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

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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.

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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 modulized [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 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.

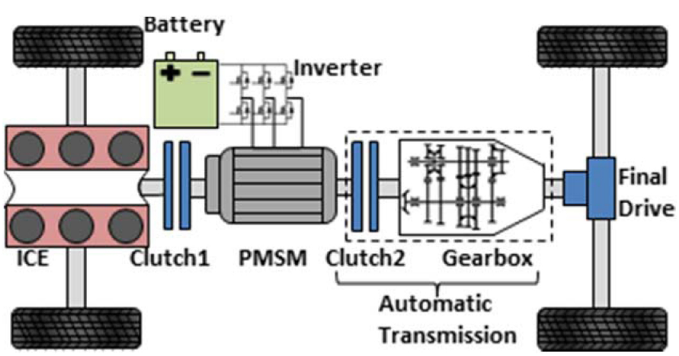

Figure 1. Single shaft parallel HEV powertrain.

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:

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

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.

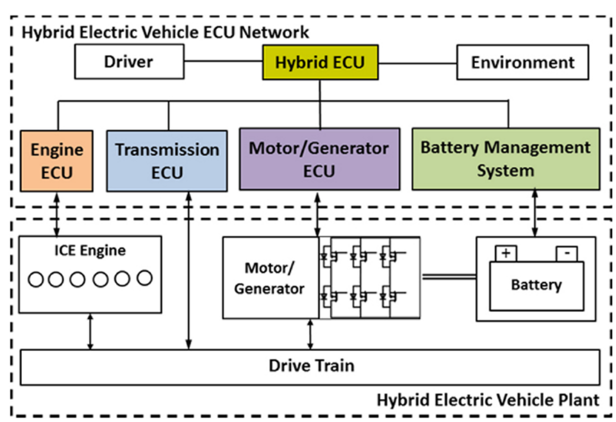

Figure 2. The ECU network of single shaft parallel HEV.

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.

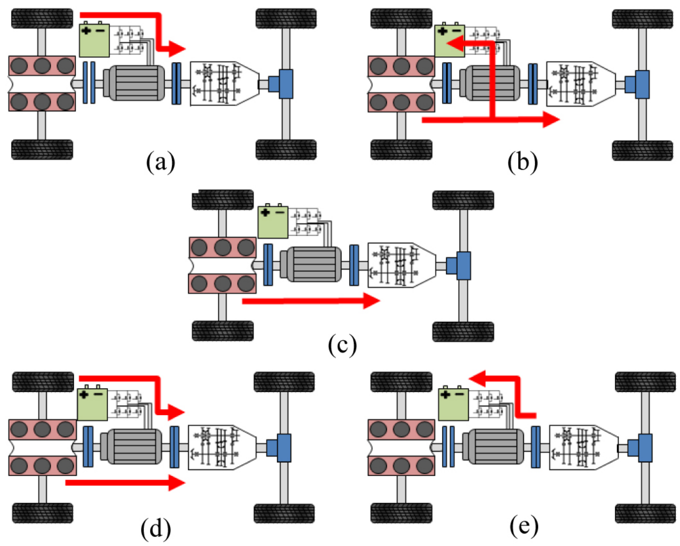

Figure 3. Vehicle operation modes and powertrain energy flow. (a) Electric only mode. (b) Battery charging mode. (c) Engine only model. (d) Hybrid mode. (e) Regenerative braking mode.

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.

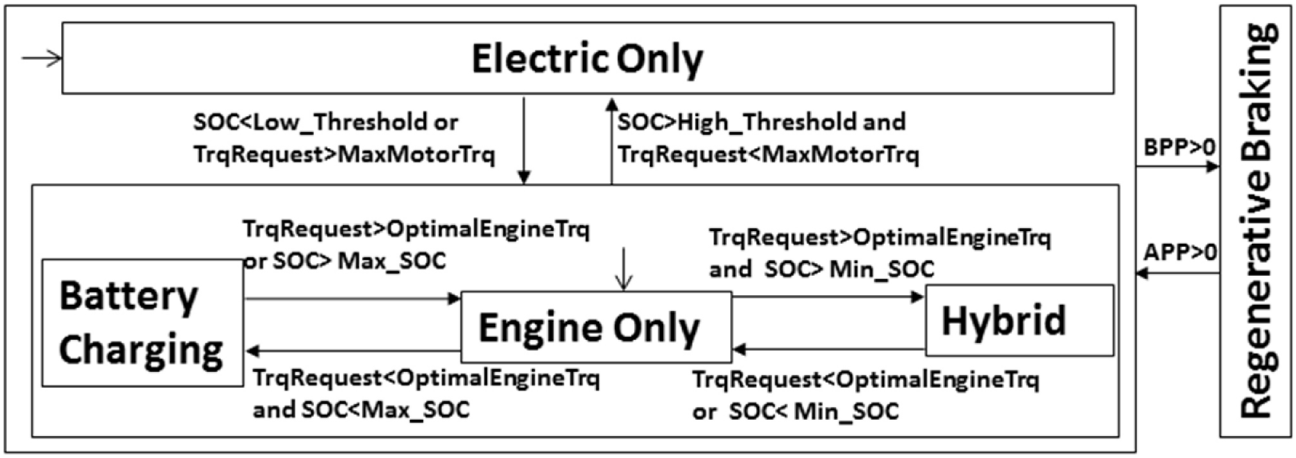

Figure 4. Vehicle operation mode control and transition conditions.

