Electrical Design of a Novel Diesel-Electric Drivetrain for Suburban Trainsets using a Power Split Variator and Energy Storage System

Design and operation strategy of the electrical part of the energy storage system and variator drive

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Abstract

Efficiency improvement of diesel suburban trainsets and reduction of emissions near stations and tunnel sections is important today. This paper presents the electric energy storage device of a novel drivetrain for suburban trainset using a power split variator drivetrain. This solution offers a diesel-emission free pull out, depending on the charge of traction battery. During power-split operation, the diesel engine can run in its maximum efficiency region, and recuperation of brake energy is used to load the battery. The design of the battery and the energy management of the power split variator are considered and an exemplary design for a suburban trainset is presented.

Keywords: hybrid rail; power split; energy storage; down sizing wireless driving; energy efficiency; innovative drivetrain; brake recuperation
1 Introduction

Nowadays, about 90% of the German rail traffic is served under catenary. The remaining 10% are run almost exclusively with diesel-powered trainsets and partial with trains driven by diesel-powered locomotives. However, the German rail transport network is electrified by only 59.8% of the whole track length [6].

At the same time, diesel traction accounted for 19373TJ [5] or 15.14% of the total primary energy consumption of 108661TJ for traction in the year 2002. These numbers reveal that diesel-powered traction is less efficient than electric traction under catenary. One reason is that diesel-powered trains with conventional propulsion are almost not able to recuperate breaking energy.

Furthermore, diesel-powered trains produce harmful exhaust fumes, which can be especially problematic at railway stations or tunnel sections. In 2002 diesel-powered trains in Germany originated 456000kg [5] of particles, which have been proven to be harmful to humans. The possibility of emission-free operation of railway stations improves the local air quality and the emission-free operation of tunnel sections extends the range of operation of diesel-powered trainsets, since some tunnel sections are not approved for conventional diesel-powered vehicles.

The novel drive train, proposed in this paper, aims at efficiency improvement of diesel-powered trainsets and additionally extends the range of operation due to time-limited emission-free operation.

The mechanical structure is shown in figure 1, the electrical part is highlighted in gray. The electrical part consists of the electric machines M1 and M2 as well as the converter S1 and S2 for the machines. One or more batteries C1..Cn are connected by one or more dc-dc converter S3..Sn. By closing or releasing one of the clutches K1 and K2, the following switching states are possible:

- Direct mode with the diesel engine (K1 closed, K2 released, M1 and M2 are operating as variator)
- Coasting (K1 and K2 released, M1 and M2 idle)
- Full electric drive or brake mode (K1 released, K2 closed, M1 and M2 are operating as motors or generators)
The structure of the simulation and the reference trainset and driving cycle are described in section 2. One exemplary combination of energy storage devices for this application is considered in section 3. The examination of the energy storage connection via dc-dc converters, or directly to the dc-link, is done in section 4. A high braking and pull out performance must be provided, which has to be taken into account for the lifetime of the storage device. The control strategy of the energy storage devices is presented in section 5. Finally, the results of the simulation are interpreted in section 6.

2 Reference Driving Cycle and Trainset

In this paper we investigate the HybridRail drive for a suburban trainset. This means that the count of stops along the track is high (mean distance between two stops about 3.0km) and the speed is moderate (up to 120kmh\(^{-1}\)). The trainset has a capacity of 206 passengers and a maximum weight of 76.8t. The schedule and track data are from a real train ride.

2.1 Driving Cycle

The driving cycle is as close as possible to the real track with the number “KBS480” between “Stolberg HBF” and “Düren” in Germany. The distance is 66.1km one way for which the train needs 91min according to the official timetable. The train shuttles the round trip one time, resulting in a total distance of 132.2km and 3h 38min of operation.
The maximum speed of the track\(^1\) is limited to 120km\(^{-1}\) and the absolute altitude\(^2\) is given in figure 2. In reality, the proposed cycle is shuttled by one trainset the whole day from 5:10AM to 10:42PM with additional two half cycles in the morning and evening and two short empty trips from and to the storage sidings.

Figure 2: Altitude and speed diagram for the examined driving cycle

The influence on the energy consumption of the auxiliary consumers on the trainset is significant. Especially the energy consumption of the air conditioning on a hot summer day. Therefore the ambient temperature\(^3\) and the utilized capacity\(^4\) of the train is taken into account and can be seen in figure 3. The train departs on 7:10AM and idles at 8:42AM for 34min in the middle of the cycle.

