

Development of a Plug-In Hybrid Powertrain System with Double Continuously Variable Transmissions

Cheng-Chi Yu, Chi-Shiun Chiou

Abstract—This study developed a plug-in hybrid powertrain system which consisted of two continuous variable transmissions. By matching between the engine, motor, generator, and dual continuous variable transmissions, this integrated power system can take advantages of the components. The hybrid vehicle can be driven by the internal combustion engine, or electric motor alone, or by these two power sources together when the vehicle is driven in hard acceleration or high load. The energy management of this integrated hybrid system controls the power systems based on rule-based control strategy to achieve better fuel economy. When the vehicle driving power demand is low, the internal combustion engine is operating in the low efficiency region, so the internal combustion engine is shut down, and the vehicle is driven by motor only. When the vehicle driving power demand is high, internal combustion engine would operate in the high efficiency region; then the vehicle could be driven by internal combustion engine. This strategy would operate internal combustion engine only in optimal efficiency region to improve the fuel economy. In this research, the vehicle simulation model was built in MATLAB/Simulink environment. The analysis results showed that the power coupled efficiency of the hybrid powertrain system with dual continuous variable transmissions was better than that of the Honda hybrid system on the market.

Keywords—Plug-in hybrid power system, fuel economy, performance, continuous variable transmission.

I. INTRODUCTION

WITH the advancement of technology, the vehicle has become an integral part of modern life for the transport. But the oil reserves for the engine fuel have been gradually reduced which caused the rise of oil prices. The emissions of internal combustion engine (ICE), such as CO, CO₂ and NO_x, are causing damage to people's health and the environment. Following the economic and environmental concern, people start to rethink the new vehicle power source. Since there is no exhaust emission during the driving of electric vehicle (EV), the EV becomes the ideal transportation of vehicle development. But with today's technology, EV still has many technology bottlenecks that need to be improved, such as driving distance, expensive batteries, battery charging time, etc. To retain the advantages of EVs and improve its existing shortages, the hybrid electric vehicle (HEV) becomes the solution.

HEVs can improve fuel economy and reduce vehicle

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emissions, and it does not have the shortages of EVs. It is the best intermediate solution for today's ICE vehicles before the technology of EV being matured. In recent years, the auto makers, such as Toyota, GM, Honda, are focusing on the development of HEVs. GM Volt and Toyota Camry, strong HEVs, use planetary gears as the power distribution mechanism between ICE, traction motor, and generator [1]. The advantage of using planetary gear is relatively smooth during the power shifting, but disadvantage is more complex control. Honda i-MMD system, a plug-in HEV, uses one clutch to integrate the power sources, ICE and traction motor. The use of clutch is relatively simple and low cost, but more shock during the power shifting.

Although HEVs are widely application on the market, the power coupled efficiency in power sources is still relatively low. As shown in Table I, the power coupled efficiency of Toyota and Honda HEVs is about 68.0% and 76.5% respectively [2], [3], where actually integrated power is the capable power provided by the system, theoretically integrated power is the sum of engine power and motor power, and power couple efficiency is defined as the ratio of actually integrated power to theoretically integrated power. That means the mechanisms applied in HEVs cannot completely couple the power provided from power sources. In this study, a new plug-in hybrid powertrain system which consisted of two continuous variable transmissions (CVTs) is developed. This integrated power system can take advantages of components, improves power couple efficiency, and decreases the required specification of power sources. The performance between this new hybrid powertrain system and Honda system will be present.

TABLE I
POWER COUPLED EFFICIENCY OF HEVS

	TOYOTA Camry [2]	HONDA Accord [3]
Engine Power (kW)	117	105
Motor Power (kW)	105	125
Actually Integrated Power (kW)	151	176
Theoretically Integrated Power (kW)	222	230
Power Coupled Efficiency (%)	68.0	76.5

II. HYBRID SYSTEMS

The mathematical models of both Honda I-MMD system and dual CVT hybrid system were presented in the following. The mathematical models of dual power sources, the transmission system, and vehicle dynamics were also constructed in this section.

