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Fundamental Research on the Operating Strategy for a Hybrid Energy Storage System in the Electric Powertrain of Autonomous Vehicles

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Abstract

The electrification of the automobile powertrain and the automation of driving functions are the major trends of the automotive industry in the 21st century. In combination, these two systems will enable novel possibilities for energy efficient driving. The autonomous driving system provides a trustworthy prediction of the future load profile, which is used for the calculation of energy optimal control trajectories. This paper presents a fundamental research on and the potentials of a predictive operating strategy for a hybrid energy storage system (HESS) supported by the autonomous driving system. A HESS is composed of a battery representing the energy storage device and a double layer capacitor (DLC) representing the power storage device. It is shown that a dynamically optimized operating strategy improves the energy efficiency and reduces the weight, the volume and the cost of the HESS.

Keywords: power management, autonomous, BEV (battery electric vehicle), EDLC (electric double layer capacitor or super capacitor), battery

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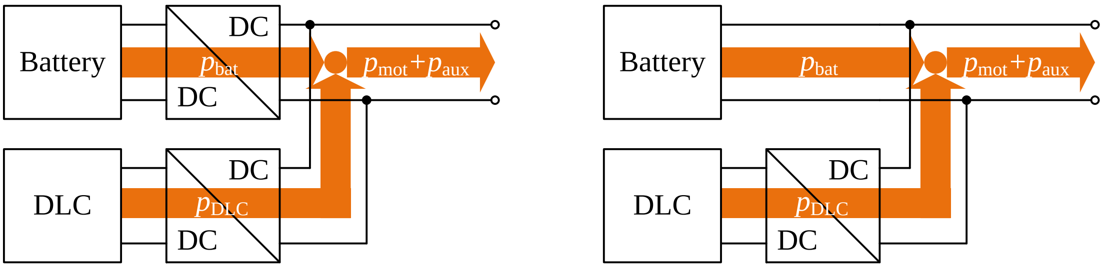
1 Introduction

The energy storage system is an exceedingly heavy and the most expensive part of an electric vehicle. Thus, the energy storage system is the key technology for mass adoption of electric vehicles [1]. In the transportation sector there are many requirements for an energy storage system. The most important demands are a high energy density for an extended drive range as well as a high power density for fast acceleration and regenerative breaking [1]. In conventional electric vehicles, the storage system includes only one component, the battery. This results in a conflict of goals between these two challenges. In comparison with battery cells, a double layer capacitor (DLC) provides a very high power density. Thus, the usage of a DLC as an extension to the battery seems natural to solve the conflict. The article [2] shows, that a hybrid energy storage system (HESS) including a high-energy battery and a high-power storage device improves the low-temperature performance of the storage system. In addition, the HESS can extend the battery lifetime by 76 % under urban driving conditions [3].

The articles [4, 5, 6, 7] propose a HESS for electric vehicles including a battery and a DLC. Both devices are connected to the DC-link via DC/DC-converters (Figure 1a). This application allows to actively control the power flow of the HESS. In addition, this topology offers the opportunity to vary the DC-link voltage independently from the battery voltage. This feature could be used for an improvement of the energy efficiency [8]. Furthermore, it is recommended to connect the high-energy battery directly to the inverter and use only one DC/DC-converter between the high-power device and the electric drive to control the power flow [3, 9] (Figure 1b).



(a) Two DC/DC-converters

(b) One DC/DC-converter

Figure 1: HESS topologies

The task of the operating strategy is to compose a power flow that minimizes the load on the battery as well as the losses from the complete HESS. Mostly, non-predictive operating strategies are used (for example [2, 3, 4, 5, 9]). These strategies calculate the optimal composition of the required power without consideration of the future load profile. A comparison of three different high power energy storage devices as extension of a lithium battery shows, that the capacity of the DLC is too small to support an entire acceleration profile if a non-predictive strategy is implemented [2]. In contrast to non-predictive strategies, predictive operating strategies use information about the future load profile [6, 7]. It is possible to distribute the whole energy between storages without interrupting the power flow required for the drive. This way, predictive operating strategies can improve the performance of the HESS and decrease the required capacity of the DLC. But the prediction of the future load profile is very complicated and inaccurate. To solve this problem, the trajectory planning of the autonomous driving system can be used, to provide a trustworthy load prediction.

This paper presents the fundamentals for a new predictive operating strategy for a HESS. The following sections illustrate the calculation of an optimized operating strategy, which minimizes the losses of the HESS as well as battery losses, with regard to the complete load profile. Furthermore, a comparison to a simple heuristic strategy is given. In future works, the results will be used to develop a new real-time predictive operating strategy for autonomous cars.

2 Optimization of the Operating Strategy

The task of the operating strategy is to compose a power flow that minimizes the losses of the HESS as well as the load on the battery. This way, an energy efficient operation of the HESS together with a reduction of dynamic stress on the battery should be enabled. The mathematical description leads to an optimal control problem, which is solved with Discrete Dynamic Programming.

