

Rapid Prototyping Energy Management System for a Single Shaft Parallel Hybrid Electric Vehicle Using Hardware-in-the-Loop Simulation

Yang Li, Pushkar Agashe, Zicheng Ge and Bo Chen
Michigan Technological Univ.

ABSTRACT

Energy management is one of the key challenges for the development of Hybrid Electric Vehicle (HEV) due to its complex powertrain structure. Hardware-In-the-Loop (HIL) simulation provides an open software architecture which enables rapid prototyping HEV energy management system. This paper presents the investigation of the energy management system for a single shaft parallel hybrid electric vehicle using dSPACE eDrive HIL system. The parallel hybrid electric vehicle, energy management system, and low-level Electronic Control Unit (ECU) were modeled using dSPACE Automotive Simulation Models and dSPACE blocksets. Vehicle energy management is achieved by a vehicle-level controller called hybrid ECU, which controls vehicle operation mode and torque distribution among Internal Combustion Engine (ICE) and electric motor. The individual powertrain components such as ICE, electric motor, and transmission are controlled by low-level ECUs. To examine the performance of hybrid ECU and low-level ECUs, vehicle mode control, speed tracking, energy distribution, regenerative braking, and engine operating region were investigated in the HIL environment with a hardware electric motor controller consisting of dSPACE MicroAutoBox II and the AC Motor Control Solution. The presented work illustrates that the HIL system is a suitable environment for the rapid prototyping of HEV control strategies.

CITATION: Li, Y., Agashe, P., Ge, Z. and Chen, B., "Rapid Prototyping Energy Management System for a Single Shaft Parallel Hybrid Electric Vehicle Using Hardware-in-the-Loop Simulation," *SAE Int. J. Alt. Power.* 2(2):2013, doi: 10.4271/2013-01-0155.

INTRODUCTION

The concern of the depletion of crude oil is forcing researchers around the world to explore new technologies to replace fossil fuel as the main transportation energy source. In addition, more stringent global emission regulations, as well as the green energy theme have pushed the automotive industry to adopt alternative energy technologies. Although the development of batteries are leaping forward to in the past decades, aiming to serve as the main vehicle powertrain energy source, the prices of batteries are still not low enough to replace the conventional internal combustion engine. As a result, popularity of hybrid electric vehicles has increased to fill the gap toward the future full vehicle electrification [1].

Multiple energy sources in the hybrid electric vehicles, however, inevitably introduce more complex control issues such as energy distribution and drivability. Facing the increased complexity, model-based rapid control prototyping has become a standard method for the development and optimization of HEV control applications [2]. The rapid

control prototyping consists of process such as system modeling, control algorithm synthesis, simulation analysis and vehicle implementation. With auto-code generation, the control algorithm is implemented using graphical language instead of manual programming [3, 4]. The high-level programming environment allows researchers to develop complicated and computation-intensive control models and optimize control algorithms as often as needed. The modular characteristics of the controllers facilitate the scalability and the flexibility of control design.

With the hardware-in-the-loop test facilities, the design and test process of powertrain components can be modularized [5, 6, 7]. dSPACE HIL system has Automotive Simulation Model (ASM) to serve as the physical simulation model to provide necessary information for the real time vehicle control. Simulated sensor signals are generated by the I/O boards and outputted to the testing controllers [8, 9, 10]. The control signals from the controllers can also be captured by the simulator to actuate plant model. In this paper, the performance of the hybrid ECU and low-level ECUs for a



Documents

Document Sharing Hub

parallel HEV was evaluated by examining the vehicle performance using a dSPACE HIL system.

The rest of the paper is organized as follows. Section 2 introduces the powertrain and control architecture of a single shaft parallel HEV. Section 3 discusses vehicle operation modes and energy management strategies in hybrid ECU. Section 4 presents the low-level ECUs, including engine ECU, motor ECU, and transmission ECU. Section 5 gives hardware-in-the-loop simulation and HIL simulation setup. Section 6 describes the HIL evaluation results of hybrid ECU and low-level ECUs. Section 7 concludes the presented work.

OVERVIEW OF SINGLE SHAFT PARALLEL HEV POWERTRAIN AND CONTROL SYSTEM ARCHITECTURE

The configuration of the single shaft parallel HEV powertrain is shown in [Figure 1](#). Tractive power can be provided by either a gasoline Internal Combustion Engine (ICE), a Permanent Magnet Synchronous Motor (PMSM), or both of them. The PMSM can operate as a generator to charge battery using the energy from ICE or regenerative braking. A Li-ion battery pack provides and absorbs electrical energy to and from PMSM through DC/AC and AC/DC converters. The ICE, PMSM and gearbox are coupled through a single shaft which contains two clutches to connect or disconnect powertrain components. Clutch 1 between the ICE and PMSM is used for coupling or decoupling the ICE. Clutch 2 and the gearbox form an automatic transmission. The tractive power is delivered to the wheels through the final drive located after the automatic transmission. The specifications for the ICE, PMSM, battery and transmission are listed in [Table 1](#).