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.

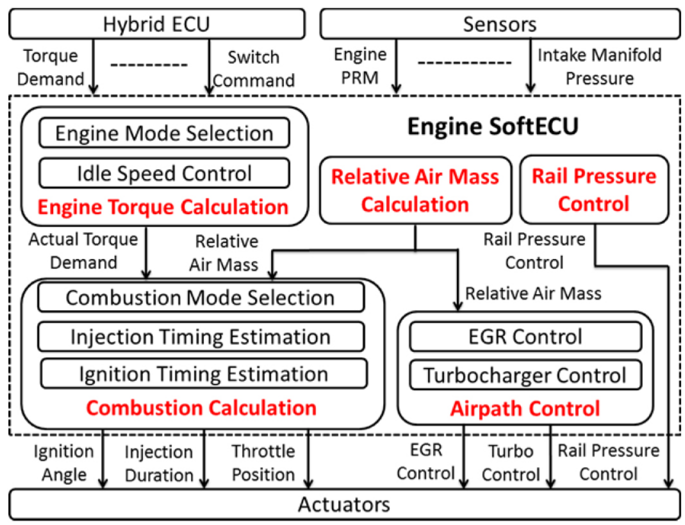

Figure 5. The block diagram of engine ECU.

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 motor for the desired torque output. The motor speed is controlled by the outer loop with the speed feedback signals and speed controller.

$$\begin{bmatrix} I_d \\ I_q \\ 0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos(\theta) & \cos(\theta-2\pi/3) & \cos(\theta+2\pi/3) \\ \sin(\theta) & \sin(\theta-2\pi/3) & \sin(\theta+2\pi/3) \\ 0.5 & 0.5 & 0.5 \end{bmatrix}\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \tag{2}$$

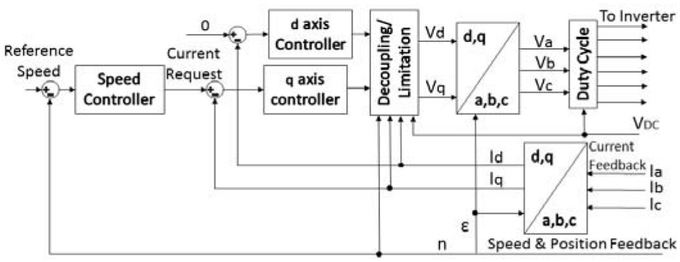

Figure 6. The block diagram of motor ECU.

Transmission ECU

The transmission ECU is used to determine the gear ratio of the gear box and the position of the lock-up clutch based on the selected level of drive and current vehicle working condition. In the drive position, the softECU shifts gears up and down according to the transmission output speed and the accelerator pedal position. The lockup clutch is also controlled based on vehicle speed and the accelerator pedal position. For the real-time control, upshifting and downshifting speeds are calibrated with accelerator pedal positions. The calibrated upshifting and downshifting maps are embedded into the control model as 2-D lookup tables. Figure 7 shows the flowchart of upshifting control. First, the upshifting speed is obtained from the embedded 2-D table based on the current accelerator pedal position. The actual transmission speed is then compared with the upshifting speed at every time step. If the transmission speed is greater than the upshifting speed, a timer is increased by 1. Otherwise, the timer is reset to zero. If the value of the timer is greater than a predefined upshift time constant and the transmission speed at current time step is greater than the previous time step, the transmission ECU generates an upshifting pulse to perform upshifting. The timer is designed to avoid frequent upshifting and downshifting when the vehicle speed is fluctuating around the shifting point. The downshifting control is similar to the upshiting control.