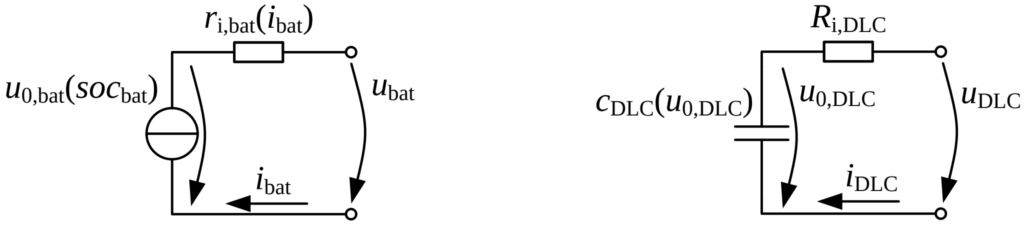
Since measurements for parameter identification are not accessible, the models are currently based on data sheets. Therefore, numeric data as well as discharge curves are used to find analytical expressions for the system dynamic behaviour, the cost functional and boundary conditions.

In the following equations, lower-case letters indicate time-variable values and upper-case letters denote constant values.

2.1 Optimisation Problem

2.1.1 Dynamics of the Hybrid Energy Storage System

Equivalent circuits are a common practice to describe the system behaviour. Figure 2 shows simple equivalent circuits of the battery and the double layer capacitor (DLC). Both circuits contain an internal resistance which symbolizes the losses. The controllable voltage source as function of the state of charge (SOC) and the nonlinear capacity as a function of the open circuit voltage define the system dynamics. An RC-network for system dynamics with smaller time constants can not implemented with information from the data sheet.



(a) Battery (b) DLC

Figure 2: Equivalent circuits of battery and DLC

Battery:
The state of charge (SOC) specifies the steady state of the battery and is calculated with the battery current from previous states $i_{\mathrm{bat}}(\tau)$, the electric charge at the beginning of the calculation $Q_{\mathrm{bat}}(t_0)$ and the maximum electric charge $Q_{\mathrm{N,bat}}$:

$$soc_{\mathrm{bat}}(i_{\mathrm{bat}}, t) = \frac{1}{Q_{\mathrm{N,bat}}} \cdot Q_{\mathrm{bat}}(t_0) + \int_{t_0}^{t} \left(i_{\mathrm{bat}}(\tau)\right) \cdot \mathrm{d}\tau \tag{1}$$

The open circuit voltage is a function of the SOC. To describe this dependency, the open circuit voltage $u_{0,\mathrm{bat}}$ is extrapolated from the discharge curves and approximated with a 4th degree polynomial. The coefficients X_{a} are calculated with the curve-fitting toolbox from Matlab® and shown in Table 1:

$$u_{0,\mathrm{bat}}\left(soc_{\mathrm{bat}}, t\right) = \sum_{a=0}^{4} \left(X_{\mathrm{a}} \cdot (1 - soc_{\mathrm{bat}})^{a}\right) \tag{2}$$

The Butler-Volmer-Characteristic defines the dependency of the internal resistance $r_{\mathrm{i,bat}}$ from the battery current i_{bat}. The resistance increases with the rising current [10]. Equation (3) inserts this characteristic into the model equations of the battery. The coefficients Y_{a} of the second degree polynomial are determined with the curve-fitting toolbox again and shown in Table 1. The resistance was calculated for several currents with the difference between the open circuit voltage $u_{0,\mathrm{bat}}$ and the clamp voltage u_{bat}. The voltage values are obtained from the discharge curves:

$$r_{\mathrm{i,bat}}\left(i_{\mathrm{bat}}, t\right) = \sum_{a=0}^{2} \left(Y_{\mathrm{a}} \cdot \left|i_{\mathrm{bat}}\right|^{a}\right) \tag{3}$$

After calculating the open circuit voltage and the internal resistance, the terminal voltage u_{bat} can be determined with the Kirchhoff's loop rule:

$$u_{\mathrm{bat}}\left(u_{0,\mathrm{bat}}, i_{\mathrm{bat}}, r_{\mathrm{i,bat}}, t\right) = u_{0,\mathrm{bat}} - i_{\mathrm{bat}} \cdot r_{\mathrm{i,bat}} \tag{4}$$

The output power of the battery is expressed with the following equation:

$$p_{\mathrm{bat}}\left(u_{\mathrm{bat}}, i_{\mathrm{bat}}, t\right) = u_{\mathrm{bat}} \cdot i_{\mathrm{bat}} \tag{5}$$

Figure 3 shows the terminal voltage of the battery cell over the state of discharge soc_{bat} during the constant current discharge process. The state of discharge is defined as follows:

$$sod_{\mathrm{bat}}(t) = 1 - soc_{\mathrm{bat}} \tag{6}$$

The orange dotted lines represent the model and the blue solid lines display the data sheet. Every pair of a solid and a dotted line shows the discharge process with another constant battery current. It can be seen that the analytical equations of the battery model are in good agreement with the data sheet data.

