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Power-Split Operation Strategy for Series Hybrid Electric Buses Based on a Cost Function

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Abstract

The series hybrid technology with a motor generator unit (MGU) and a separate electric motor /generator used as a drive unit has been widely adapted in buses. Because of the many acceleration and deceleration processes in the operation mode of the bus this hybrid concept has several benefits. In this paper we present an analytic power split operation strategy based on the cost of the battery energy and the efficiency of the MGU. On the basis of these costs it is decided when and in which operation point it is most efficient to operate the MGU. This paper shows that a minimal fuel consumption and a widely constant SOC can be achieved with the power split operation strategy. Additionally we compared a new and an aging battery in the power-split operation strategy with a single-point strategy.

Keywords: series HEV, bus, battery, battery management

1 Introduction

For a fuel-efficient operation of a series hybrid it is necessary that an operation algorithm decides if the electric motor gets the energy only from the battery or if the battery is supported by the MGU. The aim is to avoid or at least to decrease the energy losses due to multiple energy conversion (battery, MGU) with an intelligent operation strategy. In order to limit aging of the battery another aim besides fuel saving is to reduce the depth of charge (DOD) and to operate the battery at a rather constant SOC. In addition the operation strategy must also be designed for a low fuel consumption with an aging battery. At the moment there are more and more implementations of series hybrid city buses [1], [2]. [3] shows an operation strategy with a power split between the MGU and the battery with the help of a fuzzy controller. The development of this paper is based on an analytical strategy for parallel hybrid vehicle [4]. This was adjusted and expanded to a series hybrid topology [5] [6].

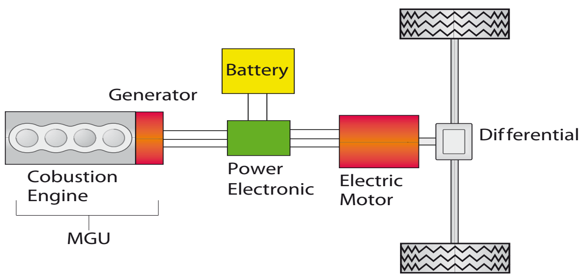

Figure 1: Drivetrain Topology of a Series Hybrid Electric Vehicle

2 Car Parameters and Driving Cycles

Fig. 1 shows the drivetrain topology of a series hybrid electric vehicle. The whole driving power of a series hybrid electric vehicle is delivered by an electric motor. The electric motor gets the energy either directly from the battery or the MGU. The MGU consists of an ICE and an electric generator. This means that the MGU can be operated independently of the power requirements of

the driving cycle. So it is possible that the MGU supports the electric motor and charges the battery or the MGU charges only the battery. In the different operation mode the whole system has different power losses because the energy has to be converted several times. The lowest power losses are in the operation mode when the MGU directly supports the electric motor and the energy is not buffered in the battery. The aim of an operation strategy has to be to operate the MGU in a point of high efficiency and to minimize the conversion losses.
A 80 kW ICE and a synchronous generator with a maximum power of 80 kW is part of the MGU. For the analysis a simulation model of a series hybrid bus was generated with the data listed in tab. 1. The 150 kW electric machine is a synchronious electric machine which is fed from a 20 Ah NiMh battery. The operation strategy was analysed for different urban and interurban driving cycles. The cycles are based on real bus cycles which were logged with a data logger [7] connected via a CAN-bus. As an example fig. 2 (a) shows the velocity profile of an analysed cycle. Altogether there were 21 bus stops during the drive. Additionally in fig. 2 (b) the altitude profile of the cycle is shown.

