Fuel-Efficient State of Charge Control in Hybrid Electric Vehicles

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***Abstract*—Load point shifting of the internal combustion engine in hybrid electric vehicles is used to control the state of charge of the high voltage battery. The control strategy has a significant impact on the achievable fuel savings. This paper presents a method, which controls load point shifting for all useable operating points of the power train by balancing cost and benefit considerations, i. e. current power expenditure versus potential future savings. The control method proposed encompasses offline as well as online optimization. Furthermore, industrial requirements such as processor calculation cycles and reduced tuning complexity are considered.**

***Index Terms*—Hybrid electric vehicles, control strategy, fuel efficiency, state of charge, energy storage.**

I. Introduction

Over the last couple of years numerous research has addressed the energy savings capacity of hybrid electric vehicles. Today, car industry faces the challenge to turn these hypotheses into practice. Central to achieving the required energy savings is the operating strategy of the hybrid power train [1], [2]. A thorough approach will have to incorporate a multitude of other vehicle design criteria, e. g. acoustics, processor capability, etc. [3]. State of charge (SOC) control of the high voltage battery significantly influences fuel consumption [4]. Two main routes of research for optimal control strategies have been discussed in the literature: These are heuristic methods and online optimization [3]-[5].

[6], for example, discusses heuristic methods such as Willans-curves and analytic evaluations. Frequently, a fixed mapping between the SOC level and the battery charge/discharge power is employed [7]. These control strategies have been integrated control based [8] or as fuzzy logic [9].

An online optimization technique is proposed in [10] using cost and weighting functions to determine an optimal control strategy based on real-time vehicle parameters.

The authors of this paper believe that the independent use of online and offline optimizations does not sufficiently explore available information. Offline optimization requires upfront knowledge of the customers driving cycles. Hence, it is difficult to consider the present vehicle's state of operation for optimization. Online optimization, however, requires computational effort and often implies a significant number of tuning parameters [3], [11]. A further critique of current techniques is that they base their decision of fuel efficient load point shifting on the current operating point of the vehicle, rather than evaluating the different operating points for energy generation and use.

The content of this paper is organized as follows: Section II presents the objective of this paper. Section III describes the new concept. In section IV the proposed control strategy is explained. It contains the definition and evaluation of the cost and benefit of load point shifting (LPS), the developed SOC control strategy and a description of how the approach provides fuel optimal SOC control. Section V presents the implemented optimization method, the offline algorithm to integrate each component´s efficiency, and the software architecture.

II. Objective

This paper presents a method to control the SOC in a fuel-optimal manner by shifting the load point of the internal combustion engine (ICE) in a full-hybrid vehicle. The objective is to include all relevant components (i. e. ICE, electric machine, etc.) as well as all operating points of a parallel hybrid power train. An integral idea of the proposed method is to evaluate not only the efficiency of energy generation in a given operation point, but also the future benefit of the energy conversion, e. g. of electric driving. Furthermore, the control strategy should facilitate also inputs from the operating strategy based on e. g. maneuver detection or prediction [12] and integrate these fuel-efficient. The control strategy should be amalgamated in the software architecture to facilitate real time processing and a flexible design process. In addition to the decision when to perform a load point shift, the method has also to determine the optimal magnitude of the load point shift. The approach uses both offline and online optimization in order to achieve optimal savings by generating electrical energy (cost) at a current point in time and its usage in the future (benefit).

III. Concept

In the presented approach, the LPS of the ICE is used to control the SOC. The power delivered to or dissipated by the battery in form of the electric motor power $P_{\mathrm{EM,\,el}}$ is the output variable. The SOC control strategy should set the optimal $P_{\mathrm{EM,\,el}}$ which minimizes fuel consumption in each operating point. $P_{\mathrm{EM,\,el}} = 0$ denotes an inefficient operating point.