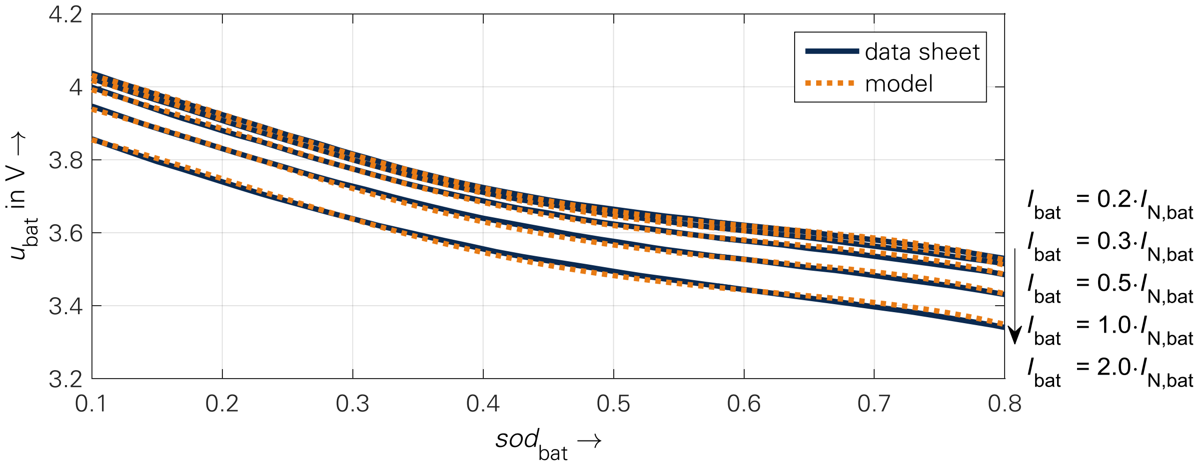


Figure 3: Discharge curves of the battery cell

Double Layer Capacitor (DLC):

The specific characteristic of a double layer capacitor (DLC) is the variable capacitance c_{DLC}. In [11] the capacitance is described as a linear function from the open circuit voltage $u_{0,\mathrm{DLC}}$:

$$c_{\mathrm{DLC}}\left(u_{0,\mathrm{DLC}}, t\right) = C_{0,\mathrm{DLC}} + \Theta \cdot u_{0,\mathrm{DLC}} \tag{7}$$

The data sheet specifies only a single constant capacitance $C_{\mathrm{N,DLC}}$. C. Romaus [12] gives the following empirical values for the parameters $C_{0,\mathrm{DLC}}$ and Θ. These values show a good conformity to the measurements in [11]:

$$C_{0,\mathrm{DLC}} \approx \frac{1}{3} \cdot C_{\mathrm{N,DLC}} \tag{8}$$

$$\Theta = \frac{C_{\mathrm{N,DLC}} - C_{0,\mathrm{DLC}}}{U_{\mathrm{N,DLC}}} \tag{9}$$

The electric charge of the DLC describes the steady state of the DLC and is calculated with the DLC current from previous states $i_{\mathrm{DLC}}(\tau)$ and the electric charge at the beginning of the calculation $Q_{\mathrm{DLC}}(t_0)$:

$$q_{\mathrm{DLC}}(i_{\mathrm{DLC}}, t) = Q_{\mathrm{DLC}}(t_0) + \int_{t_0}^{t} i_{\mathrm{DLC}}(\tau) \cdot \mathrm{d}\tau \tag{10}$$

The open circuit voltage is estimated as a function from the electric charge:

$$u_{0,\mathrm{DLC}}\left(q_{\mathrm{DLC}}, t\right) = \frac{q_{\mathrm{DLC}}}{c_{\mathrm{DLC}}\left(u_{0,\mathrm{DLC}}\right)} = -\frac{C_{0,\mathrm{DLC}}}{2 \cdot \Theta} + \sqrt{\left(\frac{C_{0,\mathrm{DLC}}}{2 \cdot \Theta}\right)^2 + \frac{q_{\mathrm{DLC}}}{\Theta}} \tag{11}$$

The transduced energy Δe_{DLC} can be determined with the open circuit voltage:

$$\Delta e_{\mathrm{DLC}}(u_{0,\mathrm{DLC}},t) = e_{\mathrm{DLC}}\left(t\right) - e_{\mathrm{DLC}}\left(t_0\right) = \int_{t_0}^{t} \left(u_{0,\mathrm{DLC}} \cdot i_{\mathrm{DLC}}\right) \cdot \mathrm{d}\tau \tag{12}$$

The current-voltage characteristic of a capacitor leads to the following equation:

$$\Delta e_{\mathrm{DLC}}(u_{0,\mathrm{DLC}},t) = \int_{u_{0,\mathrm{DLC}}(t_0)}^{u_{0,\mathrm{DLC}}(t)} \left(\tilde{u}_{0,\mathrm{DLC}} \cdot c_{\mathrm{DLC}}\left(\tilde{u}_{0,\mathrm{DLC}}\right)\right) \cdot \mathrm{d}\tilde{u}_{0,\mathrm{DLC}} \tag{13}$$

Inserting Equation (7) in (13) and solving the integral results in a simple expression of the transduced energy:

$$\Delta e_{\mathrm{DLC}}(u_{0,\mathrm{DLC}},t) = \left(\frac{1}{2} \cdot C_{0,\mathrm{DLC}} \cdot u_{0,\mathrm{DLC}}^2 + \frac{1}{3} \cdot \Theta \cdot u_{0,\mathrm{DLC}}^3\right) - e_{\mathrm{DLC}}\left(t_0\right) \tag{14}$$

