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Virtual Battery Size in Cost Function-Based Operational Strategies for Parallel Hybrid Drivetrains

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Abstract

The cost function based operation strategy for parallel hybrid cars depends strongly on the state of charge of the battery. This paper describes the influence of different ways of mapping the SOC to a base cost value and that of the restricted use of the battery to enhance its life on the fuel consumption and the charge exchange of the battery. To fulfil the restrictions of battery usage in the algorithm the size of the battery is virtually shrunk . The cost function-based algorithm adapts to the artificially reduced battery capacity and maximises the benefit of the hybrid drivetrain under restricted conditions.

Keywords: battery calendar life, hybrid electric vehicle, state of charge

1 Introduction

The lifetime of batteries depends strongly on the depth of discharge (DOD) applied [1] . For long life a DOD of 10% should not be exceeded. Of course, this reduces the amount of energy that can be used for hybrid drivetrain purposes. This paper shows the interdependence of fuel consumption and restricted battery capacity usage. The restriction is effected by reducing the battery capacity available to the operational strategy. For instance in the case of a 20 Ah battery a capacity of 2.5 Ah is provided as 100% capacity to the hybrid operational strategy . This virtually small battery is the only energy store available to the operational strategy and so it will adapt to the virtual battery size by a reduction of electric energy usage but also by means of increasing the efficiency of charge usage .

2 The Operation Strategy

The cost function-based algorithm used for this operational strategy balances the cost of energy between the internal combustion engine (ICE) and the electric motor. By dividing a base cost factor by the efficiency and multiplying it with the appropriate power equation (1) the source power is calculated. For the ICE it can be interpreted as the power extracted from the chemical energy of the fuel, and for the electric motor it is the power coming from the electro-chemical energy content of the battery.

$$K=\frac{k_{ICE,0}}{\eta_{ICE}}\cdot P_{ICE}+\frac{k_{B0}}{\eta_E\cdot\eta_B}\cdot P_E \tag{1}$$

$$k_{ICE}=\frac{k_{ICE,0}}{\eta_{ICE}} \tag{2}$$

$$k_B=\frac{k_{B0}}{\eta_E\cdot\eta_B} \tag{3}$$

These two power sources are balanced according to equation (1) [2]. For a long-term average the cost factors (equation (2) and (3)) in equation (1) must be the same: if for a long period one cost factor is greater then the other its power source will provide less energy to the drive train on average . For example if the electric cost factor is the lower one for a longer period of time, the state of charge (SOC) will decrease over time. Therefore the SOC must be an integral part of the calculation in equation (1), it must be included as a balancing factor.

2.1 Calculation of the Electric Base Cost Factor

$$k_{B0} = a \cdot SOC + b \qquad (4)$$

This could be done as a linear dependence like in equation (2) [1]. The linear factor "a" must be negative and the offset parameter "b" must be positive and is depending on "a".

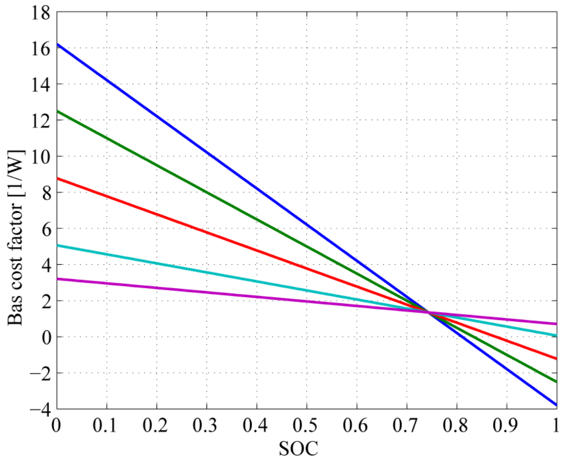

Figure 2.1: Example lines for different values of a and b

With this relation the SOC can balance the electric energy. If for example electric energy is spent the SOC is decreasing but the cost factor k_{B0} is increasing. An increasing electric cost factor makes it less interesting to spend electric energy. The characteristic of the balancing effect of this kind of SOC dependence can be varied with the linearfactor "a".