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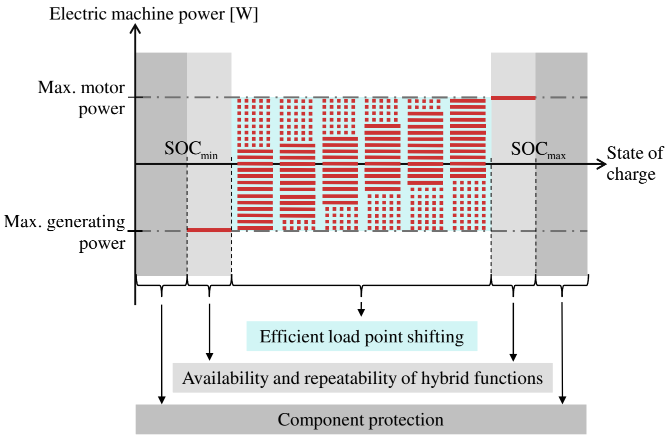

Fig. 1. Concept of SOC control: Different strategies apply for the indicated SOC ranges.

A demanded $P_{\text{EM, el}}$ solely determined on maximum efficiency may not be realized at every SOC level, i.e. at minimal and maximal SOC, due to battery protection. Thus, the control also has to ensure the availability and repeatability of the hybrid functionality in all operating conditions. Near the onset of SOC saturation the load point of the ICE has to be reduced to prevent reaching the maximum SOC and therefore to allow for energy recuperation (e. g. for down hill runs). The availability of electric driving is guaranteed by charging the battery before it is depleted (minimal allowed SOC). The described SOC ranges, and the range for which fuel efficient control is active are shown in Fig. 1.

IV. Approach

For the implementation of the presented concept a new control approach is developed, which evaluates the cost and the future benefit of a load point shift. This section defines cost and benefit and explains how these variables can be used to control the SOC. Finally the method is explained, which allows fuel efficient SOC control.

A. Cost and benefit

Integral to the proposed method is the specific fuel change of LPS modeled by

$$b_{\text{LPS}} = \frac{\dot{m}_{\text{LPS}} - \dot{m}_{\text{bas}}}{P_{\text{bat}}} \tag{1}$$

where $\dot{m}_{\text{LPS}}$ is the fuel flow during LPS, $\dot{m}_{\text{bas}}$ the fuel flow without LPS and P_{bat} the battery power.

The cost $C(k)$ is defined as the fuel mass in grams, which is necessary to generate one kWh of electric (battery) energy by a load point increase (LPI):

$$C_{\text{LPI}}(k) = \left| \frac{\dot{m}_{\text{LPI}}(k) - \dot{m}_{\text{bas}}(k)}{P_{\text{bat}}(k)} \right| \tag{2}$$

Note that k denotes the discrete time constant of the electric control unit (ECU).

The benefit $B(k)$ describes how much grams of fuel can be saved by applying one kWh of battery energy for a reduction of the load point (LPR) or for electric driving (ED):

$$B_{\text{LPR}}(k) = \left| \frac{\dot{m}_{\text{LPR}}(k) - \dot{m}_{\text{bas}}(k)}{P_{\text{bat}}(k)} \right| \tag{3}$$

$$B_{\text{ED}}(k) = \left| \frac{\dot{m}_{\text{bas}}(k)}{P_{\text{bat}}(k)} \right| \tag{4}$$

The introduction of a cost and benefit analysis allows a time decoupled view of energy generation by LPI and energy use by LPR or electric driving. Thus, it can be taken into account that the operating strategy generally assigns different operating points for energy generation and use. For instance, LPI may be performed at a vehicle speed at which electric driving is infeasible or prohibited by the operating strategy. Therefore, a direct comparison of LPI and electric driving at such operating points is not meaningful because the generated energy can only be used in a later operating point.

B. SOC control

The current SOC or an identified situation (maneuver detection) defines the maximal allowed cost $C_{\max}(k)$ of LPI as well as the minimal required benefit $B_{\min}(k)$ of LPR:

$$C_{\text{LPI}}(k) \leq C_{\max}(k) \tag{5}$$

$$B_{\text{LPR}}(k) \geq B_{\min}(k) \tag{6}$$

Following the constraints described in section III, the SOC ranges as well as $C_{\max}(k)$ and $B_{\min}(k)$ are defined according to the following conditions (cp. Fig. 2):

- SOC $<$ SOC$_{\min}$: Ensure maximum charging. Prohibit discharging.
- SOC$_{\text{opt, min}}$ $<$ SOC $<$ SOC$_{\text{opt, max}}$: Fuel efficient SOC control.
- SOC $>$ SOC$_{\max}$: Prohibit charging. Ensure maximum discharging.

