The Evolution of Electric Components in Prius

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Several types of electrified vehicles have been developed and launched as a solution for low carbon transportation. Toyota launched the first mass-produced hybrid electric vehicle, the Prius, in 1997. With the evolution of electric components in Toyota Hybrid System, 15 million Toyota hybrid electric vehicles have been sold, and reducing 120 million tons of CO2 in the real world. These electric components have some compatibility with electric vehicles and fuel cell electric vehicles.

Keywords: Toyota Hybrid System, hybrid electric vehicle, motor, generator, inverter, battery

1. Introduction

In order to prevent global warming, there has been a pressing need in recent years to reduce the volume of CO2 emissions and to improve fuel consumption of automobiles. At the same time, metropolitan areas are facing a serious problem of air pollution, prompting the enforcement of stricter automobile exhaust emission regulations all over the world. Under these circumstances, a hybrid electric vehicle (HEV) draws attention as a system compatible with the improvement of fuel economy, the reduction of exhaust emission and a customer friendly usability.

The HEV was first introduced in Europe in 1899. It was developed for the purpose of supplementing low battery capacity, but its usage declined as engine and transmission performance was improved. During the ‘60s and ‘70s, various types of HEVs were developed in the world to address emission regulations and the oil crisis but the development slowed down as a result of the innovation of engine technologies and the end of the oil crisis (Fig. 1)(1)(2).

Toyota introduced the first mass production HEV Prius in 1997 with Toyota Hybrid System (THS), and later researched other types of hybrid system after 1st generation Prius development to confirm which hybrid system was the best. 48volt-P0 (belt driven 48volt-motor/generator located in the conventional alternator position), 1-motor HEV, series HEV and diesel HEV are a few examples. Some systems were launched in the Japanese market.

However, it became clear that the 2-motor power split THS offered the overall best performance as mentioned later and therefore was widely spread over many vehicles all over the world (Fig. 2).

This paper describes the evolution of THS and its electric components (motor, inverter, battery and controller), the environmental effect, and the future prospect of HEV.

2. Hybrid Systems and Their Characteristics

Currently, various types of hybrid systems are in practical application (3)-(5). Fig. 3 shows a typical hybrid system classification by its structure. It is classified as an idle stop, a parallel HEV that is capable of transferring both the engine and motor driving force, a series HEV that has the motor driving force only generated by converting the engine output to electric energy, and a series-parallel HEV that has the characteristics of both. THS is classified as series-parallel HEV.

It is also possible to classify the hybrid system by some functions according to battery power. The most important requirement for a HEV is to improve fuel economy to achieve low carbon transportation. The improvement of fuel economy for the HEV is characteristically large in city driving where acceleration and deceleration are frequent, and small at constant speed in highway driving. This is because a HEV improves fuel economy mainly by the following functions:
Fig. 3. Hybrid system classification by structure

Fig. 4. Hybrid system classification by battery power

[1] Idle stop
[2] Energy regeneration
[3] Driving force (Motor) assist
[4] EV driving during engine stop

To provide HEV with functions of [1] to [4], it must have a battery, motor, inverter and other electrical power components. Fig. 4 shows the relationship between various functions and improved fuel economy by battery power. For example, to provide the EV driving function, a higher battery power and traction motor are required to provide effective propulsion force during engine stop. Fuel economy is thus improved by adding respective functions. THS is classified as a full HEV.

3. Toyota Hybrid System (THS)

3.1 Principle of THS

Figs. 5 and 6 show a system diagram and components layout of THS. This system is designed to control the power distribution by combining the engine output with the motor output through a planetary gear drive. Since the driving force is the combination of the engine and motor output, the engine output or torque is set at a relatively lower level and the engine can be optimized for higher efficiency.

Fig. 7 shows the engine thermal efficiency of a conventional gasoline engine vehicle and a THS vehicle during city driving mode. THS improves average engine efficiency through engine stop in the low output area and concentration of the engine operating points at the engine maximum efficiency. It is also possible for the engine to optimize for the maximum efficiency by adopting a high expansion ratio cycle, a cooled exhaust gas recirculation system and so on. Additionally, it is possible for THS to regenerate the kinetic energy of the vehicle by high power motor and battery. Consequently, THS achieved doubled fuel economy from conventional gasoline vehicle in city driving mode.