ICE	80 kW
Generator	80 kW
Electric Motor	150 kW
Battery	NiMH, 20 Ah
Vehicle mass	16 tonnes

Table 1: Parameters of the Series Hybrid Electric Vehicle

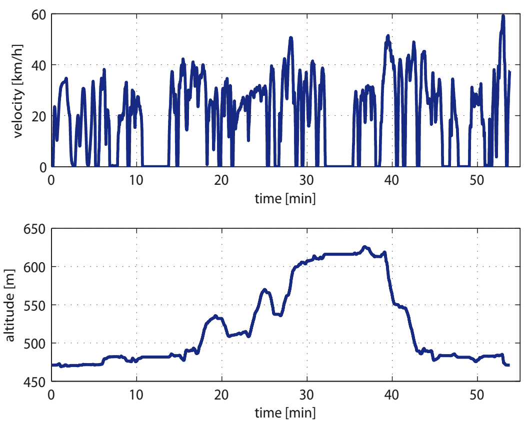

Figure 2: Velocity Profile (a), altitude profile (b) of the driving cycle

3 Cost Function-Based Power Split Operation Strategy

The analytial operation strategy chooses the optimal operation point in relation to the power requirement of the cycle. In every time step all possible combinations and costs for the power splitting between the MGU and the battery are calculated. So at all times the split factor giving minimum costs is chosen. The split factor describes the power split ratio between the battery (equ. 2) and the MGU (equ. 1). Theoretically the split factor can be chosen between $-\infty < s \leq 1$. The driving mode of the vehicle depends on the split factor as shown in tab. 2. When the split factor is between 0 and 1 the battery is supported by the MGU in operation points of high power requirements. At a split factor of 1 the whole power requirements are covered by the battery so that the vehicle drives purely electrical. In contrast at a split factor of 0 the whole power is delivered by the MGU. A negative split factor describes the load point increase (LPI) mode. In this mode the MGU covers the power requirements of the electric motor and charges the battery at the same time. This mode helps to operate the MGU with high efficiency.

$$P_{MGU} = (1 - s) \cdot P_E \tag{1}$$

$$P_B = s \cdot P_E \tag{2}$$

split-factor	operation mode
0	conventional drive
1	electric drive
$0 < s < 1$	boost
$-\infty < s < 0$	load point increase (LPI)

Table 2: Split-factor variation / operation mode

For the calculation of the cost function it is necessary to differentiate between drive mode (equ. 3) and the regenerative mode (equ. 4). The first part of equ. 3 describes the cost for the MGU support. The second part describes the costs for the battery. According to the operation mode the last part may vary because the battery is either charged or discharged. For the calculation of the costs both the battery efficiency and the efficiency of the MGU which is calculated from the efficiency of the ICE and the generator are taken into account. In addition the efficiency of the electric motor is considered.

$$K = \left(\frac{k_{MGU,0}}{\eta_{MGU}} \cdot (1 - s) + \frac{k_{B,0}}{\eta_B} \right) \cdot \frac{P_E}{\eta_E} \tag{3}$$

In the regenerative mode the cost function is simplified, because the MGU is switched off and all regenerated energy is fed into the battery. In this mode the costs consider only the battery efficiency and the electric base cost factor.

$$K = k_{B,0} \cdot \eta_B \cdot P_E \eta_E \tag{4}$$

In the calculation of the cost of the MGU and battery the cost factor k_{MGU} (equ. 5) and k_B (equ. 6) is used.

$$k_{MGU} = \frac{k_{MGU,0}}{\eta_{MGU}} \tag{5}$$

$$k_B = \frac{k_{B,0}}{\eta_B} \tag{6}$$

$k_{MGU,0}$ is the basic cost factor of the MGU and can be interpreted as the cost for the power which is extracted from the fuel and therefore is constant. $k_{B,0}$ is a function of the SOC and the efficiency of the battery which is changing during the drive. For example this means that if the battery is deeply discharged the electrical base cost factor is increasing. This leads to the fact that more energy is supplied from the MGU. If the battery is well charged the electrical base costs are decreasing and the main part of the energy will be provided by the battery.

3.1 Electric Base Cost Factor $k_{B,0}$

For the dependence of $k_{B,0}$ on the SOC a cubic or linear function can be chosen. In [8] it was shown that a cubic dependence leads to a better stabilization of the SOC around a nominal SOC. By means of the cubic cost function a big SOC range around the desired SOC value of 60 % is mapped on a small cost range. This leads to the fact that in this SOC range the application of MGU is less determined by the electric costs factor but rather by the efficiency of the MGU.

