

Development of Multi Stage Hybrid System for New Lexus Coupe

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ABSTRACT

Lexus launched the new hybrid luxury coupe LC500h in 2017 to help enhance its brand image and competitiveness for the new generation of Lexus. During the development of the LC500h, major improvements were made to the hybrid system by adopting the newly-developed Multi Stage Hybrid System, which combines a multi stage shift device with the transmission from the previous hybrid system to maximize the potential of the electrically-controlled continuously variable transmission. Optimum engine and electrical component specifications were designed for the new vehicle and transmission. As a result, the LC500h achieves a 0-to-60 mph acceleration time of 4.7 seconds, with a combined fuel economy of 30.0 mpg while satisfying SULEV emissions requirements. Two controls were constructed to help resolve the issues that arose due to adding the shift device. A model-based shift control that calculates the torque for the electrical components during shifts was established using an optimal control method. The power management control, which ensures the input and output power of the lithium-ion battery in the LC500h, was modified by applying compensators to reduce delays in detecting speeds of electrical components and providing torque request to the electrical components. Additionally, a control simulating a ten-speed transmission was established to enhance dynamic drivability in line with the intentions of the driver when accelerating, to eliminate the rubber band effect using the characteristics of the shift device.

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1. INTRODUCTION

Hybrid systems that combine multiple power sources have been developed and installed in a wide range of vehicles around the world as part of measures to help conserve the global environment from vehicle emissions and reduce consumption of fossil fuel energy sources. These systems include various different configurations. The Lexus Hybrid Drive (LHD) system, which was first adopted in Lexus vehicles in 2006, is a hybrid system comprising of an engine, an electrically-controlled continuously variable transmission (ECVT) that incorporates a power split device and two motor/generators, and a high-voltage battery that supplies power to the motor/generators via a power control unit (PCU) [1]. The characteristics of this system include high power performance, smooth and quiet drivability, and remarkable environmental performance including both fuel economy and emissions.

The new LC500h hybrid luxury coupe was launched in 2017 to lead the next generation of Lexus vehicles. One role of the hybrid system in this vehicle is to contribute to the brand image and competitiveness of Lexus by enhancing the characteristics of the vehicle. The hybrid system in the LC500h features the newly-developed Multi Stage Hybrid System, which adds a multi stage shift device to the

transmission from the previous hybrid system to maximize the potential of the ECVT in the LHD system. The construction of the system is shown in Fig. 1.

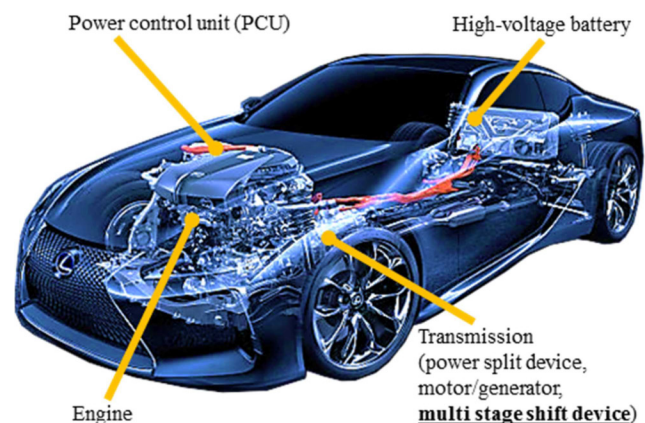


Figure 1. Structure of hybrid system in the LC500h

This paper describes the specifications of the Multi Stage Hybrid System in the LC500h and how this system helps to improve vehicle performance. It also details controls that were developed to help resolve the issues that arose due to adding the shift device, and to maximize the dynamic drivability of the vehicle.

2. OBJECTIVES OF DEVELOPMENT

The development objectives adopting the Multi Stage Hybrid System were following A to D.

- To design specifications and configuration of the new hybrid system so that the LC500h achieves the fastest 0-to-60 mph acceleration time of Lexus hybrid vehicles and class-leading fuel economy for a luxury coupe with satisfying SULEV emissions requirements (Section 3)
- To establish a shift control for the power split device in the system that applies during shifts of the multi stage shift device (Section 4)
- To modify the power management control for the high-voltage battery during shifts of the multi stage shift device (Section 5)
- To establish a control that enables dynamic drivability suitable for a coupe using the characteristics of the new hybrid system, while maintaining smooth and quiet drivability (Section 6)

3. SPECIFICATIONS AND PERFORMANCE OF MULTI STAGE HYBRID SYSTEM FOR THE LC500H

3-1 New Transmission for Multi Stage Hybrid System

The transmission has the important role converting input power to output power. For the Multi Stage Hybrid System, the transmission was modified by adding a multi stage shift device to the previous hybrid system. The cross section of the new transmission is shown in Fig. 2. The hydraulically controlled multi stage shift device was installed between the power split device and the output shaft. The effects of the reduction and overdrive by the shift device are applied to the output of the power split device, thereby improving both the power performance and theoretical efficiency of the hybrid system.

