Design and control of a hybrid PCS for railway stations utilizing energy storage, regenerative braking, and PV

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***Abstract*—A hybrid power conversion system for railway stations is designed that includes the storage of regenerative braking energy in a battery energy storage system as well as energy generation using photovoltaics. The battery energy storage system is controlled by a voltage-based algorithm. A study case with data from existing research is used to showcase the proposed method. This all is done to increase the energy efficiency of railway systems and to reduce the load on the electricity grid. Lithium-ion batteries, supercapacitors and flywheels are considered as possible energy storage systems. These options have varying costs from tens of thousands of EUR to multiple millions of EUR depending on type and size. The Lithium-ion battery system seems to be a good alternative from a technical perspective as with its size it can easily be combined with photovoltaics and the storage of surplus energy. This further decreases the energy demanded from the grid and increases the stability of the grid. Economically, a supercapacitor system is a good alternative, as the initial investment is lower than for a big Lithium-ion battery.**

I. Introduction

The energy transition has become increasingly vital in our daily lives, complicating the management of electricity consumption. Societies strive to reduce their carbon footprint and the resulting climate change, so they try to limit the use of traditional energy sources and transition towards renewable alternatives. This increasing demand makes the need for innovative approaches to energy management higher than ever. The transport sector is a major consumer of energy, with around 25% and 34% of total energy consumption worldwide and in the EU respectively [1]. In this context, the utilization of regenerative braking energy in train systems presents a compelling opportunity to address both environmental concerns and energy efficiency challenges within the transportation sector. Our aim is twofold: to minimize the overall energy usage, and to ensure that most of the energy that we consume is generated from renewable sources. Electric railways play a pivotal role in this transition, as they are among the most energy-efficient modes of transportation, catering to both passenger and cargo needs. However, the energy demand of trains is not uniform; they require significant energy for acceleration but less for maintaining a constant speed. Consequently, there's a fluctuation in energy demand, leading to variable consumption from the AC supply grid. To enhance the efficiency of electric trains, regenerative braking emerges as a key solution. This innovative system captures energy during braking, converting it into usable energy instead of dissipating it as heat, as is the case with traditional friction brakes. This generated energy can be used to cover most or parts of the energy demand in the same power supply section, including that of other trains. Effectively using this energy requires the presence of trains in need of this power. This regenerative braking energy (RBE) is currently inefficiently utilized within the railway power system (RPS). If there is a proper power conversion system (PCS) present it can be supplied back to the grid, otherwise the energy is lost [2]. Optimizing train timetables to match braking trains with those requiring power is one way to increase the utilization of regenerative braking, with a range of results. Chen et al. conclude that the practical implementation faces challenges and often yields unsatisfactory outcomes [2], while Peña-Alcaraz et al. [3] and Khodaparastan et al. [4] have more positive results ranging from 4% to 34.5% energy saving. There are more avenues to harness this surplus energy effectively. It can power internal systems in train stations such as lighting and escalators. Moreover, implementing local storage systems for otherwise wasted RBE, such as flywheels or supercapacitors, presents an opportunity to enhance the overall efficiency of railway energy usage. These systems excel in providing rapid responses to high power demands over short durations and can undergo numerous charge-discharge cycles. By storing and redistributing RBE, these systems contribute to peak shaving, reducing the strain on the AC grid during periods of high demand. Furthermore, integrating photovoltaics (PV) into the RPS offers another layer of efficiency, as it can recharge the energy storage systems. This approach not only reduces energy demand but also maximizes the utilization of renewable energy sources within the railway infrastructure.

Nowadays the remaining RBE that is not immediately used for tractive trains is dissipated in thermal resistors. This is a waste of energy and is very valuable in this time when society is more focused on reducing our carbon footprint and being as conservative with our energy use as possible. Storing this abundance of energy in a battery and using it at a later time will prevent this energy from getting lost to the environment.

Electric trains represent an efficient mode of transportation, yet their potential can be significantly enhanced through improved utilization of RBE. The goal of this paper is summarised in the research question: How to design, control, and optimize a hybrid power conversion system (PCS) for railway stations that converts from AC (electricity grid) to DC (railway grid) and also combines in the same PCS a stationary energy storage system and a PV system?

II. Methodology

Simulations in MATLAB will be used to determine what the optimal characteristics of the battery energy storage system (BESS) are to recover and use the maximum amount of RBE. Then multiple solutions for a BESS design will be discussed, looking at their individual (dis)advantages such as charging and discharging power, capacity and price.

The different methods will be compared in terms of power, storage capacity, price and payback time. The payback time calculations will be done using the current energy price and the timetable of the train station in Enschede, Netherlands.

Train departure and arrival data of Enschede station are taken from the website "Treinposities". The data of week 24 of the year 2024 is studied and shows that on average 132 trains depart from the station. To have a somewhat accurate idea of how often the situation modelled in the data occurs on average per day, 132 is divided by 2 to get that the modelled situation happens on average 66 times per day.

The time it takes for this system to pay itself back is highly reliant on the energy price. Looking at the price of energy over the past few years it went up very fast but is now lowering as can be seen in Figure 1 [5], [6]. In the figure can be seen that the electricity price is around 0.10 EUR/kWh until it went up in the last 2/3 years to around 0.21 EUR/kWh at its peak. After this peak, the price went down to around 0.19 EUR/kWh. The price that is used for the calculations is between the price that it is now, and the price that it has been for years before this sudden peak. This comes to around 0.15 EUR/kWh.

