

Optimal Control based Calibration of Rule-Based Energy Management for Parallel Hybrid Electric Vehicles

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ABSTRACT

In this paper a rule-based energy management for parallel hybrid electric vehicles (HEVs) is presented, which is based on the principles describing the optimal control behavior. Therefore we first show the general relations that can be used to describe the optimal limit of electric driving as well as the optimal torque split among the two propulsion systems. Subsequently these relations are employed to derive maps, which represent the optimal behavior depending on several input parameters. These maps are then used as inputs for the rules in the proposed energy management. This not only makes it possible to automatically calibrate the rule-based controller but also gives the optimal control in every driving situation. Given it is not fuel-efficient to turn the internal combustion engine (ICE) on or off for short intervals, it is further shown how this approach allows to adjust the established limit for electric driving by additional rules. In real-world driving conditions this extension results in a significant improvement compared to other energy management approaches. Finally, the performance of the proposed energy management is shown in a number of simulations in various real-world driving cycles.

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INTRODUCTION

The fuel consumption of HEVs strongly depends on the energy management strategy (EMS). In parallel hybrid powertrains, where the electrical propulsion system adds an additional degree of freedom to the powertrain, it needs to be decided when to use which propulsion system and how to split the driver torque demand between them. Given that the efficiency of both systems noticeably varies throughout their operating range, the overall efficiency of the vehicle is essentially determined by the operating points the ICE and the electric motor are working in. The task of the energy management is to coordinate this torque split among the two systems, so that the objective, which here is to minimize total fuel consumption, is fulfilled to the utmost extent possible.

Many different approaches of EMSs have been proposed in literature in the past. At this, two basic directions can be identified: heuristic and optimization-based methods. While the latter perform formal optimization to calculate the optimal torque split, the former work with rules and criteria defined in advance. Within the optimization-based category, numerical methods which perform a global optimization, like dynamic programming (DP) [1], [2] or genetic

algorithms [3], as well as analytical methods e.g. Pontryagin's minimum principle (PMP) [4], [5], [6] can be distinguished. Since both require the detailed knowledge of the entire driving cycle, they cannot be implemented directly. But as they guarantee a global optimal solution, they are widely used as benchmarks. Another group within the optimization-based techniques are the instantaneous minimization methods. Here the most common one is the equivalent consumption minimization strategy (ECMS), originally introduced in [7] and further developed by several authors [8], [9], [10]. The basic idea of this method is the conversion of the electric power into fuel consumption by an equivalence factor and to minimize it together with the fuel consumption of the ICE at each time step. In [11] it was shown that this in turn is a real-time implementation of the PMP.

The second category of the EMSs-the heuristic methods-mainly contains rule-based approaches. As they are completely causal and provide a much more robust control with lower computational load, most production HEVs rely on them. Seeing that there is no formal optimization and the design of the rules is mostly based on engineering intuition, most of the approaches are not able to fully exploit the potential of the hybrid powertrain. Furthermore a large number of thresholds and parameters has to be calibrated for each

powertrain configuration. Thus, it is the aim to make use of optimization methods to design and calibrate the rules, in order to be as fuel-efficient as the optimization based methods. For this purpose the rule-based approaches presented in [12], [13] and [14] are based on efficiency analyses and compares the fuel costs to charge the battery by a load point shift (LPS) to the fuel savings gained by using the electric energy at a later stage. In [15] it is shown how an initial parameter set for a rule-based EMS can be calculated by the theory of hybrid optimal control and therefore be able to dramatically reduce the time of calibration. For the same purpose, the author of [16] proposed a rule-based EMS that combines rules with the idea of an ECMS. Another approach, initially introduced in [17] and also used in [18], [19], [20], is to analyze the optimal behavior calculated by DP for various driving cycles and thereby extract rules and parameters, which can then be implemented as a causal EMS. The drawback of this method is that the calculated optimal control significantly depends on the properties of the used driving cycles and that therefore no generally valid rules can be derived.

For that reason, here the physical principles of the fuel-efficient operation of a parallel HEV were analyzed first. Thereby it was possible to deduce general relations that describe the optimal decisions of the energy management. This paper presents how these relations can be used to set up and calibrate a rule-based EMS. Seeing that the relations are based on the principles of the optimal control, this rule-based approach is able to mimic the optimal behavior and does not need much calibration. In contrast to other approaches that solve the optimal control problem as a whole offline and use the results stored in maps, here the rules and maps are based on physical relations derived for each decision of the energy management. The results presented complete the work published in [21] by a further derivation of the relations as well as an extension of the energy management approach by additional rules in order to prevent short ICE starts and stops.