A. Honda I-MMD System

Honda I-MMD system consists of an Atkinson cycle engine and an e-CVT with built-in motor and generator [3], which is the benchmark of this study and was used in Honda Accord

hybrid. This system can be operated in three operation modes explained below. The power and energy transmission path was shown in Fig. 1.

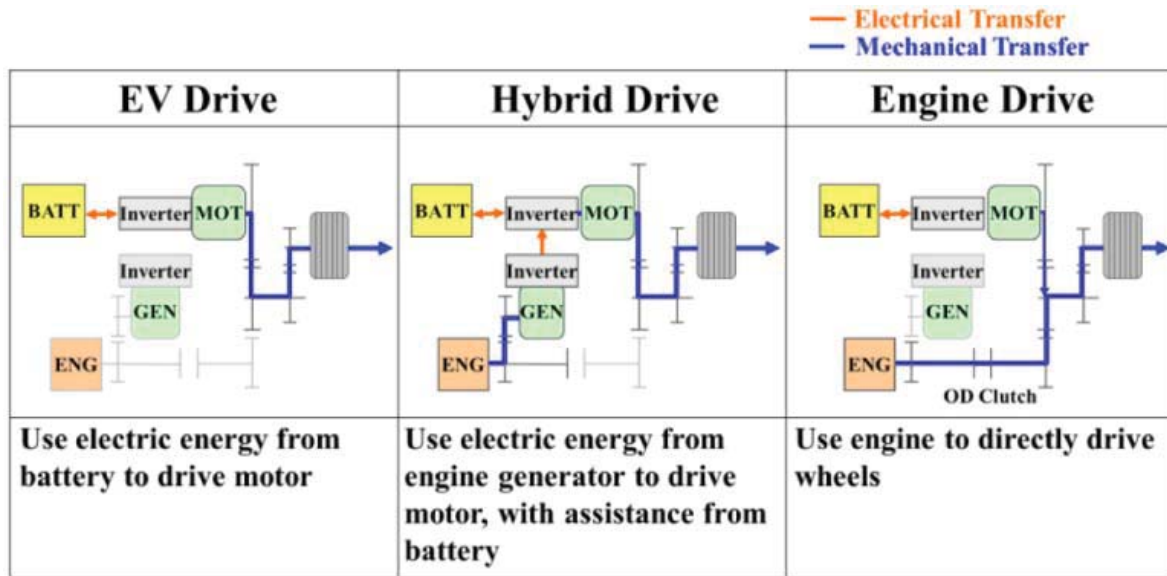


Fig. 1 Operation modes of Honda I-MMD system [3]

“EV Drive” mode: The electric motor (MOT) physically connected to the driveshaft propels by using electric energy stored in the high voltage battery (BATT). Equation (1) was the equation formula of this driving mode where ω_f and ω_m were the speed of the final shaft and the motor; T_f and T_m were the torque acting on the final shaft and the output torque of motor; P_f , P_m , and P_b were the power input to the final shaft, power output from the motor and the battery; η , η_{inv} and η_m were the efficiency of the gear, the inverter and the motor, respectively; r_m was the gear ratio of the motor.

$$\begin{aligned}
 \omega_m &= \omega_f \cdot r_m \\
 T_m &= T_f / (r_m \cdot \eta) \\
 P_m &= P_f / \eta \\
 P_b &= P_m / (\eta_{inv} \cdot \eta_m)
 \end{aligned}
 \tag{1}$$

“Hybrid Drive” mode: The electric motor is driven by electric energy generated by the generator (GEN) using output from the engine (ENG). Equation (2) was the equation formula of this driving mode where ω_e and ω_g were the speed of the ICE and the generator; T_e and T_g were the output torque of ICE and the torque acting on the generator; P_e , P_g and P_b were power output from the engine, the power input to the generator, and the power charging into the battery, respectively; r_g was the gear ratio of the engine.

