Review

Recent R&D Activities of Power Devices for Hybrid Electric Vehicles

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Abstract

Automobiles have an influence on the global environment that cannot be disregarded, not only through air pollution in cities but also through large carbon dioxide emission that leads to global warming. A hybrid electric vehicle combining a gasoline engine and an electric motor has proved to be an effective means to solve these problems. Electrical energy flow of the vehicle is controlled with inverters built into the car. These inverters consist of power modules that in turn contain many power devices. Therefore, power devices are one of the key components for the hybrid electric vehicle. In this paper, we make a survey of the role of power devices used in the hybrid electric vehicle and the technological trends they indicate. In addition, we present our recent R&D activities concerning power devices.

Keywords: Hybrid electric vehicle, Inverter, Power device, IGBT (Insulated Gate Bipolar Transistor), Diode

1. Introduction

We depend almost entirely upon fossil fuels for our energy. According to a report of the Agency for Natural Resources and Energy in Japan, world energy demand in the future[1] will be assumed to increase globally by 2 to 3% annually, as shown in **Fig. 1**. The figure indicates that the total energy supply of the year 2030 is estimated to be 1.7 times higher than that of 2000. Most of this energy comes from fossil fuels such as oil, coal and natural gas. These fuels produce emission gases such as carbon dioxide during conversion of their molecular energy into other energy forms. **Figure 2** shows world carbon dioxide emissions arising from fuel combustion[2] which is reported by the International Energy Agency (IEA). In the graph, 24% of the emissions come from transport activities, and about 18% of all CO_2 emissions are from motor vehicles. CO_2 emissions produced by energy consumption in Japan increased about 6% from fiscal year 1990 to 2001. In addition, motor vehicle exhaust also contains NO_x (nitrogen oxides), HC (hydrocarbons) and PM (particulate matter), causing air pollution in cities that have heavy traffic. For automobiles, therefore, saving energy and reducing emission gases are crucially important tasks.

We believe a Hybrid Electric Vehicle (HEV) such as "Prius" is an effective solution for saving energy and producing clean exhaust emissions. **Figure 3** shows overall efficiency of a vehicle, or well-to-wheel efficiency,[3] indicating that Prius is

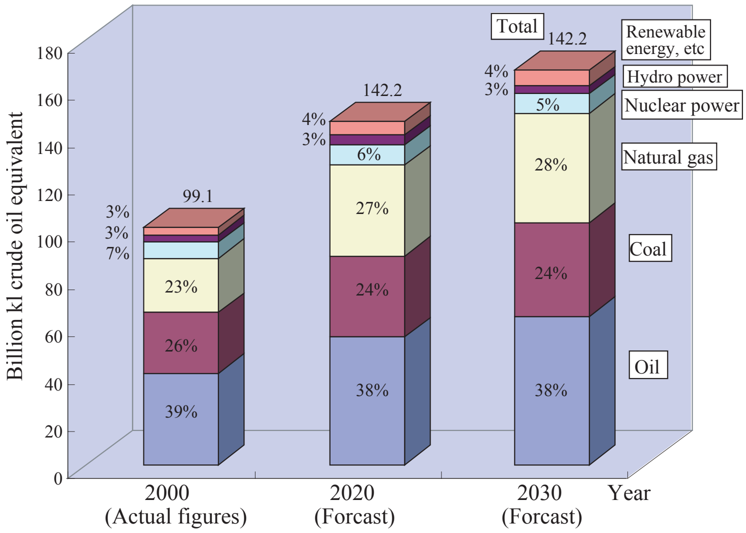

Fig. 1 Trends and forecast of world energy demand by fuel.[1] If we continue to consume energy on the current scale, we may face a petroleum shortage in the latter half of this century.

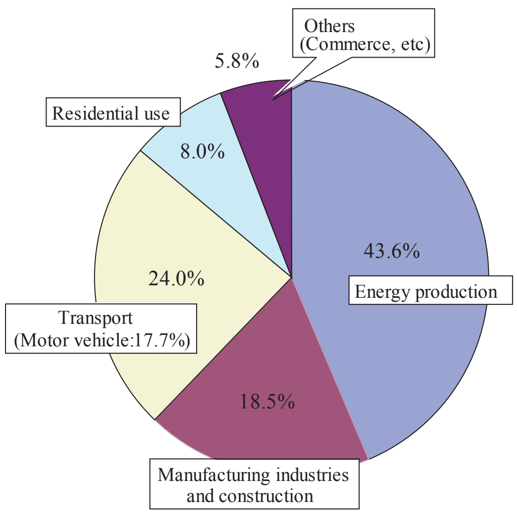

Fig. 2 Estimated world CO_2 emissions arising from fuel combustion.[2] About 18% of all the CO_2 is emitted by automobiles.

