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Evaluation of Efficiency-Enhancing Measures for Fuel Cell Vehicles Using Optimization Algorithms

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Summary

Based on two hybrid electric powertrain architectures, efficiency-enhancing measures are evaluated over a drive cycle. DC-link voltage variation increases efficiency of electrical machine and inverter. Phase switching reduces DC-DC losses. Pontryagin's Minimum Principle (PMP) and Dynamic Programming (DP) were used to evaluate these measures. PMP computes the optimal solution within minutes and DP was extended by start-up and shutdown energy of the fuel cell system to model realistic cycle consumptions. This reduces switching events by 50 %. The powertrain architecture using a single DC-DC is most efficient, whereby voltage variation reduces the required energy by 3.1 % and phase control saves 0.4 %.

Keywords: HEV, fuel cell vehicle, simulation, efficiency, optimization

1 Introduction

Fuel cell vehicles (FCV) utilize hybrid electric powertrains, comprising a battery and the fuel cell system (FCS). FCS provide a segregation of the energy and the power source such as internal combustion engines do. However, the efficiency is not limited by the Carnot process. For this reason, FCS can be a promising technology for automotive powertrains.

Since the serial application of FCV is, compared to internal combustion engine vehicles, relatively new, there is still potential to optimize the FCV powertrain. Besides the FCS and the battery, the simulated hybrid electric powertrain consists of at least one direct current converter (DC-DC), an inverter and an electric motor. For this high voltage system, efficiency can be increased by varying the DC-link voltage [1]. Such a DC-link control improves the efficiency by 2.34 % for an electric delivery truck [2]. Further optimization potential is the intelligent phase control for DC-DC [3]. Toyota reduced the DC-DC losses by 10 % with such a phase control [4].

To evaluate these efficiency-enhancing measures for hybrid electric powertrains, an operating strategy must be applied. This operating strategy is calculated by optimization algorithms to find the optimal power split between battery and FCS for an a priori known driving cycle. In the literature, Pontryagin's Minimum Principle (PMP) and Dynamic Programming (DP) have been suggested to find the optimal solution for the power split between battery and FCS. PMP has been recommended for fast computing [5] [6] [7]. This paper outlines the potential of voltage variation and DC-DC phase control for a given driving cycle by the help of an adjusted optimization algorithm.

2 Hybrid Electric Vehicle

The driving resistances of the FCS were adopted from a Tesla Model S. The propulsion system in our study comprises a permanent magnet synchronous motor (PMSM) and an inverter with 120 kW continuous power. It is assumed that 80 % of the vehicle power is provided by the FCS and 20 % by the battery. The FCS is a proton-exchange membrane fuel cell powered by an electric turbocharger. In the lithium-ion battery, there are 40 cells connected in series. Due to the two voltage sources at least one DC-DC is mandatory to connect the inverter with the two electrochemical power sources.

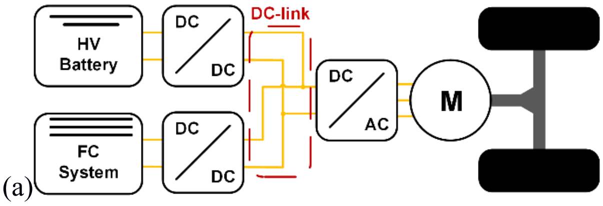

Figure 1: Hybrid electric powertrain architecture (a) with two DC-DCs and (b) a single DC-DC connect to the battery

The architecture in Fig. 1 (a) consists of two DC-DCs for each voltage source. This enables individual control of the DC-Link voltage. Fig. 1 (b) shows the architecture with a single DC-DC. Due to the small number of cells the battery voltage is too low for the DC-link. Therefore, the DC-DC is mandatory on the battery side. Contactors are used to disconnect the FCS from the DC-link when it is switched off. As a consequence, the DC-link voltage must fit to the FCS voltage, if the contactors are closed.

2.1 Voltage Variation

Within the hybrid electric powertrain mainly inverter and PMSM are affected by the voltage variation. The inverter losses are mainly caused by the switching losses of the power electronics. The switching losses rise proportionally to the DC-link voltage. Therefore, a low DC-link voltage will reduce inverter losses.