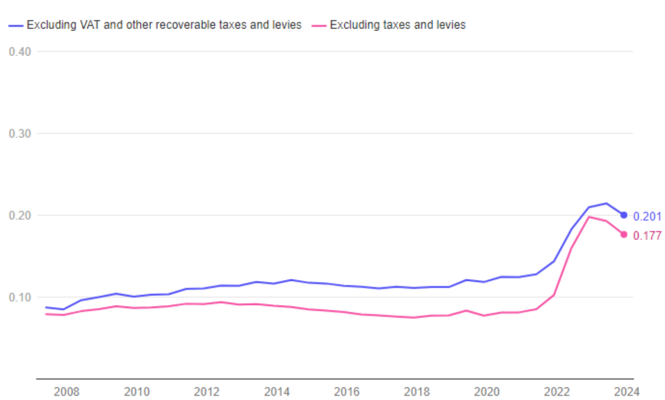

Fig. 1: Average electricity prices in the EU - 2008-2024 [6]

III. System model

An algorithm is needed to control the charge and discharge rates of the battery energy storage system (BESS). The controlling parameter is the voltage at the sending end of the supply system, the point where the energy supply, the grid, connects to the catenary. This is the location where the BESS will be connected to the system. Before a controlling algorithm can be constructed, a model of the system has to be created, an electrical representation of the system with the important electrical parameters.

A. Electrical representation

The circuit representation of the system can be seen in Figure 2 and consists of the BESS, with positive current flowing into a voltage controlled current source, this in parallel with the grid. This is modelled as a voltage source and its internal resistance. The two energy sources connect at the node called V_{SE}. This is then connected with the catenary resistance in series with the train load modelled as a current source. The catenary resistance is dependent on the position of the train, it increases as the train travels further away from the source. The voltage at the node V_{SE} is used as input to the algorithm and controls the current of the BESS.
Important parameters in this circuit are the grid voltage V_S, the internal resistance of the grid/source R_{int}, internal resistance of the BESS R_B, the power of the train load, the catenary resistance R_{cat}, and the current of the BESS I_B.

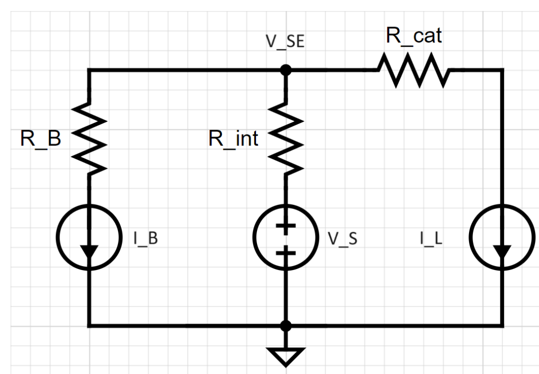

Fig. 2: Electrical representation of the system

As the power of the load increases, the current through the system increases which creates a voltage drop over the resistances in the system. This voltage drop creates the need for more current to still meet the load requirements of the train, this then creates a bigger voltage drop and so on. An equation to define the voltage V_{SE} that balances the system is introduced. (1) and (2) show the behaviour of the system if the BESS is not used, this will be the reference voltage. Simulations later on will show the difference from this voltage and will show the effect of the BESS and the algorithm.

$$V_{SE} = V_S - I_L * R_{int} \tag{1}$$

$$I_L = \frac{-V_s + \sqrt{V_S^2 - 4 * (R_{int} + R_{cat}) * power}}{-2 * (R_{int} + R_{cat})} \tag{2}$$

There are two solutions to this equation, one with a lower current, which creates a relatively small voltage drop at the train. This low current and high voltage is enough to supply the load. Another possibility is to have a high current, now the losses in the wires are significantly larger, with currents around 15.000 A. The voltage at the load is now 200 V. In physical systems with multiple solutions, the one that maximizes the voltage is preferred because it minimizes losses.

The voltage, V_{SE} for the circuit with BESS is calculated in (3). The current I_B is the result of the voltage-based control algorithm based on V_{SE} which will be discussed in section IV.

$$V_{SE} = V_S - I_B * R_{int} - \frac{V_{SE} - \sqrt{V_{SE}^2 - 4 * R_{cat} * power}}{2 * R_{cat}} * R_{int} \tag{3}$$

B. Parameter estimation

The constant circuit parameters can be estimated independent of the test data, and will be included in the simulations. For this research, the parameter values used in the work by Mo Chen et al. [7] are also used in this research and are defined in the table below.

Catenary + return rail resistance (Ω/km)	0.065
Grid internal resistance (Ω)	0.054
Grid voltage (V)	1650

The catenary resistance R_{cat} is dependent on the length of the wires and, therefore on the distance between the source and the train. The resistance increases as the train travels further away from the source. With the total length of the track, the resistance of the catenary wires can be determined for every timestamp.

The efficiency of the BESS is determined by the characteristics of Lithium-ion batteries. A typical c-rating for Lithium-ion batteries is 1C. The efficiency of Lithium-ion batteries, with a C-rating of 1C, with a depth of discharge (DoD) range between 0.2-0.8 is around 96% at its lowest. This is full cycle efficiency, so charge and discharge. Looking at the efficiency of this with the efficiency of possible DC/DC converters that could be used, the efficiency of the BESS is determined to be 96% [8], [9], [10].

C. Test data

A load profile of the train will be used as input to the system. This load profile includes the amount of power that the train draws or supplies at specific times. This will then be used to calculate the current through the load and the voltage related to that in (2) and (3).
This load profile is taken from [7]. The data includes a 106-second long power profile of a system of two trains and can be seen in Figure 3 as the blue line. The black dashed line is 0 watt as a reference. First the two trains, with 36 seconds between them, accelerate and consume power. This is followed by the trains decelerating while they generate RBE, shown as negative power. The length of the track on which the trains in this data operate is 1 km.

