TOYOTA HYBRID SYSTEM

THS II

TOYOTA

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The new Prius features THS II, Toyota's next-generation hibrid technology

Introduction

New levels of environmental & power performance compatibility based on the concept of Hybrid Synergy Drive

At the 2003 New York Auto Show, TMC President Cho unveiled the all-new Prius with THS II, a "Hybrid Synergy Drive" concept that delivers both higher power and greater fuel economy than the previous Prius.

In search of the ultimate eco-car

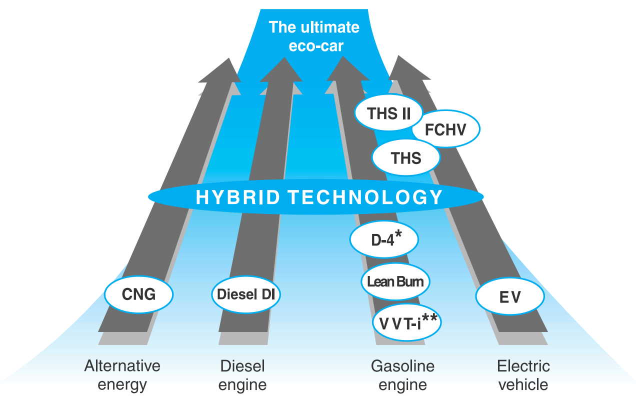
Toyota Hybrid System II (THS II)

Toyota's mission has always been to provide clean and safe products. Thus, the company has positioned the environment as one of its most important issues and has been working toward creating a prosperous society and a world that is comfortable to live in. With this goal in mind, Toyota has been actively developing various new technologies from the perspective of achieving energy security and diversifying energy sources, which is necessitated by the dwindling supply of petroleum resources. For example, in motive power sources for automobiles alone, we have been continuously improving conventional engines and have developed and commercialized **lean-burn gasoline engines**, **direct injection gasoline engines** and **common rail direct-injection diesel engines**, etc. We have also been modifying engines so that they can use alternative fuels, such as **compressed natural gas (CNG)**, instead of gasoline or light oil, and have been installing these engines in commercially sold vehicles. Toyota has also developed and has been marketing **electric vehicles (EV)** that use motors for the driving source; **hybrid vehicles (HV)** that combine an engine and a motor, fusing the advantages of these two power sources; **fuel cell hybrid vehicles (FCHV)** that use fuel cells (FC) to generate electricity based on a chemical reaction between hydrogen and the oxygen in the air and that supply this electricity to electric motors to produce driving power.

In January 1997, Toyota declared the start of the Toyota Eco Project. As part of this effort, Toyota decided to tackle the international challenge of reducing CO^2 emissions in order to prevent global warming and accelerated the development of a hybrid vehicle with the goal of achieving twice the fuel efficiency of conventional vehicles. Then, in March of the same year, Toyota announced the completion of a new power train called the **Toyota Hybrid System (THS)** for use in passenger vehicles. This power train combines a gasoline engine and an electric motor, and because it does not require external charging, as do existing electric vehicles, it works within existing infrastructures such as fueling facilities. This system also achieves nearly twice the fuel efficiency of conventional gasoline engines.

THS was installed in the passenger vehicle **Prius**, which was introduced in December 1997 in the Japanese market as the first mass-produced hybrid passenger vehicle in the world. In 2000, overseas marketing of the Prius began. The **Prius** has gained a reputation as a highly innovative vehicle, and its cumulative worldwide sales have exceeded 110,000 units. Meanwhile, **THS** has continued to evolve, and in 2001, THS-C, which combines THS with CVT (continuously variable transmission), was installed in the Estima Hybrid minivan and THS-M (a mild hybrid system) was installed in the Crown, luxury sedan, both for the Japanese market thereby contributing greatly to innovations in the automobiles of the 21st century.

This is all part of our search for the ultimate eco-car.



* Direct Injection 4-stroke Gasoline Engine
** Variable Valve Timing with Intelligence

Building on the ecology-focused **THS**, Toyota has developed the concept of **Hybrid Synergy Drive**. Based on this concept, Toyota has developed a new-generation Toyota hybrid system called **THS II**, which achieves high levels of compatibility between environmental performance and power by increasing the motor output by 1.5 times, greatly boosting the power supply voltage and achieving significant advances in the control system, aiming for synergy between motor power and engine power.

Toyota has positioned hybrid technology as its key technology. Beginning with the development of EVs and through the commercialization of **HV**s and **FCHV**s, its continued efforts have now culminated in the development of **THS II**. Toyota will continue to endeavor to make technical advances in this area.

What is a Hybrid System?