Figure 2.1 shows some lines used for the creation of the results of this paper. The blue line has a slope of -20. This high value leads to a restriction in the use of electric energy because a small change in SOC leads to a big change in the base cost factor. For discharging it means that the electric cost factor (equation (3)) rises and generates high costs, so the electric power becomes less and less interesting for propulsion purposes. For charging situations the cost factor k_B is decreasing and electric energy becomes very interesting for the use in the drivetrain. The flat purple line results in a totally different usage of the electric energy because of the small change in the base cost factor k_B even for big changes of the SOC: spending electrical energy down to low SOC values is almost always interesting. And if the SOC goes to 100 % the algorithm will not force a harsh discharge like it is done for steeper lines.

In Figure 2.1 all lines intersect at one point. The coordinates of this point are an SOC of 75 % and base cost factor of 1.75 1/W. The SOC value of 75 % is the average SOC value aimed at. The base cost factor of 1.75 is an empirical value taking into account the difference between the efficiency of the ICE and the electric components of the drivetrain. The long-time average of the cost factors (2) and (3) in equation (1) must be equal to each other as explained before. That can only be achieved if the electric base cost factor compensates the efficiency advantage of the electric components as compared to the ICE. For example the long-time average efficiency of the ICE in a hybrid drivetrain is 33 %, and the long-time efficiency of electric motor, power inverter and battery together is 58 %; the base cost factor k_{B0} must equal 1.76 to compensate the efficiency advantage. That does not mean that the short- time efficiencies and cost factor must be compensated. The short-time difference between the cost factors (2) and (3) must not compensate each other because the algorithm needs this difference to determine the power distribution of the drivetrain.

2.2 Influence of Slope Factor and Battery Size on Fuel Consumption

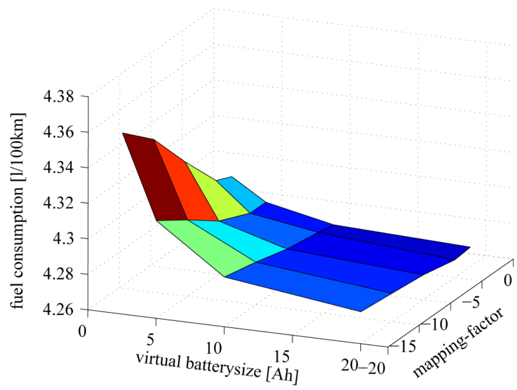

Figure 2.2: Fuel consumption depending of mapping factor and battery size

The impact of different slope factors on fuel consumption is shown in figure 2.2. In correspondence to that figure 2.3 shows the impact of different slope factors on the maximum charge difference. A high slope factor of -20 produces the highest fuel consumption but the smallest charge difference. A small factor of -2.5 produces the best fuel consumption but the biggest charge difference. A flat linear equation produces just small changes in the cost factor for changes in the SOC. Therefore a big change in SOC is necessary to increase the cost factor to such an extent as to limit the spending of electric energy. In other words, a flat linear equation leads to a more extensive use of electrical energy.

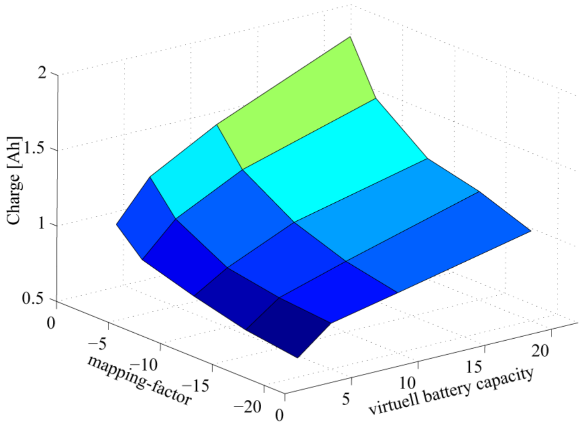

Figure 2.3: Maximal charge difference depending on battery size and mapping factor

Now the battery size shall also be varied. The smallest size was set to 2.5 Ah, the biggest to 20 Ah. The result for the fuel consumption is represented in Figure 2.2: the smaller the battery the higher the fuel consumption.