The paper is organized as follows: In the first section the model of the underlying HEV is explained. The second section outlines the derivation of the relations, on the basis of which a rule-based EMS is presented in the third section. The fourth section deals with the start and stop behavior of the ICE under real-world driving conditions and finally in the fifth section simulation results are shown and benchmarked against the optimal solution from DP.

P2-HYBRID POWERTRAIN MODEL

The hybrid powertrain considered in this paper is a pre-transmission parallel hybrid with a clutch between the electric motor and the ICE, also called p2-hybrid. The configuration of the powertrain architecture is shown in Figure 1. It consists of an automatic gearbox without a torque converter that is replaced by the electric motor, an internal combustion engine as well as a wet start-up clutch, which decouples the ICE during pure electric driving. In the electric powertrain part, the permanently excited synchronous motor is connected to a lithium-ion battery via power electronics. Here also the electric air conditioning (AC) and a DC/DC converter, that supports the 12-volt auxiliaries, are connected. Resulting from this

arrangement of the powertrain components, the vehicle allows for pure electric driving in the electric mode, regeneration while braking as well as combined propulsion of both systems in the hybrid mode.

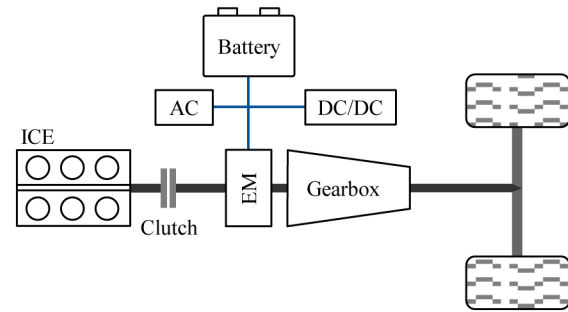


Figure 1. P2-hybrid powertrain architecture considered in this paper

To simulate the vehicle, a forward-facing simulation approach is used in order to respect the direction of the physical power flow in the vehicle. The forward approach includes a driver model, which is here realized as a proportional integral (PI) controller. By comparing the actual velocity with the desired one from the driving cycle, the driver model outputs throttle and brake commands. Received by the hybrid controller these are delivered, according to the EMS, as torque requests to the ICE, the electric motor as well as the friction brake. Depending on the status of the clutch, the gearbox input torque T_{Gbx} consists of the torque from the electric motor T_{EM} and the ICE T_{ICE} . With the ratio of the gearbox i_{Gbx} and the final drive i_{FD} as well as the losses of the powertrain components $T_{PT loss}$, the tractive force at the wheels F_{wh} is calculated with the dynamic rolling radius of the wheels r_{dyn} as follows:

$$F_{wh} = \frac{i_{Gbx} \cdot i_{FD}}{r_{dyn}} \cdot (T_{EM} + T_{ICE} - T_{PT loss}) \quad (1)$$

Together with the driving resistance of the vehicle

$$F_{res} = c_{roll} \cdot m_{veh} \cdot g \cdot \cos \alpha + \dots + 0.5 \cdot \rho_{air} \cdot A_f \cdot C_w \cdot v_{veh}^2 + m_{veh} \cdot g \cdot \sin \alpha \quad (2)$$

and the braking force F_{br} of the friction brakes as well as the vehicle equivalent mass m_{equiv} , which takes into account the inertia of all powertrain components, the acceleration of the vehicle can be calculated:

$$\frac{dv_{veh}}{dt} = \frac{F_{wh} - F_{res} - F_{br}}{m_{equiv}} \quad (3)$$

From this the actual velocity of the vehicle v_{veh} is computed through integration over time. While the wheel torque is calculated forwards in this simulation approach, the speed of the different powertrain components is calculated in backward direction. Neglecting the wheel slip these speeds result from the velocity of the vehicle according to the gear ratios and the dynamic rolling radius.

Regarding the complexity of the simulation model a quasi-static approach is used, where all fast dynamics are neglected and the powertrain components are represented through stationary maps. Furthermore the opening and closing of the clutch as well as the ICE cranking are simplified. The thermal effects are taken into account by the losses of the components, which are modeled as a function of the temperature. For the battery a zero order equivalent circuit model is used. Here the battery is represented through an open-circuit voltage V_{OC} in series with an internal resistance R_i . The open circuit voltage is assumed to be a function of the state of charge (SOC) and the internal resistance of the temperature. Using this modeling approach, the variation of the SOC can be calculated from the battery power at the terminals P_{Batt} by the following equations:

$$\text{SOC}(t+1) = \text{SOC}(t) - \Delta t \cdot \frac{I_{Batt}(t)}{Q_0} \quad (4)$$

$$I_{Batt}(t) = \frac{V_{OC} - \sqrt{V_{OC}^2 - 4 \cdot R_i \cdot P_{Batt}(t)}}{2 \cdot R_i} \quad (5)$$

where I_{Batt} is the current of the battery and Q_0 the battery capacity.