Fusion between an internal combustion engine and electric motor—achieving different functions through different power combinations

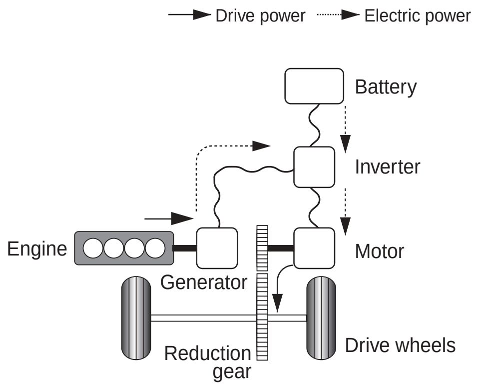
Automobile hybrid systems combine two motive power sources, such as an internal combustion engine and an electric motor, to take advantage of the benefits provided by these power sources while compensating for each other's shortcomings, resulting in highly efficient driving performance. Although hybrid systems use an electric motor, they do not require external charging, as do electric vehicles.

3 types of Hybrid Systems

The following three major types of hybrid systems are being used in the hybrid vehicles currently on the market:

1) SERIES HYBRID SYSTEM

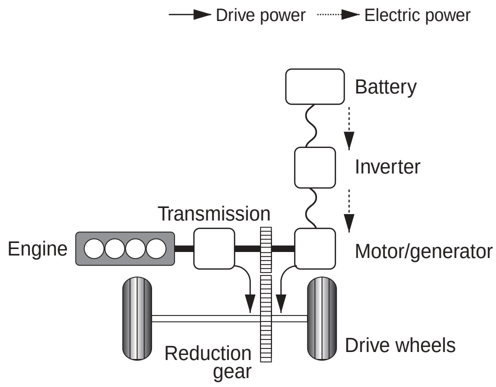
The engine drives a generator, and an electric motor uses this generated electricity to drive the wheels. This is called a series hybrid system because the power flows to the wheels in series, i.e., the engine power and the motor power are in series. A series hybrid system can run a small-output engine in the efficient operating region relatively steadily, generate and supply electricity to the electric motor and efficiently charge the battery. It has two motors—a generator (which has the same structure as an electric motor) and an electric motor. This system is being used in the Coaster Hybrid.



Series hybrid system

2) PARALLEL HYBRID SYSTEM

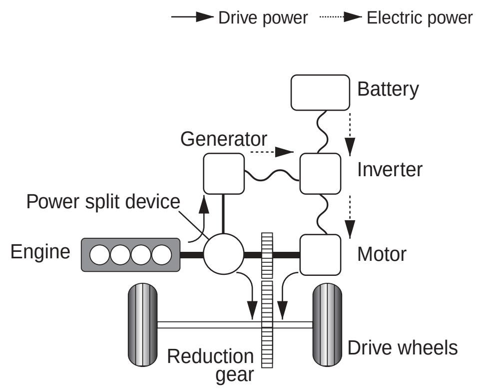
In a parallel hybrid system, both the engine and the electric motor drive the wheels, and the drive power from these two sources can be utilized according to the prevailing conditions. This is called a parallel hybrid system because the power flows to the wheels in parallel. In this system, the battery is charged by switching the electric motor to act as a generator, and the electricity from the battery is used to drive the wheels. Although it has a simple structure, the parallel hybrid system cannot drive the wheels from the electric motor while simultaneously charging the battery since the system has only one motor.



Parallel hybrid system

3) SERIES/PARALLEL HYBRID SYSTEM

This system combines the series hybrid system with the parallel hybrid system in order to maximize the benefits of both systems. It has two motors, and depending on the driving conditions, uses only the electric motor or the driving power from both the electric motor and the engine, in order to achieve the highest efficiency level. Furthermore, when necessary, the system drives the wheels while simultaneously generating electricity using a generator. This is the system used in the Prius and the Estima Hybrid.



Series/parallel hybrid system (THS in Prius)

Engine and Motor Operation in each system

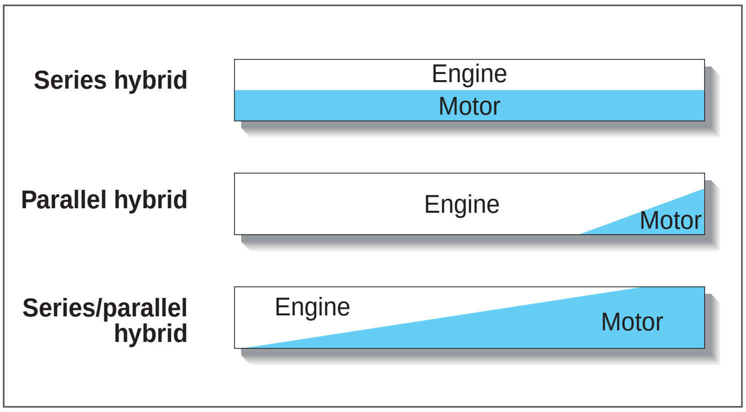
The chart below shows how the ratio of use between engine and motor differs depending on the hybrid system.