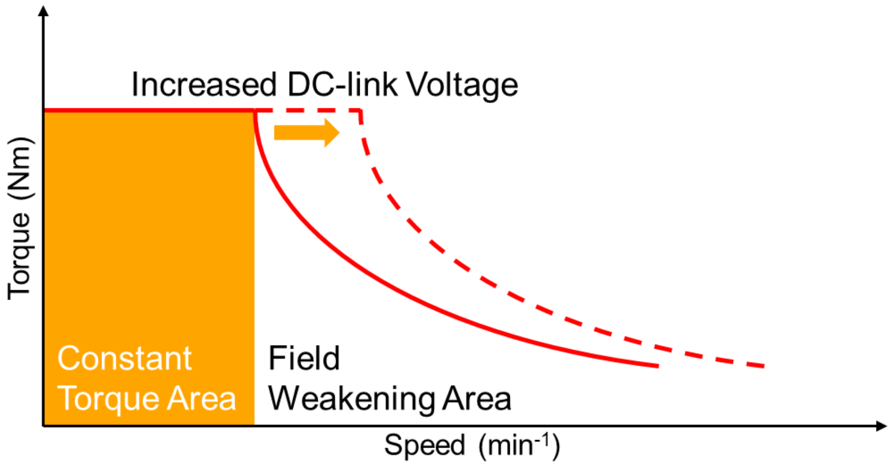

Figure 2: Typical PMSM torque – speed characteristic

The typical torque-speed characteristics of a PMSM machine is shown in Fig 2. The area can be divided into two main parts: constant torque area and field weakening area. In the constant torque area, the necessary PMSM stator voltage to generate torque is higher than the synchronous generated voltage. The DC-link voltage determines the stator voltage. The synchronous generated voltage is proportional to the shaft speed. The field weakening area starts when the synchronous generated voltage exceeds the stator voltage. In order to generate torque, the synchronous generated voltage must be lowered by an additional field weakening current. This additional current increases the reactive power. Increased DC-link voltage shifts the field weakening area of the PMSM towards higher shaft speed and thus lower losses and higher power can be achieved. The efficiency of inverter and PMSM η_{PMSM} is calculated as follows:

$$\eta_{PMSM} = \frac{n_{rotor} \cdot M_{PMSM}}{U_{DC-link} \cdot I_{inverter}} \tag{1}$$

The contrary effects for inverter and PMSM lead to the fact, that for each operating point the optimal DC-link voltage must be determined to achieve best efficiency. In this investigation, the DC-link voltage starts at 250 V and it is raised by 25 V steps until 450 V is reached. The efficiency enhancement of the variable DC-link voltage for inverter and PMSM are illustrated in Fig. 3.

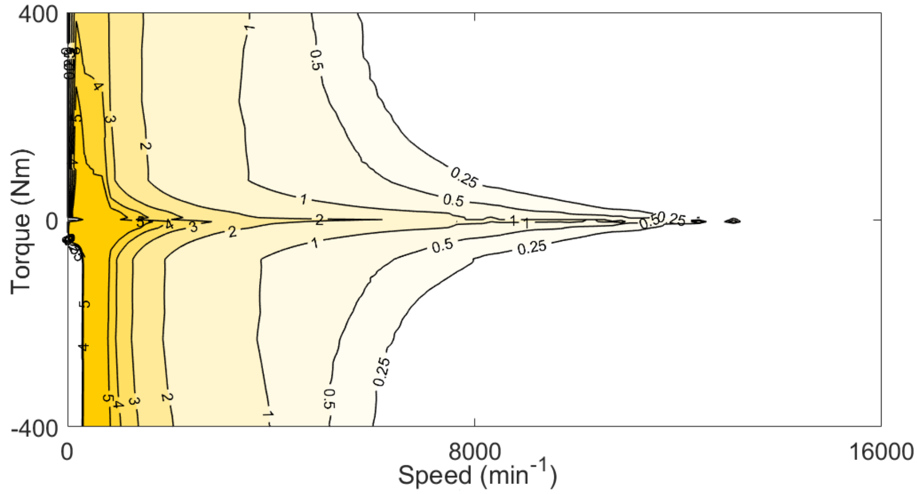

Figure 3: Efficiency enhancement of the optimal variable DC-link voltage against constant 450 V