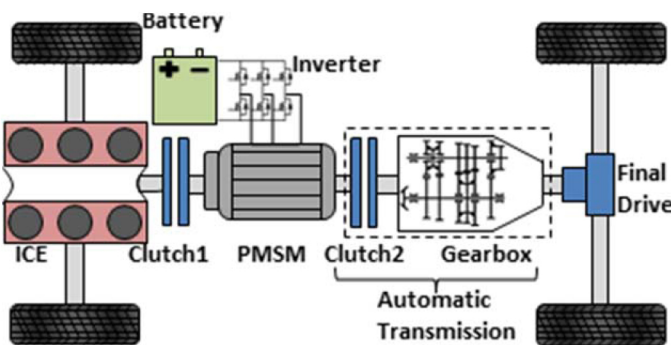


Figure 1. Single shaft parallel HEV powertrain.

Table 1. Specifications of powertrain components.

Engine	Type	2.9 L, 6 cylinder gasoline engine
	Maximum Torque	290Nm @3700rpm
E-motor	Type	Permanent Magnet Synchronous AC motor
	Maximum Torque	120Nm
	Maximum Power	21kW @1200rpm
Battery	Type	Li-ion
	Cell Number	100
	Voltage	360 V
	Peak Current	250A
Transmission	Type	Automatic
	Gear box ratios	3.5/1.89/1.32/1.03/0.86/0.73

The control architecture of the single shaft parallel HEV is shown in [Figure 2](#). The control system consists of a hybrid ECU, an engine ECU, a motor ECU, a transmission ECU, and a battery management system. The hybrid ECU optimizes powertrain energy consumption E , which is affected by the following factors:

$$E = f(T_{req}, v, SOC, R_{Trq}, R_b, R_{gear}, Key_{ICE}, Key_{clutch}) \quad (1)$$

where,

- T_{req} - driver torque request, including traction torque and braking torque
- v - vehicle speed
- SOC - battery State of Charge
- R_{Trq} - traction torque split ratio between ICE and PMSM
- R_b - braking torque split ratio between regenerative braking and friction braking
- R_{gear} - gear ratio of transmission gearbox
- Key_{ICE} - ICE start/stop request
- Key_{clutch} - open/close command of clutch between ICE and PMSM

Hybrid ECU determines R_{Trq} , R_b , R_{gear} , Key_{ICE} , and Key_{clutch} based on current vehicle working conditions, such as T_{req} , v and SOC .

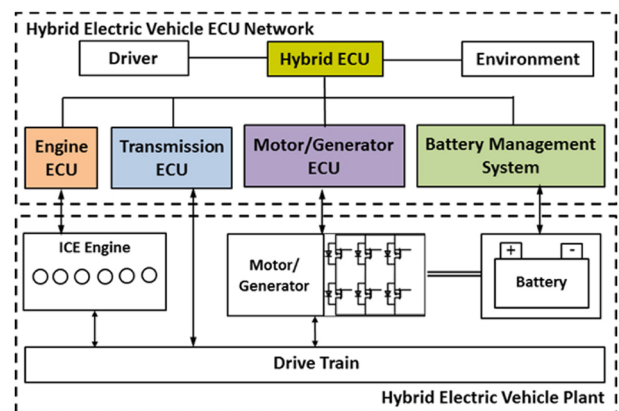


Figure 2. The ECU network of single shaft parallel HEV.

Based on the commands from the hybrid ECU, low-level ECUs control individual powertrain components to fulfill specified performance. For example, engine ECU adjusts throttle position, injection timing and spark timing based on the torque request from the hybrid ECU and current engine working conditions. It can start and stop engine or keep engine running at idle state. The motor ECU controls the PMSM either as a tractive motor or a generator according to the commands from the hybrid ECU. The output power of the motor is controlled by the motor ECU through PWM output signals to the inverter board. The transmission ECU executes shifting logic of the gearbox and determines the open and close of two clutches.