$$\begin{aligned}
 \omega_m &= \omega_f \cdot r_m \\
 \omega_e &= \omega_g / r_g \\
 T_m &= T_f / (r_m \cdot \eta) \\
 T_e &= T_g \cdot r_g / \eta \\
 P_m &= P_f / \eta \\
 P_g &= P_e \cdot \eta \\
 P_b &= P_m / \eta_{inv} + P_g \cdot \eta_{inv}
 \end{aligned}
 \tag{2}$$

“Engine Drive” mode: The engine-drive clutch located between the engine and wheels is engaged, and the vehicle is directly propelled by the engine output. In this mode, the engine provides main power, and the motor is used to adjust power output by discharging or charging the high voltage battery. Equation (3) was the equation formula of this driving mode, where η_c was the efficiency of the clutch:

$$\begin{aligned}
 \omega_f &= \omega_e / r_e = \omega_m / r_m \\
 \begin{cases} T_f = (T_m \cdot r_m + T_e \cdot r_e \cdot \eta_c) \cdot \eta, & \text{if } T_m \geq 0 \\ T_f = T_m \cdot r_m / \eta + T_e \cdot r_e \cdot \eta_c \cdot \eta, & \text{if } T_m < 0 \end{cases} \\
 \begin{cases} P_f = (P_m + P_e \cdot \eta_c) \cdot \eta, & \text{if } P_m \geq 0 \\ P_f = P_m / \eta + P_e \cdot \eta_c \cdot \eta, & \text{if } P_m < 0 \end{cases} \\
 \begin{cases} P_b = P_m / \eta_{inv}, & \text{if } P_m \geq 0 \\ P_b = P_m \cdot \eta_{inv}, & \text{if } P_m < 0 \end{cases}
 \end{aligned}
 \tag{3}$$

B. Dual CVT Hybrid System

The new dual CVT hybrid system consists of two CVT, one

electromagnetic clutch, one ICE, one traction motor (MG2), and one generator (MG1), as shown in Fig. 2. With the switch on clutch, the two power sources can operate alone, or can be integrated to drive the vehicle. Dual CVT Hybrid system provided four different driving modes including EV alone, series, parallel, and engine alone, where the first three modes are the same as those of Honda I-MMD system. The different between them is that some gears used in Honda I-MMD system are replaced with CVT. Because CVT can directly adjust the operating point of engine according to the vehicle loading, dual CVT Hybrid system proposed an extra driving mode, engine alone. When the battery state of charge (SOC) was low, the vehicle would be driven by the engine alone. The power and energy transmission path was shown in Fig. 3. Equations (4)-(7) were the formulae of EV alone mode, series mode, parallel mode, and engine alone mode, respectively where r_{CVT1} and r_{CVT2} were the speed ratio of CVT1 and CVT2; η_{CVT1} and η_{CVT2} were the efficiency of CVT1 and CVT2.

$$\begin{aligned} \omega_m &= \omega_w \cdot r_{CVT2} \\ T_f &= T_m \cdot r_{CVT2} \cdot \eta_{CVT2} \\ P_m &= P_f / \eta_{CVT2} \\ P_b &= P_m / \eta_{inv} \end{aligned} \quad (4)$$

$$\begin{aligned} \omega_m &= \omega_w \cdot r_{CVT2} \\ \omega_e &= \omega_g / r_g \\ T_m &= T_f / (r_m \cdot \eta_{CVT2}) \\ T_e &= T_g \cdot r_g / \eta \\ P_m &= P_f / \eta_{CVT2} \\ P_g &= P_e \cdot \eta \\ P_b &= P_m / \eta_{inv} + P_g \cdot \eta_{inv} \end{aligned} \quad (5)$$

$$\begin{aligned} \omega_f &= \omega_e / r_{CVT1} = \omega_m / r_{CVT2} \\ T_f &= T_m \cdot r_{CVT2} \cdot \eta_{CVT2} + T_e \cdot r_{CVT1} \cdot \eta_{CVT1} \cdot \eta_c \\ P_f &= P_m \cdot \eta_{CVT2} + P_e \cdot \eta_c \cdot \eta_{CVT1} \\ P_b &= P_m / \eta_{inv} \end{aligned} \quad (6)$$

$$\begin{aligned} \omega_e &= \omega_f \cdot r_{CVT1} \\ \omega_g &= \omega_e \cdot r_g \\ \omega_m &= \omega_e \cdot r_{CVT2} / r_{CVT1} \\ T_e &= T_f / (r_{CVT1} \cdot \eta_{CVT1} \cdot \eta_c) \\ P_e &= P_f / (\eta_c \cdot \eta_{CVT1}) \end{aligned} \quad (7)$$