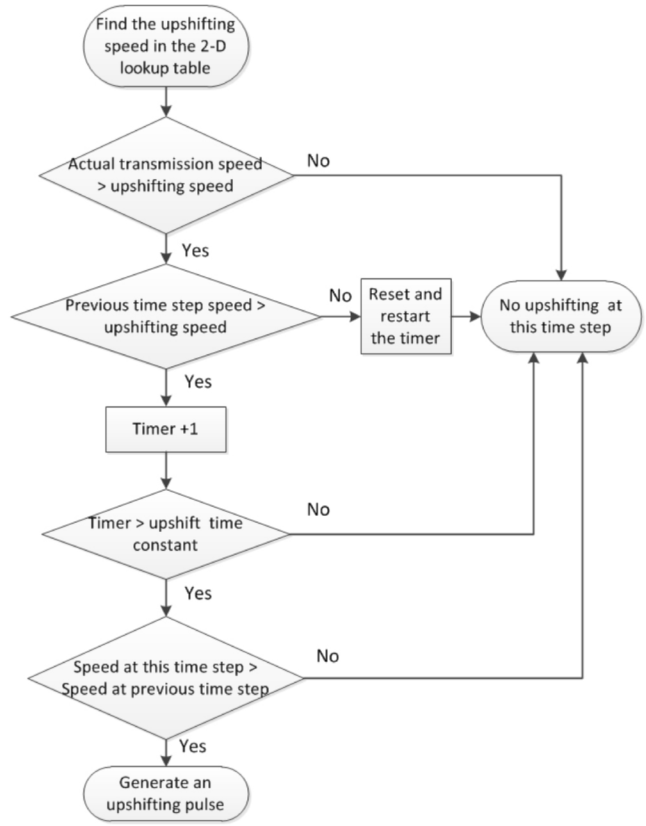

Figure 7. The flowchart of upshifting control.

HARDWARE-IN-THE-LOOP SIMULATION

Hardware-in-the-loop simulation has been proven to be an efficient rapid control prototyping environment for HEV control strategy development, implementation and validation [11, 12, 13]. HIL system allows the integration of model development, ECU architecture design, executable code generation, and performance simulation with real ECUs and I/O hardware.

dSPACE HIL Simulator Programming and Calibration Environment

dSPACE HIL Simulator provides graphical programming environment for the development of ECU control strategies and vehicle modeling. The vehicle and control models are designed in Simulink platform, which allows users to easily modify these models to meet design specifications. In addition to function blocks in Simulink, the simulator includes four categories of blockset libraries: Drivetrain, Electric Components, Engine, and Real-Time Interface. The Drivetrain blockset has blocks for drivetrain components, driving resistance calculation, driver controller and soft ECU for the transmission control. The Electric Components blockset includes blocks for battery, PMSM motor, motor ECU and three phase inverter. The gasoline engine blockset provides components for the gasoline engine modeling. The blocks can be broadly divided into fuel system, air handling, combustion, emission and soft engine ECU. The real-time interface (RTI) blockset provides function blocks to associate Simulink models with real hardware, including processor boards and I/O boards. The function blocks can generate interrupter signals, define real-time sensor signals and capture actuation signals.

The simulator is meant to conduct HIL testing but simulations can be run using softECUs if hardware ECUs are not available. For example, a soft engine ECU can be used for the engine control of spark, fuel injection, throttle and fuel metering. In the event of a real ECU being used, the softECU block can be removed and signals from the hardware ECU replace the outputs from the softECU. Once vehicle and control models are completed, Matlab Embedded Coder will be used for auto code generation to generate C code. Auto code generation makes modifying the models much simpler and time effective. The hassle with low-level coding is completely eliminated and allows users with a basic understanding of Simulink to work on embedded control system design.

Before performing simulation, the model is parameterized by the dSPACE Model Desk software. The Model Desk software provides a common platform for parameterizing all the subsystems used in the vehicle model. Parameters of all the subsystems can be defined using this software. To run the same model with a different set of parameters, parameter sets are saved. These parameter sets are then downloaded to the model before compiling it. The compiled models are then flashed to the simulator.

The real-time simulation is running in dSPACE Control Desk Next Generation (Control Desk NG). This software allows systematic configuration of simulation runs. Figure 8 shows the cockpit layout of the real-time vehicle simulation for setting up important parameters such as gear ratio, throttle position, steering angle, and so on. The simulation results, such as longitudinal position, parallel position, vehicle speed, acceleration pedal, brake pedal, and engine torque, can be displayed and plotted through the instruments in the layout. The operating condition of the vehicle is updated in real-time based on the input drive cycle, which allows the observation of the transient response of the vehicle performance rather than steady state. The simulation results can also be logged using recorders. These recorders are triggered off signals to look at signals during specific portions of the drive cycles. Predefined start and stop criterion ensures precise recording of the required portions of the drive cycle. Recorded data can be exported to Matlab for further analysis.

Figure 8. dSPACE HIL simulation environment - Control Desk NG.

HIL Simulation Setup

Figure 9 shows the HIL simulation setup and primary signals of the HIL system for the investigation of a single shaft parallel HEV energy management system. The vehicle plant is modeled using dSPACE Automotive Simulation Model. The hybrid ECU, engine ECU and transmission ECU, are soft ECUs and integrated with the vehicle model. The motor ECU is a hardware ECU implemented by MicroAutoBox II. The simulator outputs sensor signals and motor torque request to the motor ECU and captures actuation signals from MicroAutoBox II.

VEHICLE PERFORMANCE EVALUATION WITH HIL SIMULATION

To examine the performance of hybrid ECU and low-level ECUs, vehicle mode control, speed tracking, energy/ power distribution, regenerative braking and engine operating region, for specified drive cycles were investigated using HIL test. The selected drive cycles were Urban Dynamometer Driving Schedule (UDDS) and a high acceleration aggressive driving schedule (US06) drive cycles.