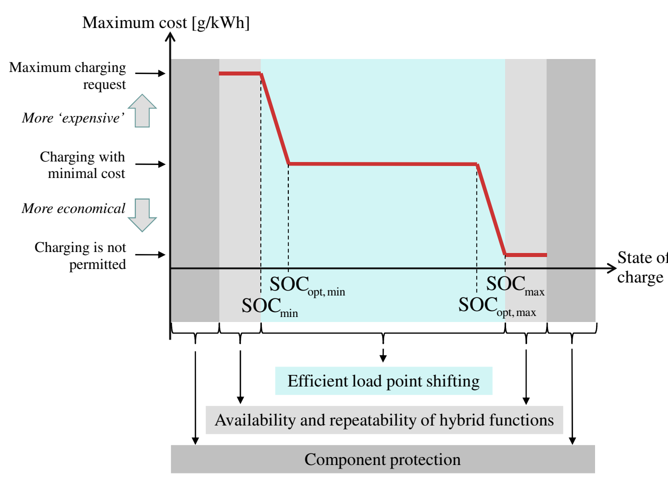

Fig. 2. Maximum cost for load point increase: Charging is only permitted if the cost is below the trajectory.

The maneuver detection calculates for each identified situation a minimum or maximum SOC. Therefore the SOC set points (i. e. $\text{SOC}_{\text{min}}, \text{SOC}_{\text{opt, min}}, \text{SOC}_{\text{opt, max}}, \text{SOC}_{\text{max}}$) are varied in the trajectory (see Fig. 2). Consider for example an upcoming declining slop: In order to profit from "cheap" energy recuperation a margin to the right of SOC_{max} has to be vacated to absorb any energy generated during the down hill drive. Additionally it is also possible to reduce the minimal benefit for LPR for discharging up to the target SOC.

C. Fuel optimization

To execute LPS fuel optimally in a driving cycle, the average cost has to be as low as possible and the average benefit as high as possible. Therefore, the control calculates online the average cost of LPI $\overline{C}_{\text{LPI}}(k)$ relating to the generated battery power:

$$\overline{C}_{\text{LPI}}(k) = \left| \frac{\sum_{i=1}^{k} (\dot{m}_{\text{LPI}}(i) - \dot{m}_{\text{bas}}(i))}{\sum_{i=1}^{k} P_{\text{bat}}(i)} \right| \tag{7}$$

Similarly, the average benefit $\overline{B}_{\text{LPI}}(k)$ relating to the used battery power is calculated for LPR and electric driving (ED):

$$\overline{B}_{\text{LPI}}(k) = \begin{cases} \left| \frac{\sum_{i=1}^{k} (\dot{m}_{\text{LPR}}(i) - \dot{m}_{\text{bas}}(i))}{\sum_{i=1}^{k} P_{\text{bat}}(i)} \right|, & \text{for LPR,} \\ \left| \frac{\sum_{i=1}^{k} \dot{m}_{\text{bas}}(i)}{\sum_{i=1}^{k} P_{\text{bat}}(i)} \right|, & \text{for ED.} \end{cases} \tag{8}$$

If $\text{SOC}_{\text{opt, min}} < \text{SOC} < \text{SOC}_{\text{opt, max}}$ (the range considered for fuel optimal SOC control) the following conditions apply for LPS:

- LPI is executed with the maximal possible power, whose cost is lower than or equal to the current average cost:

$$C_{\text{max}}(k) = \overline{C}_{\text{LPI}}(k) \Rightarrow C_{\text{LPI}}(k) \leq \overline{C}_{\text{LPI}}(k) \tag{9}$$

