

Real-Time Optimal Energy Management of Heavy Duty Hybrid Electric Vehicles

Dezong Zhao and Richard Stobart
Loughborough University

ABSTRACT

The performance of energy flow management strategies is essential for the success of hybrid electric vehicles (HEVs), which are considered amongst the most promising solutions for improving fuel economy as well as reducing exhaust emissions. The heavy duty HEVs engaged in cycles characterized by start-stop configuration has attracted widely interests, especially in off-road applications. In this paper, a fuzzy equivalent consumption minimization strategy (F-ECMS) is proposed as an intelligent real-time energy management solution for heavy duty HEVs. The online optimization problem is formulated as minimizing a cost function, in terms of weighted fuel power and electrical power. A fuzzy rule-based approach is applied on the weight tuning within the cost function, with respect to the variations of the battery state-of-charge (SOC) and elapsed time. Comparing with traditional real-time supervisory control strategies, the proposed F-ECMS is more robust to the test environments with rapid dynamics. The proposed method is validated via simulation under two transient test cycles, with the fuel economy benefits of 4.43% and 6.44%, respectively. The F-ECMS shows better performance than the telemetry ECMS (T-ECMS), in terms of the sustainability of battery SOC.

CITATION: Zhao, D. and Stobart, R., "Real-Time Optimal Energy Management of Heavy Duty Hybrid Electric Vehicles," *SAE Int. J. Alt. Power.* 2(2):2013, doi:10.4271/2013-01-1748.

INTRODUCTION

The White House announced new fuel efficiency standards for trucks, buses, and other heavy duty vehicles in August 2011. Within the standards, vehicles manufactured between 2014 and 2018 are required to reduce their fuel consumption and greenhouse gas emissions by 10% to 20%. HEVs are considered as the most promising short-term solutions in reducing the fuel consumption [1, 2]. By exploiting the capacity of a storage system installed aboard, HEVs can achieve better fuel economy and lower exhaust emissions than traditional powertrain vehicles. In a HEV, an electrical path is added to the powertrain such that part of the vehicle kinetic energy and exhaust gas energy can be captured by the electrical machines, and be used to recharge the battery. The energy assisted by the electrical machines also helps downsizing the internal combustion engine (ICE), resulting in better fuel efficiency and lower heat loss [3]. Since electrical machines provide faster boosting torque than mechanical systems, HEVs offer the improved launching performance and the reduced overall rated power comparing with traditional ICE vehicles.

A key issue in developing HEVs is the coordination of multiple energy flow of both fuel path and electrical path, that is the management of the power distribution in parallel

paths to minimize the fuel consumption, while satisfying the constraints of power demand and battery SOC [4]. The energy management strategies, also called supervisory control strategies, can be grouped into three categories: rule-based control strategies [5,6,7], optimization-based control strategies [8,9,10], and real-time control strategies [11,12,13]. In the rule-based control strategies, the rules are designed using heuristics, human expertise, or mathematical models. Although the control approaches can offer improvement on energy efficiency, it is clear that they do not guarantee an optimal result in all conditions. Using the optimization-based control strategies, the global optimum solution can be found by performing the optimization over a fixed drive cycle. Unfortunately, the global optimization approach is noncasual in nature, because the prior knowledge of the future driving information is required. The real-time optimization strategies manage the energy flow online, where the most well-known approach is the ECMS. The ECMS realizes the real-time optimization by minimizing an instantaneous cost function, so behaves as a closed-loop controller. The equivalent fuel consumption is defined as the extra energy which is offered by the battery and is effected by both the engine operating condition and the supervisory control action. It is assumed that the variation of battery SOC will be compensated in the