Vehicle Mode Control and Speed Tracking

Figure 10 shows the UDDS drive cycle and vehicle mode at different time instants. To represent five vehicle modes, a vehicle mode variable is designed in the simulation. The value of this variable is defined as: 0 - battery charging mode, 1 - engine only mode, 2 -hybrid mode, 3 - electric only mode, and 4 - regenerative braking mode. The simulation shows that

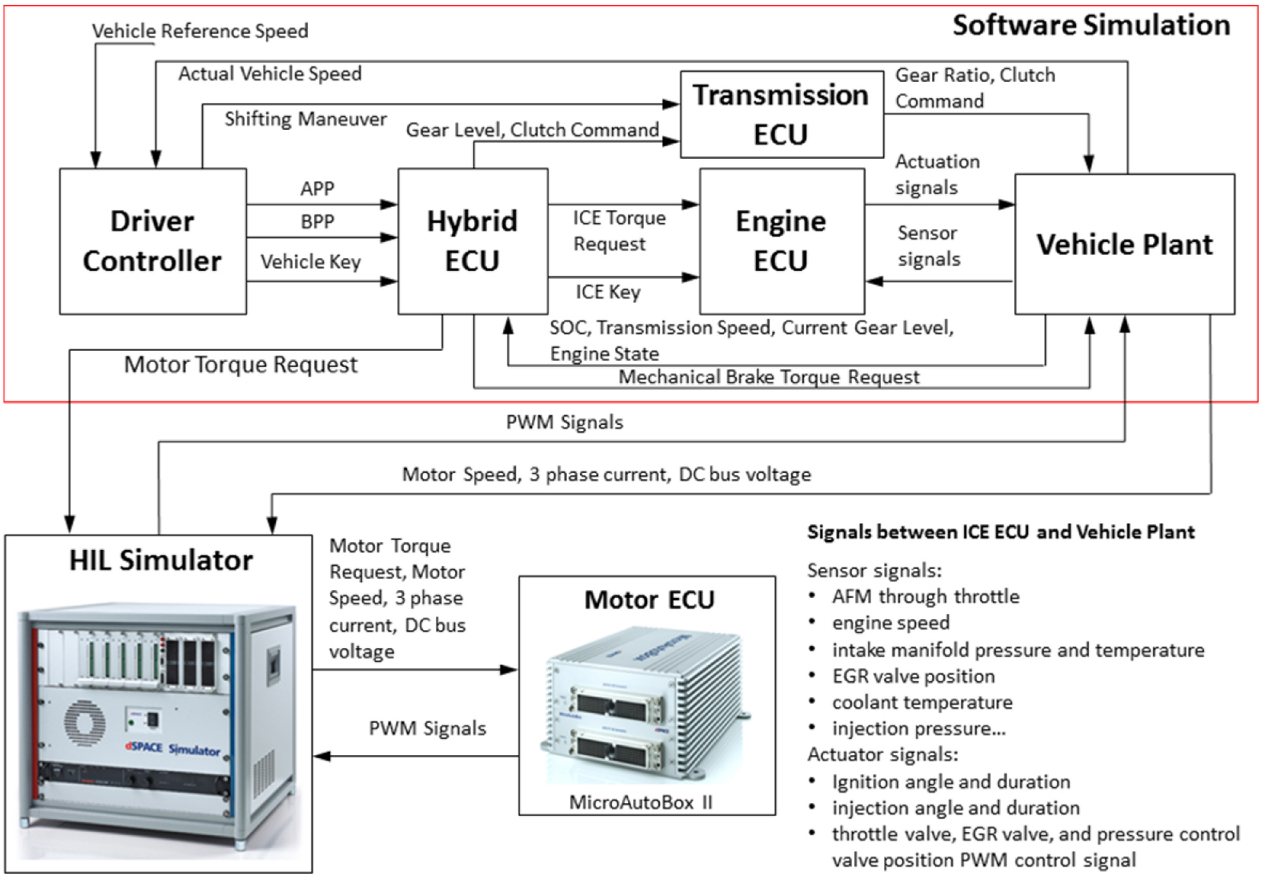

Figure 9. HIL simulation setup for single shaft parallel HEV.