VEHICLE OPERATION MODES AND ENERGY MANAGEMENT STRATEGY IN HYBRID ECU

The single shaft parallel HEV has five operation modes as shown in Figure 3. Figure 3 (a) shows the *electric only mode* in which the PMSM is the only power source of HEV. Since a PMSM has a higher energy efficiency comparing with an ICE, PMSM is used whenever its maximum torque output satisfies powertrain torque demand while battery State Of Charge (SOC) is within a reasonable range. In the *electric only mode*, the ICE is turned off and disconnected from the output shaft. If the driver's power request is beyond the capability of the PMSM or the SOC of the battery is out of a desired range, the ICE will be turned on and connected to the output shaft as shown in Figure 3 (b), (c) and (d). Figure 3 (b) is the *battery charging mode* in which the ICE charges battery and provides tractive power simultaneously. The PMSM operates as a generator in the *battery charging mode* to convert mechanical energy to electrical energy for charging battery. In *engine only model* as shown in Figure 3 (c), the ICE is the only power source of the vehicle. Figure 3 (d) shows the *hybrid mode* in which both ICE and PMSM output power to HEV powertrain. PMSM outputs maximum torque if vehicle torque request is greater than the sum of the optimal engine torque and the maximum electric motor torque. Otherwise, it outputs the torque difference between vehicle torque request and optimal engine torque. In this case, the ICE outputs optimal torque to achieve best fuel economy. Figure 3 (e) shows the *regenerative braking mode*. When vehicle is decelerating, PMSM works as a generator to recover vehicle kinetic energy. In *regenerative braking mode*, the clutch between ICE and PMSM is open and the engine is disconnected from the output shaft.

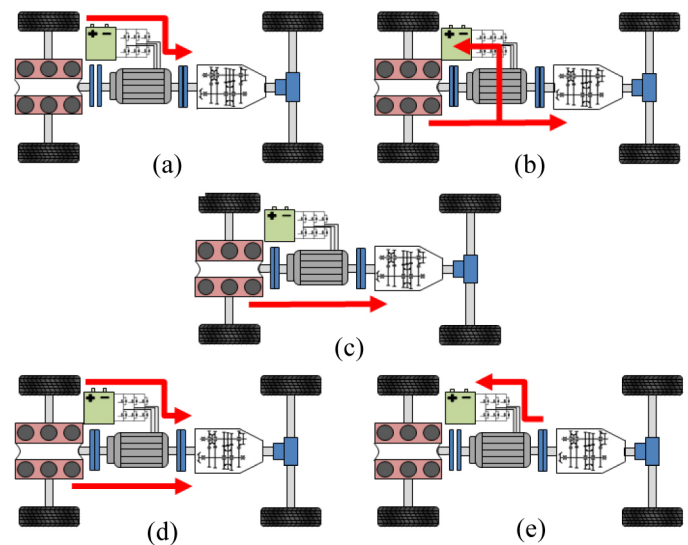


Figure 3. Vehicle operation modes and powertrain energy flow. (a) Electric only mode. (b) Battery charging mode. (c) Engine only model. (d) Hybrid mode. (e) Regenerative braking mode.

The hybrid ECU controls the overall energy flow among individual powertrain components. It optimizes the energy consumption of the entire powertrain while maintaining a desired vehicle performance. The hybrid ECU determines the torque demands for individual powertrain components based on driver's demand, optimum traction, efficiency, battery charge status, comfort and thermal conditions. The battery SOC is also maintained within a desired range through operating the electric motor as a generator recovering energy from regenerative braking or engine charging. Figure 4 shows the vehicle-level hybrid ECU which controls vehicle operation mode and torque distribution. The hybrid ECU model is modified based on the hybrid ECU provided by dSPACE. In the hybrid ECU model, the Accelerator Pedal Position (APP) and Brake Pedal Position (BPP) determine if the vehicle runs in traction or regenerative braking mode. In traction condition, the *electric only mode* is a default vehicle operating mode. However, the engine will be turned on if vehicle torque request is greater than the maximum motor torque or the battery SOC is insufficient to drive the motor. When the gasoline engine is turned on, the hybrid ECU lets the gasoline engine work at an optimal torque as often as possible. If the torque request is greater than the engine optimal torque and the SOC is greater than its minimum value, the motor is turned on for traction and vehicle works in hybrid mode. The motor provides the extra torque request beyond the engine optimal torque. If powertrain torque request is smaller than the engine optimal torque and battery SOC is less than its maximum value, the motor will work as a generator to allow the engine working in the optimal range and the vehicle is in battery charging mode. The third working mode of ICE is engine only mode. In this working mode, engine is the only tractive power source of the vehicle.

