releases it during traction machine operation. As a result, the power consumption of the elevator was reduced by approximately 25%. In the event of a power failure, SCiB™ releases the stored power instantaneously until the elevator reaches a certain speed so that it can gradually decelerate and safely stop at the nearest floor. This function helps alleviate the impact of an emergency stop.

■ Motor drive technology

Conventionally, manufacturers emphasized the importance of sufficient cooling performance at the rated output for motor drive inverters. Their efficiency generally decreases at low to intermedi-

ate output due to their design. However, statistical data show that most of the electricity demand comes from motors. In order to reduce power consumption and thereby CO₂ emissions, we can no longer ignore the decrease in efficiency at low to intermediate output. The use of an inverter to drive an AC motor at variable speeds helps save energy at low output. Therefore, its energy-saving effect could be lost if an inverter has a poor efficiency at low to intermediate output. Considering the trend in energy-saving regulations, it is necessary to improve efficiency not only at a rated output but also over a wide range of output.

Toshiba has been developing railway drive systems using permanent magnet synchronous motors (PMSMs) to improve energy efficiency and environmental friendliness. We developed high-reliability, small and lightweight 4-in-1 inverters that have a size and weight comparable to the conventional induction motor drive systems. In order to further improve energy efficiency, we have also developed inverters using low-loss SiC devices and a high-efficiency control method, which are now undergoing demonstration testing.

■ High-power technology

Renewable energy is expected to find a wider uptake worldwide. The PV market, in particular, is rapidly expanding both in Japan and abroad. In response to the market needs, Toshiba Group developed 750-kW and 665-kW power conditioning systems (PCS) for multi-megawatt solar farms targeting the Japanese market, in addition to the conventional 100-kW to 500-kW PCS. In addition, we developed a new 100-kW outdoor PCS for use on rooftops for the North American market in addition to the conventional 500-kW PCS.

In 1990, we were the first in the world to provide an adjustable-speed pumped storage system*² for utility hydroelec-

(*2) As of December 1990 (as researched by Toshiba)

tric power generation. It was realized by using a high-voltage, high-capacity cyclo-converter whose manufacture became possible due to advances in power electronics technology. Thereafter, we developed self-commutated inverters such as NPC and center-tap reactor types for pumped-storage generation applications. In addition, we are working on development projects using power electronics technologies, including the input power control function in pumping mode and the quick response function to reduce voltage fluctuations caused by renewable energy generation systems, as well as for the effective utilization of hydropower resources by improving efficiency and achieving wide-range operation.

■ Wireless power transmission technology

At present, plug-in hybrid vehicles (PHEVs) and electric vehicles (EVs) must be plugged into a charger station to charge their battery packs. Most vehicles carry large rechargeable battery packs weighing several hundred kilograms in order to increase miles per charge. The increase in weight of rechargeable battery packs causes a vehicle's running resistance to increase. In order to obtain sufficient acceleration performance and hill-climbing force, it is necessary to increase the output of the drive system. This results in an increase in weight of the driving motors and vehicle structures. This vicious circle can be broken if we reduce the weight of automotive rechargeable battery packs and thus the overall weight of a vehicle. To achieve this, it is essential to simplify frequently required charging.

Toshiba has been committed to the R&D of a wireless power transmission technology that will significantly simplify charging. A receiving pad of a contactless charger is mounted on the underside of a vehicle, and the transmitting pad is placed on the ground. We succeeded in wireless transmission of 7-kW power using a converted car. The contactless charger has a system efficiency of 89 %,

which is close to the efficiency of plugged charging. For wireless power transmission, it is necessary to generate a frequency as high as 85 kHz. Increased use of new high-speed and low-loss power devices, including SiC power devices, is expected for this application.

Future outlook

Power electronics handles large power with a collection of tiny cells of power devices that are in the order of microns in size. Therefore, power devices are the most important and basic components in power electronics. Power devices will rapidly evolve from now on. Toshiba will endeavor to realize epoch-making high-performance equipment by combining innovation in power devices with the supporting circuit and cooling technologies. Regarding circuit technology, the building blocks of a circuit should be small and simple in order to reduce a circuit's stray inductance and stray capacitance and to make it easier to improve circuit performance. It is considered that, accompanying the performance improvement of power devices, intelligence and communication functions will be incorporated into individual small building blocks in the future so that they can connect and cooperate with each other.

Toshiba will continue to provide state-of-the-art power electronics technologies for optimal efficiency of electricity operation in each process from electricity generation through to transmission, storage and consumption, aimed at the construction of smart communities.



MOCHIKAWA Hiroshi

Senior Fellow

Power and Industrial Systems Research and Development Center, Power Systems Company He is engaged in R&D of power electronics equipment. He is a member of the Institute of Electrical Engineers of Japan.