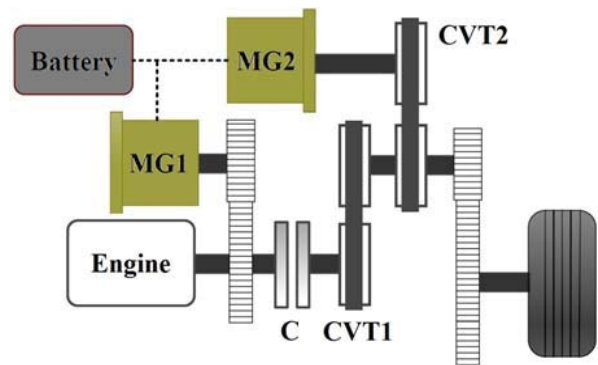
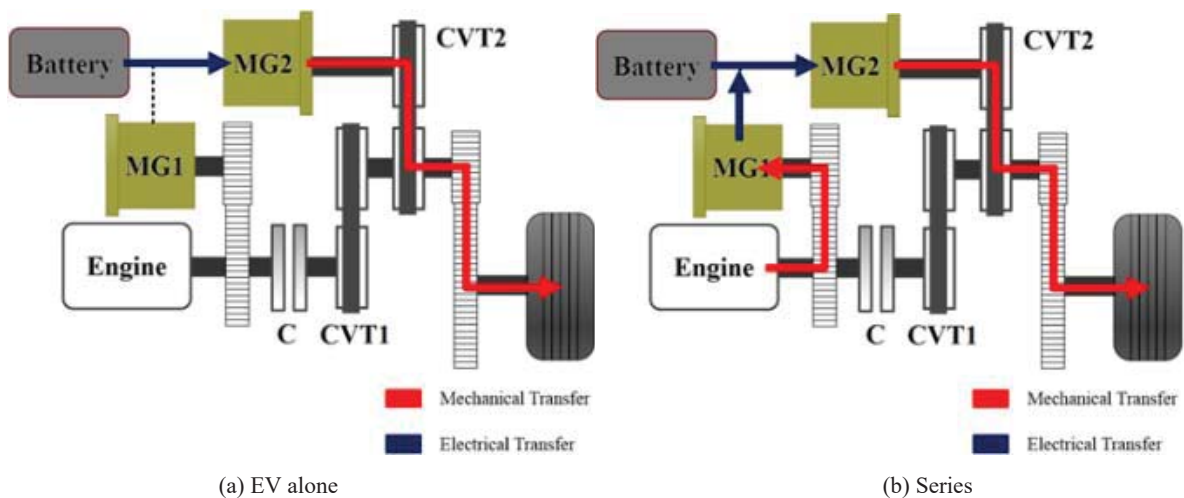


Fig. 2 Dual CVT hybrid system

C. Power Sources

In this study, there were three major power sources, ICE, motor, and generator. These components' data were using the similar data as Advisor model or the same data as Honda model. Depending on the driving condition and battery SOC, the function of motor could be generating or motoring. The efficiencies of motor and generator were shown in Figs. 4 (a) and (b), respectively. The engine performance characteristics were shown in Fig. 4 (c) [4].



