Comparative Analysis of Energy Storages and Reversible Substations for Braking Energy Recovery in Different Traffic Scenarios

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I. Abstract

In today's world, several measures are taken to achieve sustainable use of energy. The railway sector can be improved by recovering the braking energy. This recovering can only happen when a train is leaving, while another train arrives. To address this challenge there are two solutions. Temporary energy storage or supplying the braking energy back to the main grid by means of a reversible substation. This study compares the general characteristics of three energy storage systems (battery, flywheel, and supercapacitors) and two reversible substations (thyristor inverter and IGBT inverter). Additionally, an analysis and simulation of the two types of inverters is conducted. Different commutation classes for turning off the thyristor in the inverter are discussed and compared. An energy analysis is conducted on the arriving and leaving trains for a busy station and a calm station (Utrecht Centraal and Deventer), and the different recovery systems are compared for the two cases. The results show that energy capacity is a significant factor in the amount of recovered energy. Another finding is that, relative to the station's activity level, energy storage has a greater impact on a calm station than on a busy station. However, in absolute terms, the busy station recovers the most energy.

II. Introduction

Global warming is an important topic these days. The transportation sector covers a significant role in this, as fossil fuels are the main source for this sector. Within this branch, the railway transport is one mean of transport that mostly operates with electricity. Although the electricity in the railway sector is not always generated by non-renewable sources, the energy should be used with care. Therefore a close look should be taken at losses in the system. One of the biggest losses is the energy that is lost during breaking. By using the motor as a generator, the electricity can be recovered and used by other leaving trains.

However, there is not always a train leaving at the same time a train arrives. Timetable optimization can be performed, but people have to change trains as well, making it impossible in the first place to let all trains arrive and leave simultaneously. The catenary can temporarily store a small amount of energy, but not enough to recover all the brake energy of one train, let alone multiple trains. An energy storage and a reversible substation are means that can recover that excess energy. The most used storage types for this application are supercapacitors, flywheels and batteries. Common types of inverters in reversible substations are the thyristor inverter and the insulated gate bipolar transistor (IGBT) inverter. How do these storage types and inverters compare to each other?

Stations can differ a lot in traffic density. At one station a train arrives and leaves every couple of minutes, while at other stations the gaps are half an hour. Because of that the difference in braking energy between these stations is significant. This arises the question: what is the difference in effectiveness of energy storages and reversible substation systems for stations with different traffic densities?

III. Theory

A. General comparison

The general characteristics of the five recovery systems are now discussed to gain some more insight of them.

1) Battery

The two types of batteries that are mainly used for wayside storage applications are the nickel–metal hydride (Ni-MH) battery and the lithium-ion (Li-ion) battery. These batteries generally have a higher power density than other battery types (1), which is an important aspect considering recuperating braking energy. The efficiency of Li-ion batteries is high, i.e. in the range of 90-98%, while the efficiency of Ni-MH batteries is around 65-70%. Because the Li-ion battery is better, it is also more expensive (2). The lifetime of the Li-ion is generally between 8-15 years, but 15-20 years for Ni-MH (1). However, this is also dependent on how extensive the battery is used. The costs of various complete systems are diverse. Therefore the cost is related to the amount of energy or power. For batteries the $/kWh is slightly lower than the $/kW.

2) Supercapacitors

Supercapacitors are known for their high power capability, but at the cost of a low energy density. They operate at efficiencies of around 90-97%. An advantage is the high cycle life, causing long lifetime. As this device is specialised in power, it has low costs per kW, but on the contrary, high costs per kWh. (1)

3) Flywheel

The flywheel is a system that stores the energy mechanically instead of electrically, by rotating a mass in a vacuum. It has a better power density than energy density. The efficiency is around 90-95%. The lifetime is intermediate, it operates for around 20 years. (1) In general, flywheels have higher investment costs (3).

4) Thyristor inverter

An inverter based on thyristors is capable of converting DC to AC at very high powers, 3 MW in (4). The amount of energy that can be stored is not applicable for inverters, as the grid

	Energy Storage Systems			Inverters	
	Battery	**Supercapacitors**	**Flywheel**	**Thyristor**	**IGBT**
Power	200-2000 W/Kg	5000-10000 W/Kg	400-1500 W/Kg	3MW	1.5MW
Energy (Wh/Kg)	54-250	5-15	5-100	-	-
Efficiency (%)	65-70/90-98	90-97	90-95	96-97.5	97-98
Lifetime (years)	10-20 yrs	10-30 yrs	20 yrs	20+ yrs	20+ yrs
Cost ($/kWh)	240-1200	300-2000	1000-5000	-	-
Cost ($/kW)	420-1300	100-300	250-350	73.3	213

TABLE I: General characteristics of different energy storages and reversible substations

they are supplying to is very big. The efficiency of a thyristor inverter is around 96-97.5% (5) (6). The lifetime is 20+ years and the cost per kW is approximately $75/kW (4).