Since a series hybrid uses its engine to generate electricity for the motor to drive the wheels, the engine and motor do about the same amount of work.

A parallel hybrid uses the engine as the main power source, with the motor used only to provide assistance during acceleration. Therefore, the engine is used much more than the motor.

In a series/parallel hybrid (THS in the Prius), a power split device divides the power from the engine, so the ratio of power going directly to the wheels and to the generator is continuously variable. Since the motor can run on this electric power as it is generated, the motor is used more than in a parallel system.

Ratio of engine and motor operation in hybrid systems (conceptual diagram)



Characteristics of Hybrid Systems

Hybrid systems possess the following four characteristics:

1) ENERGY-LOSS REDUCTION

The system automatically stops the idling of the engine (idling stop), thus reducing the energy that would normally be wasted.

2) ENERGY RECOVERY AND REUSE

The energy that would normally be wasted as heat during deceleration and braking is recovered as electrical energy, which is then used to power the starter and the electric motor.

3) MOTOR ASSIST

The electric motor assists the engine during acceleration.

4) HIGH-EFFICIENCY OPERATION CONTROL

The system maximizes the vehicle's overall efficiency by using the electric motor to run the vehicle under operating conditions in which the engine's efficiency is low and by generating electricity under operating conditions in which the engine's efficiency is high.

The series/parallel hybrid system has all of these characteristics and therefore provides both superior fuel efficiency and driving performance.

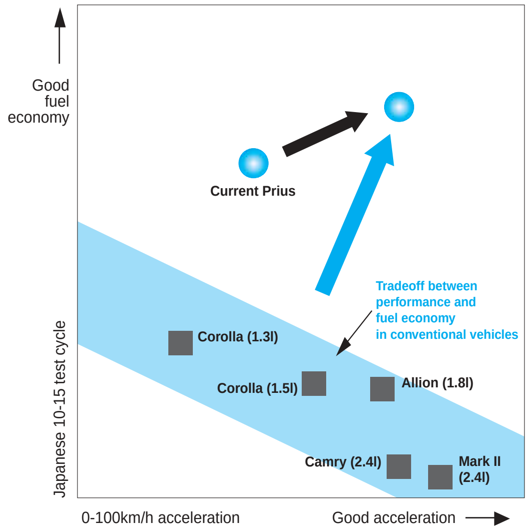
Hybrid system comparison

	Fuel economy improvement				Driving performance	
	Idling stop	Energy recovery	High-efficiency operation control	Total efficiency	Acceleration	Continuous high output
Series	●	◎	●	●	○	○
Parallel	●	●	○	●	●	○
Series/ parallel	◎	◎	◎	◎	●	●

◎ Excellent ● Superior ○ Somewhat unfavorable

Three Objectives of THS II Development

A new-generation hybrid system that seeks enhanced efficiency and greater power



Compatibility of Environmental & Power Performance

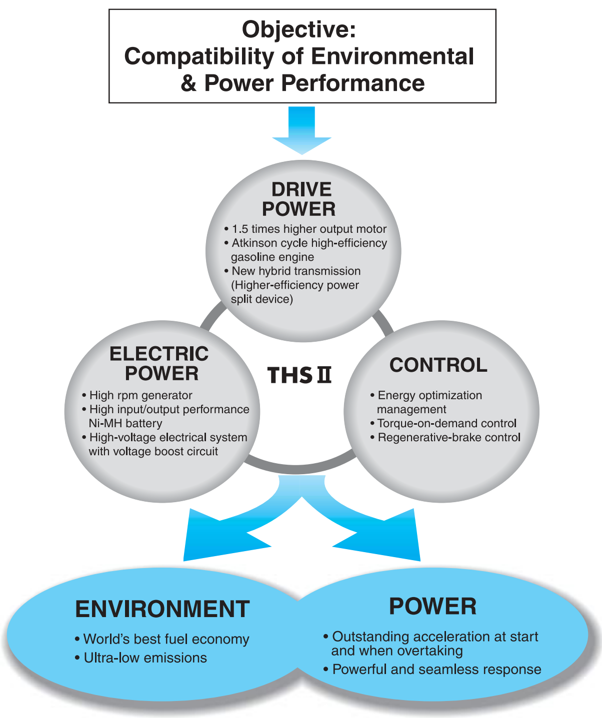
Automobiles of the future must increase both environmental and safety performance, while significantly increasing the all-important motor vehicle characteristic of being fun to drive. To achieve superior driving performance, which is the basis for driving enjoyment, the conventional approach has been to increase output and torque by increasing engine displacement or using supercharging. However, this approach decreases fuel efficiency, making it difficult to achieve compatibility of environmental performance and power. In other words, fuel efficiency and power are in a trade-off relationship. By using the Toyota Hybrid System (THS), the Prius was able to escape the inevitability of this relationship in a paradigm shift. The goal of the Hybrid Synergy Drive concept is to achieve compatibility of high levels of both environmental performance and power.