The state of charge is defined as the ratio of the present energy content $e_{\mathrm{DLC}}\left(t\right)$ to the maximum energy content calculated with the last preceding equation:

$$soc_{\mathrm{DLC}}(u_{0,\mathrm{DLC}},t) = \frac{\frac{1}{2} \cdot C_{0,\mathrm{DLC}} \cdot u_{0,\mathrm{DLC}}^2 + \frac{1}{3} \cdot \Theta \cdot u_{0,\mathrm{DLC}}^3}{E_{\mathrm{max,DLC}}} \tag{15}$$

In addition, the terminal voltage and the output power can be determined equivalent to the battery model:

$$u_{\mathrm{DLC}}\left(u_{0,\mathrm{DLC}}, i_{\mathrm{DLC}}, t\right) = u_{0,\mathrm{DLC}} - i_{\mathrm{DLC}} \cdot R_{\mathrm{i,DLC}} \tag{16}$$

$$p_{\mathrm{DLC}}\left(u_{\mathrm{DLC}}, i_{\mathrm{DLC}}, t\right) = u_{\mathrm{DLC}} \cdot i_{\mathrm{DLC}} \tag{17}$$

2.1.2 Cost Functional

There are two targets of the operating strategy:

- Improved efficiency to increase the range of the electric vehicle
- Reduced battery losses to extend the battery life time

The internal resistance represents the losses of the battery and the DLC. Thus, the losses can be calculated with the following simple expressions:

$$p_{\mathrm{L,bat}}\left(i_{\mathrm{bat}}, r_{\mathrm{i,bat}}, t\right) = r_{\mathrm{i,bat}} \cdot i_{\mathrm{bat}}^2 \tag{18}$$

$$p_{\mathrm{L,DLC}}\left(i_{\mathrm{DLC}}, t\right) = R_{\mathrm{i,DLC}} \cdot i_{\mathrm{DLC}}^2 \tag{19}$$

To improve the system efficiency and to reduce the load on the battery, the cost functional is defined as the integral of the weighted sum of the losses of the DLC and the losses of the battery:

$$C\left(p_{\mathrm{L,DLC}}, p_{\mathrm{L,bat}}, t\right) = \int_{t_0}^{t} \left(W_{\mathrm{DLC}} \cdot p_{\mathrm{L,DLC}} + W_{\mathrm{bat}} \cdot p_{\mathrm{L,bat}}\right) \cdot \mathrm{d}\tau \tag{20}$$

With the weighting factors of the battery losses W_{bat} and the DLC losses W_{DLC} it is possible to control the focus of the operating strategy. The highest efficiency will be reached if the losses are equally weighted. The least battery load is developed if the weighting factor for the DLC losses is zero.

2.1.3 Boundary Conditions

The first boundary condition involves the load profile. The sum of the power of the battery p_{bat} and the DLC p_{DLC} must be the same as the sum of the power required from the electric drive p_{mot} and the auxiliary consumers including the air conditioning unit p_{aux}:

$$p_{\mathrm{bat}} + p_{\mathrm{DLC}} = p_{\mathrm{mot}} + p_{\mathrm{aux}} \tag{21}$$

This relation is used to reduce the degrees of freedom from two to one. Therefore the SOC of the DLC represents the state variable. The transition between two states is characterized by the DLC-current. Thus, the system behaviour and the losses of the DLC can be calculated. The power of the battery is defined with Equation (21). As a result, the system behaviour and the losses of the battery can be calculated, too.

To prevent invalid operating points, there are some more boundary conditions which are observed:

- Limitations of the SOC of the battery and the DLC
- Maximum discharge and charge currents of the battery and the DLC

In addition, existing predictive operating strategies define a power reserve [7]. This reserve is necessary to react to unpredictable events. Mostly, this boundary condition is included in the cost function C as an additional part. In case of a prediction of the future load profile from the autonomous driving system, the confidence region of the prediction is very large. Thus, a small power reserve included in the limitations of the SOC should be sufficient.

2.2 Solving Algorithm

The method of Discrete Dynamic Programming (DDP) is characterized by robust convergence and easy implementation. Therefore, it is suitable for solving the optimization problem. The DDP algorithm is explained in [13] and is composed of the following four steps. Figure 4 illustrates the algorithm with a reduced optimization problem:

Step 1 ***Discretization of the state variable soc_{DLC} and the time t*** - Figure 4a shows the discretized system states as circles.

Step 2 ***Calculation of the cost of all possible transitions between two successive time steps*** - In Figure 4b, the transitions and the costs are represented with the dotted arrows and the numbers on the arrows respectively.