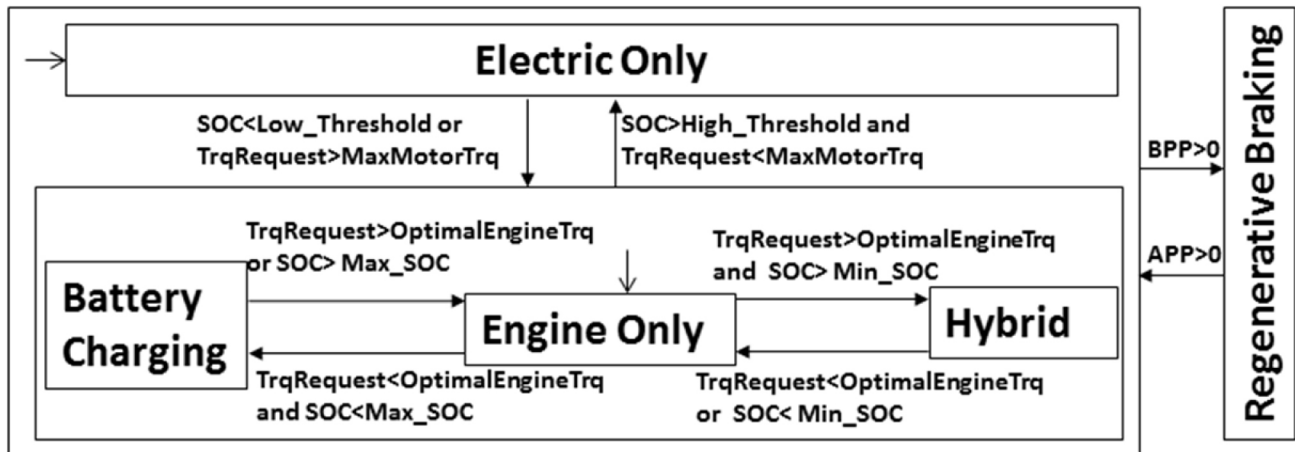


Figure 4. Vehicle operation mode control and transition conditions.

LOW-LEVEL ECU FUNCTIONALITY

dSPACE blockset libraries provide low-level soft ECU (softECU) for the control of engine, motor, or transmission. This section introduces the functionalities of these softECUs.

Engine ECU

Engine control is one of the major control tasks of hybrid electric vehicles. For the HIL simulation, either a softECU or hardware ECU can be used. The dSPACE engine softECU consists of five functional blocks, engine torque calculation, relative air mass calculation, rail pressure control, combustion calculation, and airpath control, as shown in Figure 5. The engine softECU simulates a real ECU to read in engine operational signals such as engine speed and intake manifold pressure, as well as the environmental signals such as temperature and pressure along with the engine torque demand signal. These sensor signals are calculated based on Automotive Simulation Model, a physical model developed by dSPACE company. The engine torque demand is determined by the hybrid ECU. Having known the engine torque demand and real-time engine operating conditions from sensor signals, the engine softECU calculates the ignition timing, injection duration and throttle position based on the rule-based control algorithm in the combustion calculation block. In addition to combustion calculation, the airpath related control tasks and rail pressure control, mainly determining and maintaining the set EGR level, turbo pressure setpoint, and rail pressure, are implemented in this softECU. Users could access to some critical parameters related to EGR, turbocharger and rail pressure control such as the maximum EGR valve flow area and the fuel system high pressure pump volume.

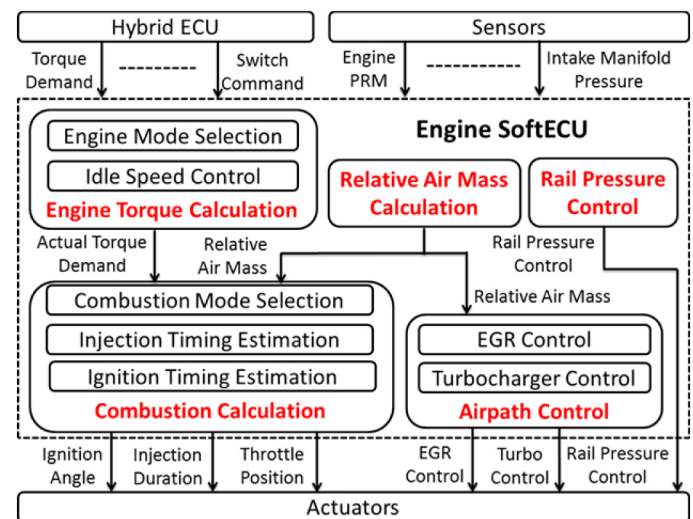


Figure 5. The block diagram of engine ECU.

Motor ECU

Motor ECU controls motor output torque and speed based on torque request from hybrid ECU and desired vehicle speed. The cascade control architecture is adopted in the motor ECU as shown in Figure 6. The inner loop is current/torque loop and the outer loop is speed loop. The current for the PMSM motor are regulated in the dq reference frame. The q -axis current command is generated by the outer loop speed controller and the d -axis current command is set to zero. The current feedback signals from three-phase motor coils, I_a , I_b and I_c , are transformed to dq axes using equation (2). With the current feedback information, the dq current commands are converted into dq voltage commands. The dq voltage commands are then transformed into abc reference frame for the motor ECU to generate three phase high side and low side Pulse Width Modulated (PWM) signals based on the inverter DC bus voltage. The PWM signals are used to control the switches on the each half bridge of inverter to control the