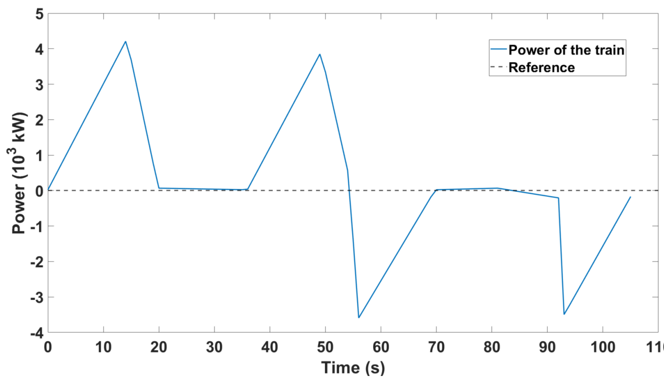

Fig. 3: Load profile of the trains used as test data [7]

IV. Algorithm

The BESS needs an algorithm that controls the current flow into and out of this system. This algorithm is based on the voltage at the connection between the grid and the catenary wire. The algorithm used in this research is defined by David Roch-Dupré et al. [11] and is shown in Figure 4. The algorithm shows a voltage controlled current source, the BESS, where the x-axis represents the voltage at the connection with the grid. The y-axis represents the current of the BESS. The voltage at the origin is the no-load voltage of the system, 1650 V in this case [7].
Below, the parameters of the algorithm are defined based on [11]:

- V_{RHE}: Voltage at which rheostatic braking is used.
- V_{2MAX}: the voltage at which the BESS has reached the maximum charging current.
- V_2: voltage at which the BESS starts charging.
- V_1: voltage at which the BESS starts supplying.
- V_{1MIN}: voltage at which BESS is supplying maximum current.
- I_{MIN}: maximum supply current.
- I_{MAX}: maximum charge current.

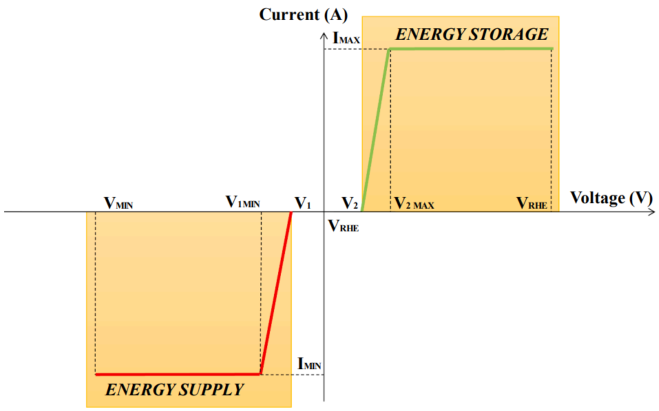

Fig. 4: Voltage-based control algorithm of the BESS [11].

The algorithm is a piecewise defined function with 5 different parts: a positive and a negative maximum current, two linear increasing parts, and a part with zero BESS current. In this area of zero BESS current, the excess energy is dissipated by rheostats. All different sections are defined below:

$$I_B = \begin{cases} I_{MIN} & for \quad V_{SE} \leq V_{1MIN} \\ y_1 & for \quad V_{1MIN} < V_{SE} \leq V_1 \\ 0 & for \quad V_1 < V_{SE} \leq V_2 \\ y_2 & for \quad V_2 < V_{SE} \leq V_{2MAX} \\ I_{MAX} & for \quad V_{2MAX} < V_{SE} \end{cases}$$

Where y_1 and y_2 are linear lines defined in (4) and (5):

$$y_1 = \frac{-I_{min}}{V_1 - V_{1min}} * V_{SE} + \frac{I_{min} * V_1}{V_1 - V_{1min}} \tag{4}$$

$$y_2 = \frac{I_{max}}{V_{2max} - V_2} * V_{SE} - \frac{I_{max} * V_2}{V_{2max} - V_2} \tag{5}$$

The algorithm is flexible and can be used to get various results. The parameters can be changed such that its behaviour changes from peak shaving to charging and discharging as much energy as possible. All the parameter values shown in this section can be adjusted. The minimum and maximum voltage change how much power the BESS will be able to deliver and take from the system. The voltage range between V_{1MIN} and V_1 is the range for which the discharge current of the BESS changes linearly from maximum to zero. The charge current of the BESS changes from zero linearly to maximum in the voltage range from V_2 to V_{2MAX}. The voltages at which the BESS starts to supply or store energy are V_1 and V_2 respectively. Setting these values further away from the no-load voltage allows the voltage to deviate more from this no-load voltage before the BESS starts to (dis)charge. This generates and uses less energy, but it could be used for peak shaving in combination with smaller batteries.

In the end, to capture as much energy as possible the linear phase is made very short to get a lot of current when the voltage deviates from the no-load voltage.

V. BESS Design

There are different options to store energy, common ways are Lithium-ion batteries, supercapacitors and flywheels. All these three options have their own (dis)advantages, making them useful for specific situations. In this section, the possibilities are researched and compared to what is needed in this case based on the results of simulations.

A. Requirements

Simulation of the model with the algorithm in MATLAB is used to get the power and size requirements for the BESS. The parameters, as introduced in section IV, are determined through an iterative process. In order to capture and use as much energy as possible, the voltage range around the no-load voltage, for which the current is zero, is made small, $\pm 5V$. This threshold is introduced to prevent situations where the BESS needs to switch very frequent between charging and discharging small amounts of energy. This would increase the stress on the BESS. The 5 V is determined by visual inspection of the data and analysis of the results of the simulation. Looking at the test data in Figure 3, the BESS should only (dis)charge during the four peaks. That means that the current should be zero between second 20 and 36 and again between second 70 and 90.