THS, which is a series parallel hybrid, contains a power split device that splits power into two paths. In one path, the power from the gasoline engine is directly transmitted to the vehicle's wheels. In the other path (electrical path), the power from the engine is converted into electricity by a generator to drive an electric motor or to charge the battery. This unique configuration achieves idling stop, stopping of the gasoline engine while the vehicle is running, running of the vehicle using the electric motor, motor assist at any speed, and highly efficient energy regeneration, without using a clutch or transmission. This is achieved through the use of a motor having large low-speed torque and large output.

The newly developed hybrid system, THS II, targets both greater power and improved motor power transmission efficiency, advancing energy management control for the entire vehicle. As a result, Hybrid Synergy Drive has been developed, which markedly increases power performance, improves acceleration performance, and at the same time achieves the highest degree of environmental performance in the world.

Pursuit of World's Highest Fuel Efficiency

The new hybrid system THS II is based essentially on THS. In a bid for even higher efficiency, the new system adopts a high-voltage power circuit between the motor and generator, and greatly reduces energy loss during energy transmission to deliver optimal energy efficiency. THS II significantly increases the use of the electric motor, and under conditions in which the engine experiences poor efficiency, the engine is stopped and the vehicle runs using only power from the electric motor. Under conditions in which engine efficiency is high, THS II operates the engine at optimal fuel efficiency and generates optimum electricity. It also achieves greater energy regeneration during deceleration and braking, thereby increasing the electricity input/output efficiency, in pursuit of the world's highest fuel efficiency. In terms of environmental performance, THS II aims to meet the ATPZEV (Advanced Technology Partial Zero Emission Vehicle) Regulations in California, U.S.A, which are proposed to go into effect in 2005, the Ultra-Low Emissions Level in Japan, as well as the EURO IV Regulations, scheduled to go into effect in 2004, thus realizing the world's highest level of clean emissions.



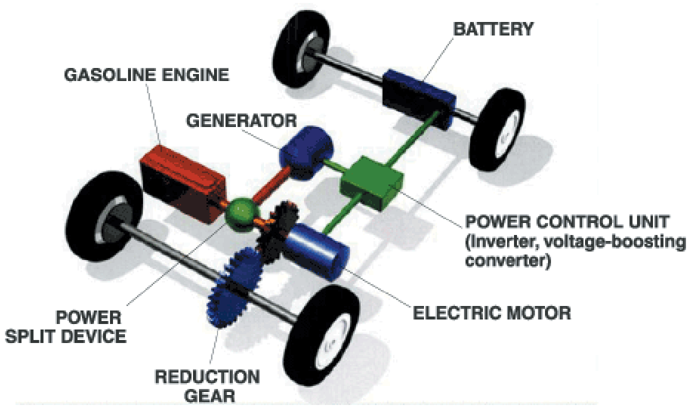
Innovative Hybrid Vehicle Driving Experience

THS II boasts by 1.5 times more power from the motor thanks to a higher rpm of the engine, motor, and generator. It adopts a high-voltage power circuit and a higher-performance battery for increased power supply. As a result, the motor power and engine power together provide a more powerful yet smoother running performance.

How the THS II System Works

Superb coordination between engine and motor

Motor power is used for starting the vehicle. For normal operation, the engine and the motor are optimally controlled to increase fuel efficiency. When powerful acceleration is needed, the high-output motor and the engine generate optimum power. This represents further evolution in smooth yet powerful running performance.

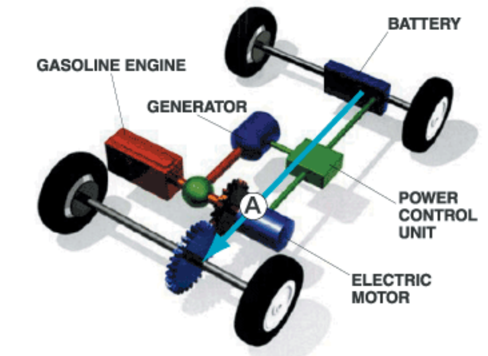


System Configuration

All of the major components of THS II have been developed by Toyota on its own. The high-voltage power circuit, the motor, the generator and the battery have all been designed anew, enabling further evolution of the hybrid system.