Figure 3: Temperature and utilized capacity diagram for the proposed driving cycle

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1 These values are received by riding a train on the track and noting the position and limits while tracking the actual position by the help of the GPS signal
2 The altitude is estimated with the help of [2]
3 Values for the 1st of June, taken from [8]
4 The time variation curve is taken from [11] and ratings while riding the train
2.2 Trainset

The trainset has a dead mass $m_d$ of 57.5t. It has six axles in the arrangement of B'(2)'B', resulting in four driven axles, holding wheels with a diameter of 760mm. The acceleration is limited to $0.7 \text{m/s}^2$, while the deceleration is limited to $1.2 \text{m/s}^2$. It has two independent power-packs $n_{pp}$. Thus, the trainset can be compared to the German train series 643.2.

The train resistance $W_t$ is calculated by (1) with the empiric factors $\alpha = 0.36$, $\beta = 0.025 \text{(N-h)/(t·km)}$ and $\gamma = 1.7 \times 10^{-3}$, the normalized frontal area $A = 10 \text{m}^2$, the speed of crosswind factor $v_{\text{wind}} = 15 \text{km/h}$, the total mass of the trainset $m$, the air density $\rho$ and the gravitation $g$ [14, 10]. The static friction $W_s$ is neglected as it is only present at standstill.

The curve resistance $W_b$ is taken into account and calculated by the equation of Protopapadakis [18] with the curve data determined from [2]. Also the grade resistance $W_m = m \cdot g \cdot p / \sqrt{1 + p^2}$ with the grade $p$ determined from the absolute altitude is included.

$$W_t = \alpha \cdot 0.5 \cdot \rho \cdot A \cdot (v_{zug} + v_{\text{wind}})^2 + \beta \cdot m \cdot v_{zug} + \gamma \cdot m \cdot g + W_b + W_s + W_m$$

The auxiliary load profile consists of a fixed base load of 24.7kW and a varying power of up to 16kW for the air conditioning compressor at full cooling. The data is taken from the CleanER-D “Clean European Rail-Diesel” project [3], which is the basis for the mechanical data of the reference trainset.

2.3 Engine and Drive Train Operation Strategy

At standstill, the diesel engine is switched off and the auxiliary consumers are powered from the battery. If the trains stands longer than 5min, the air conditioning is switched off and the auxiliary consumers are reduced to 500W$^5$.

During full electric mode from pull-out to 60kmh$^{-1}$, M1 and M2 as well as the auxiliary consumers are powered from the energy storage. During acceleration above 60kmh$^{-1}$ the driving strategy changes to the direct drive. In this strategy the resulting power in the energy storage device from the drive is zero. The energy storage only powers the auxiliary consumers.

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$^5$ Simulating a train shut-down, common for conventional diesel trains
When the train coasts and drives above \(60\text{kmh}^{-1}\), three different strategies can be used depending on the energy in the storage. The amount of energy in the storage can be written by the normalized state of charge value \(\text{SOC}\). At low \(\text{SOC}\), the diesel engine stays on to charge the storage and to supply the auxiliary consumers through \(M1\) and \(M2\). At high \(\text{SOC}\), \(M1\) and \(M2\) idle, the auxiliary consumers are powered from the storage and the diesel engine is switched off. Otherwise, the diesel engine powers the auxiliary consumers via \(M1\) and \(M2\) and the power to and from the storage is zero. The last strategy can also be used as a cruise control. Below \(60\text{kmh}^{-1}\) the diesel engine is normally switched off and the auxiliary consumers are powered from the energy storage, \(M1\) and \(M2\) idle.

At breaking \(M1\) and \(M2\) are used as generator to charge the energy storage and supply the auxiliary consumers over the complete speed range. The diesel engine is switched off\(^6\).

A detailed look into the control of the mechanical section and the operation strategy of the drive is presented in [9].

### 3 Battery System

The following dimensioning is just an example to demonstrate the design process for minimum size and weight of the storage device. For the real application, the Li-Ion battery proposed here should be replaced by a specially designed, shock resistant, long live, LiIon battery. The Li-Ion battery data in this paper, is based on the Nissan Leaf battery pack [1]. The internal resistance and capacity of the battery is taken from [21, 20]. As an additional storage, supercapacitors for the peak power shaving [19], are taken into account. For redundancy each power-pack has its own energy storage device. All data in this section corresponds to one power-pack, thus the values must be multiplied by two (the count of power-packs \(n_{pp}\)) for the trainset.