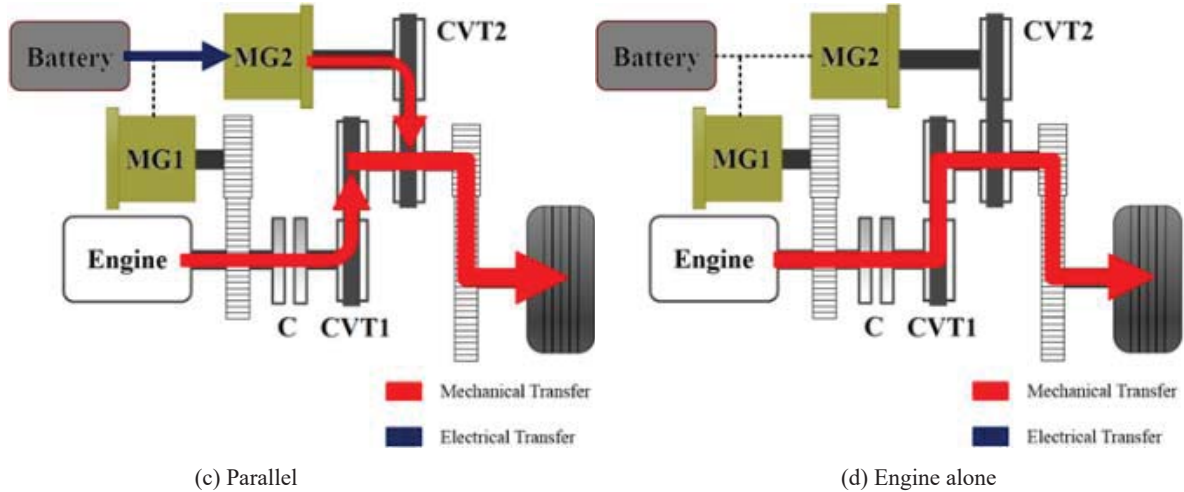
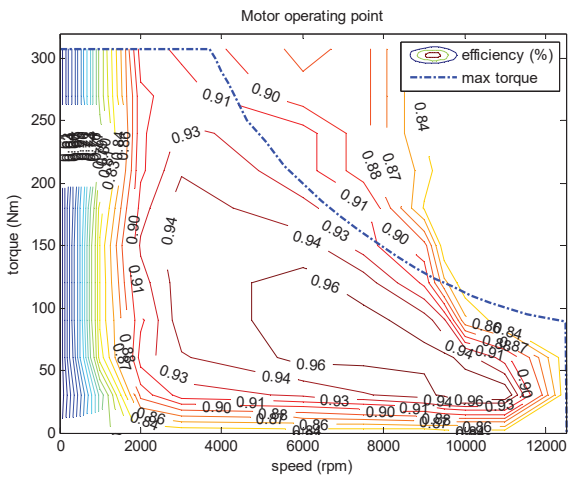
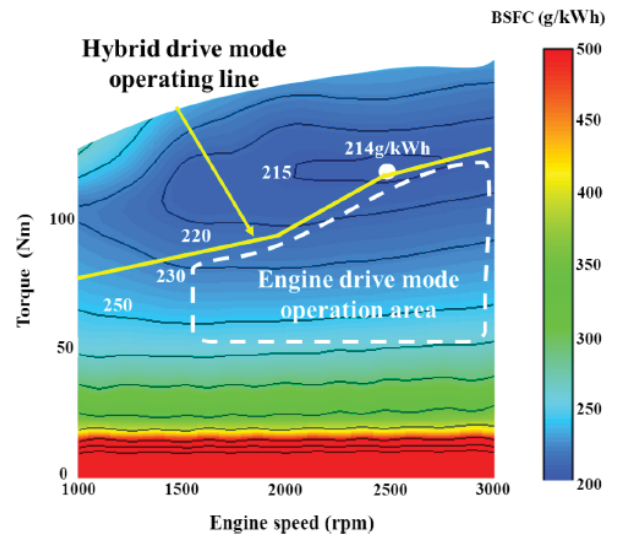