- LPR is executed with the maximal possible power, whose benefit is higher than or equal to the current average benefit of LPI:

$$B_{\text{min}}(k) = \overline{B}_{\text{LPI}}(k) \Rightarrow B_{\text{LPR}}(k) \geq \overline{B}_{\text{LPI}}(k) \tag{10}$$

To minimize fuel consumption, the cost of generating energy should be at least equal or smaller to the benefit of using this energy. The control of LPS is extended as follows:

- LPI is only executed, if the cost is lower than the average benefit:

$$C_{\text{LPI}}(k) \leq C_{\text{max}}(k) \;\wedge\; C_{\text{LPI}}(k) \leq \overline{B}_{\text{LPI}}(k) \tag{11}$$

- LPR is only executed, if the benefit is higher than the average cost:

$$B_{\text{LPR}}(k) \geq B_{\text{min}}(k) \;\wedge\; B_{\text{LPR}}(k) \geq \overline{C}_{\text{LPI}}(k) \tag{12}$$

V. Optimization method

This section describes the method to implement the presented approach.

A. Objective

The objective of the optimization is to consider all operating points of all for LPS relevant components to minimize fuel consumption. First a reference point in the power train is defined, which determines the operating point of the involved components. In the case of SOC control, the gearbox input is appropriate, because the torque transmitted by the gearbox must be kept constant. Consequently, the operating point in the optimization is defined by the gearbox input torque $M_{\text{GI}}(k)$ and gearbox input rotational speed $n_{\text{GI}}(k)$. $P_{\text{EM, el}}(k)$ can be used as actuating variable and the reference variables are cost and benefit.

B. Offline algorithm

An algorithm is developed, which determines offline the optimal power $P_{\text{EM, el}}$, taking into account the components efficiencies (e. g. ICE, electric motor, battery, etc.) as well as defined cost and benefit (see conditions (5) and (6)). The calculation is carried out iteratively on all operating points (M_{GI} and n_{GI}), all SOC levels, predefined maximal costs C_{max}, minimal benefits B_{min} and all permitted $P_{\text{EM, el}}$. The algorithm returns LPI maps, which define $P_{\text{EM, el}}$ as a function of M_{GI}, n_{GI} and C_{max}:

$$P_{\text{EM, LPI, opt}} = f(M_{\text{GI}}, n_{\text{GI}}, C_{\text{max}}) \tag{13}$$

Since the cost of $P_{\text{EM, LPI, opt}}$ may be lower than C_{max}, additional maps are needed, which define the related actual cost $C_{\text{LPI, opt}}$:

$$C_{\text{LPI, opt}} = f(M_{\text{GI}}, n_{\text{GI}}, C_{\text{max}}) \tag{14}$$

Similarly, for LPR the following maps are computed:

$$P_{\text{EM, LPR, opt}} = f(M_{\text{GI}}, n_{\text{GI}}, B_{\text{min}}) \tag{15}$$

$$B_{\text{LPR, opt}} = f(M_{\text{GI}}, n_{\text{GI}}, B_{\text{min}}) \tag{16}$$

A sensitivity analysis shows that the dependency of SOC to battery efficiency has an insignificant impact on the calculation of $P_{\text{EM, LPI, opt}}$, $C_{\text{LPI, opt}}$, $P_{\text{EM, LPR, opt}}$ and $B_{\text{LPR, opt}}$. Thus, the SOC is set to a constant level in equations (13) - (16) to minimize complexity for online use in a vehicle environment (cp. section II).

Each iteration takes into account the torque and power limits for the components, the relative efficiency of the electric motor, the fuel flow of the ICE, the battery´s charge and discharge efficiency and the maximally allowed power for LPS. Furthermore, it is possible to consider acoustic limits in the offline calculation.