The volume of the battery pack is \(0.119\text{m}^3\) and the mass of 294kg. To achieve a minimum required lifetime of 10years, cycling has to be taken into account. The battery should not be charged above 0.8SOC\(^7\) and below 0.2SOC. Also the DOD is important for the ageing [13] so the cycling itself should be small and around 0.5SOC. Figure 4 (left) shows the voltage of the battery over the SOC and the maximum charge / discharge power, taken from [20]. The internal resistance for charging is 85m\(\Omega\) and for discharging 148.3m\(\Omega\), these values are taken from [1].

\(^6\) An additional strategy has to prevent the diesel engine from being permanently switched on and off

\(^7\) SOC: State of charge; DOD: deep of discharge
The storage operation strategy aims at a full cycling of the supercapacitor, utilizing the battery for mid and long term storage. The voltage of the capacitor bank is important for the losses in the capacitors. The pack voltage is shown in figure 4 (right) for the capacitor-bank configuration. From the equation of the stored energy $E_C = \frac{1}{2} \cdot C \cdot U_C^2$ and the power $P_C = U_C \cdot I_C$, the voltage dependence of the load current becomes obvious. To avoid high currents and ohmic losses in the capacitor and the converter, the minimum voltage in the capacitor-bank is limited to 200V (see section 4).

The capacitors shall be able to take at least 75% of the energy needed to accelerate the train up to 60km/h on a levelled track. This is the speed, where the system changes from full electric mode to direct mode. Above 60km/h, no energy is needed from the energy storage for the drive, so it is sufficient to dimension the capacitors to supply a main part of the acceleration energy up to 60km/h. The kinetic energy needed to accelerate is calculated by $E_{\text{kin}} = \frac{1}{2} \cdot m \cdot e_i \cdot v_{zug}^2 \cdot \frac{1}{n_{\text{zy}}} \cdot \frac{1}{n_{\text{np}}}$ to the value of 1.4kWh assuming that the utilized capacity of the train is 50%\(^8\). The train resistance can be neglected in the calculation, but the rotating mass factor $e_i$ of 1.08 and the losses in the drive have to be taken into account. Therefore, the capacitors end of life capacity is estimated to 1.05kWh.

By using [12], two parallel strings of 12 capacitors in series are needed to store the required energy\(^9\) in the capacitors. The capacitors have a volume of 0.555m\(^3\), a mass of 403kg and survive 1mio duty cycles. When the capacitance decreases, more energy will be stored in the Li-Ion battery (see section 5). This means that an increased ageing rate of the Li-Ion battery [13] is directly linked to the ageing of the capacitors. [15, 7] describes a good model to calculate the real ageing of the Li-Ion battery. To keep the calendaric ageing low,

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\(^8\) A utilized capacity of 50% means that all seat places are taken and the fuel tank is half full. Then the trainset has a total weight of 67.15t

\(^9\) New capacitors: 1.46kWh, aged capacitors 1.1kWh (capacitance decrease 25%)
the SOC during normal operation of the battery will be held around 0.55. The batteries and capacitors are air cooled using the outgoing air of the body, so the temperature of the storage devices is assumed to be around 20°C to 30°C.

4 Connection of the Battery System to the Dc-Link

To adjust the differing storage voltages to a fixed 750V dc-link voltage $U_{dc}$, dc-dc converters are employed. To reduce the losses in the converters and gain a flexible modular system, a parallel connection of multiple 35.8kW converters are proposed. The data of the converters is taken from [17].

For the Li-Ion battery, five parallel converters (178.9kW) are sufficient, while for the capacitors eight parallel converters (286.3kW) are required. This leads to a maximum peak power of 465.2kW for the storage system. By switching-off a part of the dc-dc converters at partial load, the efficiency of the dc-dc converter stack is increased. The efficiency of the system depends on the storage and the converter efficiency. Therefore, the losses of the storages internal resistance are calculated together with the losses of the converters. This leads to the efficiency maps shown in figure 5, where the power boundaries of the converters are also shown. One can see that the current limit in the capacitor diagram (right) limits the possible charging and discharging power at small SOC values. Therefore, the SOC in the aged capacitor is kept above 0.1.

5 Operation Strategy of the Storage System

The operation strategy of the storage system tries to handle the fluctuating power with the capacitors, while the long term power is covered by the Li-Ion battery. If the control itself has no information of the slope of the track, the weight of the trainset or if the train...
driver will brake or accelerate in the next time, this task is quite complex. Estimators are used to observe the track and train data to keep the system in a state from where almost all next steps of the driver can be handled\(^{10}\).

