

Power Management of Hybrid Electric Vehicles based on Pareto Optimal Maps

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ABSTRACT

Pareto optimal map concept has been applied to the optimization of the vehicle system control (VSC) strategy for a power-split hybrid electric vehicle (HEV) system. The methodology relies on an inner-loop optimization process to define Pareto maps of the best engine and electric motor/generator operating points given wheel power demand, vehicle speed, and battery power. Selected levels of model fidelity, from simple to very detailed, can be used to generate the Pareto maps. Optimal control is achieved by applying Pontryagin's minimum principle which is based on minimization of the Hamiltonian comprised of the rate of fuel consumption and a co-state variable multiplied by the rate of change of battery SOC. The approach delivers optimal control for lowest fuel consumption over a drive cycle while accounting for all critical vehicle operating constraints, e.g. battery charge balance and power limits, and engine speed and torque limits. The methodology has been verified through comparison with the production VSC strategy of the 2013 HEV Fusion and it shows comparable performance. The approach is effective for evaluation of new system configurations and for early analysis of next generation HEV systems before VSC calibrations are developed.

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INTRODUCTION

The optimal control of HEV vehicles is a topical area of research due to continuing quest of major car manufactures to achieve best in class fuel economy. The complexity of HEV power management system which coordinates operation of different power sources, i.e. engine, battery and electric motors, not counting increasingly stringent vehicle regulatory requirements, e.g. emission and CO2 reduction requirements, makes HEV vehicle control a very challenging task. Due to mentioned above complexity, the optimal control of the power management systems can be a valuable method for estimation of the HEV powertrain design potential and development of an optimal design.

The major approaches reported on optimal control of HEVs include: a) dynamic programming (DP) optimization method [1,2] which guarantees a global optimal solution but computationally intensive; b) stochastic dynamic programming with driving pattern recognition [3]; and c) the Equivalent Consumption Minimization Strategy (ECMS) which relies on heuristic concept that electric energy is equivalent to fuel usage [4], [5], [6]. As of late Pontryagin's minimum principle (PMP) approach became increasingly popular for HEVs optimal control applications [7], [8], [9], [10]. The PMP approach relies on minimization of the Hamiltonian which can be constructed from static power-split HEV model [8], or by using high-fidelity HEV vehicle models [11], [12]. The PMP

method is simple enough since it is based on instantaneous optimization and it has potential for real-time implementation. Also PMP control concept could deliver global optimal solution under reasonable assumptions on system dynamics [8]. The major step in PMP approach which reduces the dimension of the optimization problem is introduction of inner-loop optimization routine which defines engine Pareto optimal operating line (OOL). The notion of engine optimal operating line for general power-split architecture was first introduced in [13]. PMP method implementation for generation of control target for simulation of HEV vehicles as a part of the modeling tool Autonomie has been reported in [9]. One of the recent interesting applications of PMP method is optimal power management of plug-in PHEV vehicles with example of GM Chevrolet Volt [10].

The paper presents implementation of PMP method for simulation of HEVs with power-split architecture. The focus is on inner-loop optimization procedure which defines engine optimal operating line. The OOL construction method is described which is based on static engine operating maps and machine and transaxle loss maps. The OOL method implements accurate static torque/speed equations of power-split powertrain including components loss torque. The engine 3D Pareto maps are calculated using OOL optimization algorithm as a core of computation code. The 2D Pareto maps introduce interpolation error, then a second Pareto method is

introduced which calculates Pareto operating points based on drive cycle vehicle operating points. The second method does not introduce interpolation error but it is specific to the cycle. The modeling approach of HEV vehicles based on Pareto maps is described. The simulation results of 2013 Fusion HEV are presented and discussed.

OPTIMAL CONTROL FORMULATION FOR HEVs

We start with the standard formulation, see e.g. reference [8], of the hybrid electric vehicle control problem as the minimization of the total fuel consumption in a drive cycle: given a vehicle drive cycle defined by a trace of vehicle speed versus time, $V(t)$, find the optimum trace of engine speed and torque, $\omega_e^*(t)$, $T_e^*(t)$, and battery power, $P_b^*(t)$ that minimizes

$$\int_0^T \dot{m}_f(\omega_e(t), T_e(t), P_b(t)) dt, \quad (1.1a)$$

subject to:

$$P_b(t) \in \tilde{P}_b \quad (1.1b)$$

$$\omega_e(t) \in \tilde{\omega}_e \quad (1.1c)$$

$$T_e(t) \in \tilde{T}_e \quad (1.1d)$$

$$SOC_b(t) \in \tilde{SOC}_b \quad (1.1e)$$

$$|SOC_b(0) - SOC_b(T)| \leq \varepsilon \quad (1.1f)$$

$$m \frac{dV(t)}{dt} = F_w(P_e(t), P_b(t)) \quad (1.1g)$$

$$F_w(P_e(t), P_b(t)) = F_t(P_e(t), P_b(t)) - \left[\frac{1}{2} \rho C_d V^2(t) + C_{rr}(V(t)) mg \cos(\alpha) + mg \sin(\alpha) \right] \quad (1.1h)$$

$$P_b(t) = P_{m,el}(t) + P_{g,el}(t) + P_{aux}(t) \quad (1.1i)$$

where the superscript ** qualifies the signal as optimal; T is the total duration of the drive cycle; t is time; $\dot{m}_f$ is the fuel mass flow rate (mass per unit time); symbols with a tilde on top (e.g., $\tilde{P}_b$) denote the space of feasible values of the variable; ω_e and T_e are the engine speed and torque; engine power is the product of engine torque and speed ($P_e(t) = T_e(t) \times \omega_e(t)$); $SOC_b(t)$ is the state of charge of the battery (capacity at time t divided by its maximum capacity); ε is a small positive real number that controls how much battery energy imbalance is allowed over the drive cycle with duration T ; m is the vehicle mass; F_w is the net force at the tire-road contact area as a function of the vehicle speed V , air density ρ , aerodynamic drag coefficient C_d , rolling resistance coefficient C_{rr} , gravity g , and the road's angle of inclination α .

Constraint (1.1b) ensures that the battery power is within allowed limits. Constraints (1.1c) and (1.1d) guarantee that the engine operating point is inside the allowed torque and speed ranges, considering as well the lack of operating points below the engine idle speed. The engine operation constraints allow negative engine torque and engine speed below idle if the vehicle operates in electric vehicle (EV) mode, i.e. with engine fuel rate equal to zero, $\dot{m}_f = 0$. Constraint (1.1e) imposes limits on the maximum and minimum battery SOC. Equation (1.1f) is a battery charge-sustaining constraint required in fuel consumption drive cycle regulatory tests. The final and initial battery SOC cannot differ by more than ε .

One important point regarding the modeling of the powertrain power flows is the accounting of auxiliary electric loads. Equilibrium of power at node A in Figure 1 produces the equation stated in (1.1i) where $P_{m,el}$, $P_{g,el}$ are electric powers that go to the motor and generator, respectively, and P_{aux} is the electric auxiliary power used by lights, radio, air conditioning, and other miscellaneous components in the vehicle. In this work we assume a constant auxiliary load for the entire drive cycle. This constant load was obtained as the average auxiliary load during vehicle tests.

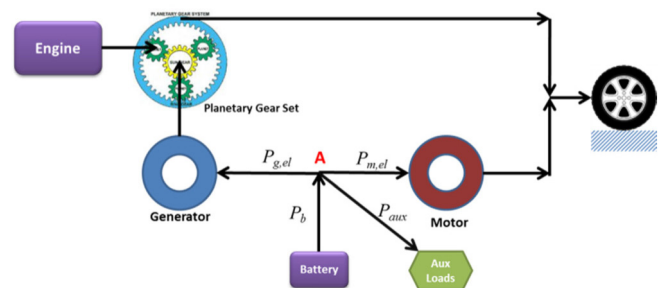


Figure 1. Power flow of a power-split HEV powertrain

PARETO OPTIMAL MAPS

Engine Optimal Operating Line

Now we introduce inner-loop optimization process which calculates engine optimal operating points vs battery power given vehicle wheel speed and power demand [8], [13]. The optimization is based on a power-split HEV static model formulation (see schematics in Figure 2)

$$\begin{aligned} T_g &= T_{s,loss} - \frac{1}{G_{ge}} (T_e - T_{c,loss}), \\ \omega_g &= G_{ge} \omega_e + G_{sr} G_{rw} \omega_w \\ T_m &= T_{cm,loss} - G_{gm} (T_g - T_{s,loss}) + \\ &+ G_{wm} (T_w + T_{diff,loss} + T_{cv,loss}) + G_{rm} (T_{r,loss} + T_{rc,loss}) \\ \omega_m &= G_{mw} \omega_w \end{aligned} \quad (2.1)$$