3.2 Specification and Evolution of THS

Table 1 shows the specification and evolution of THS for Prius. THS has been improved for lower CO₂ emission, higher power performance and lower system cost.

The following are the main objectives and new technologies which were adopted in each generation of THS.

[1] 1st generation: The objective of the 1st generation Prius was doubled fuel economy. The main components of this system are a 1.5-liter Atkinson cycle engine, 2 permanent magnet motors, a power split device utilizing a planetary gear, and a nickel-metal hydride battery. The 1st generation Prius penetrated into the market as an environment-friendly vehicle with lower fuel consumption, but feedback from customers was poor power performance.

[2] 2nd generation: The objective of the 2nd generation was to improve vehicle power performance. THS adopted the boost converter which boosts the motor operating voltage.
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Fig. 8. The evolution of fuel consumption

Fig. 9. Toyota HEV sales volume and CO₂ reduction

from battery voltage. Consequently, the motor output power was much higher than 1st model even though the motor size was the same, and the vehicle performance and popularity drastically improved.

3rd generation: The objectives of 3rd generation were to improve real-world fuel consumption and a wider range of applicability for different vehicle models, while the previous system was specific for Prius. The new 1.8-liter engine adopted a cooled exhaust gas recirculation system, an exhaust heat recirculation system, and a beltless accessory drive to improve winter season and high speed driving fuel economy. The traction motor adopted a reduction gear between motor and planetary gear to downsize and reduce the weight of the motor by increasing the maximum motor speed from 6400 to 13500 rpm.

4th generation: The objectives of 4th generation were to improve fuel consumption and compactness, and to reduce cost. The transaxle adopted a parallel shaft reduction gear structure instead of the former single shaft planetary reduction gear structure. This parallel gear was able to achieve a wider reduction ratio without increasing mechanical friction. The wider reduction ratio makes the motor size smaller and the cost lower than the previous model by increasing motor maximum speed from 13500 to 17000 rpm.

Consequently, the volume of the motor has been reduced by 59% (5.1 to 2.1 liter), the power density has improved by 4 times, while the maximum power was increased by 1.8 times (30 to 53 kW).

Fig. 11 shows the design of the motor. The thickness of electromagnetic steel affects the iron loss of the motor by eddy current. The electromagnetic steel of the 4th generation has achieved 0.25 mm thickness compared to 0.35 mm of the 1st generation. On the other hand, the magnetism design of the rotor utilizes the reluctance torque and relatively reduces...
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4.2 PCU

Fig. 13 shows the evolution of the PCU and the integrated power module (IPM) which is a main component in the PCU. The IPM for motor, generator and boost converter were gradually integrated and reduced in size. The following are the new technologies and objectives which were adopted for each generation.

[1] 1st generation: Each motor and generator had individual IPM for high efficiency and easy motor control.

[2] 2nd generation: The IPM for motor and generator were integrated into one module to reduce size and cost. The additional IPM for boost converter was separate.

[3] 3rd generation: All IPM were integrated into one module. A direct cooling structure was adopted for improving IPM cooling performance.

[4] 4th generation: A newly developed layered structure was adopted to improve compatibility of the IPM. The layered structure can be utilized from small size to large size vehicles by changing the number of layers. Furthermore, the cooling system of the IPM was changed to both-side cooling structure to improve the compatibility and cooling performance.

The volume of 4th generation PCU has been reduced by 52% (17.4 to 8.4 liter), the power density has been improved by 2.5 times, while the maximum power has increased by 1.8 times (30 to 53 kW).

Fig. 14 shows the evolution of the power semiconductors. The following are the new technologies and objectives which were adopted for each generation.

[1] 1st generation: Insulated-gate bipolar transistor (IGBT) was primarily adopted for automobile with planer gate structure.

[2] 2nd generation: 8-inch wafer was primarily adopted for automobile to reduce cost.

[3] 3rd generation: Trench gate IGBT was primarily adopted for automobile to reduce loss by thinner bulk wafer.

[4] 4th generation: Carrier accumulation structure was adopted to reduce loss. The boost converter has been adopted since the 2nd generation and the motor operating voltage has been enhanced from 200 V to 500 V or 650 V, thus the motor current has been reduced to less than half. This helps the device area and electric loss reduction. Additionally, the trench gate and carrier accumulation structure affect the device thickness and finally electric loss reduction. The device area and thickness of 4th generation have been reduced by 53% and 57% from the 1st generation. Consequently, the electric loss of the device has been reduced by 79% from the 1st generation.