2.2 Phase Control

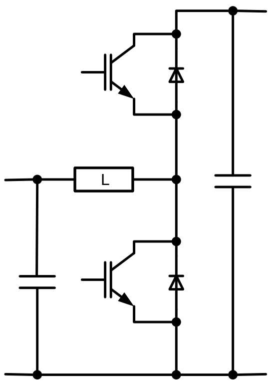

Figure 4: Electric circuit of one bidirectional DC-DC phase

The DC-link voltage can be influenced by the DC-DC. The “fuel cell” DC-DC is unidirectional and the DC-DC connected to the battery is bidirectional to enable power supply and charging. Both DC-DCs consist of multiple phases Fig. 4. Based on measurement data from the Bidirectional Charge- and Traction-System (BCTS) powertrain, a simulation model for the DC-DCs was developed. As in the inverter, the losses of the DC-DCs are determined by the switching losses of the power electronics. Once a phase is active, the power electronics generate switching losses. On the other hand, the losses are also proportional to the phase current. As a result, the number of active phases varies during operation for reduced DC-DC losses.

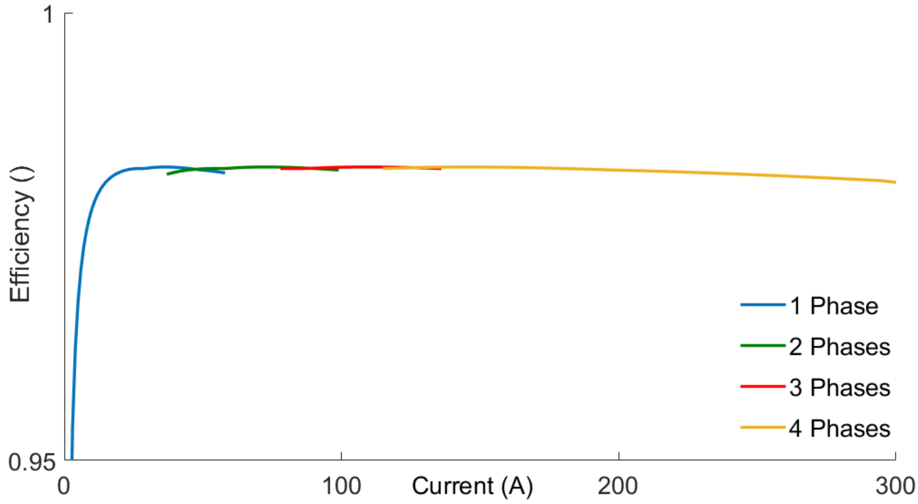

Figure 5: DC-DC efficiency for four phases and phase control

The phase control Fig. 5 shows the number of active phases in dependence of the current to guarantee the best efficiency at the example of maximum four phases. The efficiency η_{DC-DC} for the case of traction is calculated by:

$$\eta_{DC-DC} = \frac{U_{DC-link} \cdot I_{out}}{U_{source} \cdot I_{in}} \quad (2)$$

In addition, a passive mode was applied. In this case the DC-DC establishes a direct connection with all phases between the voltage source and the DC-Link. Consequently, there are no switching losses and the ohmic losses are minimized. In the DC-DC off mode, the component is switched off and does not consume energy.

3 Optimization Algorithms

To evaluate the effects of voltage variation and phase control an optimal hybrid operating strategy must be found under fixed conditions. The hybrid electric vehicle described in section 2 is evaluated with the world harmonized light vehicles test cycle (WLTC). The electrical system load is assumed to be constant at 250 W. The battery state-of-charge (SOC) is limited to a range from 20 % to 80 %. At the beginning and at the end of the driving cycle the SOC must be 50 %. This enhances the comparability because the entire consumed energy is provided by hydrogen.

Within these boundary conditions, optimization algorithms provide the optimal operating strategy for the a-priori known driving cycle. The optimization algorithm uses the fuel cell power as a control variable to achieve the lowest energy consumption. The SOC of the battery is the state variable. A commonly applied optimization algorithm is the Pontryagin's Minimum Principle (PMP). The advantage of the PMP is its fast computing for complex simulation models.

3.1 PMP

In 1956, Lev Pontryagin formulated the PMP based on the Euler-Lagrange equation [8]. In this case, the PMP is applied with constraints on the state $SOC(t)$, due to the limits above. The PMP provides necessary but not sufficient conditions for global optimality in linear systems. This means that the optimal solution fulfils these conditions, but the solution of the PMP does not have to be optimal.