RELATIONS DESCRIBING THE OPTIMAL TORQUE SPLIT AND ELECTRIC DRIVING

In parallel HEVs, which allow pure electric driving as well as combined propulsion of both systems, the energy management has to make two crucial decisions, which build on one another. The first is whether the vehicle should be propelled purely electrically or the ICE should be turned on. If the decision is made to turn on the ICE and the vehicle operates in hybrid mode, the second decision to be made is the torque split among the two propulsion systems. The further decision for regeneration is not discussed here, whereas regeneration is always chosen if the driver brakes and therefore the torque request is negative.

In the following it is discussed by which principles these two decisions can be described in case of the optimal control behavior with minimal fuel consumption. To reduce the complexity, the entire optimization problem is thereby split accordingly to the two decisions of the energy management problem.

Relation for optimal Torque Split

To analyze the optimal torque split, only the operating points in hybrid mode are considered. The segments of electric driving or regeneration-where the ICE is turned off-are masked out and just taken into account by the energy taken from or charged to the battery. Thus the entire energy management problem can be ascribed to the reduced one of finding the particular LPS of the ICE in each hybrid mode operating point which leads to charging or discharging the required amount of electric energy E_{LPS} with minimal fuel consumption.

$$E_{ED} + E_{Reg} + E_{Aux} + E_{LPS} = \Delta E_{Batt} \quad (6)$$

In order to make the analyses as simple as possible, first a situation with only two different operating points is considered. Here the optimization problem can be solved by a brute-force search. In doing so, every potential combination of torque shifts in both operating points is tried out. This approach not only allows to calculate the optimal solution easily, but further makes it possible to illustrate the underlying relations, as can be seen in Figure 2. Here the results for all possible combinations of LPSs that fulfill the boundary condition of charging the specified amount of energy E_{LPS} are plotted. While along with the combinations the torque of the LPS in the first operating point increases, the one in the second operating point declines accordingly. The parameter lambda outlined in the bottom plot represents the derivative of the additional fuel mass flow in consequence of the performed LPS with respect to the thereby resulting power of the battery:

$$\lambda = \frac{d \dot{m}_{Fuel}}{d P_{Batt}} \quad (7)$$

Looking at the total fuel consumption in the upper plot of Figure 2, it becomes apparent from this study that the optimal combination arises in the case that the LPS is chosen in each operating point so that this parameter lambda has the same value.

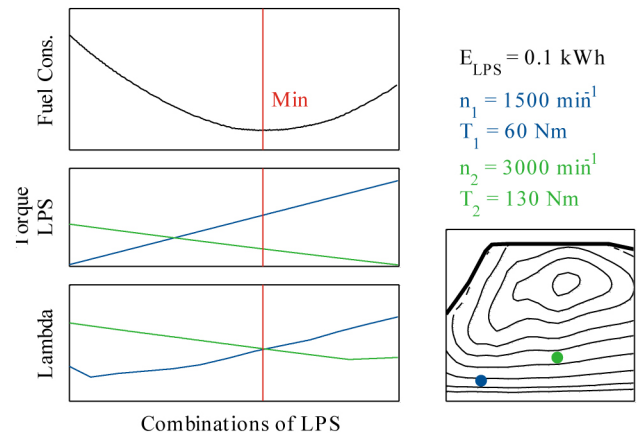


Figure 2. Results from brute force search with different LPSs in two operating points

In Figure 3 the meaning of lambda in the context of an LPS is illustrated. The solid curve represents the fuel mass flow of the ICE as a function of the engine power for a constant speed (known as Willans lines). By an LPS the operating point of the ICE is shifted along this line and produces the additional power ΔP_{ICE} by using the additional fuel mass flow $\Delta \dot{m}_{Fuel}$. Due to the losses in the electric motor and the battery, the reduced power ΔP_{Batt} , represented by the dashed curve, is received by the battery. Lambda as the gradient of this curve, states therefore the change of the fuel mass flow with respect to the power of the battery in the shifted operating point.