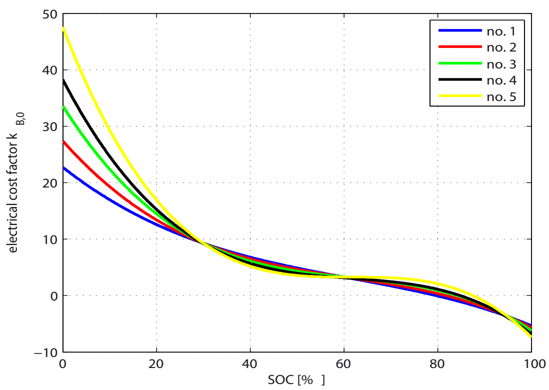

Figure 3: Example cubic electric base cost functions

3.2 Influence of Electric Cost Factor on the Fuel Consumption

Fig. 4 (a) shows the dependence on the fuel consumption of the specific cost function chosen (curve no.) and the battery size. Also fig. 4 (b) shows the maximum charge difference. The charge difference describes the minimum and maximum SOC in relation to the battery size. As expected the fuel consumption reduced with increased battery size as the vehicle can be driven purely electrically more often. The lowest fuel consumption of 24.6 $\frac{l}{100\ km}$ is produced with the cost curve no. 4 (fig. 3) and a 25 Ah battery but this results in the biggest charge difference. Curve no. 1 produced the highest fuel consumption but the smallest charge difference. The fuel increase of curve no. 5 is explicable by the fact that the gradient of the cost function is zero in the range $58\ \% < SOC < 70\ \%$ and the electric base cost factor for the electric energy is higher than in curve no. 4. Therefore in this SOC range a more frequent use of the MGU is required which explains the higher fuel consumption.

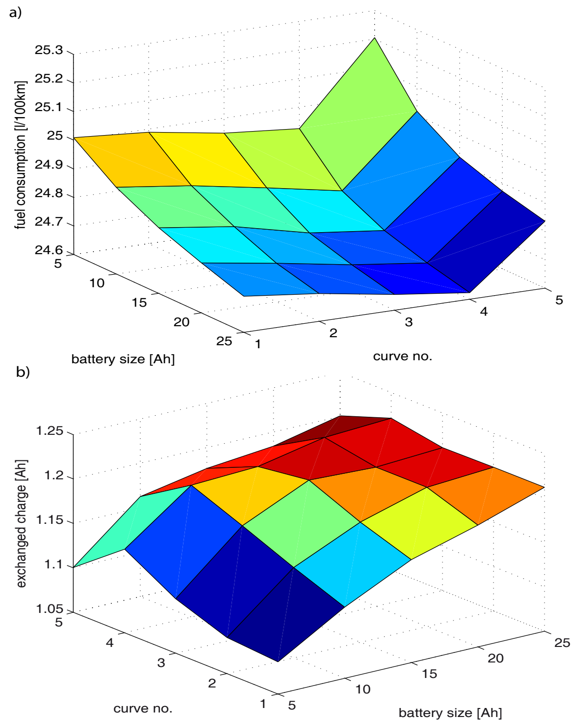

Figure 4: Fuel consumption depending of the curve no. and the battery size (a), maximum charge difference (b)

3.3 Dependence of $k_{B,0}$ and the Operation Mode

Fig. 5 shows the relation between electric machine power on the x-axis and the electric base cost factor on the y-axis. The z-axis describes the battery power. In fig. 5 (a) the driving modes with no limits of the battery power are given. During phases of low power requirements and a low SOC of the battery the operation strategy operates in the LPI mode. If the required power exceeds 100 kW and if the electric base factor is decreasing below $k_{B,0} <= 2.7$ (this is a SOC of 63 %) the driving mode is chances from "LPI" to electric drive mode. During phases of high power requirements over 100 kW and a low SOC the battery is supported by the MGU. Here it is also obvious that above an SOC of 63 % the required power is purely provided by the battery. Depending on the power needed the switching point from boost to purely electrical driving is shifted higher SOC values. Figure 5(b) shows the driving modes with a battery power limited to 25 kW. As can be seen it is necessary that the battery is supported by the MGU more frequently. The range of purely electrical driving is clearly limited this lead to an increase of the fuel consumption. At the same time it is possible to reduce the exchanged charge and the stress for the battery.