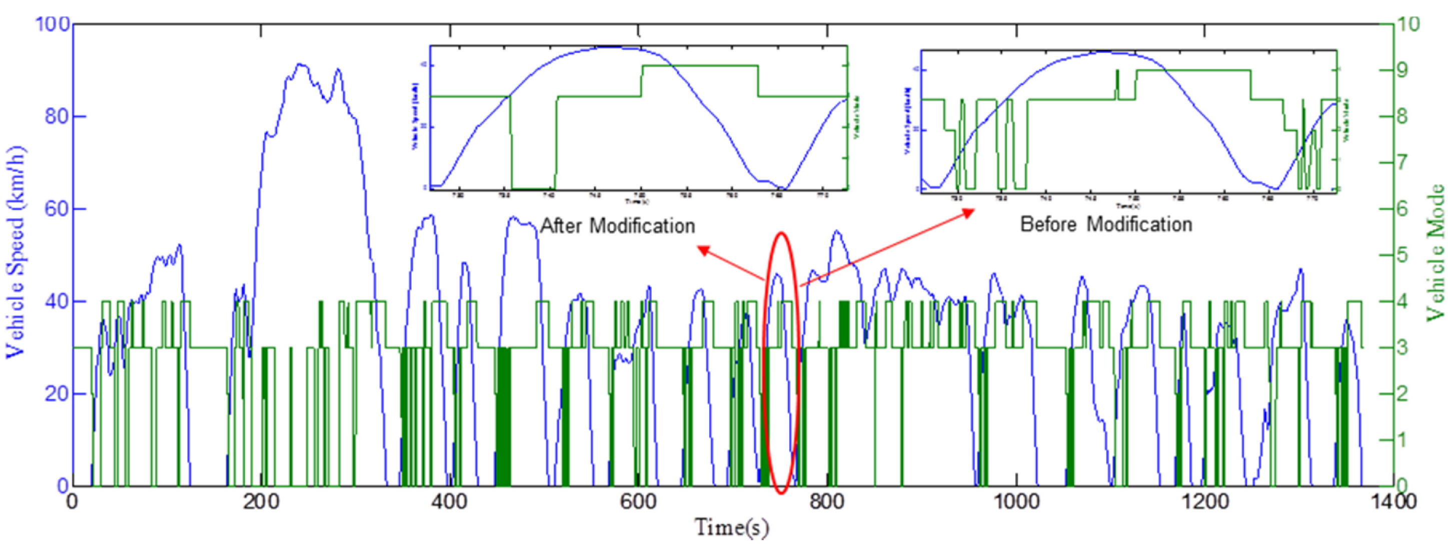

Figure 10. Vehicle operation modes in UDDS drive cycle.

the vehicle runs in electric only mode at most times. This means that the maximum motor torque is greater than vehicle torque request and the battery SOC is within a desired range. If the battery SOC is below the lower boundary of the desired range, the vehicle mode enters the battery charging model. When vehicle decelerates, the vehicle mode is in regenerative braking model. The motor recovers vehicle kinetic energy to electrical energy for charging battery.

By examining vehicle mode signal in Figure 10, a frequent mode switch was observed with original hybrid ECU implementation. As shown in the right enlarged subfigure, some of vehicle mode only last for about 1 second. This will cause frequent turn on/off powertrain components and power electronics. To avoid frequent change of vehicle mode, the hybrid ECU was modified. With modified hybrid ECU, the vehicle mode changes only when the transition conditions are met for a predefined consecutive number of time steps. The comparison of vehicle mode signal with original/modified hybrid ECU is shown in Figure 10 in two enlarged subfigures. The modified hybrid ECU shows improved vehicle mode control performance.

Figure 11 shows the speed tracking performance of the single shaft parallel HEV running on UDDS drive cycle. In general, vehicle speed tracks the reference speed well. The large speed tracking error occurs during the coupling of ICE to the shaft. This is due to the current clutch 1 control is a simple open/close control (0 means close and 5 means open). The clutch 1 control algorithm will be further studied in the future work to reduce vibration and speed error during engine engagement.

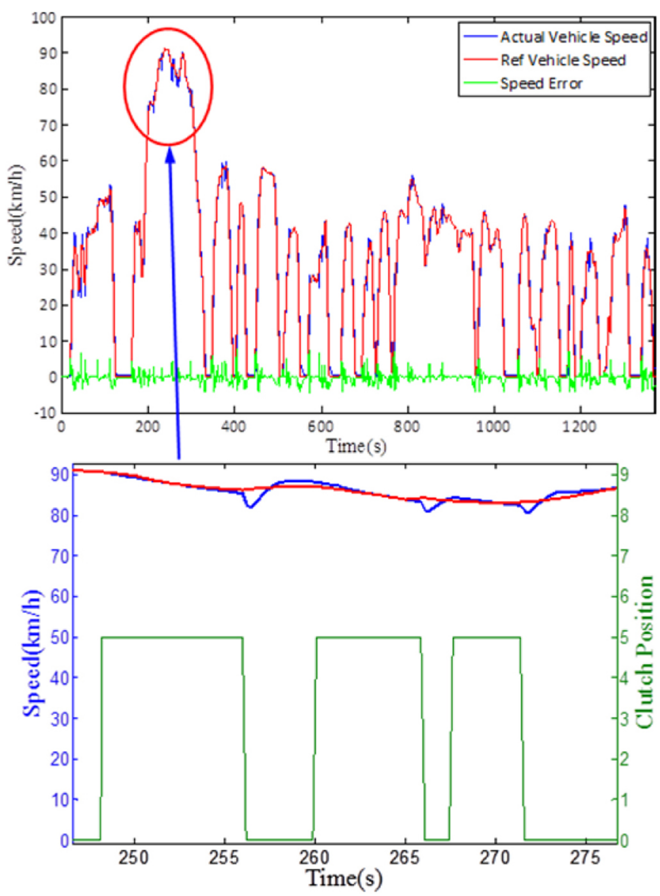

Figure 11. Vehicle speed tracking.