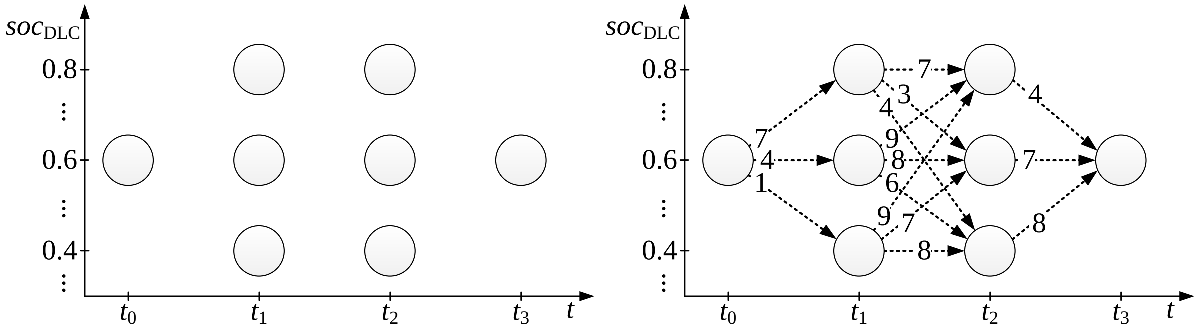
Step 3 ***Backward calculation for each state at every time step: find the transition that causes the least sum of costs with regard to the following states*** - The numbers inside the circles represent the cost of the optimal trajectory starting with this state. Thus, the optimal transition of a state can be calculated with the sum of the numbers on the arrows and the following circles. The optimal transition of every system state is illustrated as a solid arrow in Figure 4c.

Step 4 ***Evaluation of the optimal trajectory: start at the first time step with the state that causes the least sum of costs during the whole trajectory and choose the transition which was calculated in step 3 at every following time step*** - The optimal trajectory is marked with colored circles and arrows in Figure 4d.

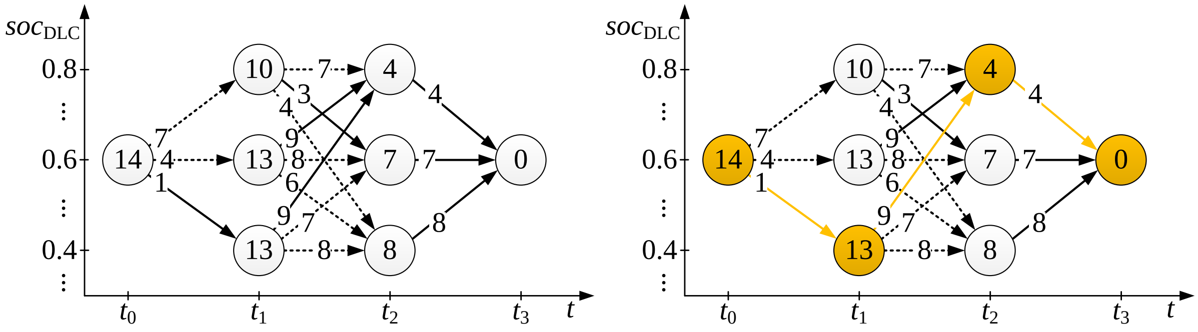
To speed up the calculation, the search space is scaled down by some additional analytical limitations. The limitations were deduced from calculations without these additional constraints. The following two limitations are defined:

- Maximum and minimum SOC of the DLC as a function of the vehicular velocity
- Maximum and minimum grade of the DLC-SOC slope as a function of the required power

With the implementation of these limitations, it is possible to calculate an optimized operating strategy for the complete driving cycle (duration approx. $40\,\mathrm{min}$) in approx. five minutes.



(a) Step 1 (b) Step 2



(c) Step 3 (d) Step 4

Figure 4: Algorithm of Discrete Dynamic Programming

3 Comparison to an Heuristic Strategy

3.1 Heuristic Strategy

The heuristic strategy is based on a simple rule: the faster the vehicle is the greater the kinetic energy of the vehicle that should be stored in the DLC during braking [9]. As a consequence, the SOC of the DLC should be minimal at the peak velocity and maximal at stop. Thus, Equation (22) is used to calculate the reference-SOC. A PI-controller ensures that the SOC of the DLC corresponds with the calculated reference values. The output of the PI-controller is the input of the current controller of the DC/DC-converter between the DLC and the DC-Link. Thus, the power flow can be controlled.

$$soc_{\text{DLC,ref}}\left(v,t\right) = \left(SOC_{\text{DLC,min}} - SOC_{\text{DLC,max}}\right) \cdot \frac{v^2}{V_{\text{max}}^2} + SOC_{\text{DLC,max}} \tag{22}$$

3.2 Load Profile and System Parameters

The load profile used for this analysis is provided by the project partner IAV GmbH and is based on the driving cycle presented in [14] and shown in Figure 5 at the top. The load calculation uses a dataset of a VW Golf Variant. In addition, a constant efficiency of the electric drive ($\eta = 0.9$) and a constant load by auxiliary consumers ($p_{\text{aux}} = 3.5\,\text{kW}$) is assumed. This power is given from the project partner IAV GmbH and corresponds to the typical consumption of auxiliary consumers including an activated air conditioning unit. In a real electric autonomous car, the energy efficiency of the drive system and the power consumption of the auxiliary consumers are time-variant values. Thus, the constant values are an approximation with effect on the load profile. Because the load profile is the same for every operating strategy, these assumptions have not a great influence to the results of the comparison.