Another set of parameters that have a large influence on the behaviour of the BESS is V_{1MIN} and V_{2MAX}. These control the voltage for which the BESS-current is maximum. Between V_{1MIN} and V_1 and between V_2 and V_{2MAX} the current increases linearly with the voltage. Moving V_{1MIN} and V_{2MAX} further away from the origin, i.e. from the no-load voltage, will increase the voltage range for which the current increases from 0 to I_{MIN} or I_{MAX}. This allows a higher voltage peak or dip from the no-load voltage. The value of V_{1MIN} is set at 0.99 times the no-load voltage and V_{2MAX} is set at 1.01 times the no-load voltage. This $\pm 1\%$ is chosen to maximise power supply and RBE capture of the BESS.

Analysing the test data, it shows that 22.6 kWh is used and 14.6 kWh of RBE is generated by the train. So, in this case, a battery of at least 14.6 kWh is needed if all the energy is captured, and a capacity of at least 22.6 kWh is needed if all the consumed energy is supplied by the batteries.

Looking at the outcomes of the simulation, the BESS supplied 19.4 kWh and stored 10.9 kWh of energy. So, with this algorithm, the battery needs to have a capacity of at least 10.9 kWh if it needs to be able to capture the RBE. The capacity needs to be at least 19.4 kWh if it needs to be able to not only supply the RBE but also the remainder of the required energy. To get this extra energy, PV can be used or moments when energy is cheap can be utilized to charge the BESS. The power that the BESS ideally would be able to supply to the load is around 3.7 MW, and for charging it is ideally capable of around 2.8 MW. This is a large amount of

power for a relatively short time, but it is really important that the BESS can handle this, as otherwise a lot of energy would be lost to the environment.
The estimates of prices that will be given in the coming sections only include energy storage. It does not include the costs of other systems such as converters, battery management systems, and cooling systems.

B. Lithium-ion battery

A Lithium-ion type BESS is great for storing large quantities of energy and for longer periods. For Lithium-ion batteries to last as long as possible it is advised to keep them within the range of 20% to 80% state of charge (SoC). Considering this constraint, the required capacity of 19.4 kWh is then 60% of the total battery capacity, so a capacity of 32.3 kWh is needed. In terms of power, it ideally has, as mentioned before, 3.7 MW of discharge and 2.8 MW of charging power. This combination of megawatts of power and kilowatt-hours of storage is not common. A typical c-rating for Lithium-ion batteries is 1C, which means that a 1 MW power battery, has a capacity of 1 MWh [8]. Using this, the needed Lithium-ion battery would have 3.7 MW of power with a capacity of 3.7 MWh. The price of this technology is determined to be 139 EUR/kWh [12].

C. Supercapacitor

The requirements for a system with supercapacitors (SCs) are equal to that of the Lithium-ion battery, so the same 19.4 kWh is supplied to the system. As the SCs can have 100% depth of discharge (DoD) they only need to be around 19.4 kWh big, significantly smaller than the Lithium-ion battery of 32.3 kWh. The same power of at least 3.7 MW is needed to capture the energy that is regenerated. SCs that can handle the 3.7 MW of power and have this amount of storage at the same time are not common. The limiting factor for SCs is their storage capacity. So, to get an estimation of the price of a system with SCs, it is necessary to look at the price per kWh. A supercapacitor costs somewhere between 2.500 EUR/kWh and 10.000 EUR/kWh [13], [14].

D. Flywheel

A flywheel is a mechanical device that stores energy in rotational momentum and can also be used to store the RBE coming from the train. The requirements for this system are the same as for a supercapacitor system. The expected costs for a system with a flywheel vary a lot. Power-to-energy ratios can go up to 100, and prices can be around 250 EUR/kWh. [15], [16]. However, this high power-to-energy ratio is not common, values are more commonly around 4 [17]. More realistic prices are higher with a cost of 2700 EUR/kW.

VI. PV SYSTEM DESIGN

When capturing RBE it is not possible to get as much energy back as is put into the train to accelerate. There is still the need to put new energy into the system. In the scope of reducing the carbon footprint of transportation, the addition of photovoltaics to generate the extra energy would fit very well. It can generate the remaining energy that the BESS can supply to the tractive train. The addition of PV panels will increase the initial costs of the system, however it will reduce the variable costs of running the trains. This way the trains can mostly rely on recaptured and renewable energy. Including this PV requires the system to have extra battery space.

The amount of energy that PV panels generate is highly dependent on the amount of solar irradiance it receives. This irradiance is dependent on several factors such as geographical location, weather conditions, seasons, and time of day. For this research, an average output is used over all seasons in Amsterdam, Netherlands. This gives an indication of how many PV panels on average are needed to generate the needed new energy. In summer, with longer days, an average daily production of 5.42 kWh/kW of installed PV panels is achieved. This drops down to 4.36 kWh/kW in spring, 2.14 kWh/kW in autumn and it is at its lowest of 1.01kWh/kW in winter [18]. This brings the average over a year to 3.23 kWh/kW.

As discussed in section II, the operation of the train that is modelled in the data happens on average 66 times per day. Of the 22.6 kWh that is used in the data, 19.4 kWh is supplied by the BESS. Of this, 10.9 kWh is recaptured RBE. This means that 8.5 kWh multiplied by 66 times per day, is 561 kWh of PV energy that needs to be generated per day. With an average of 3.23 kWh/kW, a PV power capacity of 174 kW is needed. Expressing this in numbers of panels with 400 W power, results in a PV system with 435 panels [19], [20].