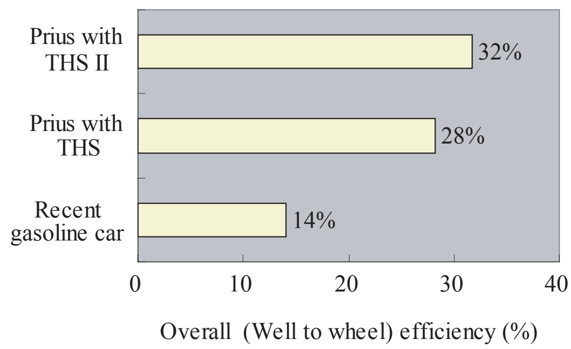

Fig. 3 Overall energy efficiency of THS II, THS and recent gasoline car. THS II has achieved higher overall efficiency by the best combination of both a gasoline engine and an electric motor.[3]

more than two times more efficient than the recent gasoline car. In the figure, THS is the abbreviation for Toyota Hybrid System, and THS II is a new generation of THS that was developed in 2003. The Prius with THS II has fuel efficiency as high as 35.5km/l: the value is measured by the Japanese 10-15 mode test. Although it has a 1.5-liter gasoline engine, it shows a powerful acceleration equivalent to that achieved by a 2-liter gasoline car[3] as shown in **Fig. 4**. The combination of both the best gasoline engine and the best battery-power system gives Prius high performance as well as the fuel efficiency. The inverters built in a power control unit of the HEV control the battery-power system. Therefore, the inverter is one of key components of the HEV with great effect on its performance.

In the next chapter, we give an overview of the hybrid system and then technological trends indicated by power devices used in the inverter. After that, we will review our recent activities.

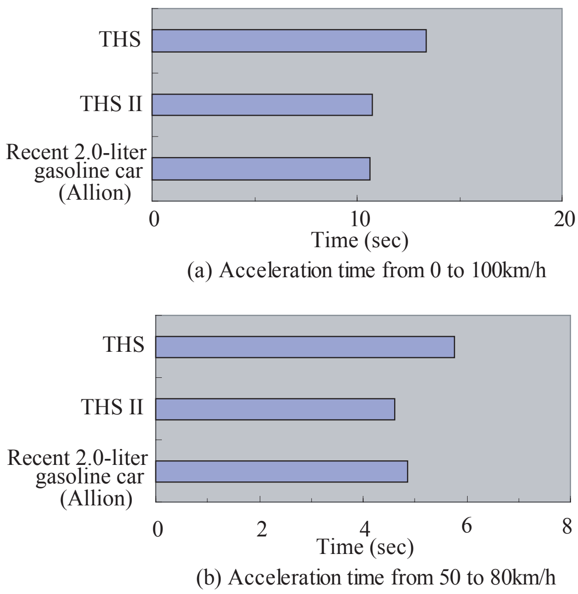

Fig. 4 Acceleration time of hybrid electric vehicles (THS and THS II) and a 2.0-liter gasoline car.[3] Acceleration performance has improved as a result of higher motor voltage. Output in the low-medium speed range is almost the same as that of a 2.0-liter gasoline engine vehicle.

2. Hybrid electric vehicle and power devices

2. 1 Hybrid electric vehicle system

There are three types of hybrid electric vehicle systems: series, parallel and series/parallel. Among these, Prius has the series/parallel hybrid system because it gives energy-saving benefit of a series hybrid system together with acceleration benefit of a parallel system. THS is based on this series/parallel hybrid system.[3-5]

Figure 5 shows a schematic view of the THS II system of Prius. A battery voltage of 202V is boosted up to 500V and then supplied to the motor through the inverter. This high-voltage power circuit creating a maximum voltage of 500V enables the motor output power to be 1.5 times higher without increasing the battery output or changing the motor size. In addition, electricity generated by the generator charges the battery via the inverter. As just described, the inverter plays the crucially important role of controlling the electricity flow among a motor, a generator and a battery. **Figure 6** schematically illustrates how the vehicle utilizes the electric motor and the gasoline engine. The inverter realizes the optimal operation of the motor and engine for the road and vehicle conditions.

