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Explicit optimal control policy and its practical application for hybrid electric powertrains

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ABSTRACT

This paper presents a simplified, yet realistic, model of a hybrid electric powertrain and derives the explicit solution of the optimal energy management. The explicit solution of this optimal control problem consists of simple rules that rely on powertrain parameters only. The simplified model is validated on a more complex model relying on measured data. Finally, a causal, real-time control strategy including anti-windup is presented. This strategy relies on the optimal control of the simplified model and is successfully evaluated on the complex model that relies on measured data.

1. Introduction

The minimization of the integral fuel consumption of hybrid electric vehicles (HEVs) requires an appropriate control of the power distribution between the primary and the secondary power converter. This optimal control problem is often referred to as the energy management problem in literature. Various proposed solutions have been published so far. These approaches are typically divided into two groups, namely heuristic strategies and optimal strategies (Sciarretta & Guzzella, 2007).

Heuristic approaches are often applied in real-time implementations. Low fuel consumption can be achieved, but the performance is very sensitive to the tuning of the rules. A typical rule-based method is fuzzy logic, which was used by Schouten, Salman, and Kheir (2003) and Won and Langari (2005). Such heuristic control strategies are in general not scalable, since these rules are often not model-based. Lin, Kang, Grizzle, and Peng (2001) presented a different approach using the results obtained from dynamic programming to extract rules.

On the other hand, strategies minimizing a local cost function to find the actual control proved to achieve low fuel consumption. This local cost function is typically an equivalent fuel consumption that consists of the actual fuel consumption and a weighted electric consumption. These approaches were introduced by Paganelli et al. (1998, 2000) and Brahma, Guezennec, and Rizzoni (2000) and further improved by Sciarretta, Back, and Guzzella (2004) and Musardo, Rizzoni, Guezennec, and Staccia (2005). The local minimization strategies require a model of the powertrain, but are easily scalable. However, such strategies typically require more computational power than rule-based methods, since an online optimization has to be carried out in real-time operation. Delprat, Guerra, and Rimaux (2002) and Cipolone and Sciarretta (2006) used Pontryagin's minimum principle to derive similar strategies that minimize a local cost function.

This paper focuses on a parallel hybrid electric powertrain and yields a solution that is specific to this architecture. However, the method of deriving the explicit optimal control can also be used for other hybrid topologies.

In the first part of this paper, a simplified model is presented, where all parameters are independent of the rotational speed of the components and no constraints are present. This model is referred to as the *speed-independent, unconstrained model*. It allows for an analytical solution of the optimal control, resulting in clearly defined rules. This rule-based control is one of the main findings in this paper. All rules are well defined by powertrain parameters only and close the gap between optimal and heuristic strategies.

In the second part of this paper, the simplified model is extended to the *speed-dependent, input-constrained model*. The analytical optimal control for the extended model is found similarly to the one for the first model. The control can still be expressed as clearly defined rules being now speed-dependent.

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This control is computationally very efficient allowing for real-time applications. Since the control law is fully defined by powertrain parameters, it even allows for online-adaptation of the powertrain parameters during operation of the vehicle. The analytical solution is finally used to derive a causal controller. This solution allows the derivation of an anti-windup scheme for the integrator in the causal controller, using only powertrain parameters.

The paper is organized as follows: The optimal control of a simplified, unconstrained model is being presented and derived in Section 2. In Section 3 the derivation is repeated for the constrained, speed-dependent model. This model is validated in Section 4. The application of the control developed in this paper is shown in Section 5. Finally, Section 6 summarizes the main results.

2. Simplified optimal control

In this section, the simplified, unconstrained model of a parallel hybrid electric powertrain is presented. Based on this model, the optimal control is derived and illustrated.

