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Flatness-based Trajectory Planning for the Battery State of Charge in Hybrid Electric Vehicles

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Abstract: In this contribution an energy management framework for hybrid electric vehicles (HEV) is presented. Particularly, the energy management strategy is extended by a trajectory planning level for the battery state of charge (SoC). For the design of the SoC reference trajectory generator the differential flatness property of the system is exploited to formulate a nonlinear static optimization problem. Its performance is evaluated in combination with the Equivalent Consumption Minimization Strategy (ECMS) which is a commonly applied technique for the fuel consumption optimization of hybrid electric vehicles. Therefore, we apply an adaptation law for the equivalence factor, relating electric energy to fuel consumption, which requires a SoC reference value as input. Compared to the case when ECMS assumes a constant SoC reference, the application of a time varying SoC reference, as introduced in this work, improves the overall performance of the energy management controller on the considered driving cycle.

Keywords: Flatness, hybrid electric vehicles (HEVs), predictive control, nonlinear programming, trajectory planning

1. INTRODUCTION

One attractive solution on our way to sustainable and environment-friendly transport is to increase the share of hybrid electric vehicles on the global roads. This kind of vehicles has at least two prime movers (Guzzella and Sciaretta (2013)) and therefore significant potential to improve the fuel economy if the advantages of the propulsion machines are combined properly. In order to improve the HEV performance various energy management strategies (EMS) including dynamic programming (DP) (Bertsekas (2000), Sciarretta et al. (2004), Liu and Peng (2008), Sundstrom and Guzzella (2009), Johannesson et al. (2007), Serrao et al. (2011), Larsson et al. (2014), Patil et al. (2014), Larsson et al. (2015)), equivalent consumption minimization strategy (ECMS) (Musardo et al. (2005), Serrao et al. (2009), Onori et al. (2010), Kim et al. (2011)) and model predictive control (MPC) (Ripaccioli et al. (2009), Borhan et al. (2012)) have been proposed. The performance of these strategies strongly depends on the available information about the driving profile. If the entire driving profile and terrain information is exactly known DP can provide a global optimal solution over the driving cycle (Guzzella and Sciaretta (2013)). Nevertheless the assumption of a fully known driving profile is mostly idealistic and is hardly met in practice. Therefore DP is applied as a benchmark as it defines the upper performance bound for the specific EMS. Unlike DP, ECMS is a control strategy which is based on instantaneous optimization, i.e it determines the control action at every time instant of the driving cycle rather than over the entire horizon. If the costate factor, also known as equivalence factor, which relates electric energy to fuel consumption is well determined the solution of the ECMS is close to the global optimal solution provided by DP (Serrao et al. (2009)). Various adaptation rules for the equivalence factor have been introduced among them those based on state feedback (e.g battery state of charge feedback). The state of charge is the most important state in the hybrid power train when it comes to the HEV energy management. The generation of its reference for a part or the entire driving cycle leads to an enhanced approximation of the equivalence factor and consequently to an improvement of the energy management strategy in general. In (Ambühl and Guzzella (2009)), an approach for SoC reference generation based on quadratic programming is presented that exploits information about the elevation profile ahead.

1.1 Main Contribution

As indicated in (Ambühl and Guzzella (2009)), having some *a priori* knowledge about the driving profile (e.g from the navigation system), the HEV control strategy can be enhanced. In this contribution, we utilize preview information about the velocity profile and the requested torque profile ahead. Compared with conventional ECMS-based strategies, the control framework presented in our work includes a supervisory battery SoC planning level to improve the controller performance. An optimal reference trajectory for the SoC can be generated by solving an optimization problem which is aimed at minimizing fuel

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consumption while being charge sustaining at the same time. However the reference SoC trajectory is computed from the solution of a static nonlinear optimization problem. The original dynamic optimization problem is transformed into a static optimization problem by exploiting the differential flatness property of the system and by expressing the system states and control inputs in terms of the so called flat outputs (Nijmeijer and van der Schaft (1995), Fliess et al. (1995), Van Nieuwstadt and Murray (1997), Fliess and Márquez (2000),Oldenburg and Marquardt (2002), Milam (2003), Graichen (2006)). The SoC reference governor operates at a higher sample time than ECMS and provides a sequence of SoC reference values to the ECMS controller. ECMS then applies the reference values to determine the equivalence factor through an adaptation law.

This paper is organized as follows. The model of the considered parallel hybrid electric vehicle is presented in Section 2. Section 3 details the non-predictive ECMS. The predictive flatness-based SoC trajectory generation is outlined in Section 4. Finally, the results and conclusion are presented in Section 5 and Section 6 respectively.

2. MODELING OF A PARALLEL HEV

2.1 Hybrid Propulsion System Model

A full parallel HEV is analyzed and modeled in this case study. In the considered configuration, both internal combustion engine (ICE) and electric motor (EM) operate on the same drive shaft and therefore can propel the vehicle either individually or simultaneously. The speed profile $v(t)$ for certain time horizon is estimated and is considered to be a disturbance defined to the HEV system. The road grade σ is also modeled as a disturbance, however in our work we assume this quantity to be zero (evaluation on standard driving cycles).