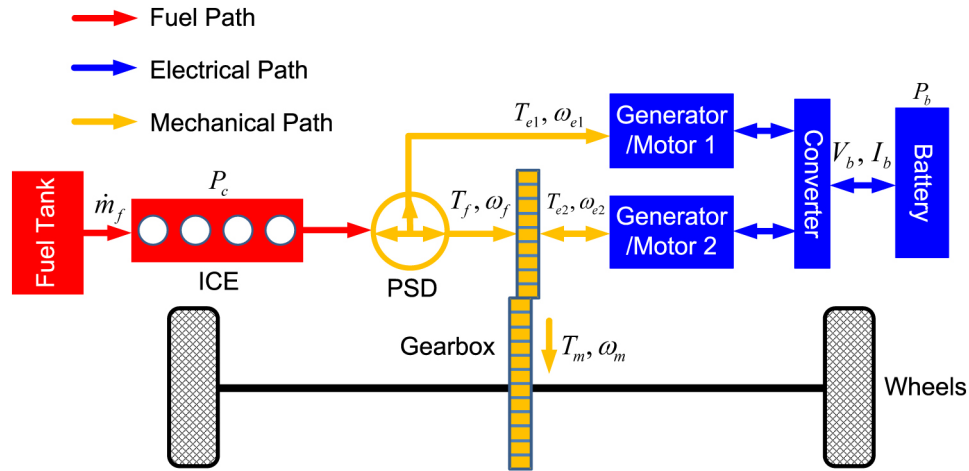


Figure 1. Schematic of a power-split HEV

near future by engine running, which is treated as a tough constraint on the battery sustainable usage [14].

In this paper, an intelligent real-time energy management algorithm is proposed to find the optimal power distribution for a heavy duty HEV. The HEV is a conceptual vehicle designed for a heavy haul duty with frequent start-stop operation. Fuel economy is of prime concern and as a consequence the cost function for the operation of the vehicle combines a fuel economy and emissions control. A real-time cost function is defined with weighted fuel power and electrical power, and the optimization of the control variables is formulated as minimizing the cost function. A fuzzy rule-based method is applied on the weight tuning of the cost function, to satisfy the tough constraint of the battery SOC.

POWER-SPLIT HEAVY DUTY HEV MODEL

The schematic of a power-split heavy duty HEV is shown in Figure 1. The HEV is driven by the power through both of the fuel path and the electrical path. The power flow in the HEV starts with the fuel in the tank being supplied to the diesel engine, then the generated power is transmitted to the gearbox to drive the vehicle. The power flow in the HEV starts with the fuel in the tank being supplied to the ICE. A planetary split device (PSD) is employed to transmit the ICE power to the vehicle. The shaft of ICE is linked to the PSD carrier gear, which passes ICE power to inner-sun gear and outer-ring gear. The sun gear is linked to generator/motor 1 (G/M1), which enables part of the ICE power to be transmitted through the electrical path and be transformed into electricity. This part of power is then either stored in the battery or sent to generator/motor 2 (G/M2) via the converter. G/M2 is also linked to the rotating shaft of ring gear, which transmits the traction force of G/M2 to the gearbox. The PSD enables the ICE to run at a continuously variable ratio with respect to the vehicle speed, and offers a seamless capability to decouple the road load torque demand from the ICE, which

benefits through improved fuel economy. In this paper, the inefficiencies of electric motors, embedded controllers and the DC/DC converter are not considered.

Fuel Path

The operating conditions of the engine are determined by the engine speed and load torque. The available generated power from the engine combustion is

$$P_c(t) = H_{LHV} \dot{m}_f(t), \quad (1)$$

where H_{LHV} is the lower heating value of the fuel and $\dot{m}_f(t)$ is the fueling rate. Consequently, the energy consumed by the engine is

$$E_f(t) = \int_0^t H_{LHV} \dot{m}_f(\tau) d\tau. \quad (2)$$

The transmitted power from the engine to the gearbox is calculated by

$$P_f(t) = \eta_c P_c(t), \quad (3)$$

where η_c is the energy transmission efficiency from engine combustion to mechanical propulsion considering friction and pumping. Therefore, the available torque of the fuel path is

$$T_f(t) = P_f(t) / \omega_f(t), \quad (4)$$

where $\omega_f(t)$ is the rotating speed of the crankshaft linking the engine and the gearbox.

Electrical Path

Using power electronics devices, the battery stores and outputs the electrical energy alternatively, depending on the vehicle driving condition and supervisory control action.