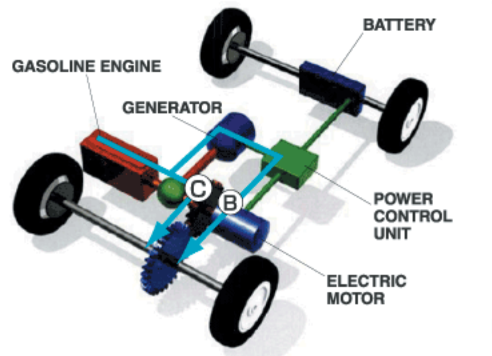
The system consists of two kinds of motive power sources, i.e., a high-efficiency gasoline engine that utilizes the Atkinson Cycle, which is a high-expansion ratio cycle, as well as a permanent magnet AC synchronous motor with 1.5 times more output, a generator, high-performance nickel-metal hydride (Ni-MH) battery and a power control unit. This power control unit contains a high-voltage power circuit for raising the voltage of the power supply system for the motor and the generator to a high voltage of 500 V, in addition to an AC-DC inverter for converting between the AC current from the motor and the generator and the DC current from the hybrid battery. Other key components include a power split device, which transmits the mechanical motive forces from the engine, the motor and the generator by allocating and combining them. The power control unit precisely controls these components at high speeds to enable them to cooperatively work at high efficiency.

System Operation



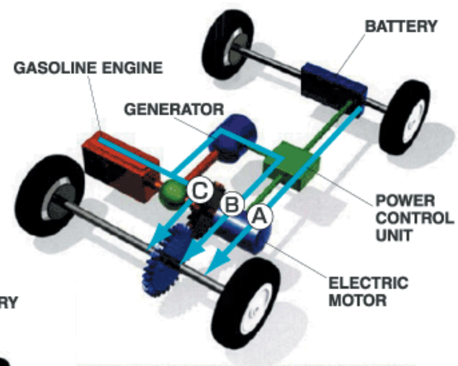
1 Start and low to mid-range speeds

The engine stops when in an inefficient range, such as at start-up and in low to mid-range speeds. The vehicle runs on the motor alone. (A)



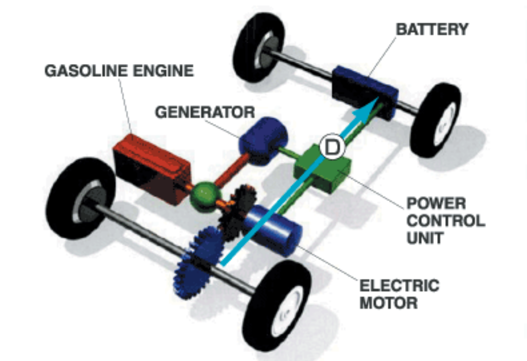
2 Driving under normal conditions

Engine power is divided by the power split device. Some of the power turns the generator, which in turn drives the motor. (B)
The rest of the power drives the wheels directly. (C)
Power allocation is controlled to maximize efficiency.



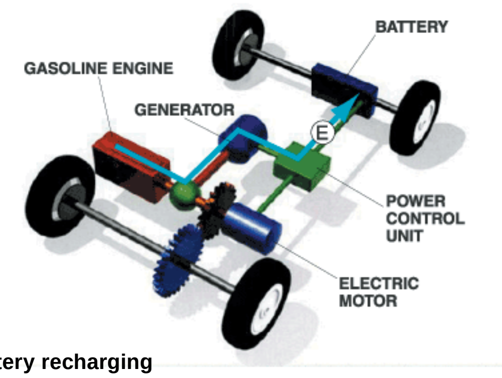
3 Sudden acceleration

Extra power is supplied from the battery (A), while the engine and high-output motor provide smooth response (B+C) for improved acceleration characteristics.



4 Deceleration, braking

The high-output motor acts as a high-output generator, driven by the vehicle's wheels. This regenerative braking system recovers kinetic energy as electrical energy, which is stored in the high-performance battery. (D)



5 Battery recharging

Battery level is managed to maintain sufficient reserves. The engine drives the generator to recharge the battery when necessary. (E)

6 At rest

The engine stops automatically.

High-voltage systems — motor and generator

Greater motor output through increased voltage

High-voltage Power Supply System

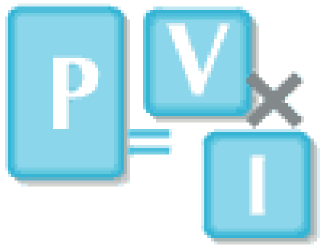
HIGH-VOLTAGE POWER CIRCUIT

The high-voltage power circuit is a new technology that supports the new THS II system. By providing a newly developed high-voltage power circuit inside the power control unit, the voltage of the motor and the generator has been increased from 274V in THS to a maximum of 500V in THS II. As a result, electrical power can be supplied to the motor using a smaller current, thus contributing to an increase in efficiency.