VII. RESULTS & DISCUSSION

An electrical representation of the system with the grid, train and BESS is created and equations relating important parameters are derived. The equations for a system without a BESS are as follows:

$$V_{SE} = 1650 - I_L * 0.054 \tag{6}$$

I_L as used in (6) is defined in (7) and is still dependent on the variable values of power, coming from the data, and R_{cat}, being distance dependent.

$$I_L = \frac{-1650 + \sqrt{1650^2 - 4 * (0.054 + R_{cat}) * power}}{-2 * (0.054 + R_{cat})} \tag{7}$$

The equation for a system with BESS is shown below, where I_B itself is a function of V_{SE}. How the value of I_B is determined is explained in subsection VII-A.

$$V_{SE} = 1650 - I_B * 0.054 - \frac{V_{SE} - \sqrt{V_{SE}^2 - 4 * R_{cat} * power}}{2 * R_{cat}} * 0.054 \tag{8}$$

A. *Voltage-based control algorithm*

Taking the values determined in this paper and using them in (4) and (5) results in the following equations used in the algorithm as depicted in Figure 4.

$$y1 = 261 * V_{SE} - 4.3 * 10^5$$

$$y2 = 261 * V_{SE} - 4.3 * 10^5$$

These represent the relation between the voltage at the connection to the catenary and the current of the BESS in the linear phase of the control algorithm.

Using the equations above, and the parameters as discussed in subsection V-A, the full relation between the voltage, V_{SE} and BESS current I_B can be expressed as shown below. The detailed values are shown in the appendix in Figure 12.

$$I_B = \begin{cases} -3000 & for \quad V_{SE} \leq 1633.5 \\ 261 * V_{SE} - 4.3 * 10^5 & for \quad 1633.5 < V_{SE} \leq 1645 \\ 0 & for \quad 1645 < V_{SE} \leq 1655 \\ 261 * V_{SE} - 4.3 * 10^5 & for \quad 1655 < V_{SE} \leq 1666.5 \\ 3000 & for \quad 1666.5 < V_{SE} \end{cases}$$

Changing the different parameters of the algorithm has different effects on the voltage V_{SE}. The figures below show these effects, where the orange line represents the voltage in a system without a BESS, while the blue line represents the voltage in a system with a BESS. The dashed black line is the no-load grid voltage.

1) Different threshold voltages: The first parameter to look at is the threshold voltage at which the BESS starts to supply or draw current. The other parameters are kept constant with V_{1MIN} at 0.99 and V_{2MAX} at 1.01 times the no-load voltage. The effect of not having a threshold can be seen in Figure 5. As soon as the voltage deviates from the no-load voltage, the BESS starts (dis)charging. This effect can be seen as the blue line immediately deviates from the orange line, the moment the orange line moves away from the reference line. This keeps the voltage close to this no-load voltage, more so than without BESS.

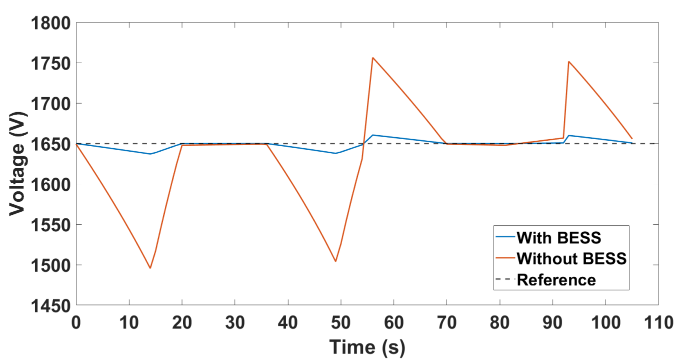

Fig. 5: Voltage behaviour without threshold voltage

Looking at the results of using a threshold of $\pm 30\ V$ gives Figure 6 below:

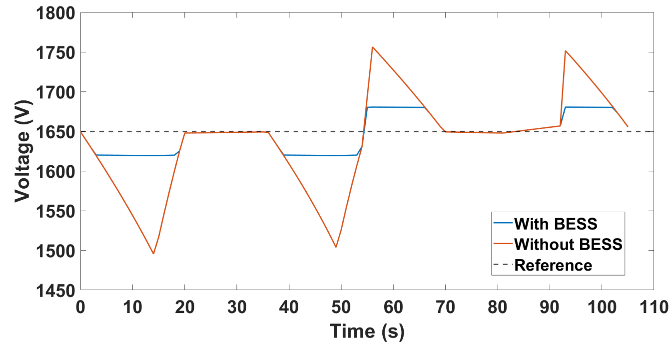

Fig. 6: Voltage behaviour with $\pm 30\ V$ threshold voltage

In this case, it takes a lot longer until the BESS starts to (dis)charge. The effect of this is that the system is used more for peak shaving rather than saving and supplying the maximum amount of energy possible. The BESS remains off when the voltage deviates small amounts from the no-load voltage. This can be seen in Figure 6 when the blue and orange lines overlap between the peaks/drops.

In Figure 7 the threshold is set at ± 5 V, a compromise of the previous examples. Here it can be seen that the BESS only starts to (dis)charge at the four peaks/drops. In between these, the blue line overlaps with the orange one, showing that the BESS is off. This is better than the first-mentioned situation without threshold, as this reduces stress on the BESS, and better than the second-mentioned situation as it uses more of the RBE. This version of the algorithm is the one that is used for calculations regarding the parameters of the BESS.

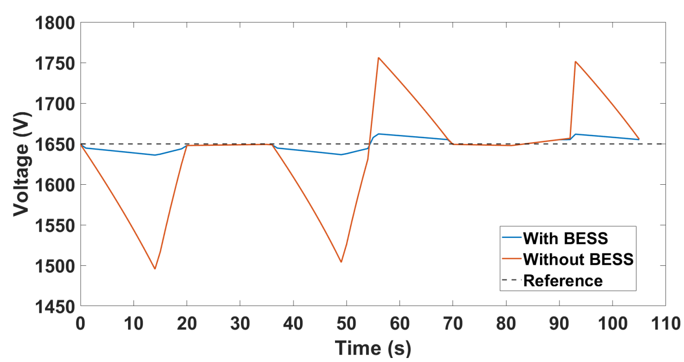

Fig. 7: Voltage behaviour with ± 5 V threshold voltage

2) Voltage at which maximum current is supplied or drawn: Continuing with the threshold of ± 5 V of Figure 7, now the voltage at which maximum current is delivered or drawn is changed. The previous examples had maximum current at a $\pm 1\%$ from the no-load voltage, while Figure 8 has this maximum current at $\pm 10\%$.