The first condition is that the control variable $P_{\mathrm{FCS}}(t)$ element of all possible FCS powers U minimizes the Hamiltonian H at each instant of time.

$$P_{\mathrm{FCS}}(t) = \arg \min_{P_{FCS} \in U} \left(H(\lambda(t), SOC(t), P_{\mathrm{FCS}}(t), t) \right) \tag{3}$$

$$H(\lambda(t), SOC(t), P_{\mathrm{FCS}}(t), t) = \dot{m}_{H_2}(P_{\mathrm{FCS}}(t), t) + \lambda(t) \cdot f(SOC(t), P_{\mathrm{FCS}}(t), t) \tag{4}$$

Secondly, the co-states $\lambda(t)$ are given by the following equation:

$$\dot{\lambda} = -\frac{dH}{dSOC} = -\frac{\lambda(t) \cdot f(SOC(t), P_{FCS}(t), t)}{dSOC} \tag{5}$$

And finally, the boundary conditions are adhered to by the initial and final SOC:

$$SOC(t_{inital}) = SOC(t_{final}) = 50\ \% \tag{6}$$

The definition of the initial SOC allows to transform the third condition into an initial value problem of the co-state. The applied method is known as shooting method. At the beginning of this method two co-states are chosen which results in a lower and higher SOC than the final SOC. Subsequently, the correct co-state, which fulfils the boundary conditions, can be found iteratively by numerical methods.

The solution for the power split between FCS and battery can be calculated within minutes. However, the optimality must be proven by a different algorithm.

3.2 DP

The DP is based on the Bellman equation and guarantees the global optimal solution. Therefore, the time of the drive cycle and the state variable are discretized, as shown in Fig. 6. Subsequently the simulation calculates the energy consumption J from the start state to all possible states after one time step.

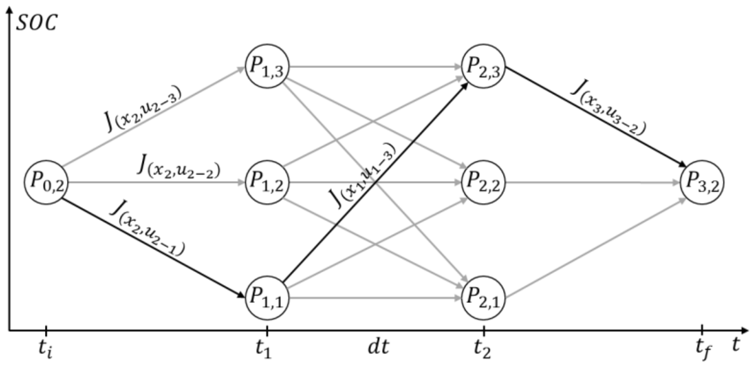

Figure 6: Discretization of time and SOC with arc costs J

After the simulation, the energy consumptions are summarized backwards from t_f to t_i. The states from the path with the lowest energy consumption are stored. From these states the optimal power split between FCS and battery can be inferred. This algorithm requires high computational efforts.

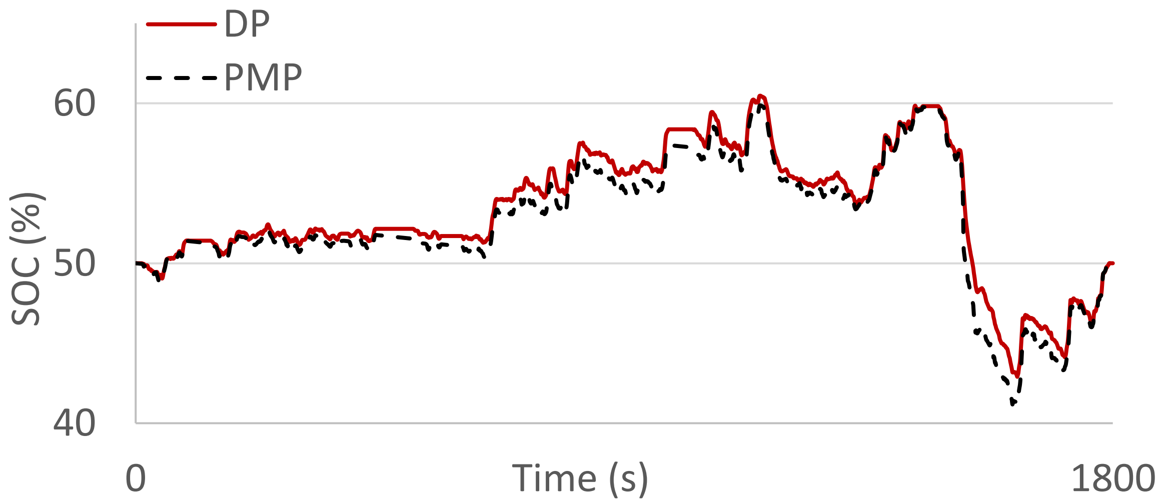

Figure 7: Trajectory of the battery state-of-charge for the WLTC

The similar progression of PMP and DP in Fig. 7 confirms that PMP is close to the global optimum solution. The largest SOC deviation is 3,5 %.