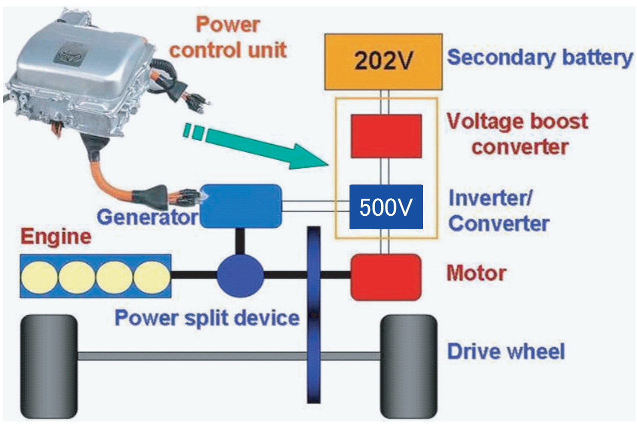

Fig. 5 Schematic view of THS II system of Prius. The power control unit contains an inverter and a DC/DC converter. In THS II, a high-voltage power circuit that increases the voltage up to 500V is added.

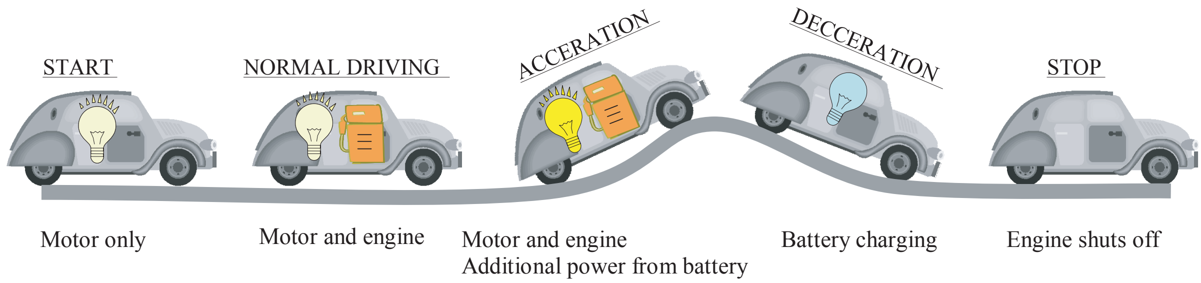

Fig. 6 Schematic view to show how both a gasoline engine and a motor work.

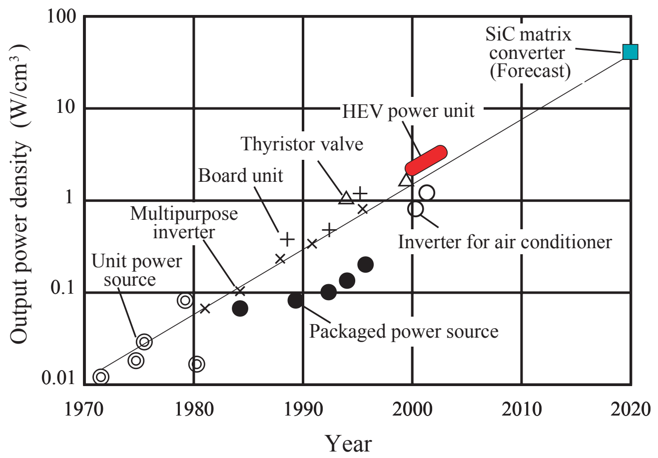

Fig. 7 Technological trend of various inverters.[6)]

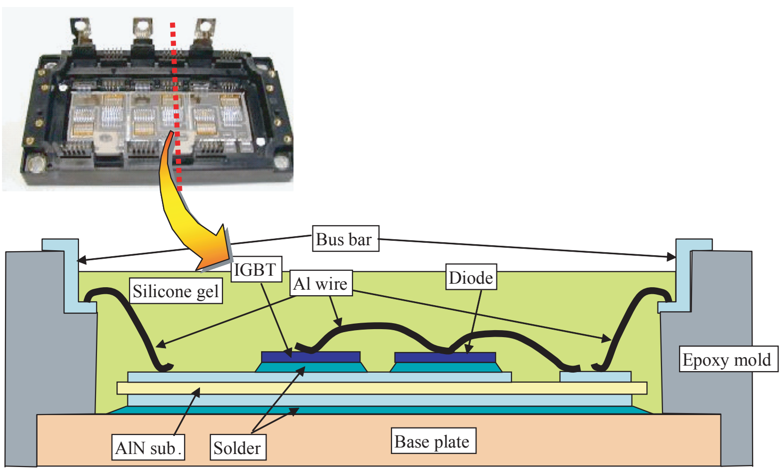

Fig. 8 Schematic view of cross section of a power module.