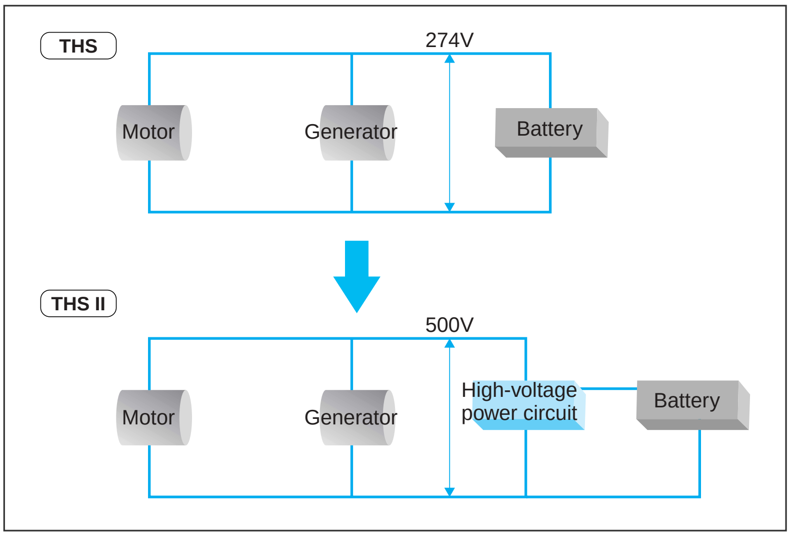
POWER (P) = VOLTAGE (V) X CURRENT (I)

Power, which expresses the work performed by electricity within a given amount of time, is calculated by multiplying voltage by current. If the power necessary for driving the motor is held constant, the above formula indicates that doubling the voltage reduces the current by 1/2.

Next, by following Joule's Law (Calorie = Current^{2}x Resistance), the power loss in terms of calories is reduced to 1/4 (1/2 Current x 1/2 Current) if the resistance is held constant. The high-voltage power circuit in THS II increases power by increasing the voltage while keeping the current constant. Furthermore, for the same power level, increasing the voltage and reducing the current reduces energy loss, resulting in higher efficiency.



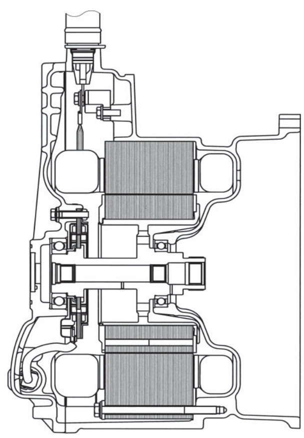
High-voltage electrical system



Motor

The motor has been developed based on the technologies that Toyota has nurtured while working on electric vehicles. THS II uses an AC synchronous-type motor, which is a high-efficiency DC brushless motor with AC current. Neodymium magnets (permanent magnets) and a rotor made of stacked electromagnetic steel plates form a high-performance motor. Furthermore, by arranging the permanent magnets in an optimum V-shape, the drive torque is improved and the output is increased. This, combined with a larger power supply achieved by an increase in the power supply voltage, has increased power output by approximately 1.5 times from THS, i.e., to 50 kW from 33 kW, even with a motor of the same size, producing the highest output per unit of weight and volume in the world.

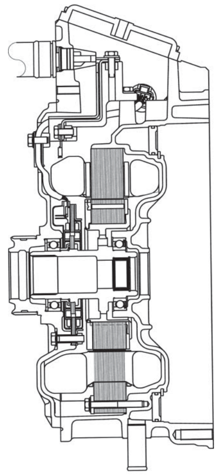
For motor control, a newly developed over-modulation control system has been added to the medium-speed range, in addition to the existing low- and high-speed control methods. By improving the pulse width modification method, the output in the medium-speed range has been increased by a maximum of approximately 30%.