2.1. Speed-independent model

For a parallel hybrid electric powertrain whose structure is illustrated in Fig. 1, a simplified model is introduced relating the total power demand $P_d(t)$, the motor power $P_m(t)$, and the engine power $P_e(t)$ to the fuel power $P_f(t)$, the battery power $P_b(t)$, and the energy content in the battery $E_b(t)$. Assuming a battery model with a voltage source V_{OC} in series with a resistor R, the battery current I_b is given by

$$I_b = \frac{V_{OC} - \sqrt{V_{OC}^2 - 4RP_b}}{2R}. \tag{1}$$

The total power loss over the resistance is

$$P_l(P_b) = RI_b^2 = \frac{(V_{OC} - \sqrt{V_{OC}^2 - 4RP_b})^2}{4R}. \tag{2}$$

Approximating the power loss using a Taylor series around $P_b = 0$ yields

$$P_l(P_b) \approx P_l(0) + \left.\frac{\partial P_l}{\partial P_b}\right|_0 \cdot \frac{P_b}{1!} + \left.\frac{\partial^2 P_l}{\partial P_b^2}\right|_0 \cdot \frac{P_b^2}{2!} + \mathcal{O}(P_b^3) \tag{3}$$

$$= 0 + 0 \cdot P_b + \frac{R}{V_{OC}^2} \cdot P_b^2 + \mathcal{O}(P_b^3). \tag{4}$$

Throughout this paper, the battery power loss in the simplified model is therefore assumed to be

$$P_l(P_b) = \frac{R}{V_{OC}^2} \cdot P_b^2 = \alpha P_b^2. \tag{5}$$

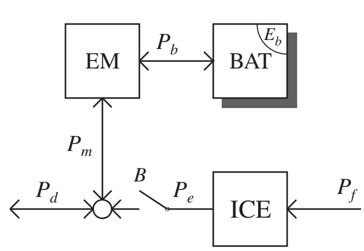

Fig. 1. Topology of the parallel hybrid electric powertrain. EM and ICE are static blocks while BAT is a dynamic block with the state variable E_b. The variable B decides whether the engine is on and the clutch is closed.

The model equations are

$$P_e(t) = P_d(t) - P_m(t), \tag{6}$$

$$P_f(t) = \frac{P_e(P_m(t), P_d(t)) + P_0}{e} \cdot B(t), \tag{7}$$

$$P_b(t) = P_m(t) \cdot \eta^{-\mathrm{sign}(P_m(t))}, \tag{8}$$

$$\frac{d}{dt} E_b(t) = -P_b(P_m(t)) - \alpha P_b(P_m(t))^2, \tag{9}$$

where $B(t)$ is equal to one when the fuel injection is active (engine on) and the clutch between engine and motor is engaged, ($P_e(t) > 0$), P_0 is the engine friction power, e its internal efficiency, η the efficiency of the electric motor,[1] and $\alpha = R/V^2$. The only state variable of this model is the energy content of the battery $E_b(t)$ given by (9). In the remainder of this paper the time dependencies of the variables P_d, P_e, P_m, P_f, P_b, B, and E_b in the model equations (6)–(9) are omitted to increase readability.

Initially, the only constraint to the model is that the engine cannot provide any negative power,

$$P_e \in [0, \infty), \tag{10}$$

$$P_m \in (-\infty, \infty). \tag{11}$$

However, in Section 3.1 constraints are added to the model in order to achieve a more realistic behavior.

2.2. Optimal control

The optimal control problem consists of finding the optimal power signal for the electric motor P_m^o such that the fuel consumption is minimized and the charge in the battery is sustained over the driving cycle. The requested power profile P_d is given by the driving cycle as a disturbance and the final time t_f, being the duration of the cycle, is fixed. In real-time operation of a vehicle, the requested power P_d is not given by a driving cycle, but rather by the driver's power request. This power demand is determined by the positions of the throttle and brake pedals which are converted into the power demand for the control.

The optimal control problem is formulated by the cost functional, the system dynamics, input constraints and state constraints, and the initial and the final conditions. The cost functional to be minimized, which is the total fuel (energy) consumption over the driving cycle is

$$J = \int_0^{t_f} P_f(\tau)\, d\tau. \tag{12}$$

While the system dynamics and input constraints are given by (6)–(11), the state constraints are neglected throughout this paper. The initial and the final conditions are chosen equal to zero such that charge sustenance is guaranteed

$$E_b(0) = E_b(t_f) = 0. \tag{13}$$

Hence, a positive (negative) battery energy content $E_b(t)$ indicates that the battery is charged (discharged) at time t compared to the initial condition. Note that the energy content of batteries is in general bounded. However, the optimal control problems solved in this paper neglect the bounds on the state. This assumption allows for explicit solutions. Nevertheless, as it will be shown in Section 5, the battery's energy content can still be kept within reasonable bounds by an appropriate causal control.

[1] Throughout this paper the term electric motor is used for the combined unit consisting of the electric machine and the corresponding power electronics.