4.3 Battery

Fig. 15 shows the evolution of the battery. The following are the new technologies and objectives which were adopted for each generation.

[1] 1st generation: Nickel metal hydride (Ni-MH) battery cell with plastic case was adopted for high input and output power. Configuration of the battery cell was changed from cylindrical type to prismatic type during the 1st generation to reduce the battery pack volume.

[2] 2nd generation: Newly developed Ni battery cell with plastic case was adopted for higher maximum input/output...
The maximum in/output power was drastically improved by incorporating the boost converter, by changing the electrical connection structure, and by reducing the electric resistance of electrode materials.

3rd generation: Momentary maximum output power was enhanced by improving the battery power control to improve acceleration feeling of the HEV.

4th generation: The maximum input power of Ni-MH battery was enhanced by improving the electrode materials to increase regeneration power of the HEV. Volume of the Ni-MH battery pack was reduced by improving battery pack structure. Some of the 4th generation adopted a lithium ion battery to reduce the volume of the battery pack.

Consequently, the volume of 4th generation battery pack has been reduced by 67% (96 to 31 liter) from the 1st generation. The smaller battery pack has enabled the battery location to be under the rear seats to improve space utility of the HEV. The maximum input/output power has been improved by 60%/28% from the 1st generation.

4.4 Controller

Motor controller has also been contributing to superior driving performance, improving fuel consumption, downsizing each component, and reducing cost. Fig. 16 shows the evolution of the motor controller. The following are the new technologies and objectives which were adopted for each generation.

1st generation: PWM (Pulse Width Modulation) vector control was adopted to the interior permanent magnet synchronous motor for high response and efficiency. Rectangular wave control was adopted in the late model to improve the motor power performance.

2nd generation: Boost converter control was adopted to enhance the motor operating voltage up to 500 V on demand. In addition, over modulation PWM was adopted to expand the operation area of high-power output.

3rd generation: The operating voltage was increased up to 650 V. Resolver error correction control was newly developed to reduce motor power fluctuation and downsize the smoothing capacitor.

4th generation: The boost converter achieved 2.5 times higher control speed than 3rd generation. Rectangular wave control was also speeded up with newly dedicated IC circuit in a microprocessor. Due to these technologies, the smoothing capacitor and the reactor size in the PCU were reduced significantly.

Consequently, the volume of the motor has been reduced by 57% and the capacitance of smoothing capacitor in the PCU has been reduced by 95% from 1st generation, while the maximum motor power has been enhanced by 1.8 times (30 to 53 kW).

Fig. 17 shows the evolution of system voltage controller. The boost converter, which was adopted since the 2nd generation, improves motor power and response at high load. On the other hand, the boosting loss reduces motor efficiency at low load. The operating voltage was optimized to achieve both low fuel consumption in city driving and high power performance and response at overtaking or acceleration on highway ramp. The motor operating voltage control of the 4th generation was further sophisticated by a system loss minimization algorithm which calculates overall electric system loss in every operating area by various system parameters, and the fuel consumption of 4th generation was further improved.

5. Future Prospect

HEVs have become popular because of their low fuel consumption, therefore drastic reduction of CO2 has been achieved as shown in Fig. 9. The sales volume of HEV is expected to be higher in the future as a practical way to reduce CO2 emission from vehicles.

On the other hand, zero CO2 vehicles are required to achieve a carbon neutral society. A battery electric vehicle (BEV), fuel cell electric vehicle (FCEV) and plug-in hybrid electric vehicle (PHEV) with CO2 free fuel are the candidates to achieve a zero CO2 vehicle. THS and its electric components are compatible with PHEV, BEV, and FCEV as shown in Fig. 18. Fig. 19 shows a good example of this approach.
The electric components adopted for Toyota FCEV are the same one or based on HEV.

It is said that the technology can only have a truly positive effect on the environment when customers accept and use that technology widely. The usability of BEVs and FCEV is gradually expanding thanks to recent improvements in batteries and charging infrastructures. However, the technology must be practicable and in harmony with social systems. Therefore, Toyota believes that “diversified electrification” is required and THS and its electric components are the core technology to achieve sustainable mobility.

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