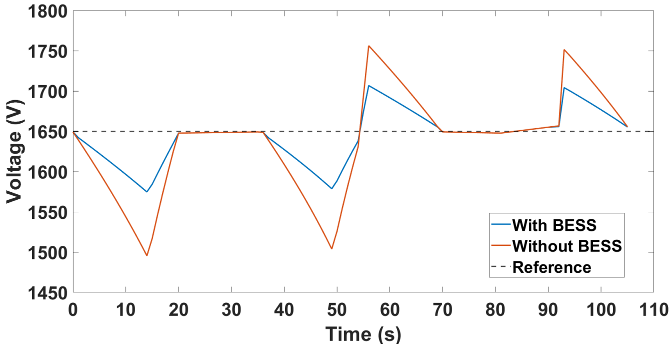

Fig. 8: Voltage behaviour with maximum current at ±10%

The result of this change is that the BESS has a lower (dis)charge current for the same voltage. The voltage has to move 10 times further from the no-load voltage to get the same current. The blue line does not stay as close to the dashed line as in the previous examples, which means that less RBE is captured from and supplied to the train. This, again, makes it better for peak shaving but not for maximum energy efficiency.

3) Reduced maximum current: Figure 9 shows what happens when the BESS reaches its maximum (dis)charge current. Especially until second 20 and between second 35 and 55 this effect can be seen very well. As the voltage drops, the discharge current of the BESS increases, reducing the voltage drop. Eventually, at around second 8, the BESS cannot further increase the discharge current to counteract the voltage drop and continues to drop at the same rate as the system without BESS.

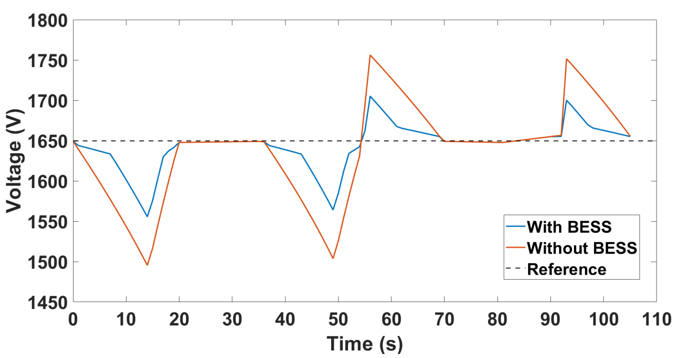

Fig. 9: Voltage behaviour with reduced maximum current

4) Keeping track of state of charge: During the simulations, the SoC of the battery is continuously checked to see if it can store/supply enough energy. In case there is not enough stored energy or available capacity, the system will act as if there is no BESS. This can be seen in Figure 10 and Figure 11 where the voltage and SoC are shown as a function of time. The same parameter values are used as for Figure 7 in section subsubsection VII-A1. The BESS that is modelled is a Lithium-ion battery, the SoC is kept between 20% and 80%. The initial SoC is set at 80%.

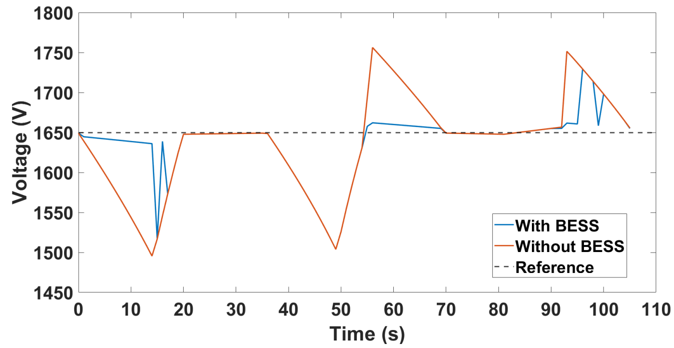

Fig. 10: Voltage behaviour with limited SoC

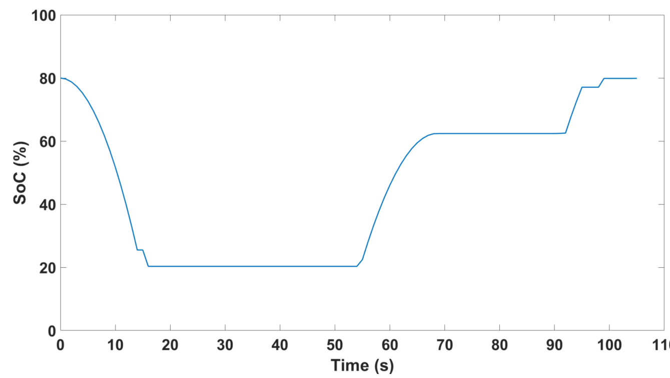

Fig. 11: State of charge of Lithium-ion BESS

The jumps in voltage that can be seen around second 15 are the result of the BESS not having enough energy stored to supply what the algorithm wants to supply, so the BESS does not supply anything. This makes the voltage jump to what it would be without BESS until the voltage rises enough such that the BESS can supply what the algorithm dictates. This happens twice between second 10 and 20. The situation around second 95 has a similar origin. The BESS does not have any capacity left to store the RBE, so it turns off, making the voltage peak to whatever it is without BESS. The BESS starts storing again when the voltage drops enough such that it is able to store what the algorithm dictates. This happens twice between second 90 and 100.