Vehicle Power and Energy Distribution

The longitude vehicle dynamics can be described by equation (3), where F_T is the tractive force to propel the vehicle; F_{roll} is the rolling resistance force; F_{Ad} is the aerodynamic drag force; and F_{Gf} is the gravitational force. The rolling resistance force, aerodynamic drag force, and gravitational force can be calculated by equations (4), (5), (6), where m is the total mass of the vehicle; g is the gravitational acceleration constant; θ is the grade angle with respect to the horizon; f_r is the coefficient of rolling resistance; v is vehicle speed; ρ is the air density; c_d is the aerodynamic drag coefficient; and A is the equivalent frontal area of the vehicle. If a vehicle runs on a flat road, the instantaneous power request of the vehicle over a drive cycle can be calculated by equation (7) using vehicle speed profile.

$$\sum F_x = ma = F_T - F_{roll} - F_{Ad} - F_{Gf} \tag{3}$$

$$F_{roll} = mg\cos\theta f_r \tag{4}$$

$$F_{Ad} = \frac{1}{2}\rho c_d A v^2 \tag{5}$$

$$F_{Gf} = mg\sin\theta \tag{6}$$

$$P_{req} = F_T \cdot v = (ma + F_{roll} + F_{Ad} + F_{Gf}) \cdot v \tag{7}$$

Figure 12 shows the instantaneous vehicle power request, rolling resistance power, and wind drag power for the UDDS drive cycle. The gravitational force $F_{Gf} = 0$ since the grade angle $\theta = 0$. The positive power request is for the vehicle traction and the negative power is braking power. The traction power can be divided into several parts, including acceleration power, rolling resistance loss, and wind drag loss. The negative power is the braking energy which may be recovered by regenerative braking. Figure 13 illustrates the breakdown of traction energy over a UDDS drive cycle. The values of simulation parameters are listed in Table 2.

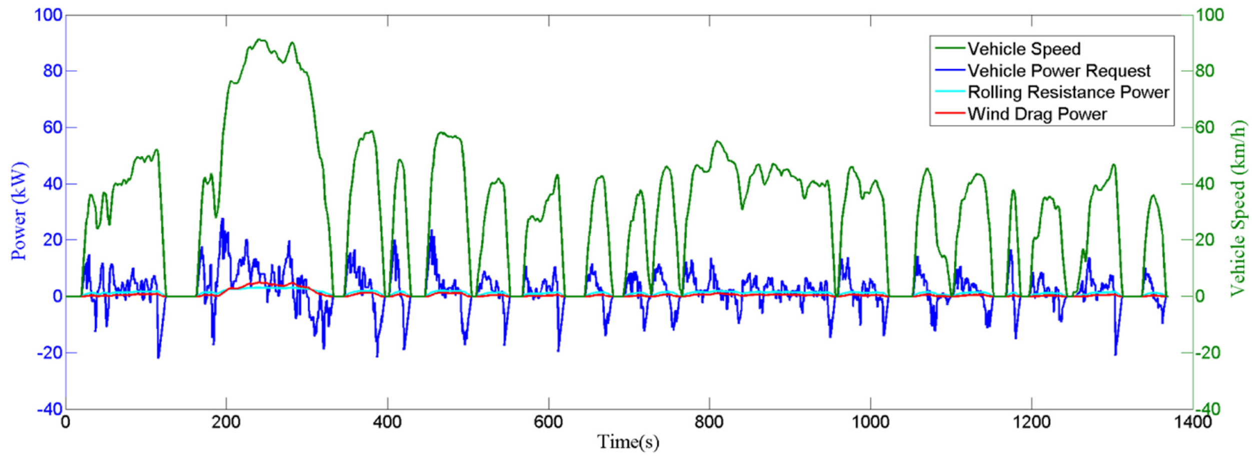

Figure 12. Vehicle power request, rolling resistance power, and wind drag power over a UDDS drive cycle.