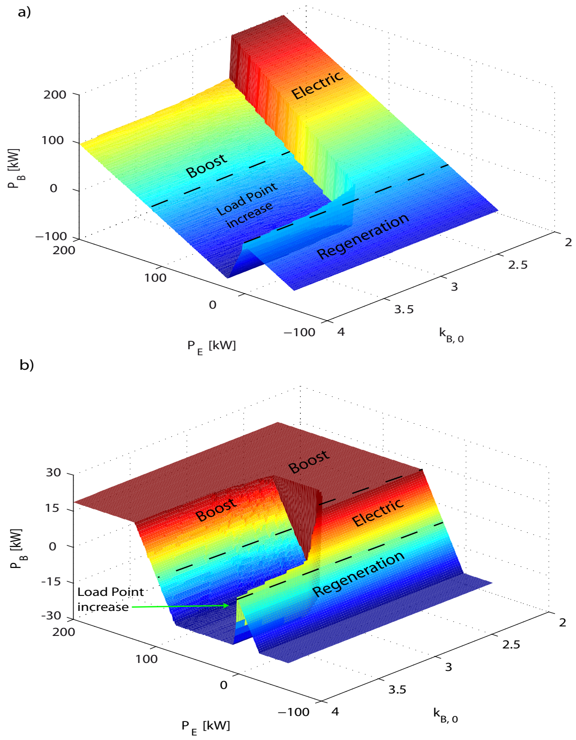

Figure 5: Operation mode depending on the required power and the electric base factor, normal configuration (a), battery power limited to 25 kW(b)

4 Results

4.1 Operation Points of the MGU

Fig. 6 shows the efficiency map of the MGU. The green points describe the operation points of the MGU with a new battery. As can be seen the MGU is operating close to the optimal operation point, i.e. mostly in a one point strategy in boost or LPI mode. The yellow points describe the operation points with an aged battery (η_B 70%). It is not possible to always operate the MGU in the optimal operation point. The reason for this is that with a low η_B the battery cost increases. This results in a recharging of the battery only during regenerative braking, LPI mode takes place only rarely. So it is frequently necessary that the MGU supports the battery. As can be seen the operation strategy chooses operation points near to the maximum efficiency trajectory (blue line).

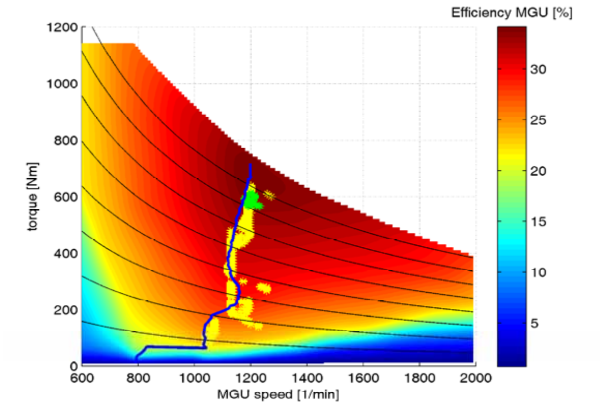

Figure 6: Efficiency map of the MGU with the optimal operation trajectory (blue), operation point with a new battery, green and with an older battery ($\eta_B = 70\%$) yellow

Finally the effects of an aging battery on the SOC and the fuel consumption were analysed fig. 7. It can be seen that with an aging battery is shifted the desired SOC value to higher SOC values. This is reflected by the rising electric costs due to the lower battery efficiency. The more frequent support of the battery by the MGU is also recognizable in the fuel consumption. Here we have a rise form $24,6\ \frac{l}{100\ km}$ to $31,6\ \frac{l}{100\ km}$ this is an increase of 28,4 %.