B. BESS

Simulating the system with the algorithm and test data gives the size and power requirements for the BESS. The requirements for the system are that it needs to have a discharge power of 3.7 MW and a charge power of 2.8 MW. In terms of storage capacity, it needs 10.9 kWh if it only needs to be able to capture the RBE, and 19.4 kWh if the BESS is charged next to the captured RBE by e.g. PV panels.

Three different BESS options are explored, starting with Lithium-ion batteries. A system using this technology will have a power capacity of 3.7 MW, to (dis)charge as fast as desired. The characteristics of a Lithium-ion system with this much power will cause it to have a storage capacity of around

3.7 MWh. This is a lot more than what is strictly needed, but it is needed to get the power requirements.
The extra storage capacity can be used to help the grid in times when energy is abundant, storing for possibly negative prices. It can also be used to store PV-generated energy. The difference in what the BESS wants to supply and what it recaptures in RBE can be generated by PV. As explained in section VI, a 435-panel sized PV system of 400 W panels can be used to generate the 561 kWh that is needed per day. This is calculated for average conditions of all seasons in Amsterdam, Netherlands. In summer it will generally produce more, and in winter it will generally produce less than desired.
The characteristics and price per kWh result in a cost of this Lithium-ion battery of around half a million EUR. If one solely looks at the payback time of this system, considering how much energy is saved by storing RBE, a price of 0.15 EUR/kWh and the test data, it would take around 12 years to pay it back. This does not consider the fact that the load on the grid is reduced, preventing further costly upgrades to the electricity network.

In the case of SCs, the storage capacity is much smaller for the same amount of power when compared to Lithium-ion batteries. The limiting factor for a SC system is the storage capacity, so the price per kWh is considered. Looking at a system that can store all the RBE available and supply according to the algorithm, it needs to have a capacity of 19.4 kWh. This would cost somewhere between 50.000 EUR and 200.000 EUR. Using PV to generate the extra energy is possible, however SCs are typically not used for this. Lithium-ion batteries would serve this purpose better. Considering this, it is possible to look at a system that only captures and uses the RBE, the rest of the energy will be supplied by the grid to keep the costs of the BESS down. In this case, the system would cost somewhere between 27.000 EUR and 109.000 EUR.
Possible new research could look into a system that includes both SCs for the high power requirements and Lithium-ion batteries for the larger storage size, PV generation and grid stabilization.

The last option considered in this research is a flywheel [16]. As the system needs a large amount of power, but relatively little storage, the power requirements are a bigger concern than the storage requirements. The same 3.7 MW and 19.6 kWh are desired. The wide range in costs per kWh and power-to-energy ratios gives a wide range in costs for this system. Ranging from 10.000 EUR to around 10 million EUR. This uncertainty in price will clear up when the requirements are discussed with a company that could supply such a system. For now, it was not possible to get pricing for such a specific system. This makes it hard to judge if this is a good option to use.

VIII. Conclusion

The designed system shows through simulation that it can store the RBE of a decelerating train, and supply it back to an accelerating train. The operation of the BESS is determined by the voltage-based control algorithm. In a system that does not include PV, 48.2% of the required energy can be supplied by the BESS with captured RBE. In a system with PV 85.8% of the required energy can be supplied by the BESS. This energy comes from captured RBE and generated PV. The advantage of using a BESS is that it is a good solution to reduce the impact of railway networks on the already congested electricity grid. The energy in the system is used more efficiently and the system can take energy from the grid when there is overproduction, helping to stabilize it. Systems like these can prevent the need to make expensive and complicated grid upgrades. Below, a summary of the different BESS technologies is shown:

Type	Price (10^3 EUR)	(dis)advantages
Lithium-ion	Around 500	A lot more storage than needed, makes it expensive, but PV is added easily
Supercapacitor	27 - 200	Less expensive than Li-ion, but PV and grid stabilization require extra storage capacity
Flywheel	10 - 10.000	Wide range of costs, could be very expensive.

Looking at these BESS technologies from an economic perspective, the supercapacitor system seems to be a good alternative as it meets the requirements while the expected costs are low. Looking at the technical aspects of the solutions, the Lithium-ion system has more potential than the other options, making it a good alternative. It is more expensive than a system with supercapacitors, but it has a greater impact on the system because of the addition of PV and the possibility of using it to stabilize the grid.

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IX. Appendix

During the preparation of this work, the author used Grammarly in order to spell- and grammar-check the text. During the preparation of this work, the author used the chatbot ChatGPT in order to help ideate. After using these tools/services, the author reviewed and edited the content as needed and takes full responsibility for the content of the work.

The detailed version of the current of the BESS with the algorithm parameters discussed in section subsection V-A is shown in Figure 12.

$$\begin{cases} -3000 & \text{if } V_{\mathrm{SE},t} \le \frac{3267}{2} \\ \frac{6000\,V_{\mathrm{SE},t}}{23} - \frac{7372404732438261}{17179869184} & \text{if } V_{\mathrm{SE},t} \in \left(\frac{3267}{2}, 1645\right] \\ 0 & \text{if } V_{\mathrm{SE},t} \in (1645, 1655] \\ \frac{6000\,V_{\mathrm{SE},t}}{23} - \frac{3708610891241739}{8589934592} & \text{if } V_{\mathrm{SE},t} \in \left(1655, \frac{3333}{2}\right] \\ 3000 & \text{if } \frac{3333}{2} < V_{\mathrm{SE},t} \end{cases}$$