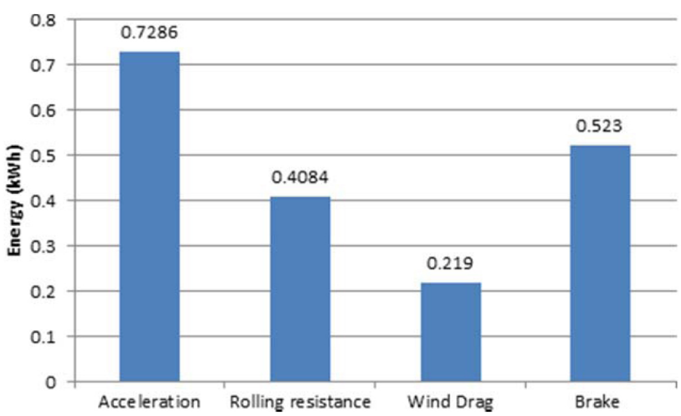

Figure 13. The breakdown of traction energy over a UDDS drive cycle.

Table 2. Simulation parameters.

Vehicle Mass (kg)	1250
Air density (kg/m^3)	1.25
Frontal Area (m^2)	2
Rolling resistance coefficient	0.01
Wind drag coefficient	0.3

Regenerative Braking

For the regenerative braking control, the motor is designed to recover as much braking energy as possible based on its torque capacity and shaft speed. The regenerative braking is disabled when the vehicle is lower than 0.1 km/h or the SOC value exceeds high charging threshold. When the braking power is greater than the regenerative braking, the additional amount is consumed in friction braking. For aggressive drive cycles, only part of the braking power can be recovered. This is because the braking power sometimes is greater than the maximum motor power. Figure 14 shows the instantaneous braking power and regenerative braking power running over US06 drive cycle. For US06 drive cycle, the energy recovered in regenerative braking is 0.4638kWh and friction braking energy is 0.1089kWh. The regenerative braking recovered 81% of braking energy in US06 drive cycle.

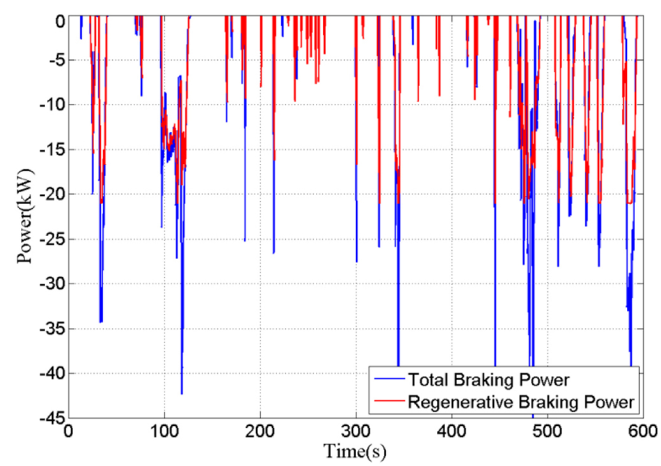

Figure 14. Braking power in US06 drive cycle.

Engine on/off and Operating Region

Due to low energy efficiency of ICE, the time percentage of engine operation in a drive cycle is an important indication of vehicle fuel economy. In addition, the operating region of the ICE is crucial to the vehicle fuel consumption. With rapid prototyping system, it is easy to analyze the engine state and operating range during a drive cycle and to design appropriate control strategies. Figure 15 shows the engine state change during UDDS drive cycle. The *Engine State* variable indicates different engine working states, whose value is defined as: 0 - engine turned off, 1 - engine idling, 2 - only engine providing traction power, 3 - engine providing traction power and charging battery, and 4 - engine providing traction power with e-motor. For UDDS drive cycle, the ICE is turned on 30.8% of time. When ICE is on, approximately 53.3% of time is at idling state. The engine idling state is designed to avoid quick engine on/off.

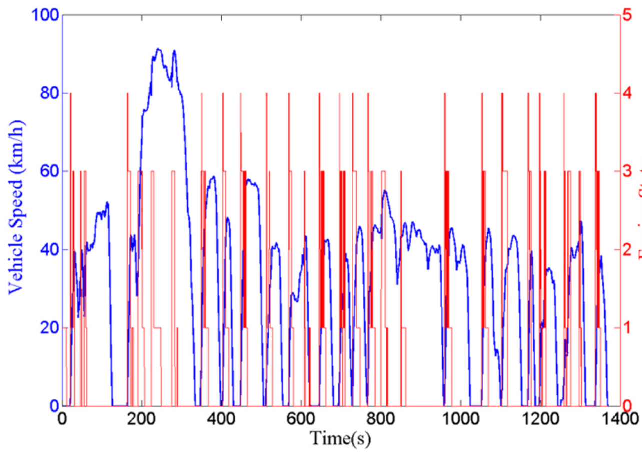

Figure 15. Engine states in UDDS drive cycle.

Figure 16 illustrates the engine Brake Specific Fuel Consumption (BSFC) map when it operates either as the source of traction or battery charging. The operating points (red circles) in the figure are for a simulation running UDDS drive cycle. The engine has only a few operating points in the low speed, low torque region as most of the torque demand in this region is met by the electric motor. The engine operates in a BSFC range of 240 and 356 g/kWh. When torque demand is below approximately 100 Nm, the electric motor provides traction and above that the engine is switched on. In the low speed region whenever the torque demand is greater than what the motor can supply, the engine is the source of traction and it operates at optimum torque providing additional torque for charging. At higher speeds where the motor is not able to supply the required torque, the engine supplies torque. The concentration of the markers at the lower left hand corner indicates engine idling. This is because the hybrid ECU keeps the engine running for a predetermined time after every engine operation.