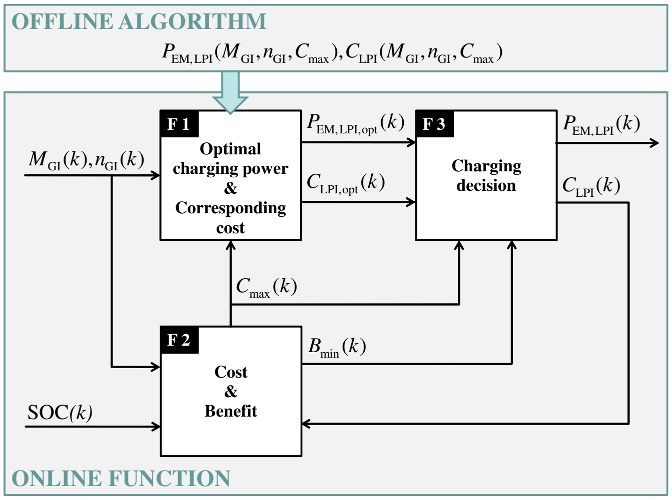

Fig. 3. Functional architecture for LPI: Offline generated data are used in an online control, which outputs the electric machine power.

C. Software architecture

The software architecture is based on data generated offline as well as a function which is evaluated online. Fig. 3 shows the architecture exemplary for LPI.

The algorithm presented in the previous section computes maps for the demand of $P_{\text{EM, LPI, opt}}(k)$ as well as the corresponding cost $C_{\text{LPI, opt}}(k)$ to generate this power. The maps are grouped in F 1 of the online calculation (see Fig. 3). They consider the current operating point and the maximally permitted cost C_{max}, which is determined in F 2.

F 2 calculates the average cost for LPI $\overline{C}_{\text{LPI}}(k)$ on the basis of the vehicular operating parameters – e. g. torque, speed, the battery´s charge and discharge power (7). Additionally, the function calculates the average benefit $\overline{B}_{\text{LPI}}(k)$ of electric driving and LPR (8).

The average values are only used as maximal charge cost $C_{\text{max}}(k)$ while $\text{SOC}_{\text{opt, min}}(k) \leq \text{SOC}(k) \leq \text{SOC}_{\text{opt, max}}(k)$ (9). Outside this SOC range, $C_{\text{max}}(k)$ is cross-faded to values, which provide or prohibit charging in all operating points (see Fig. 2). Furthermore, the SOC requested for a predicted situation can be incorporated in this function, which may vary also the calculated SOC-thresholds.

The decision to charge the battery based on the cost and benefit is determined in F 3. It is checked whether the current cost $C(k)$ is lower than the average benefit $\overline{B}_{\text{LPI}}(k)$ (11). If the condition is met, charging is permitted and $P_{\text{EM, el}}(k)$ is returned.

VI. Simulation Results

To validate the control strategy a simulation model in Matlab/Simulink is developed. The model considers the efficiency of the main components in the parallel hybrid power train, i. e. ICE, electric machine, energy storage, power electronics and automatic transmission. It is used to analyze both the functional capability and the achievable fuel savings.

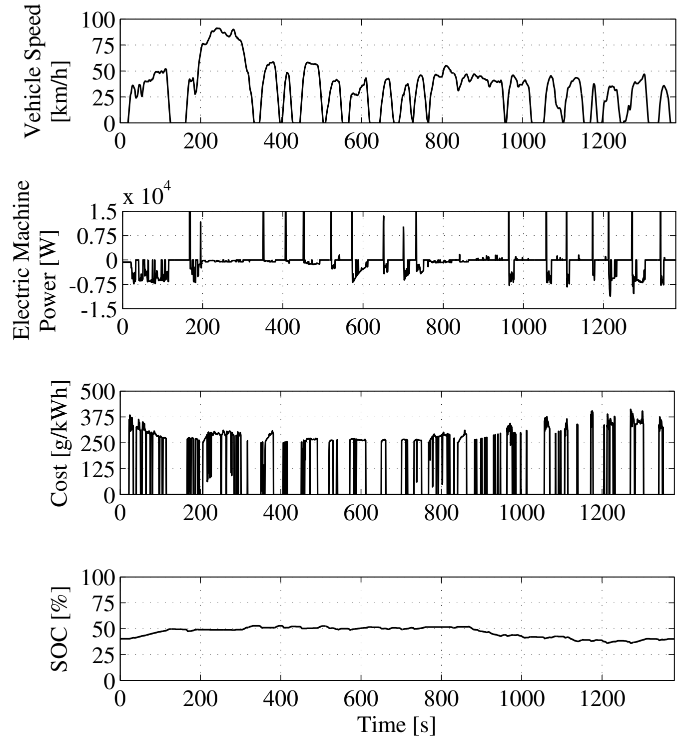

Fig. 4. Reference control strategy: Simulation results for the first half of FTP-75 show high charging cost

