Development of Electric Motors for the TOYOTA Hybrid Vehicle "PRIUS"

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Abstract

In December 1997, TOYOTA put the world's first mass-produced hybrid vehicle on the market in Japan. It realizes remarkable improvement in terms of fuel economy compared with a conventional gasoline vehicle. It does not need to be charged externally like EVs (electric vehicles). For this hybrid vehicle, we developed two new, highly efficient, compact motors (a motor and a generator).

The motor and generator are designed as interior permanent magnet motors, which achieve high output power density by utilizing reluctance torque in addition to magnetic torque. Its motor control system achieves high efficiency by the optimum control of motor current. The structure of the motors has been improved to achieve mass-production and lower costs.

1. Introduction

In March 1997, Toyota Motor Corporation announced the development of the TOYOTA Hybrid System (THS), and in December, the "PRIUS," the world's first mass-produced hybrid vehicle, which is installed with the THS, was introduced to the market in Japan. So far, more than 33,000 PRIUS cars have been sold. The PRIUS has gained popularity due to both its operability (which is equivalent to that of conventional gasoline vehicles) and its improved fuel efficiency. Before introducing the PRIUS to the US and European markets in the middle of 2000, Toyota improved the engine, the motor, and the transmission to ensure sufficient motive power in US and European driving conditions, and to achieve even higher fuel efficiency. (Figures 1,2 and 3)



Figure. TOYOTA NEW PRIUS

The THS is a gasoline engine-electric motor combined power source, and no external charging is required, unlike for EVs(Electric Vehicles). It is therefore usable with existing infrastructure. In addition, compared with conventional gasoline engines, remarkable improvement in fuel efficiency has been achieved.

Environmentally-friendly vehicles will not be able to achieve popularity if they are inferior to conventional vehicles in terms of basic functions (such as running performance, driving distance, and refueling procedures), if efforts are required of drivers in driving, or if the relative cost is much more than for conventional vehicles. As conventional technologies seem unable to resolve the various issues mentioned above, we have developed a new engine-motor hybrid system, not the simple series type nor parallel type previously proposed in order to aid mass production. The newly developed hybrid system, the THS, is a combination of a high expansion ratio engine and an exclusive transmission. The transmission includes a motor and generator placed on axes of a planetary gear system. Coordinating and controlling the engine, motor and generator through the planetary gear achieves extremely higher fuel efficiency.



Figure 2 Comparison of Fuel Efficiency

Drivers will feel the acceleration performance to be as powerful as that of a 1.8 L AT vehicle.

Figure 3 Comparison of Motive Power

2. Outline of the THS

Figure 4 shows the configuration of the THS.

The main power source is an engine, though both a gasoline engine and an electric motor are provided. The engine power is divided into driving force for wheels, and electricity generating force by the torque split device which constitutes the planetary gear. The torque split device is controlled electronically to ensure that the highly efficient engine only operates in the range of high efficiency. The electricity generated is used to activate the motor, and is stored in the battery after being converted to direct current by the inverter.



Figure 4 Configuration of the THS

Figure 5 Comparison of Efficiency of Engine

When the battery charge is insufficient, the battery is charged by the generator. Unlike EVs, the new system does not need to be charged externally.

Figure 5 shows a comparison of efficiency of engines during city driving mode, between a conventional gasoline vehicle and THS-mounted vehicle.

3. Hybrid transmission

The transmission, newly developed exclusively for the THS, incorporates a motor and a generator. By controlling generator speed, the hybrid transmission realizes smooth changes in gear ratio as with a CVT (Continuous Variable Transmission). Engine stop/start during running and electricity generation by the engine enhance the efficiency of the system. The generator functions both as an alternator and a starter, so that the system is simple and compact.

The transmission is composed of four axes. On the first axis, a damper/limiter, a generator, a torque split device and a motor are arranged in this order from the engine. For speed reduction and torque multiplication, chain, counter gear and final gear are provided between the first and the second axes, between the second and the third axes, and between the third and the fourth axes, respectively. On the fourth axis, differential gear is placed.

Figures 6 and 7 show the cross section and outline of transmission, respectively.