2. 2 Technological trend of power inverters

Improvement of power inverters means making them higher output power and smaller size. In other words, power output density is an important benchmark for evaluating the inverter performance. **Figure 7** shows the output power density of various inverters,[6)] plotted chronologically. From the figure, we can see that the output power density is also a good index to show the technological trend of inverters. Regarding the inverter of hybrid electric vehicles, the index at present is more than 1W/cm^3, and the value will exceed 10W/cm^3 soon after 2010. In that case, the inverter volume will be five liters and output power will be 50kW. This should improve the design flexibility of hybrid power trains greatly.

2. 3 Power devices for hybrid electric vehicles

As shown in Fig. 5, the power control unit contains three power modules for the motor, the generator and the voltage booster. Each of the power modules consists of several Insulated Gate Bipolar Transistors (IGBTs) and Free-Wheeling Diodes (FWDs) as shown in **Fig. 8**. Since actual current and voltage controls are implemented by the power devices, they are key components for improvement of the performance of the inverter. For fulfillment of higher output power density of the inverter in a hybrid electric vehicle application, the power devices need several features.

First, reduction of power losses coming from the switching and conduction of high currents is crucially important for power devices to improve the performance of the inverter. Even though the power modules in hybrid electric vehicles are subjected to water-cooled heat sinks, ΔT_{jmax} of the system operation is reported to be about 50°C.[8] Since an increase in ΔT_{jmax} threatens the device safety operation, devices with lower power dissipation are required.

Next, the ruggedness under the rather severe environment of an automobile is required. For example, conventional PT-IGBTs tend to show a somewhat high surge voltage during the turn-off period at high voltage operation, because of abrupt di/dt and stray inductance of the module at that time. The surge voltage causes not only harmful EMI noise in hybrid electric vehicles but also device destruction. Therefore, suppression of the surge voltage is necessary for the inverter during high voltage operations. In addition to the surge voltage, ruggedness against short circuit-causing conditions is also indispensable because increasing the voltage of the inverter applied to the motor drive is an effective way to increase the motor output power. Furthermore, raising the applied voltage normally results in a reduction in the device short-circuit ruggedness. Therefore, the short-circuit robustness has to be increased enough to compensate for its reduction and to withstand the stress in high voltage operations.

The other feature required for the inverter is thermal management. The power modules with capability of high temperature operation are also required of the automotive electronics because temperatures of operating environments are rather high, as listed in **Table 1**.[7] Power devices as well as power modules that enable higher temperature operation are thus required to make the modules more compact and have higher power density.

Table 1 Operating temperatures for automotive electronics.[7]

Location	Max. temperature (°C)
Passenger compartment	85 ～ 120
Engine compartment	150
Transmission	150
Exhaust system	590

3. Quick review of our activities

To realize higher power density inverters, we have been focusing on power devices from the point of the power loss reduction, ruggedness and reliability for application in vehicles.

As the result of our efforts for power loss reduction in collaboration with Toyota Motor Corp., we have developed a local lifetime control technique for IGBTs[9] and FWDs[10] using high-energy ions of He^+. Using a sub-micron and a trench-process technology, trench IGBTs with an on-voltage of 1.55V[11] have also been developed. For these devices, defects arising during the device fabrication affect the device performance. We are, therefore, investigating defect states produced by He^+ and H^+ ion implantation, using deep-level transient spectroscopy (DLTS).[12-14]

Recently, there have been great expectations for GaN power devices as well as those of SiC for the next-generation of power devices, and we have started basic research on GaN[15-16] aiming at realizing an inverter with an output power density exceeding $10 W/cm^3$.

In our efforts to achieve ruggedness and thermal management in power devices, we have developed IGBTs and FWDs that are suitable for automobile environments.[17-19]

In this special issue, we present five papers on IGBTs and the related technology. Two of the papers are concerned with device concepts to improve characteristics such as the on-voltage. Investigations of the gate oxide's reliability and IGBT's short-circuit ruggedness are described in two other papers. The last report is an electro-thermal simulation approach to power modules, which gives a useful insight for analyzing the thermal issues of modules.

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