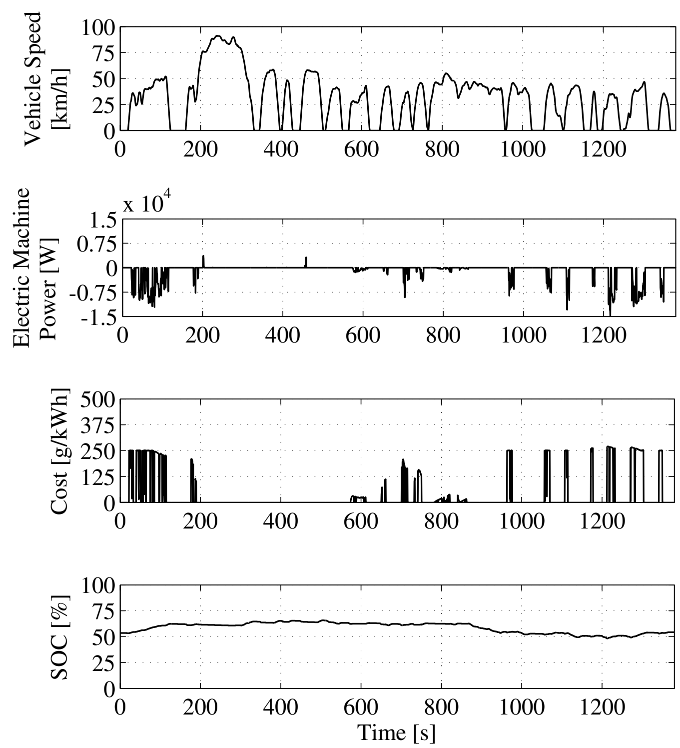

Fig. 5. Optimized control strategy: Simulation results for the first half of FTP-75 show low charging cost

The model is capable to simulate standardized driving cycles, e. g. FTP-75 or the New European Driving Cycle (NEDC).

Fig. 4 and Fig. 5 show the simulation results of the first half of the FTP-75. The optimized control of load point shifting (see Fig. 5) is compared with a reference control strategy, which controls a target SOC range (see Fig. 4).

Diagram one displays the vehicle speed. The second diagram shows the electric machine power of load point shifts. In the third diagram the corresponding cost is illustrated. The forth diagram shows the SOC. To analyze the fuel consumption, the SOC at the beginning of the driving cycle has to be equal to the SOC at the end of the driving cycle.

The simulation results demonstrate the advantages of the presented control method. The evaluation of the cost and the future benefit of a load point shift enables the calculation of a fuel optimal charging and discharging power. Thereby the present vehicle's state of operation is considered. All over the driving cycle, the cost of the charging power is lower than the charging cost of the reference control strategy. Especially avoiding very low charging powers significantly reduces the cost. Furthermore in comparison with the conventional control of a target SOC range, the consideration of the benefit of load point reductions eliminates inefficient discharging powers. Thus, there is less charging power required in the driving cycle.

The optimized control strategy reaches an overall fuel reduction of 2% in the FTP-75.

VII. Conclusion

This paper presents a novel approach to control load point shifting in hybrid electric vehicles. Central to this method is to consider the cost incurred by a load point increase to the benefit gained by spending it at a later stage for load point decrease or electric driving. The proposed strategy employs offline as well as real time calculations, merges well into existing software architecture and takes into account all operating points of the hybrid vehicle components. Also, the approach incorporates, that energy generation and use may be distributed amongst different operating points by the operating strategy.

Simulations of driving cycles prove the functional capability of the control method. In the FTP-75 a fuel reduction of 2% is obtained.

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