The discharging power from the Li-Ion battery (figure 5 left) is limited at small SOC values, while the charging power is high. In contrary, at high SOC values, the battery cannot accept high charging. The limited power acceptance is not direct problem, as the mechanical brakes could be used to decelerate the train. However, energy is lost and the drive cycle efficiency will decrease. The limited discharge capability a low battery SOC, has more impact on the system operation, as the train cannot accelerate electrically any more. Therefore, the Li-Ion battery must be kept above the energy needed to change the operation strategy to the direct mode (see section 2.3). It is possible to decrease the shutter speed down to 40km\(^{-1}\) with a loss in efficiency. Also the acceleration performance can temporary be reduced. If the Li-Ion battery is completely empty, the train must be braked, K1 closed and the diesel engine started to charge the Li-Ion battery with M1. With this method, the train can always be recovered into operational state which means reliability of operation.

The auxiliary consumers do not matter, because their power consumption can be measured and their changes in power are neglect able. If the air tanks contain enough air, the air compressor is only served during braking. Otherwise it is powered from the Li-Ion battery at coasting or idling.

The train mass \(m_a = \frac{F_a}{a}\) can be calculated from the acceleration \(a = \frac{dv_{zug}}{dt}\) and the accelerating force \(F_a\) of the trainset at low speeds. Doing this, the mass \(m_a\) also contains information of the slope of the track. The trains resistance \(W_t\) (see section 2.2) thereby is pre-calculated for low speeds and subtracted from the drives traction force \(F_{trac}\) to get the accelerating force \(F_a\). At higher speeds the value of the air resistance \(W_t = \alpha \cdot 0.5 \cdot \rho \cdot A \cdot (v_{zug} + v_{wind})^2\) will give an error, because the crosswind \(v_{wind}\) is not exactly the value of 15km\(^{-1}\). With the train mass \(m_a\), the energy needed to accelerate to 60km\(^{-1}\) can be calculated by \(E_{kin} = \frac{1}{2} \cdot m_a \cdot e_w \cdot v_{zug}^2 / n_{p\_w}.\) \(e_w\) represents a speed depending correction factor for the air resistance.

The energy recuperated from braking the train can be calculated almost the same way, but the sign of the train resistance and efficiency of the drive inverts. The energy from braking can be much higher than for accelerating, because the regenerative braking can start at the full speed of 120km\(^{-1}\). If the requested braking force exceeds the force which can be

\(^{10}\) Braking is always possible by using the mechanical brakes, but it should be avoided
delivered from M1 and M2, the mechanical brakes are used. The amount of energy gained from the motors in relation to the mechanical brakes is calculated and stored in a lookup table. To correct the energy calculation, the equivalent calculated energy is multiplied by this factor $\beta_{br} (v, a^*)$.

If the train is coasting at speeds below $60 \text{km}^{-1}$, the energy needed to accelerate or decelerate is calculated, but the energy to hold the speed can only be calculated roughly. The energy demand for coasting is much smaller than for acceleration or deceleration. Therefore the energy for coasting is directly taken from the Li-Ion battery without cycling the capacitors.

The real consumption or generation of energy may be different from the calculated. Therefore a P controller is used to balance between the Li-Ion battery and the capacitors, when the train coasts or accelerates. This controller only works for speeds above $19 \text{km}^{-1}$ and is limited in its power transfer to $1/3$ of the installed drive power. This is done time constant at standstill within $20 \text{s}$ by calculating the minimal power $P_{\text{Licap}} = \frac{dE}{20 \text{s}}$ needed to transfer the energy.

When the capacitor ages, it cannot store the complete braking energy any more. A factor $\gamma_{\text{age}}$ is calculated which describes the energy share between Li-Ion battery and capacitors. $\gamma_{\text{age}}$ is limited to 1.0 and if it falls below 1.0, the Li-Ion battery is also used for the acceleration or recuperation power by $P_{\text{traction}} = \gamma_{\text{age}} \cdot P_{\text{cap}} + (1 - \gamma_{\text{age}})P_{\text{bat}}$. This will lead to additional cycling and, therefore, ageing of the Li-Ion battery (see section 3).