3.3 Extended DP

The analysis of Fig. 8 shows that, depending on the driving situation, there are frequently switching on and off events of the FCS. To prevent this, the optimization algorithm must consider start-up and shutdown energy for the FCS. The PMP is a mathematical method which cannot take discrete events into account. Therefore, the DP must be extended for the FCS status. Besides the energy consumption, the simulation additionally stores the FCS status. Consequently, when the FCS status changes, the switching costs can be regarded. The start-up and shutdown energy of the FCS is 1 MJ at above 20 °C ambient temperature [9]. This procedure is advantageous because it does not increase the dimension of the DP and thus the required computing power is the same.

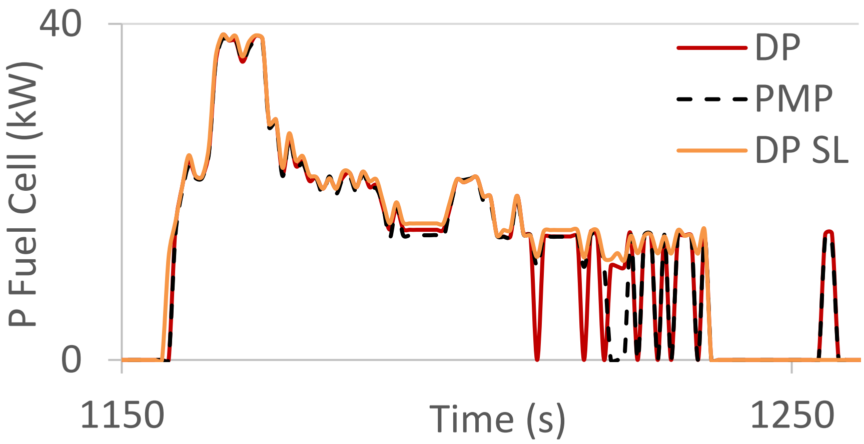

Figure 8: Comparison of different optimization algorithm for hybrid electric vehicles

DP SL considers the switching events of the FCS and is shown in orange in Fig. 8. It avoids frequent switching and uses the battery for short power peaks in the DC-link. In summary, the start-up and shutdown events were reduced by 50 % in the WLTC. Thus, the calculated power split with DP SL is more realistic.

4 Results

Efficiency-enhancing measures such as DC-link voltage variation and DC-DC phase control are evaluated for hybrid electric powertrains using the introduced optimization algorithms. At first the PMP is applied, to limit the state space for the DP SL. Subsequently, the DP SL calculates a realistic control strategy for the power split and the energy consumption for the cycle.

The results for this procedure are shown in Tab. 1 for hybrid electric powertrains with a single (Battery DC-DC) or two DC-DC. Additionally, the optimization measures voltage variation and phase control are applied. To show the benefit of the optimization algorithm, a standard control is added. The standard control starts-up the FCS and shuts it down at a certain DC-link power demand while fulfilling the boundary conditions of section 3.

Table 1: Energy consumption (kWh) over the WLTC drive cycle

	2 DC-DC	Battery DC-DC
Standard Control	29.6	29.3
Optimal Algorithm	29.0	28.9
Optimal Algorithm + Voltage Variation	28.5	28.0
Optimal Algorithm + Voltage Variation + Phase Control	28.4	27.9

The Battery DC-DC architecture with voltage variation and phase control achieves 1.8 % less energy consumption than the comparable two DC-DC architecture. The reason is that the entire energy required for the WLTC drive cycle is provided by hydrogen. In the two DC-DC architecture the whole energy must pass the converter at the FCSC. The resulting losses cannot be compensated by the greater degree of freedom of the voltage variation. For the Battery DC-DC architecture, the voltage variation reduces the energy consumption by 3.1 % and the phase control by 0.4 %.

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