Powertrain Model: The force at the wheels that can be supplied by the vehicle is affected by losses in the powertrain. If the vehicle has the total weight $m = m_v + m_l$, where m_v and m_l represent the weight of the empty vehicle and the load respectively, the following equation describes its longitudinal dynamics (Eckstein (2013)):

$$F_{wh} = \underbrace{m\,g\,f_r\cos\sigma}_{F_r} + \underbrace{m\,g\,\sin\sigma}_{F_g} + \underbrace{0.5\,c_w\,A\,\rho\,v^2}_{F_d} + \underbrace{(e_i\,m_v + m_l)\,a_x}_{F_a}, \tag{1}$$

where F_r denotes the rolling friction force, f_r is the rolling friction coefficient, g is the gravitational acceleration, F_g is the road grade resistance, F_d is the aerodynamic drag, A is the frontal area of the vehicle, ρ is the air density, c_w is aerodynamic drag coefficient, F_a is the resistance caused by acceleration, while e_i and a_x are the mass factor and the longitudinal acceleration.

The torque T_{wh} and the angular velocity ω_{wh} at the wheels are expressed as follows:

$$T_{wh} = F_{wh}(v,\sigma)r_{wh} \tag{2}$$

$$\omega_{wh} = \frac{v}{r_{wh}}, \tag{3}$$

where r_{wh} represents the dynamic radius of the wheel.

Transmission Model: The wheel angular velocity ω_{wh} and the wheel torque T_{wh} determine the angular velocity $\omega_{gb,in}$ and the torque $T_{gb,in}$ at the input stage of the transmission according to:

$$\omega_{gb,in} = \omega_{wh}\,i_{gb} \tag{4}$$

$$T_{gb,in} = \begin{cases} T_{wh}/(\eta_{gb}\,i_{gb}), & T_{wh} \geq 0 \\ (T_{wh}\,\eta_{gb})/i_{gb}, & T_{wh} < 0 \end{cases} \tag{5}$$

where i_{gb} and η_{gb} denote the transmission ratio for the current gear (including differential gear) and the transmission efficiency respectively. Additionally, the corresponding torques at the input and output stage of the transmission are coupled according to following relations:

$$\omega_{gb,out} = \omega_{gb,in}/i_{gb} \tag{6}$$

$$T_{gb,out} = \begin{cases} T_{gb,in}\,i_{gb}\,\eta_{gb}, & T_{gb,in} \geq 0 \\ (T_{gb,in}\,i_{gb})/\eta_{gb}, & T_{gb,in} < 0 \end{cases} \tag{7}$$

In the assumed parallel configuration, the torque $T_{gb,in}$ at the gearbox input is provided by the electric motor and the internal combustion engine such that, given that the clutch is closed, the following torque balance is satisfied:

$$T_{gb,in} = T_{ice} + T_{em} \tag{8}$$

while for the angular velocities holds:

$$\omega_{gb,in} = \omega_{ice} = \omega_{em}. \tag{9}$$

Starting with the requested torque at the wheels in (5), the situation when the torque balance (8) can not be met during the propulsion ($T_{gb,in} > 0$) is prohibited as it would result in a powertrain which is not able to satisfy the driver torque request. From the optimization point of view such situation would lead to an infeasible solution. However during deceleration this situation is allowed ($T_{gb,in} < 0$) and corresponds to the usage of conventional friction brakes when recuperation is not possible anymore because the EM torque limit has been reached. For ECMS, the control input is defined as the split-factor,

$$u = \frac{T_{ice}}{T_{gb,in}}, \tag{10}$$

while the electric motor torque follows from:

$$T_{em} = (1-u)\cdot T_{gb,in}. \tag{11}$$

Engine Model: The ICE fuel consumption rate $\dot{m}_f$ depends non-linearly on the engine torque T_{ice} and the angular velocity ω_{ice}. This relation can be expressed as:

$$\dot{m}_f = f_{ice}(T_{ice},\omega_{ice}) \tag{12}$$

In the design of both, ECMS as well as the SoC reference governor, the fuel mass flow function f_{ice} is approximated by a third order polynomial of the engine torque T_{ice} and speed ω_{ice}:

$$\dot{m}_f(T_{ice},\omega_{ice}) \approx \sum_{i=0}^{3}\sum_{j=0}^{3} a_{ij}\cdot\omega_{ice}^{i}\cdot T_{ice}^{j} \tag{13}$$

In addition, the admissible engine torque is limited within the range:

$$T_{ice} \in [0, T_{ice,max}(\omega_{ice})] \tag{14}$$

Electric Motor Model: The electric motor is modeled using a quasi-static map of the electric power P_{em} supplied to or generated by the motor which depends on the electric torque T_{em} and angular speed ω_{em}:

$$P_{em} = f_{em}(T_{em},\omega_{em}). \tag{15}$$