Regenerative braking is used from all speeds, so the power must mostly be split between the Li-Ion battery and the capacitors. Therefore the amount of energy recuperated $E_{\text{rec}}$ is calculated with the described method above. Then the energy for the auxiliary consumers $E_{\text{aux}}$ is subtracted to get the energy for the storage $E_{\text{bs}} = E_{\text{rec}} - E_{\text{aux}}$. The current energy in the capacitor $E_{\text{cap}}$ is subtracted from the maximum storable energy in the capacitor $E_{\text{cap,max}}$, to obtain the storable Energy $E_{\text{store}} = E_{\text{cap,max}} - E_{\text{cap}}$ for the next braking event. Now the excess energy $E_{\text{bat}} = E_{\text{bs}} - E_{\text{store}}$, which must be directly stored in the Li-Ion battery, is known. To reduce the current in the battery, the power $P_{\text{bat}}$ should be small, so the time $t_{\text{brake}}$ to brake the train until blending to the mechanical brake at about $3 \text{km}^{-1}$ is predicted. Now the medium power to the battery $P_{\text{bat}} = E_{\text{bat}}/t_{\text{brake}}$ is known and this power is stored in

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11 To maximize the drive-cycle efficiency the train driver should be informed about the current regenerative braking share with a gauge in the driver’s cab

12 This reduces the ESR losses in the storage devices
the Li-Ion battery during the complete braking time. It may be that the braking will stop at higher speeds, then the control switches over to the balancing strategy described above.

Every time the train brakes from above $60 \text{kmh}^{-1}$ energy is stored in the Li-Ion battery, but it may be that this energy is not sufficient to maintain a nearly constant SOC of the Li-Ion battery over the complete driving cycle, and the Li-Ion battery will be discharged. Then the diesel engine is used to charge the Li-Ion battery at speeds above $60 \text{kmh}^{-1}$ while coasting. The control calculates the charge power by a P controller. Then the P-output is raised by the power of two so that small derivations will not lead to a large power demand. This power is limited to $1/3$ of the drives maximum power, so that the current in the Li-Ion battery will be moderate. The auxiliary consumers now are powered by the diesel engine as long as the charge power is greater than the power for the auxiliary consumers. Another point is, that the diesel engine will run at a good efficiency range (see [4]). When the overall gained power is not sufficient and the battery discharges further, power from the diesel engine can also be received during the acceleration, or even by setting the shutter speed down to $40 \text{kmh}^{-1}$\textsuperscript{13}. In contrary, when there is too much energy in the battery, M2 can be used to drive the train during coasting.

6 Simulation Results

For the simulation, the efficiency maps of all components are pre-calculated with MATLAB and stored in lookup tables. The simulation is performed in SIMULINK, using a fixed time step solver with 20ms resolution. Figure 6 shows the behaviour of the control from section 5 for a levelled track, empty trainset and 50% aged capacitor. The power split for recuperation and full cycling of the capacitors can clearly be seen in the left diagram. From 80s to 130s one can observe the recharging of the Li-Ion battery during coasting. In the right graphs, the speed is limited to $60 \text{kmh}^{-1}$ and the diesel is not in service. From 153s to 183s balancing is performed because the control’s calculation error, described in section 5, is simulated for the braking beyond 135s.

\textsuperscript{13} By doing this, the performance of the drive will decrease by 0.2 to 0.3
For the simulation of the cycle described in section 2.1, the SOC of the battery at the beginning of the cycle is set to 0.499. The SOC, speed and energy are shown in figure 7. The throughput energy in the battery is 56.0kWh and in the capacitor 66.5kWh. The overall efficiency for charging the storages is 92.43% and for discharging 92.44%. The auxiliary consumers need 42.9kWh, whereof 21.4kWh is gained from recuperation. The difference and the losses are supplied by the diesel engine while coasting above 60kmh$^{-1}$. The overall efficiency of the drive and trainset, in comparison to a conventional hydro-mechanical trainset is shown in [9].

7 Conclusion

7.1 Summary

The control of the power split is implemented into a simulation and verified by simulating a train run over real track data. Different exceptional circumstances of the storage are figured out and solutions for the respective problems are proposed. One exemplary design
Figure 7: Simulation of a train ride on the real track, presented in section 2.1

for a Li-Ion battery and supercapacitors is dimensioned for lowest weight and size of the storage devices.

### 7.2 Outlook

The described storage in this paper is the first layout for the smallest values (weight, size) of the devices, and should be considered further. Especially the ageing model from [15] should be implemented into the simulation and calculate the real lifetime. After this the balance between the capacitors and the batteries must be set that the requirement in lifetime of both devices will be fulfilled. This may lead to larger devices, but the ability to store more energy may be beneficial for the overall efficiency of the trainset even if the weight of the train will increase.

The voltage level of the dc-link is fixed at 750V in this paper, but [16] shows that it is advantageous to have a varying voltage level. Also two batteries can be connected is series, which makes it possible to eliminate the dc-dc converter for the battery. Further simulations and designs with varying voltage should be done.

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