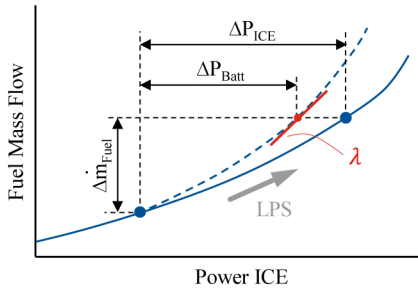


Figure 3. Meaning of lambda in context of an LPS

In the case of more than two operating points, the prior regarded optimization problem can be solved by using the Euler-Lagrange equation, as proposed in [22]. That way the following cost functional in Eq. (8), consisting of the delta fuel mass flow as a function of the speed and torque request as well as the torque shift, needs to be minimized for all operating points in hybrid mode. The energy E_{LPS} which needs to be charged or discharged, is considered in Eq. (9) as a boundary condition.

$$J(\Delta P_{Batt}) = \int_{t_0}^{t_f} \Delta \dot{m}_{Fuel}(T_{Req}, n, \Delta P_{Batt}) dt \quad (8)$$

$$\int_{t_0}^{t_f} \Delta P_{Batt} dt = E_{LPS} \quad (9)$$

Applying the Euler-Lagrange equation also leads to the following relation for an optimal LPS

$$\frac{d \Delta \dot{m}_{Fuel}}{d \Delta P_{Batt}} = const \quad (10)$$

and confirms the principle established in Figure 2 for the simplified case of two operating points.

Hence the general valid relation for the optimal torque split can be deduced, that the LPS of the ICE has to be set in all hybrid mode operating points so that the derivative in Eq. (10), which in fact is lambda, always has the same value. Hereby the electric energy is charged overall with minimal fuel consumption. Lambda is at that a value for the dimension of the LPS respectively the energy that needs to be charged.

Relation for Optimal Electric Driving

The other decision of the energy management, whether the vehicle should be propelled in electric mode or if it is more efficient to turn on the ICE, mainly depends on the amount of fuel which was or will be used to produce the required energy for electric driving. In [21] it

was shown, that the required fuel consumption per electric energy reaching the battery increases with a rising LPS. Secondly it was also shown that the fuel savings, which can be achieved by electric driving, decrease with an increasing torque request. Consequently electric driving with energy charged by LPS is only fuel-efficient up to a certain limit, which depends on the distribution of the operating points of the driving profile.

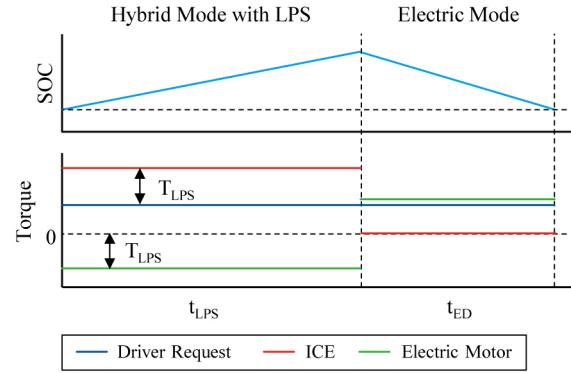


Figure 4. Constant driving situation (first hybrid mode, then electric driving) used for the analysis of the optimal limit of electric driving

The following analyzes where this limit of electric driving is and by which general relation the optimal control behavior of electric driving and LPS can be described. Again a simplified case is considered first, on the basis of which the relations can easily be discussed. For this purpose a constant driving situation is best suited, in which the vehicle is propelled in hybrid mode at the beginning and the driving mode is switched to electric driving after a certain time (see Figure 4). During the hybrid mode the ICE's load point is shifted by a constant torque, so that exactly the energy is charged, which is taken from the battery during the electric driving section. By this boundary condition the periods of the two sections are defined as a function of the torque of the LPS:

$$t_{LPS} = t_{total} \cdot \frac{P_{Batt ED}}{P_{Batt ED} + P_{Batt LPS}} \quad (11)$$

Considering that in the electric driving section the fuel mass flow of the ICE is zero, the total fuel consumption is only a function of the torque of the LPS:

$$m_{Fuel total} = t_{LPS} \cdot \dot{m}_{Fuel}(T_{Req} + T_{LPS}, n) \quad (12)$$

In Figure 5 the results of multiple simulations in such a driving situation with different LPSs are plotted. Here it can be seen that the total fuel consumption initially decreases with rising torque of the LPS, because more energy is available for electric driving. At a certain point this trend reverses, since the efficiency of the LPS declines with increasing torque and consequently more electric driving is not profitable.