This is not surprising because the electric energy is more limited for smaller batteries. And with this limited capacity the electrical drive support is also limited. A reduced electric drive support means that more conventional driving power has to be used. But surprisingly the increase in fuel consumption is not as big as might be expected because of the decrease of battery capacity.

If we look at small linear factors the fuel consumption just goes up from 4.27 l/100 km for a 20 Ah battery to 4.3 l/100 km for a 2.5 Ah battery. But even for the big linear factor of -20 the fule consumption rises only from 4.28 l/100 km to 4.36 l/100 km.

Now it is interesting to look at the charge difference in figure 2.3. Charge difference here means the difference between the highest and the lowest SOC occurring in a driving cycle. For a small virtual battery and small linear factors the charge difference is just about 1.09 Ah. For a 20 Ah battery with the same linear factor the charge difference increases to 1.9 Ah. The charge difference increases by a factor of about 1.75 between a 2.5 Ah and a 20 Ah battery. But the change in fuel consumption for a linear factor of -2.5 and a capacity change from 2.5 Ah to 20 Ah is just about 0.03 l/100 km. The increasing factor for fuel consumption is just 1.01.

A look at the two SOC-curves in figure 2.4 shows the difference between a real 20 Ah battery and a

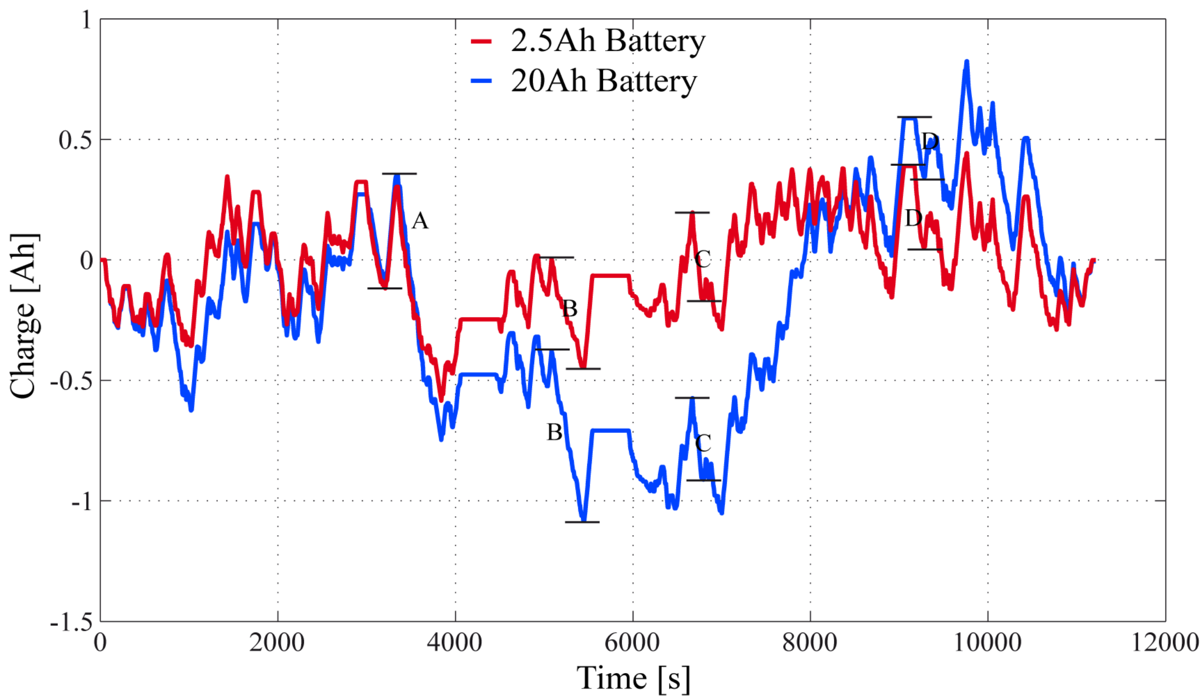

Figure 2.4: Comparison of SOC characteristics of two different battery capacities in the same driving cycle