Motor cross-sectional view

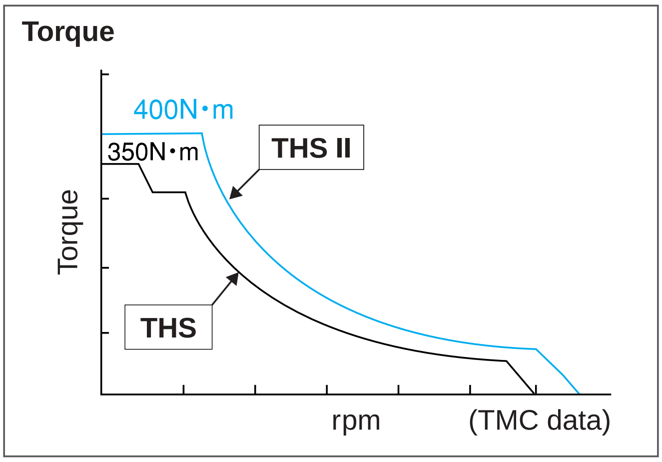
Generator

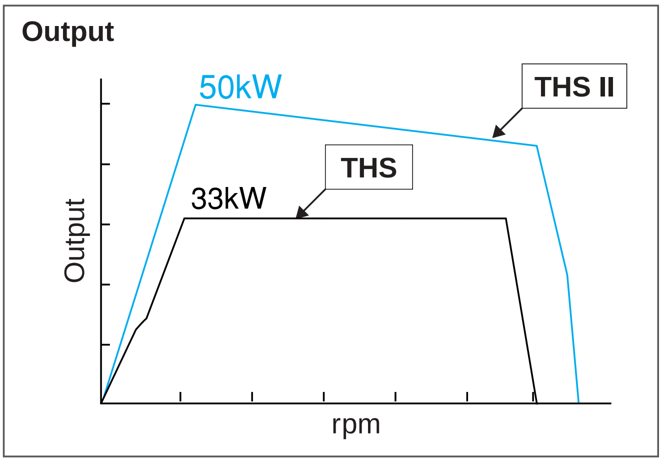
Like the motor, the generator is also an AC synchronous type. In order to supply sufficient power to the high-output motor, the generator is rotated at high speeds, increasing its output. Measures such as rotor strength enhancement have increased the rpm range for the maximum possible output from 6,500 (in the conventional type) to 10,000 rpm. This high rpm has significantly increased the power supply up to the medium-speed range, improving the acceleration performance in the low/medium-speed. As a result, an optimum combination of a high-output motor and an engine has been achieved.



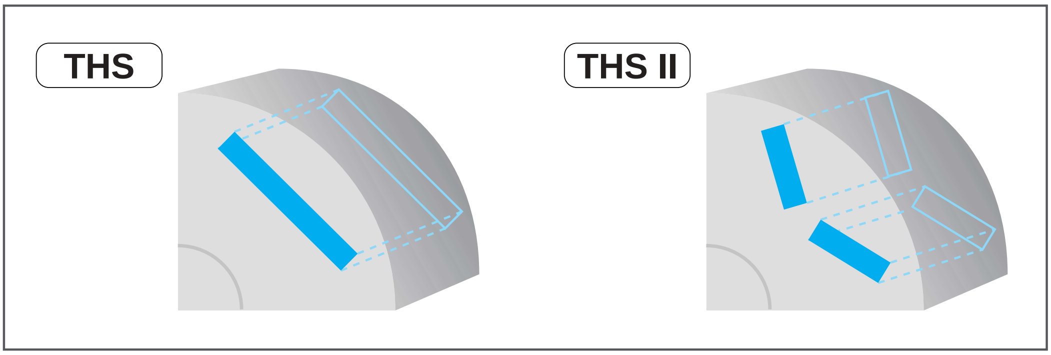
Generator cross-sectional view

Motor performance curves

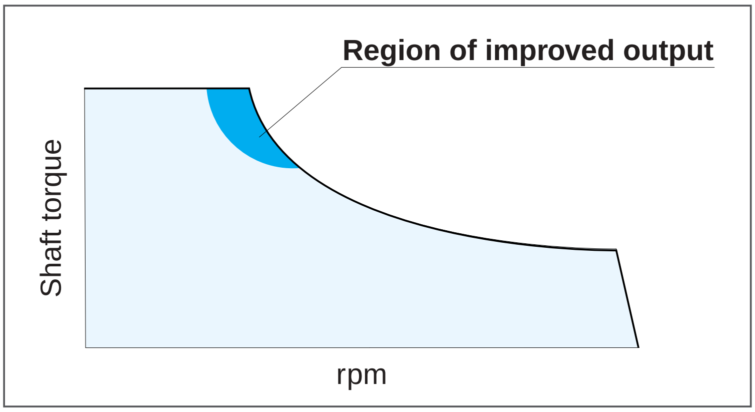




Permanent magnet shape (conceptual diagram)



Effect of over-modulation control



Power Control Unit, Battery and Regenerative Braking System

The world's highest output density

Power Control Unit

The power control unit contains an inverter that converts the DC from the battery into an AC for driving the motor and a DC/DC converter for conversion to 12V.