The calculated results are presented for a HESS composed of 36 battery cells from Kokam Co., Ltd. of the type SLPB160460330 characterized by a very high energy density and 18 DLC cells from Maxwell

Technologies, Inc. of the type BCAP3400 characterized by a very high power density. The model parameters are shown in the Tables 1 and 2.

Table 1: Model parameters of the battery

Parameter	Symbol	Value	Unit
Nominal electric charge	$Q_{\mathrm{N,bat}}$	240	Ah
Nominal current	$I_{\mathrm{N,bat}}$	240	A
Coefficients of open circuit voltage	c_0	4.129	V
	X_1	-3.245	mV
	X_2	-438.6	µV
	X_3	9.363	µV
	X_4	-56.17	nV
Coefficients of internal resistance	Y_0	666.5	µΩ
	Y_1	-794.7	$\mathrm{n\Omega A^{-1}}$
	Y_2	0.6326	$\mathrm{n\Omega A^{-2}}$
Max. discharge current	$I_{\mathrm{max,bat}}$	480	A
Max. charge current	$I_{\mathrm{min,bat}}$	-240	A
Max. state of charge	$SOC_{\mathrm{max,bat}}$	0.9	
Min. state of charge	$SOC_{\mathrm{min,bat}}$	0.2	

Table 2: Model parameters of the DLC

Parameter	Symbol	Value	Unit
Nominal capacitance	$C_{\mathrm{N,DLC}}$	3400	F
Nominal voltage	$U_{\mathrm{N,DLC}}$	2.85	V
Internal resistance	$R_{\mathrm{i,DLC}}$	0.22	mΩ
Max. discharge current	$I_{\mathrm{max,DLC}}$	2000	A
Max. charge current	$I_{\mathrm{min,DLC}}$	-2000	A
Max. state of charge	$SOC_{\mathrm{max,DLC}}$	0.8	
Min. state of charge	$SOC_{\mathrm{min,DLC}}$	0.3	

3.3 Results

Reducing losses and improving the energy efficiency are the first objectives of the operating strategy. Table 3 shows the simulated losses and energy efficiencies for the heuristic and several optimized strategies. The energy efficiency ε is defined as the ratio between usable energy and supplied energy. With the knowledge of usable energy and total losses, the energy efficiency can be calculated with the following equation:

$$\varepsilon = \frac{E_{\mathrm{out}}}{E_{\mathrm{out}} + E_{\mathrm{L,tot}}} \cdot 100\,\% = \frac{\int_{t_0}^{T} (p_{\mathrm{mot}} + P_{\mathrm{aux}}) \cdot \mathrm{d}t}{\int_{t_0}^{T} (p_{\mathrm{mot}} + P_{\mathrm{aux}}) \cdot \mathrm{d}t + \int_{t_0}^{T} \left(p_{\mathrm{L,bat}} + p_{\mathrm{L,DLC}}\right) \cdot \mathrm{d}t} \cdot 100\,\% \tag{23}$$

The difference between the optimized strategies is the ratio of weighting factors W_{bat} and W_{DLC} included in the target function (Equation (20)). The first number of the ratio represents the weighting of the battery losses and the second number the weighting of the DLC losses (ratio: $W_{\mathrm{bat}} : W_{\mathrm{DLC}}$).

Table 3 allows the conclusion that the operating strategy with equal weighted losses (ratio 1:1) causes minimum total loss and maximum energy efficiency. The losses can be reduced by up to 9 $\%$ in comparison to the heuristic strategy. The optimization with three times more weighting for the battery losses (ratio: 3:1) effects fewer losses than the heuristic and slightly more losses than the equal weighted optimization. The strategy without attention to the battery losses produces the highest total losses. Also, this strategy is less efficient than the heuristic strategy. So it could be concluded that the weighting 1:0 is not suitable for a good operating strategy. But with respect to the required energy the efficiency improvement of the storage system is still lower than $1.3\,\%$. Thus, the weighting factors of the cost functional do not have a great effect to the range of the autonomous electric car (Table 3).

Table 3: Comparison of total losses and energy efficiency

	Heuristic	Optimized ratio: 1:1	Optimized ratio: 1:0	Optimized ratio: 3:1
Energy efficiency ε in $\%$	96.9	97.2	95.9	97.0
Total losses $E_{\mathrm{L,tot}}$ in Wh	148	134	197	143
Range in km	156	156	155	156

Figure 5 shows the simulated DLC-SOC for the heuristic and the optimized strategies at the bottom. For equal weighted losses (ratio: 1:1), the DLC-SOC is shown with the red dotted line. The blue dotted line represents the strategy without attention to the DLC losses (ratio: 1:0) and the orange dashed line illustrates the strategy with three times more weighting for the battery losses (ratio: 3:1).