virtually shrunk 2.5 Ah battery both with a slope factor of -20. The energy input for both batteries is exactly the same as can be seen at the rising edges (marked with A). For the energy output both characteristics show actions at the same time but with different slopes (marked with B). If the battery is small an energy output generates a faster increase of k_{B0} because of the faster decrease of the SOC. If electric support of the drivetrain gives only a small advantage as compared to non-supported driving the fast increase of cost will restrict the use of electric energy for this purpose. But not every electric support is limited; some have the same shape as for the big battery (marked with C) and some even have a markedly different characteristic (marked with D). This is due to high efficiencies in this operating point which can compensate a fast rising of costs.

By cheating the operation strategy with a virtual small battery the charge difference between the minimal and maximal SOC can be decreased, and the fuel consumption rises only a little bit.

2.3 Correct Parametrisation of the Operation Strategy

We have seen that virtually small batteries noticeably shrink the charge difference but subtly rise the fuel consumption. Now the apropriate slope factor for small batteries must be found.

On the left side of Figure 2.5 the SOC characteristics for 2.5 Ah battery with a slope factor of -2.5 (red) and a slope factor of -20 (blue) are given. The right side of Figure 2.5 displays the corresponding electric base cost factor k_{B0}. The small slope factor leads to a slight variation of k_{B0}. Due to the small influence of SOC changes on the base cost factor it never becomes smaller than zero. That happens quite often when a regeneration process bring back energy back to the battery and the slope factor is -20. Because of the negative cost factor the operational strategy is forced to spend as much electrical energy as possible. If k_{B0} in equation (1) becomes negative the total cost can be minimised by increasing the electrical output power to its maximum. A drawback of a big negative slope factor is that the electric base cost factor easily becomes negative. A big negative slope factor on the other side limits the output of energy if this would lead to a discharge below the average SOC planned. That can be seen in figure 2.5: on the right side the base cost factor in a discharge situation easily reaches values above 2.5 and therefore limits the output of electrical energy through its influence in equation (1). In contrast to this for small negative slope factors (red) the depth of discharge (DOD) in the left diagram of figure 2.5 is increased.

A small negative slope factor leads to a better use of the small virtual capacity, and as demonstrated in figure 2.2 it also leads to the lowest fuel consumption in systems using small capacities. But small negative slope factors also have a drawback: the deviation of the SOC from its planned average value is not so easy to control. With a small negative slope factor in equation (1) the influence of a varying SOC on the base cost factor k_{B0} is limited. The energy balancing effect of this equation vanishes with a small negative factor "a". Additional control mechanisms must be implemented to ensure that the SOC stays within the allowed limits of the particular battery.