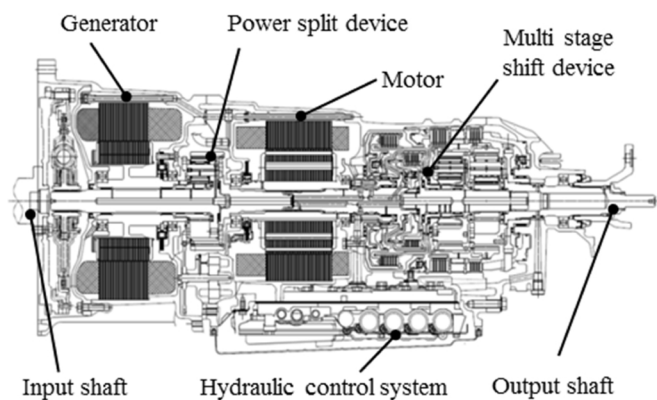


Figure 2. Cross section of new transmission

The reduction effect of the shift device increases the torque transmitted to the output shaft. While the previous hybrid system uses a two-stage motor speed reduction device attached to the motor, which increases only motor torque as shown in Equation 1, the new hybrid system in the LC500h increases both motor and engine torque using multi stage shift device as shown in Equation 2. The amount of

engine torque transmitted to the output shaft in the new system is up to 3.5 times larger than in the previous hybrid system as shown in Fig. 3.

$$T_o = \gamma T_e + T_m \times Gr_m \quad (1)$$

$$T_o = (\gamma T_e + T_m) \times Gr_o \quad (2)$$

Where,

T_o = Output torque

T_e = Engine torque

T_m = Motor torque

Gr_m = two – stage motor speed reduction device gear ratio

Gr_o = Multi stage shift device gear ratio

γ = Coefficient of power split device gear ratio

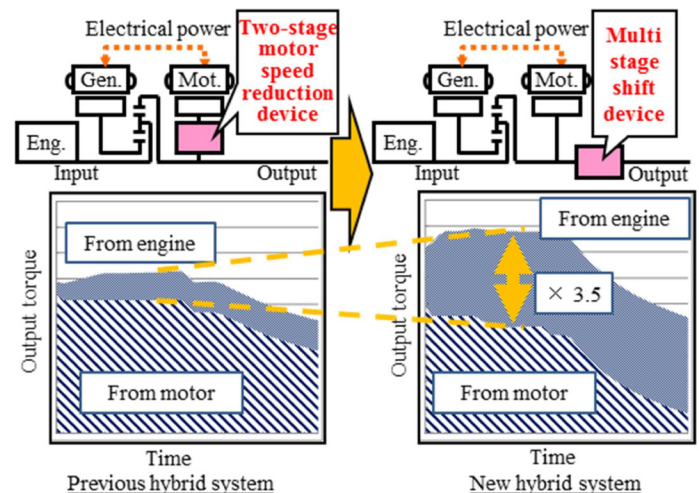


Figure 3. Improvement of output torque

The reduction and overdrive effects create a choice of driving points of the power split device. Figure 4 shows the theoretical efficiency of the previous and new hybrid systems, and frequency of highway drives and city drives. Theoretical efficiency here is efficiency of the transmission calculated with a certain power conversion loss between mechanical and electrical power in motor/generators. While the previous hybrid system has a single efficiency curve, the new hybrid system has multiple efficiency curves. Although the mechanical loss increases because of complexity of the transmission, the overall efficiency of the transmission is improved by the optimally designed number of stages and selection of an optimum stage of the multi stage shift device over a wide input to output speed ratio range. The new hybrid system thus achieves the higher efficiency for both highway drives and city drives.