In THS II, a high-voltage power circuit that can increase the voltage from the power supply to 500V, has been added. Based on the relationship of Power = Voltage x Current, increasing the voltage makes it possible to reduce the current, which in turn makes it possible to reduce the size of the inverter.

Also, because the control circuits have been integrated, the size of the power control unit itself has remained almost the same as before.

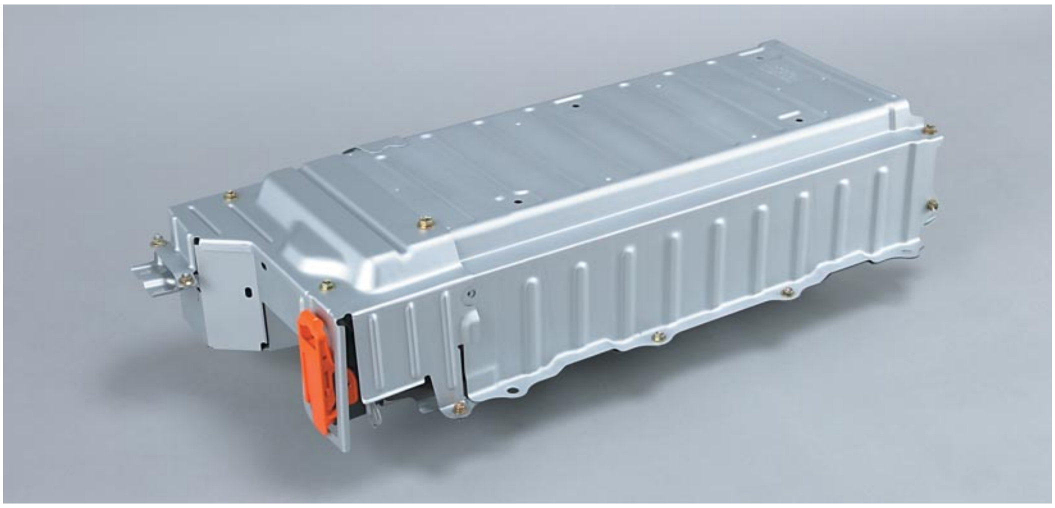
Power control unit

Semiconductor Switching Device (IGBT)

This semiconductor switching device (IGBT: Insulated Gate Bipolar Transistor) boosts the voltage from the battery and converts the boosted DC power into AC power for driving the motor. Since the current that must be switched is large, minimizing heat generation is important. Therefore, Toyota has developed a unique transistor finely tuned down to the crystal level. This device is 20% smaller than the similar device used in THS and has achieved low heat generation and high efficiency.

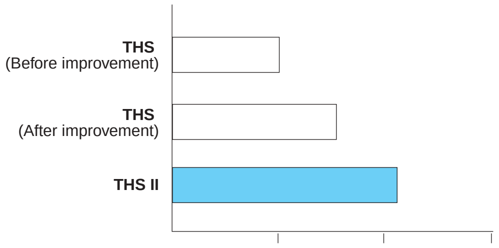
Hybrid Battery

In THS II, further enhancements have been made to the compact, high-performance nickel-metal hydride battery developed for THS. Having reduced the battery's internal resistance by improving the electrode material and by using an entirely new connection structure between (battery) cells, the new battery's input/output density is 35% better than the battery used in THS, achieving the highest output density (output per unit of weight) in the world. To maintain a constant charge, the new battery is discharged or receives charging energy from the generator and the motor, and therefore does not require external charging, as do electric vehicles.



Battery

Battery output density comparison



Note: The Japanese-market Prius was upgraded in August 2002.

INVERTER AND CONVERTER

An inverter is a device that converts a direct current (DC) from a battery into an alternating current (AC). When DC is converted into AC, it can be used to drive an AC motor. In THS II, a DC/DC high-voltage power circuit has been added in front of the inverter circuit. Because this converter can boost the voltage, the electrical power increases even at the same current level, resulting in higher output and higher torque for the motor drive.

Regenerative Braking System

A regenerative braking system is used which, during engine braking and braking using the foot brake, operates the electric motor as a generator, converting the vehicle's kinetic energy into electrical energy, which is used to charge the battery. The system is particularly effective in recovering energy during city driving, where driving patterns of repeated acceleration and deceleration are common. When the footbrake is being used, the system controls the coordination between the hydraulic brake of the ECB and the regenerative brake and preferentially uses the regenerative brake, thereby recovering energy even at lower vehicle speeds. Furthermore, by improving the battery input performance, more energy is recovered.

Additionally, by reducing the friction loss in the drive system, such as in the transmission, the energy that used to be lost as driving system loss during deceleration is now recovered, significantly increasing the total amount of recovered energy.

Motor and hydraulic braking allocation