Fig. 12: Detailed BESS current from the control algorithm

The code used to simulate the system is shown below.

```
clear;
close all;
clc;
clear workspace;
format shortG;

D=importfile("Data.csv");
time=D.Time;         %s
power=D.Power*10^6; %W
Tracklength=1;
km=0:(Tracklength)/(height(D)-1):Tracklength;   %length of the track is 1km
km(1)=0.001;
t=length(time);      %# of samples
V_s=1650;            %V
R_int=0.054;         %ohm
R_cat=0.065*km;
R_tot=R_int+R_cat;
dt = 1/3600;         %1 second in hours
I_load1=zeros(1,t);
V_drop1=zeros(1,t);
syms x;
syms V_SE_t;
V_SE1=zeros(1,t);
V_SE2=zeros(1,t);

%battery parameters, positive current is into the battery
E_max = 50000;               %Wh, battery size, amount of energy that can be stored
V1 = V_s - 5;                %- Start supplying at this voltage
V2 = V_s + 5;                %+ Start storing energy at this voltage
V1_min = min(0.99*V_s, V1-1); %maximum supply rate at this voltage
V2_max = max(1.01*V_s, V2+1);  %maximum storage rate at this voltage
I_max = 3000;                %maximum storage current
I_min = -3000;               %maximum supply current, negative
eff = 0.96;                  %efficiency of BESS
SoC = zeros(1,t+1);
SoC_min = 20;
SoC_max = 80;
SoC(1) = SoC_max;            %state of charge initial value in %
R_BESS = R_int;              %internal battery resistance
I_BESS=zeros(1,t);           %BESS current
P_BESS_ideal = zeros(1,t);
P_BESS_possible = zeros(1,t);

y1=(-I_min/(V1-V1_min))*V_SE_t+((I_min*V1)/(V1-V1_min));
y2=(I_max/(V2_max-V2))*V_SE_t-((I_max*V2)/(V2_max-V2));
total_consumed = 0;          %total that is used by the train
total_captured=0;            %RBE generated
%%
for i = 1:1:t %for every sample, run the loop
I_load1(i)=(-V_s+sqrt((V_s)^2-4*R_tot(i)*power(i)))/(-2*R_tot(i));
V_drop1(i)=I_load1(i)*R_int; %voltage drop over internal resistance of source as all the load current is coming from the grid
V_SE1(i)=V_s-V_drop1(i);     %sending end voltage

%BMS - how much will the BESS supply
%use voltage V_ES to determine output
I_B = piecewise(V_SE_t<=V1_min, I_min, (V1_min<V_SE_t)&(V_SE_t <= V1), y1, (V1 < V_SE_t)&(V_SE_t<=V2),0,(V2<V_SE_t)&(V_SE_t<=V2_max),y2,V2_max<V_SE_t, I_max);
temp = subs(I_B, V_SE_t, x);
eqn = x==V_s-temp*R_int-((x-sqrt((x^2)-4*R_cat(i)*power(i)))/(2*R_cat(i)))*R_int;

V_SE2_ideal = double(solve(eqn, x));
I_BESS_ideal= double(subs(I_B, V_SE_t, V_SE2_ideal));

% Check if battery current is zero - deadzone
if I_BESS_ideal == 0
    V_SE2(i) = V_SE1(i);
    SoC(i+1) = SoC(i);
    I_BESS(i) = 0;


% Check if voltage is above the desired voltage (charging)
elseif V_SE2_ideal > V_s
    P_BESS_possible(i) = ((SoC_max-SoC(i))*E_max)/(eff*(dt*100)); %Power possible to fit in the battery
```

```
    P_BESS_ideal(i) = (V_SE2_ideal * I_BESS_ideal - (I_BESS_ideal^2*R_BESS))*eff;
    % Check if ideal power is within possible range
    if P_BESS_ideal(i) <= P_BESS_possible(i)
        V_SE2(i) = V_SE2_ideal;
        SoC(i+1) = SoC(i) + (P_BESS_ideal(i)*(dt*100))/E_max;
        I_BESS(i) = double(subs(I_B, V_SE_t, V_SE2(i)));
    else
        V_SE2(i) = V_SE1(i);
        SoC(i+1)=SoC(i);
        I_BESS(i) = 0;
    end

% Check if voltage is below desired voltage (discharging)
elseif V_SE2_ideal < V_s
    P_BESS_possible(i) = ((SoC(i)-SoC_min)*E_max*eff)/(dt*100);
    P_BESS_ideal(i) = abs((V_SE2_ideal * I_BESS_ideal + (I_BESS_ideal^2*R_BESS))/eff);

    % Check if ideal power is within possible range
    if P_BESS_ideal(i) <= P_BESS_possible(i)
        V_SE2(i) = V_SE2_ideal;
        SoC(i+1) = SoC(i) - (P_BESS_ideal(i)*(dt*100))/E_max;
        I_BESS(i) = double(subs(I_B, V_SE_t, V_SE2(i)));
    else
        SoC(i+1)=SoC(i);
        V_SE2(i) = V_SE1(i);
        I_BESS(i) = 0;
    end

% Handle unexpected cases
else
    fprintf("No supply or demand? - %d\n", i);
end
if SoC(i) <0 || SoC(i) > 100
    fprintf("Incorrect battery levels");
end

if power(i) < 0
 total_captured = total_captured + P_BESS_ideal(i)*dt;
elseif  power(i) > 0
    total_consumed = total_consumed + P_BESS_ideal(i)*dt;
end
end
SoC(1)=[]; %remove initial value

%%
plot(time,P_BESS_ideal, 'color', [0.8500 0.3250 0.0980])
xlabel("Time (s)"); ylabel("P-BESS (W)");
legend('ideal', 'Location','best');

figure
plot(time,V_SE2,'Linewidth',2)
hold on
plot(time,V_SE1,'Linewidth',2)
yline(1650, '--', 'Color', 'k', 'LineWidth', 2); %create reference line at 1650V
hold off
xlabel("Time (s)"); ylabel("Voltage (V)");

figure
plot(time, SoC,'Linewidth',2)
xlabel("Time (s)"); ylabel("SoC (%)");
```