Figure 6 Cross Section of Transmission

Figure 7 Outline of Transmission

4. Motor specifications

Table 1 shows the main specifications of the motor.

The drive motor, producing most driving force, is characterized by its compact size, light weight and high efficiency. To provide drivers with a smooth feeling during operation and to achieve high system efficiency, it covers a wide driving range from low speed high torque to high speed low torque. When the brakes are applied, the motor converts kinetic energy to electric energy and stores it in the battery. A permanent-magnet type AC

synchronous motor is adopted to achieve higher performance, higher reliability and downsizing. To cool the motor, a water cooling system is adopted.



Before the placement of the PRIUS on the US and European markets, the drive motor has been improved. The performance curve, shown in Figures 8 and 9, indicates that both output power and torque are enhanced, and at the same time, electric and mechanical losses have been decreased. This means that higher efficiency has been achieved. Figure 10 shows a comparison of the various losses at a representative point of city driving mode between the new and previous models. A significant reduction of inverter loss and mechanical loss can be seen.





Figure 9 Comparison of Output Power



New Model Previous Model

Figure 10 Comparison of Motor Loss

Main improvements of the motor for the new model:

- Adoption of 1-pulse switching control in the high revolution range to ensure higher output power and higher efficiency
- Improvement in electromagnetic circuit design to ensure higher output power and higher efficiency
- Reduction in mechanical loss
- Enhancement in manufacturing productivity and noise reduction

Characteristics and improvements of the new motor are described in the following sections.

5. Rotor configuration

The rotor for general vehicles (Figure 11-1) adopts the SPM (Surface Permanent Magnet) system. Magnets are attached on the surface of the cylindrical rotor core.

The rotor for RAV4-EV, which have been sold by TOYOTA Motor Co. since '96 (Figure 11-2) adopts the reverse salient pole type SPM system. An iron salient pole is provided between the magnetic poles.

The rotor for the PRIUS (Figure 11-3) adopts the reverse salient pole type IPM (Interior Permanent Magnet) system. Magnets are embedded inside the rotor, where electromagnetic steel sheets are laminated to avoid winding on the magnet surface, leading to cost reduction.



The reverse salient pole type rotor has realized higher torque and higher efficiency by adding reluctance torque to magnetic torque. We have optimized the electromagnetic circuit design based on simulation by electromagnetic analysis, so that the IPM rotor efficiently outputs torque. (Figure 12)

Current phase control helps the IPM rotor to output torque efficiently. As Figure 13 shows, magnetic torque is almost in proportion to current value. By controlling the current phase with the current phase angle fixed to 90 degrees ahead of the magnet, the maximum magnetic torque can be obtained. To obtain the maximum torque when reluctance torque is added, the current phase angle to the magnet should be advanced.



Figure 12 Torque Simulation by Electromagnetic Analysis



Figure 13 Torque-Current Phase Angle Characteristic

6. Motor control

6-1. Flux-weakening control for high-speed operation

The permanent-magnet type AC synchronous motor is not appropriate for high speed operation, as it becomes uncontrollable when the motor terminal voltage exceeds the battery voltage due to an increase in induced electromotive force generated by revolutions of the magnet-mounted rotor. By advancing the current phase angle from the maximum torque outputting angle, a flux that suppresses that of magnets is generated. As a result, the terminal voltage is reduced, which enables motor operation in the high-speed range.

6-2.Optimum flux-weakening control (battery voltage follow-up)

As described above, in the high-speed range, the motor terminal voltage is controlled by flux-weakening control not to exceed the battery voltage. In the flux-weakening control range, motor efficiency is lower than at the maximum torque outputting current phase angle. With regard to hybrid vehicles, voltage sharply fluctuates in accordance with remaining capacity of batteries and power volume taken from batteries. Therefore, by frequently conducting the minimum flux-weakening control in accordance with battery voltage, high efficiency has been achieved. (Figure 14)



Revolution Speed



6-3. One-pulse switching control

The motor of the previous PRIUS was controlled using the PWM (Pulse Width Modulation) switching method. The improved motor of the new PRIUS is controlled using the PWM switching method in the low-speed range and the 1-pulse switching method in the high-speed range. By adopting the 1-pulse switching method in the high-speed range, 27% higher basic wave voltage can be applied to the motor, compared with the PWM switching method. As a result, the output of the motor is increased from 30 kW to 33 kW (Figure 9). Figure 15 shows the outline of the 1-pulse switching control.