The charge difference for a slope factor of -2.5 on

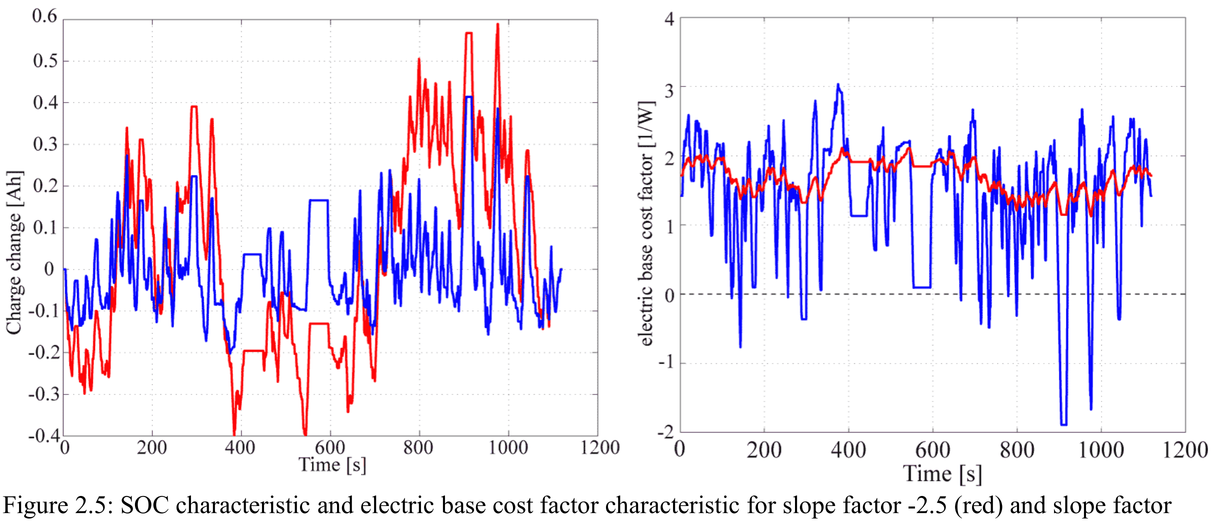

Figure 2.5: SOC characteristic and electric base cost factor characteristic for slope factor -2.5 (red) and slope factor -20 (blue)

a virtual battery of 2.5 Ah in figure 2.5 reaches 1 Ah. If the real size of the battery is 20 Ah this means the usage of just about 5 % of the maximum battery capacity. For reasons of comparability the planned SOC of 75 % was not shifted. If the average planned SOC is shifted to 50 % the usage of the actually available capacity can be improved. By proper choice of the virtual battery size and an appropriate slope factor the used capacity of a real battery can be regulated to the desired values.

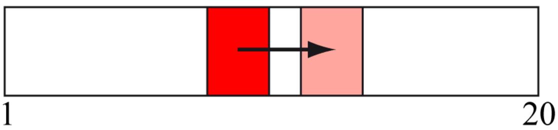

Figure 2.6: Shift of the virtual battery size in the charge area of the real battery

However, long regenerative braking can always lead to an amount of incoming charge that would exceed the borders of the virtual battery. It is easily possible to shift the virtual battery in the charge area of the real battery as shown in figure 2.6. Therefore the virtualization of the battery size according to the operational strategy generates a more flexible use of the battery.

3 Conclusion

With a virtual shrinking of battery size it is possible to limit the use of the battery to SOC areas beneficial for battery health. The parameters 'virtual battery size' and 'slope factor' can be used to optimise the charge usage in combination with fuel consumption. The shifting of the virtual battery inside the real charge area of the real battery means one more degeree of freedom by the adaptation of the operational strategy to the battery.

The algorithm described adapts to the limited battery capacity by cutting off less efficient drivetrain support. If electric drivetrain support is highly efficient it will be used as if the battery size was unrestricted. Because of this only less efficient drivetrain conditions are avoided and the algorithm will use the electric energy only for more efficient supports. The behavior of the algorithm is also well suited to be used with super capacitors in hybrid energy storage systems.

4 Symbols

P_{ICE} = power of the ICE
P_E = power of the electric motor
ΔE_B = Energy change for one calculation step
E_B = Energy stored in battery
η_{ICE} = efficiency of the ICE
η_E = efficiency of the electric motor
η_B = efficiency of the battery
K_{tot} = total Cost
k_{ICE0} = base cost factor of the ICE
k_{B0} = base cost factor of electric energy
k_{ICE} = cost factor of the ICE
k_B = cost factor for the electric power
M_E = torque of electric motor
n_E = speed of electric motor
Δt = time of one calculation step

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