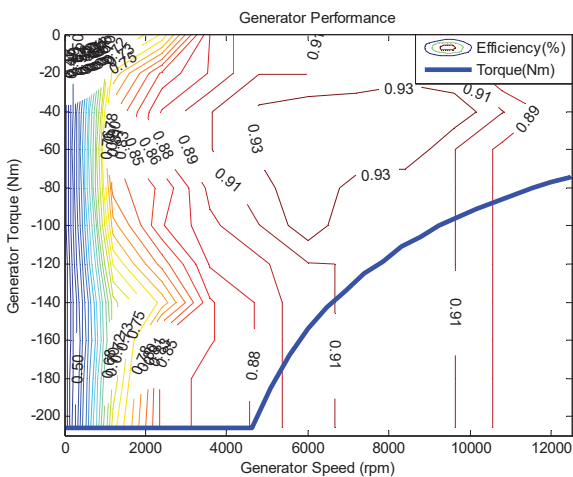
Fig. 3 Operation modes of Dual CVT hybrid system



(a) Motor efficiency



(c) Engine specific fuel consumption [4]



(b) Generator efficiency

Fig. 4 Data maps of motor, generator, and engine

D. CVT and Clutch

The specifications of CVT were listed in Table II [5]. The efficiency of CVT included two parts, speed loss and torque loss. Because the speed loss was only 3%, it should be ignored in this study [6]. The torque loss was presented in Table III [7]. In this study, electromagnetic clutch was applied between engine and CVT.

E. Vehicle Dynamic Equation

The vehicle dynamic equation was presented as (8). Where M , ΔM , a , T_f , r_f , R_w , F_R , F_A , and F_G were vehicle mass, the equivalent mass of rotating parts, acceleration, torque output from power sources, final gear ratio, tire effective radius, rolling resistance, air dynamic resistance, and grade resistance, respectively:

$$(M + \Delta M) \cdot a = T_f \cdot r_f / R_w - F_R - F_A - F_G \quad (8)$$

III. VEHICLE DYNAMIC SIMULATION AND COMPARISON

This section described the control strategy of the hybrid system, and performed dynamic analysis of Honda I-MMD system and dual CVT hybrid system. These simulations were done in Matlab/Simulink environment. The Honda I-MMD system established in this study would be verified with the model announced by other paper.

A. Vehicle Specifications

In this study, Honda Accord hybrid was the reference vehicle, and the vehicle specifications were listed in Table IV [8].

TABLE II
CVT SPECIFICATIONS

Items	Value
Max. Speed	6500
Min. Speed	0
Max. Speed Ratio	2.51
Nin. Speed Ratio	0.5

TABLE III
POWER COUPLED EFFICIENCY OF HEVs

	Low-Input Torque	Mid-Input Torque	High-Input Torque
Low-speed ratio	77%	86%	84%
Mid-speed ratio	80%	89%	86%
High-speed ratio	76%	85%	83%

B. Energy Management Strategy

Energy management strategy was based on the SOC to control the engine operation. There were two cases of SOC conditions [9-10].

Case 1: SOC was high. When engine speed was below the engine idle speed, or vehicle required driving torque was below the engine optimal operating region, engine was shut down. The vehicle was powered by motor. When engine speed was higher than the idle speed, and engine was operating in the optimal region, the vehicle was driven by engine. When engine speed was higher than the idle speed and vehicle driving torque was above the engine limit, both engine and motor provided the required power to drive vehicle.

Case 2: SOC was low. Engine was operated in the optimal region, and the generator was charging the battery. If the vehicle driving torque requirement was above the limit of the engine optimal region, the generator would be turned off.

C. Vehicle Dynamic Simulation

In this study, both hybrid systems, Honda Accord hybrid and dual CVT hybrid, were simulated. The simulation included fuel economy and acceleration performance. The UDDS (Urban Dynamometer Driving Schedule) for CS (charge sustaining) mode was applied for fuel economy simulation, and 0 to 60 mile/hour acceleration was applied for performance simulation.