Modeling the battery as an equivalent circuit, the voltage of the battery is introduced as

$$V_b(t) = V_{oc}(t) - I_b(t)R_b(t), \quad (5)$$

where $V_{oc}(t)$, $I_b(t)$ and $R_b(t)$ are the open circuit voltage, charging/discharging current, and internal resistance of the battery, respectively. $V_{oc}(t)$ and $R_b(t)$ are polynomial functions of the battery SOC. The electrical power generated by the battery is

$$P_b(t) = V_b(t)I_b(t), \quad (6)$$

and accordingly, the consumed electrical energy of the battery is

$$E_e(t) = \int_0^t V_b(\tau)I_b(\tau) d\tau. \quad (7)$$

The battery SOC can be calculated by

$$\text{SOC}(t) = \text{SOC}_0 - \frac{1}{C_b} \int_0^t I_b(\tau) d\tau, \quad (8)$$

where SOC_0 is the initial value of SOC and C_b denotes the nominal capacity of the battery. In battery charging and discharging, C_b has different values. The generated/consumed mechanical power of the electrical path is:

$$P_{e2}(t) = T_{e2}(t)\omega_{e2}(t), \quad (9)$$

where $T_{e2}(t)$ and $\omega_{e2}(t)$ are the available torque and rotating speed of G/M2 which is linked on the gearbox, respectively.

Mechanical Path

The demand power to drive the vehicle is calculated under a quasistatic model. At a given vehicle speed $v(t)$ and road slope $\alpha(t)$, the required force to drive the wheels is

$$F_m(t) = m\dot{v}(t) + 0.5\rho C_d A_d v(t)^2 + mg \sin(\alpha(t)) + mg C_r \cos(\alpha(t)), \quad (10)$$

where the four terms are vehicle acceleration force, aerodynamic drag force, resistive gravity force, and rolling resistance force, respectively; m , g , ρ , C_d , A_d , and C_r are the vehicle mass, gravity constant, air density, air drag coefficient, frontal area, and rolling resistance, respectively. The load torque and angular speed of the vehicle are

$$T_m(t) = F_m(t)r_w, \quad (11)$$

$$\omega_m(t) = v(t)/r_w, \quad (12)$$

respectively, where r_w is the radius of the wheels. The demand power to drive the vehicle is

$$P_m(t) = T_m(t)\omega_m(t), \quad (13)$$

and therefore, the mechanical energy delivered to the wheels is

$$E_m(t) = \int_0^t T_m(\tau)\omega_m(\tau) d\tau. \quad (14)$$

According to the power balance principle, the driving demand power $P_m(t)$ is always assumed to be fulfilled by the power delivered by the fuel path and electrical path:

$$P_m(t) = P_f(t) + P_{e2}(t). \quad (15)$$

The power split ratio is defined as

$$u(t) = P_{e2}(t)/P_m(t), \quad (16)$$

which is the control variable to regulate the power distribution between the parallel paths. By setting different values on $u(t)$, the HEV works at different modes, which are listed in the following:

1. If $u(t) = 1$, the HEV works in the motor mode, the driving demand power is provided by G/M2, i.e., $P_m(t) = P_{e2}(t)$;

2. If $0 < u(t) < 1$, the HEV works in the hybrid mode, the driving demand power is provided by both the engine and G/M2, and the battery is discharging;

3. If $u(t) = 0$, the HEV works in the pure thermal mode, the driving demand power is provided by the engine, i.e., $P_m(t) = P_f(t)$;

4. If $u(t) < 0$, the HEV works in the regenerative mode, the driving demand power is provided by the engine, and the battery is charging where G/M2 works as a generator.

It is expected that the decision of the energy management, that is the online output $u(t)$ of the supervision controller leads to the optimal fuel economy while fulfilling the driving command and maintaining the battery SOC within an allowed range.

PROBLEM FORMULATION

The aim of the real-time energy management strategy is online finding the optimal $u(t)$ to minimize a cost function, which consists the fuel consumption and battery SOC. The control variables should be restricted in an admissible region:

$$u_{\min} \leq u(t) \leq u_{\max}. \quad (17)$$