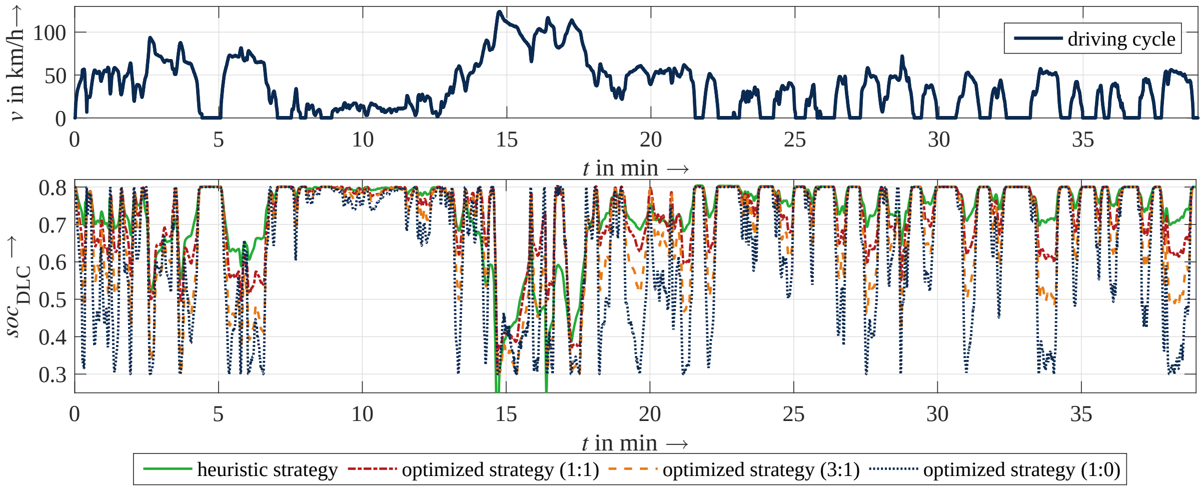


Figure 5: SOC of the DLC of different strategies

Figure 6 provides a more detailed view on the SOC of the DLC. At high velocity (Figure 6 left), the SOC of the DLC using the heuristic strategy is lower than the SOC limit $SOC_{\mathrm{min,DLC}}$. Thus, the energy content of the DLC is too small to provide the required power. If one of the optimized strategies is implemented, the SOC is never lower than the minimal SOC $SOC_{\mathrm{min,DLC}}$. Hence it can be concluded that the optimized strategies enable the application of a DLC with reduced capacitance. In case of the heuristic strategy, 34 DLC cells are required to ensure that the minimum SOC of the DLC is not exceeded. Only 18 cells are necessary for the optimized strategies. Thus, the predictive operating strategies reduce the weight of the HESS by up to $4\,\%$ and the volume by up to $7\,\%$. This results in a smaller, lighter and cheaper storage system.

Furthermore, Figure 6 on the right and Figure 5 show that the DLC-SOC is smaller when using a strategy with more impact of the battery losses on the target function. It can be concluded that the DLC current and the power of the DLC are increased. Thus, the battery current is reduced. Figure 7 verifies this statement. The DLC current increases with the weighting of the battery losses. In contrast, the battery current decreases with the weighting of the battery losses. The heuristic strategy causes the least DLC and the highest battery current. The strategy without respect to the DLC losses produces the highest DLC current and the least battery current. The root mean square values of the battery and the DLC current shown in Table 4 point out the same fact.

Table 4 shows that the operating strategies have a great effect on the currents as well as on the battery and DLC losses. Low battery losses result in lower heating and a more gentle operation of the battery regarding to the lifetime. Because the losses of the storage devices are a function of the current (Equations (18) and (19)), the statements of the last paragraph can be transferred. Thus, the strategy without respect to the DLC losses causes the least battery current as well as the least battery losses. In comparison to the heuristic strategy the battery losses can be reduced by up to 30 %, but the DLC losses are increased by up to 86 %. The weighting ratio 3:1 points out a reduction of the battery losses of 32 Wh and a raise of DLC losses of 27 Wh.