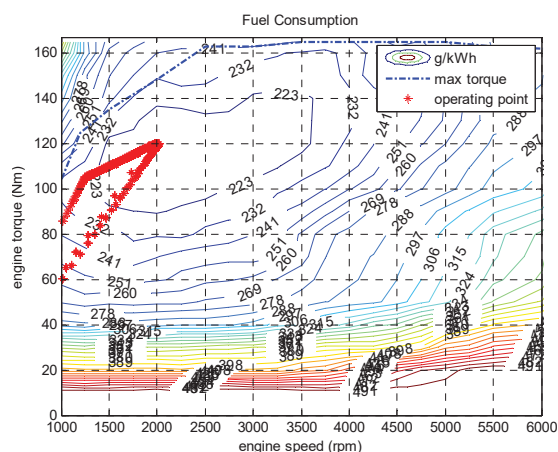
Fuel economy: The engine operating points of two different hybrid systems, Honda Accord hybrid and dual CVT hybrid, were shown in Fig. 5. The Honda Accord hybrid system had better fuel economy comparing with the dual CVT hybrid system, 19.0 km/l to 15.88 km/l.

Acceleration performance: The dual CVT system took 7.5 seconds for 0 to 60 mph acceleration, and the Honda I-MMD

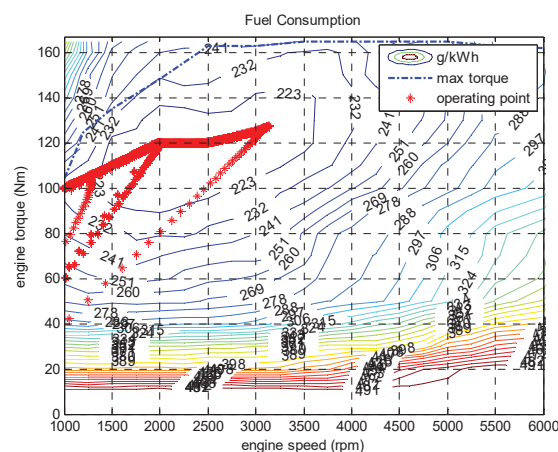
system took 8.75 seconds. The dual CVT hybrid system had better acceleration performance comparing with the Honda Accord hybrid system. The motor operating points of two hybrid systems were shown in Fig. 6.

TABLE IV
VEHICLE SPECIFICATIONS

Items	Value
Mass (kg)	1700
Tire radius (m)	0.319
Front Area (m ²)	2.16
Rolling resistance coefficient	0.015
Air dynamic dragging coefficient	0.29



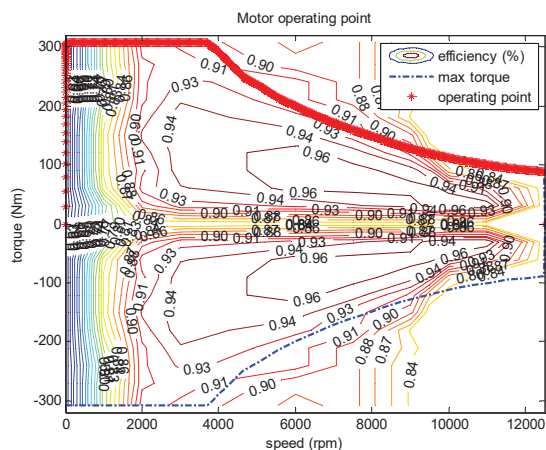
(a) Honda Accord hybrid



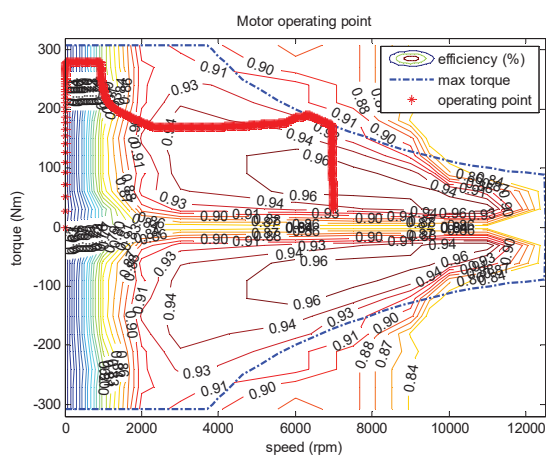
(b) Dual CVT hybrid

Fig. 5 Engine operating points of two hybrid systems

Honda Accord simulation comparison: Comparing the announced model from other paper with Simulink Honda I-MMD model established in this study, the simulation results of fuel economy was similar, 19.64 km/l to 19.36 km/l, and the error between them is just 1.4 %. This verified the accuracy of Simulink model established in this study.