4.2 Comparison to a Single-Point Strategy

The power-split operation strategy was compared with a single-point strategy, which operates the MGU only in the point of optimal efficiency. The single-point strategy has been chosen such that the MGU recharges the battery if the SOC is below 50 % and the charging process stops if an SOC of 80 % is reached. A new battery leads to a fuel consumption of $26,63\ \frac{l}{100\ km}$ which means a saving of the power-split strategy in comparison to the single-point strategy of 7.6 %. With an aging battery the fuel consumption of the single-point strategy is rising to $44,22\ \frac{l}{100\ km}$, this corresponds to an increase of 66 % compared with a new battery. Above all, clearly better results can be achieved here with the power split operation strategy i.e. savings of 28.5 % with an aging battery. One reason for the increase of the fuel consumption in the single point strategy with an aged battery is that the battery is always recharged to 80 %, independent of the power requirements of

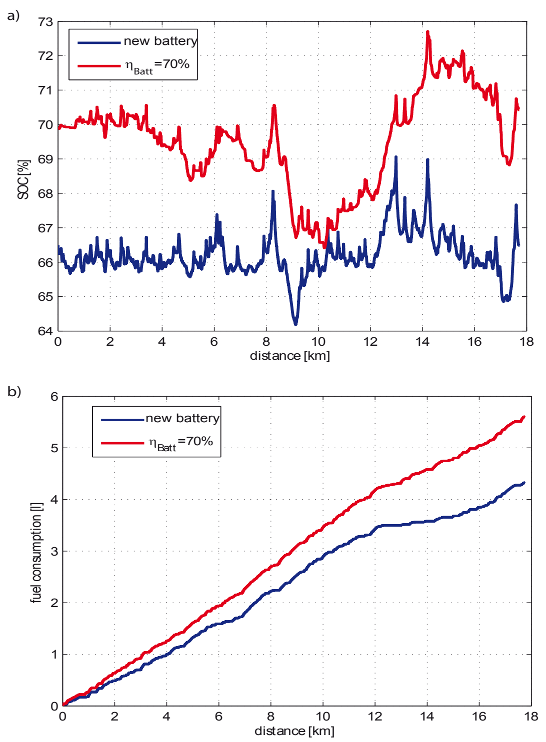

Figure 7: Comparison of the SOC (a) and the fuel consumption (b) between an aging and new battery.

the electric motor and because an aged battery has a clearly lower efficiency losses rise with the intermediate storage of the energy in the battery. Therefore it is important to avoid unnecessary conversion of the energy to keep the converting losses as low as possible.

5 Conclusion

The analytical cost function-based operation strategy provides a good and easy-to-implement operation strategy for series hybrid buses. By the coupling of the cost function to the power splitting and the SOC the operation strategy guarantees, that the SOC can be kept in a narrow area during the whole cycle and deep discharge can be avoided. Also we showed the interrelations between the required power, the electric base cost factor and the resulting driving mode. In addition, we could show that with a new battery the MGU is operating in the best efficiency area. The comparison to a single-point operation strategy shows that with the power-split strategy remarkable fuel savings can be obtained even with an aging battery if an intelligent charging of the battery and an proper splitting of the required energy between battery and MGU is implemented.

P_{MGU}	Power of the MGU
P_E	Power of the electric motor
P_B	Power of the battery
s	Split factor
$k_{MGU,0}$	base cost factor of the MGU
$k_{B,0}$	base cost factor of the battery
k_{MGU}	cost factor for the MGU
k_B	cost factor for the battery power
η_{MGU}	efficiency of the MGU
η_B	efficiency of the battery
η_E	efficiency of the electric motor
ICE	Internal Combustion Engine
SOC	State Of Charge
DOD	Depth Of Discharge
MGU	Motor Generator Unit
LPI	Load Point Increase

6 Symbols

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