Here T_g is a generator torque, T_m is a motor torque, $T_{r,loss}$, $T_{c,loss}$, $T_{s,loss}$ are ring, carrier, and sun losses, respectively; ω_e , ω_m , ω_g , ω_w are engine speed, motor speed, generator speed and wheel speed, respectively; $T_{diff,loss}$, $T_{cv,loss}$, $T_{rc,loss}$ are differential loss, cv-joint loss, and ring-to-counter (RC) loss, respectively; G_{ge} , G_{sr} , G_{gm} , G_{wm} , G_{rm} are power-split transaxle ratios: generator to engine, sun to ring, generator to motor, wheel to motor, and ring to motor, respectively.

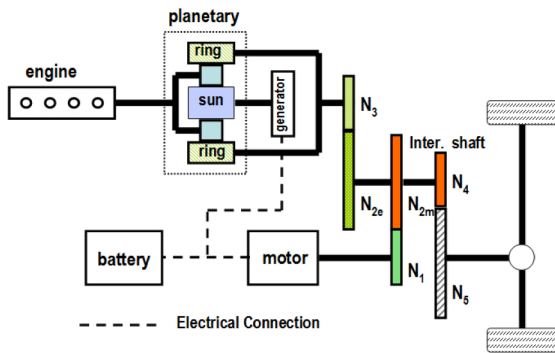


Figure 2. Schematics of a power-split HEV powertrain

The electric power balance is defined by equation

$$\begin{aligned} P_b &= P_{g,el} + P_{m,el} + P_{aux} = \\ T_g \omega_g &+ P_{g,loss} + T_m \omega_m + P_{m,loss} + P_{aux} \end{aligned} \quad (2.2)$$

Here $T_{g,loss}$, $T_{m,loss}$ are generator and motor electrical loss, respectively.

Next, system of equations (2.1), (2.2) can be reformulated as

$$\begin{aligned} T_e \cdot \omega_e &= T_w \omega_w - P_b + P_{g,loss} + P_{m,loss} + P_{gbx,loss} + \\ &P_{diff,loss} + P_{cv,loss} \end{aligned} \quad (2.3)$$

where $P_{gbx,loss}$ is combined gearbox loss.

Note, that equation (2.3) represents energy conservation principle.

Then the OOL optimization process is defined by minimization of engine fuel over all admissible engine speed range

$$\min_{\omega_e} [m_f = f(\omega_e, T_e)] \quad (2.4)$$

such that power balance equation (2.3), and system constraints (1.1b), (1.1c), (1.1d) are hold.

The example of engine optimal operating line is shown in Figure 4, where green lines represent engine fuel consumption at constant battery power vs. engine speed. The red line consists of engine optimal operating points given vehicle wheel speed and power. The points with high engine fuel values represent conditions of engine maximum torque violation.

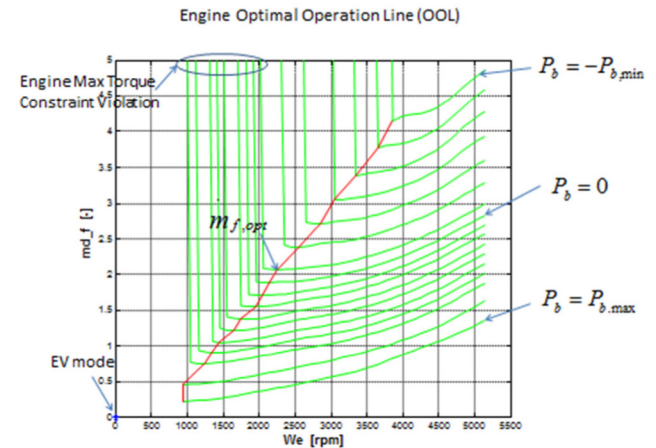


Figure 4. Engine fuel OOL line: engine fuel vs engine speed; 2013 Fusion HEV example; wheel speed $V=50\text{mph}$, $P_w = 20\text{kW}$

Figure 5 shows engine torque OOL line (red) in engine torque/speed coordinates; green lines are the constant battery power levels. The blue dashed line limits the engine speed search area to improve search algorithm computational efficiency. The search area reduction is based on the fact that engine optimal operating points are located close to the maximum torque line.