(a) Honda Accord hybrid



(b) Dual CVT hybrid

Fig. 6 Motor operating points of two hybrid systems

IV. MODIFIED DUAL CVT HYBRID SYSTEM

By observing Fig. 6, the operating points of motor between Honda I-MMD system and dual CVT system is different in acceleration performance simulation. When motor speed was over 950 rpm, the output torque of motor in dual CVT system decreased obviously. That means the motor applied in dual CVT system was too large, so this study tried to scale down the motor, from 125 kW to 80 kW. A modified dual CVT hybrid system was the dual CVT hybrid system which made use of a smaller motor applied in Nissan Leaf [11]. At the same time, the weight of the modified dual CVT hybrid system also decreased 50 kg.

After the simulation including fuel economy and acceleration performance was performed, fuel economy data of UDDS and performance data between the three hybrid systems were presented in Table V. Because of lower transmission efficiency of CVT, fuel economy of the modified dual CVT system is still a little worse than Honda i-MMD system but a better than dual CVT system. The modified dual CVT hybrid system still had better acceleration performance comparing with the Honda Accord hybrid system, even though the modified dual CVT system equipped with a smaller motor.

The power coupled efficiency of power sources between hybrid systems was shown in Table VI. Both dual CVT systems had a higher efficiency than Honda i-MMD system. That means the dual CVT mechanisms could more completely couple the power provided from power sources. The modified dual CVT system had a little higher efficiency than the dual CVT system, although it equipped with a smaller motor.

V. CONCLUSION

This study developed a new plug-in hybrid powertrain system which consists of two continuously variable transmissions. By matching between the engine, motor, generator, and dual CVT system, this integrated power system can take advantages of components, and then more completely couple the power provided from power sources, so reduce the cost of power sources. The dual CVT system can be operated in four operation modes-EV alone, series, parallel, and engine alone. The energy management of this integrated system controls the power systems based on rule-based control strategy to achieve better fuel economy. When the vehicle driving power demand is low, the ICE which is operating in the low efficiency region, so the ICE is shut down, and the vehicle is driven by motor only. When the vehicle driving power demand is high, ICE would operate in the high efficiency region. The vehicle could be driven by ICE. When battery state-of-charge (SOC) is too low, Engine is operated in the optimal region, and the generator is charging the battery. This strategy would operate ICE only in optimal efficiency region to improve the fuel economy. In this research, fuel economy test is based on UDDS, and performance estimate is according to vehicle acceleration test. The vehicle simulation model was built in MATLAB/Simulink environment. The analysis and discussion of the simulation results and the comparison of fuel economy and performance between this dual CVT hybrid powertrain system and Honda i-MMD (Intelligent Multi Mode Drive) system were present. Because of lower transmission efficiency of CVT, the fuel economy of dual CVT systems was a little worse than that of Honda i-MMD system, but the performance was better, even though the modified dual CVT system equipped a smaller motor.

TABLE V
COMPARISON OF FUEL ECONOMY AND PERFORMANCE BETWEEN HYBRID SYSTEMS

	I-MMD	Dual CVT	Modified Dual CVT
Fuel economy (km/l)	19.0	15.88	17.55
Acceleration (sec)	8.75	7.5	7.8

TABLE VI
POWER COUPLED EFFICIENCY OF HYBRID SYSTEMS

	I-MMD	Dual CVT	Modified Dual CVT
Engine Power (kW)	105	105	105
Motor Power (kW)	125	125	80
Actually Integrated Power (kW)	176	202	163
Theoretically Integrated Power (kW)	230	230	185
Power Coupled Efficiency (%)	76.5	87.8	88.1

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