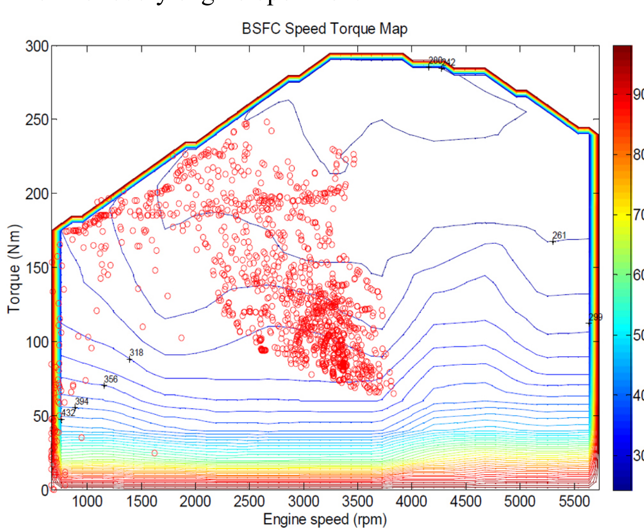

Figure 16. BSFC speed torque map for engine in HEV running on UDDS.

Comparing with ICE in a conventional vehicle, the operating region of the HEV ICE has higher fuel efficiency. Figure 17 shows the same engine operating in a conventional vehicle. There are a lot of operating points located in the high BSFC range. This is because the ICE is the only energy source for the conventional vehicle. These low efficiency points occur when the torque demand is below 100 Nm. In the case of HEV, the torque demand below 100 Nm is met by the electric motor. Thus these operating points of high specific fuel consumption are eliminated in HEV and the engine operates in a comparatively lower BSFC range.

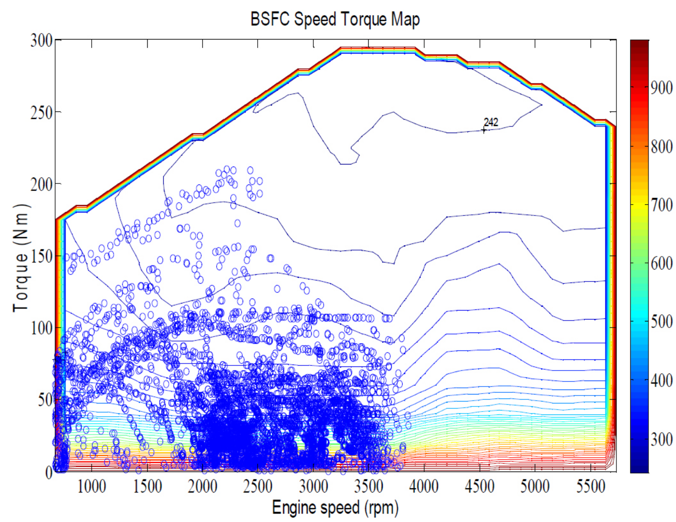

Figure 17. BSFC speed torque map for engine in conventional vehicle running on UDDS.

SUMMARY/CONCLUSIONS

Rapid prototyping of energy management system for a single shaft parallel hybrid electric vehicle using dSPACE HIL simulator is introduced in this paper. The control architecture and the detailed functionalities of vehicle-level energy management system - hybrid ECU and low-level engine ECU, motor ECU and transmission ECU, are discussed. The performance of the ECUs is evaluated with the HIL simulation by examining the vehicle performance, including vehicle mode control, speed tracking, energy/power distribution, regenerative braking, and engine on/off condition and operating range. The presented work shows that the dSPACE HEV HIL simulator provides a convenient environment for the design, modeling, simulation, and validation of HEV control strategies.

The future work includes:

- Design improved clutch control strategy to reduce vibration, vehicle speed tracking error and enhance vehicle drivability
- Replace softECUs such as engine ECU, transmission ECU or hybrid ECU with hardware ECUs

- Develop optimization-based HEV supervisory control strategies and compare the performance of these control strategies with rule-based control design.

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DEFINITIONS/ABBREVIATIONS

HEV - Hybrid Electric Vehicle

HIL - Hardware-In-the-Loop

ASM - Automotive Simulation Model

ECU - Electronic Control Unit

SOC - State of Charge

PMSM - Permanent Magnet Synchronous Motor

ICE - Internal Combustion Engine

APP - Accelerator Pedal Position

BPP - Brake Pedal Position

PWM - Pulse Width Modulation

BSFC - Brake Specific Fuel Consumption

UDDS - Urban Dynamometer Driving Schedule