Based on the 1-pulse switching method, the design of the electromagnetic circuit has been reviewed to further enhance the efficiency of the system. An increase in number of turns leads to a drop in the current, reducing both inverter loss and copper loss. Generally, however, an increase in the number of turns increases torque if the current level is the same, but in the high-speed range, increases induced electromotive force and reduces output. The 1-pulse switching method is adopted to make up for the reduction of output.

Figure16 shows a comparison of electric efficiency at a representative torque value between the new and previous models of the PRIUS. The improvement of efficiency in low-speed range is significant, which means the actual fuel consumption is noticeably improved.



Figure 15 Outline of 1-pulse switching control

Comparison of Electric Efficiency

7. Reduction of mechanical loss

Figure 17 shows a cross section of the motor.

With regard to the motor for previous the PRIUS, the gear section is separated from the motor and generator chamber to prevent transmission oil from entering the motor (generator) chamber. However this is not favorable in terms of fuel efficiency, as the sealing structure increases dragging torque.

The resin material has been changed in the improved motor for the new PRIUS to enhance the oil resistance of the motor body; therefore, the oil seals are no longer required and friction of the bearing is reduced. This leads to reduction of mechanical loss.

In addition, by reducing loss of oil pump and loss of oil stirring, mechanical loss of the overall transmission (including torque split device) can be reduced by approximately 40%. (Figure 18)



8. Enhancement of manufacturing productivity, noise reduction

For the previous generator for the PRIUS, thermal resistance between the coils and the case is reduced by combining the stator and the case using resin to obtain high cooling performance. However, there are several issues, including heavy body weight and a complicated production process.

With regard to the new type of generator, to solve these issues, resin molding is limited to the stator. As a result, enhancement of manufacturing productivity, noise reduction and lighter weight can be achieved. (Figure 19)

On the other hand, lower cooling performance due to increase in thermal resistance is compensated by reduction in loss from the generator by improving the electromagnetic design.



Figure 19 Resin Molding

• Enhancement of manufacturing productivity

- The following improvements have been achieved by limiting resin molding to the stator.
- 1. Heating energy and heating/cooling time required for molding are reduced.
- 2. Cost and weight are reduced as the mass of the resin is reduced.
- 3. Case machining process is simplified.
- For the previous model, to correct deformation of the case caused by molding, a finishing process is required after molding. For the new model, however, this process is omitted.
- Noise reduction

In most cases, electromagnetic noise is caused by the vibration of the stator in the radius direction, transmitted to the case. For the previous generator of the PRIUS, the stator and case vibrate simultaneously, because resin combines them.

By limiting resin molding to the stator, the vibration, directly transmitted via resin, is reduced, and noise of the new type generator can be reduced by approximately 10 dB, compared with the conventional model. In addition, the vibration level of the stator is further reduced by optimizing the shape of magnets and rotor based on electromagnetic simulations. As a result, noise reduction of approximately 20 dB in total can be achieved. (Figure 20)



Figure 20 Vibration Characteristics

9. Conclusions

The hybrid vehicle, the "PRIUS," placed on the Japanese market by Toyota Motor Corporation for the first time in the world, has managed to popularize advanced technology. Before introducing it to the US and European markets, we have improved its engine, motor and transmission to achieve higher output power and higher fuel efficiency. This paper describes technologies and improvements in the new drive motor and the generator for the THS. The main characteristics of the improved motor and generator are as follows:

- Permanent magnet-embedded rotor for higher output power, improved efficiency and down- sizing
- Optimum flux-weakening control in accordance with battery voltage for higher efficiency
- 1-pulse switching control for higher output power and efficiency in high revolution range
- Oil seal-less motor for lower mechanical loss

10. References

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