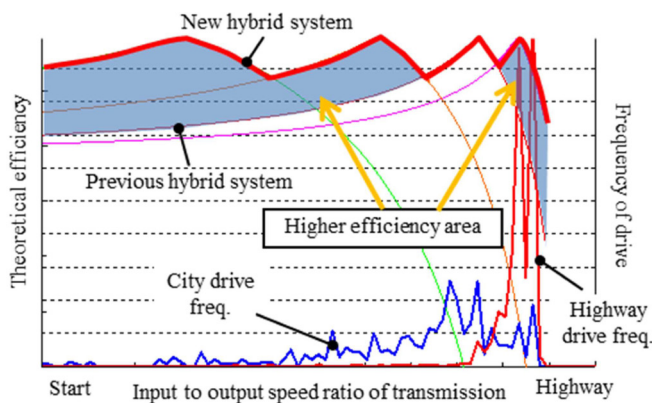


Figure 4. Improvement of theoretical efficiency of transmission

3-2 General Specifications

The general specifications of the new hybrid system are shown in Table 1. The optimum specifications were designed in combination with the characteristics of the new transmission described in the previous section, balancing both power and environmental performance. A smaller V6 engine was chosen instead of a V8 engine, and the maximum engine speed was increased from 6,000 to 6,600 rpm to boost its power. A lithium-ion battery was selected since this type of battery has higher energy and power capacities than a nickel-metal battery.

Table 1. General specifications of LHD with Multi Stage Hybrid System in the LC500h

Engine	Type	8GR-FXS (3.5 L V6)
	Max. output	220 kW @6600 rpm
	Max. torque	350 Nm @5100rpm
Motor	Type	Permanent magnet motor
	Max. output	132 kW
	Max. torque	300 Nm
	Max. speed	9300 rpm
High-voltage battery	Type	Lithium-ion
	Voltage	310.8 V
PCU	Max. voltage	650 V
Power split device gear ratio		0.436
Differential gear ratio		3.357

3-3 System Configuration

The system configuration is shown in Fig. 5. The arrangement of the ECUs is basically the same as in the 4th generation Prius, except the battery ECU, which was separated into a main ECU and a satellite battery module (SBM) to enable a more compact battery package [2]. The hybrid system controller, hybrid driving controller, and shift device controller to control the transmission were modified greatly in line with the modifications to the transmission.

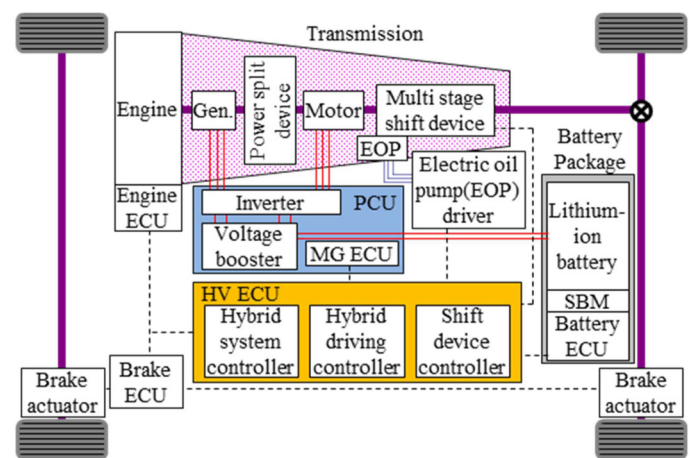


Figure 5. Hybrid system configuration

3-4 Performance

Based on the specifications and configuration of the new hybrid system, the high performance was achieved as shown in Fig. 6. The 0-to-60 mph acceleration time was improved to 4.7 seconds, 13 % faster than existing Lexus hybrid vehicles. The LC500h also achieved a combined fuel economy of 30.0 mpg (city: 26.0 mpg and highway: 35.0 mpg) while satisfying SULEV emissions requirements.

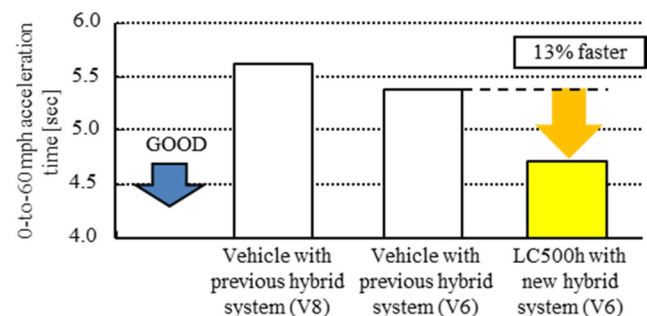


Figure 6. Acceleration performance of the LC500h

4. MODEL-BASED SHIFT CONTROL FOR POWER SPLIT DEVICE AND ELECTRICAL COMPONENT

One of the main issues in the development of the Multi Stage Hybrid System was the construction of the shift control for the power split device. The power split device in the LHD system consists of a planetary gear set with the engine, motor, and generator each attached to a component of the planetary gear set. In the previous hybrid system, the output of the power split device is proportionally connected to the output shaft of the transmission, which is connected to the heavy inertia of the vehicle. In contrast, in the new hybrid system, the output of the power split device is disconnected from the output shaft during shifts of the shift device. Therefore, in the new