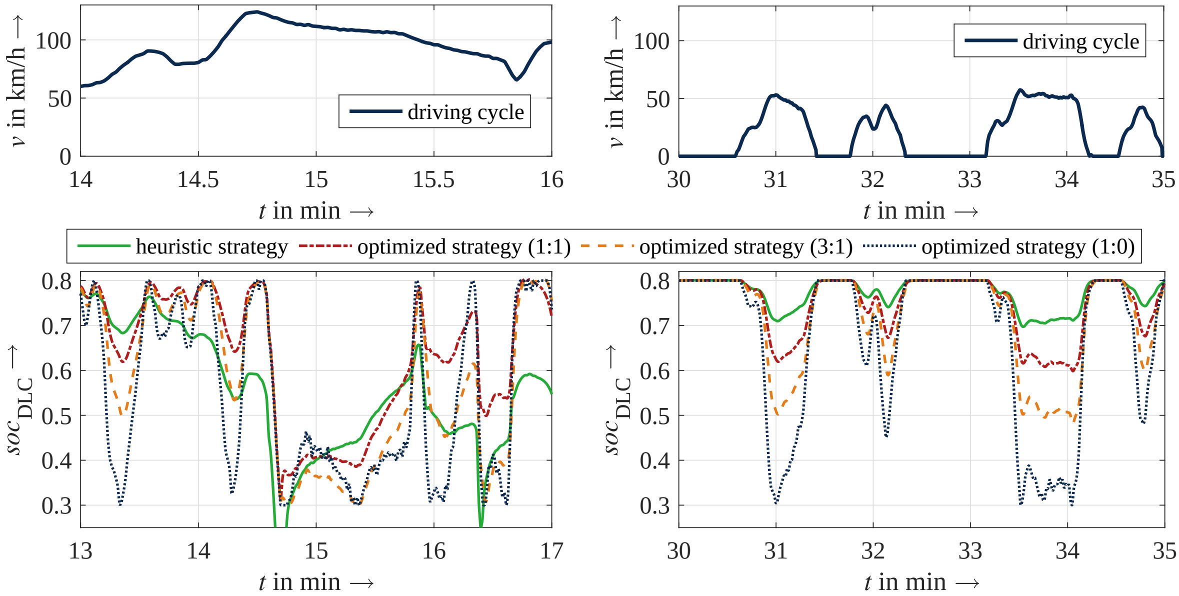


Figure 6: Details of the SOC of the DLC of different strategies

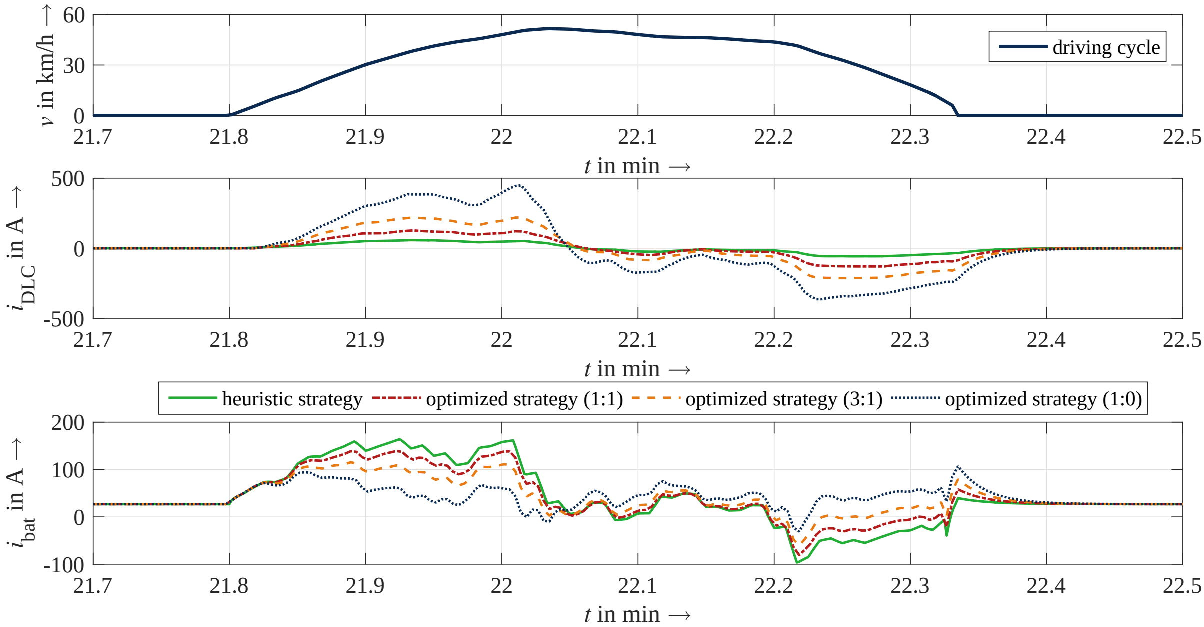


Figure 7: DLC and battery current

In conclusion, predictive operating strategies reduce the required capacitance of the high power storage device. Furthermore, the optimization without regard to the DLC losses provides the gentlest operation regarding to the battery lifetime and the least energy efficiency. The lowest total losses result from the equally weighted (ratio: 1:1) optimization. The best tradeoff between high energy efficiency and low battery losses is given from the operating strategy with three times more weighted battery losses.

Table 4: Comparison of currents and losses

	Heuristic	Optimized ratio: 1:1	Optimized ratio: 1:0	Optimized ratio: 3:1
Battery current $I_{\mathrm{rms,bat}}$ in A	103	96	86	90
DLC current $I_{\mathrm{rms,DLC}}$ in A	75	83	200	127
Battery losses $E_{\mathrm{L,bat}}$ in Wh	134	117	94	102
DLC losses $E_{\mathrm{L,DLC}}$ in Wh	14	17	103	41

4 Conclusion and Outlook

This paper presents optimized operating strategies for a HESS with regard to the complete load profile. The results show that the battery losses as well as the total losses can be significantly decreased by up to $30\,\%$ and $9\,\%$, respectively, if an optimized operating strategy with trustworthy load prediction from the autonomous driving system is used. Furthermore, a DLC with reduced capacity is applicable compared to the one necessary for a simple heuristic strategy. As a result, the weight and the volume of the HESS can be decreased by up to $4\,\%$ and $7\,\%$, respectively.

In future work, the losses of the DC/DC-converters should be included in the cost functional. Furthermore, the rating of the storage components will be determined depending on the applied optimized strategy. In addition, the optimized strategies and the introduced optimization method will be used to create a real-time predictive operating strategy for autonomous vehicles. After that, the developed strategy will be implemented and tested on a test setup.

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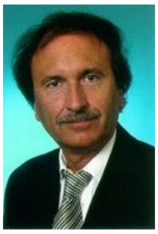

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