5) IGBT inverter

The inverter based on the IGBT is an inverter operating at medium power, 1.5MW in (4). It has a efficiency of 97-98% (7) (8). As the cost of the IGBT inverter is higher and the power lower, the cost per kW is approximately 215$/kW (4).

B. Inverter topologies

To convert DC to AC at high powers of the level of a train station, (high power) MOSFET's are not used anymore. Other components, such as the IGBT and thyristor, are used for this application. These two inverter topologies are now further explained and simulated.

1) Thyristor inverter

The thyristor is a semiconductor component that contains four layers, P-N-P-N. It acts like a switching diode, as it contains an anode, cathode and a gate to control the flow. Without an initial pulse, the thyristor blocks forward and reverse currents. But when a pulse is applied to the gate, the device conducts in forward direction. As a thyristor is very capable of withstanding high currents and voltages, it is a useful component to use in a high power inverter, which can be used to convert DC power from the catenary back to the AC grid.

The configuration in which the thyristor is used, is the H-bridge, which can be seen in Figure 1. The pairs T1 & T4 and T2 & T3 are given gate pulses alternately, such that the direction over the load changes alternately as well. In this way it will create an alternating current across the load, which is in our case the AC grid.

a) Forced commutation

There is one characteristic of the thyristor that adds a challenge. The device doesn't turn off when the gate pulse is removed. There are two methods to still force the component to turn off. First, by applying a reverse voltage over the thyristor, known as voltage commutation. The second option is lowering the current below the holding current, known as current commutation. Different classes of commutation will now be discussed.

Class A The class A commutation is a relative simple circuit. An inductor and a capacitor are placed after the thyristor and before the load, which can be seen in Figure 2. This is the series variant of this class. There is also a parallel variation, in which the capacitor is in parallel with the load, but that one is used for high loads (9). Since the grid, to which the inverter will supply, is not a high load, only the series circuit will be discussed.

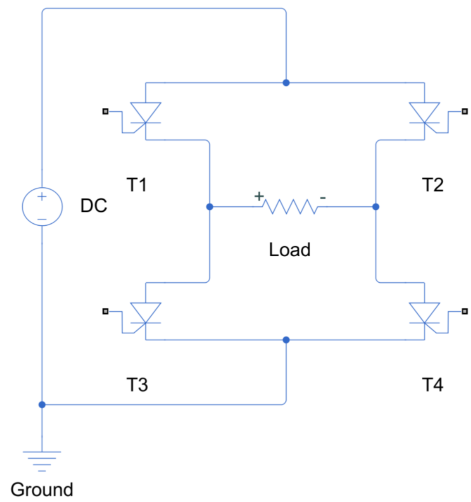

Fig. 1: H-bridge with thyristors

The operation is based on the charging of the capacitor. After the thyristor has been turned on with a gate pulse, there is a current flow, charging the capacitor to the supply voltage. When that voltage is reached, the inductor has also stored energy that now will further charge the capacitor. When the inductor has supplied all its stored energy, the thyristor experiences reversed polarity due to the capacitor and turns off. The capacitor will discharge afterwards.

Class A commutation is a rather simple configuration, as only an inductor and capacitor are added. Since these components are added in series, they will also carry the load current. This causes that this circuit is more suitable for frequencies above 1000Hz (10).

Class B In the class B configuration, the LC combination is placed in parallel with the thyristor. The circuit is shown in Figure 3.

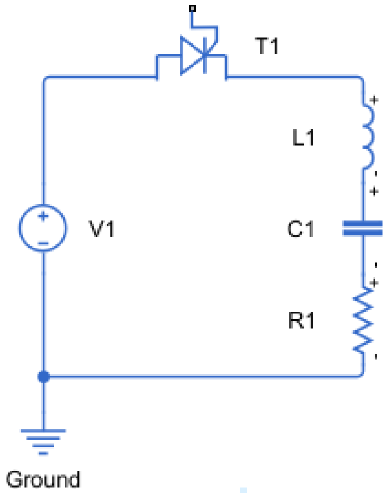

Fig. 2: Circuit of class A configuration

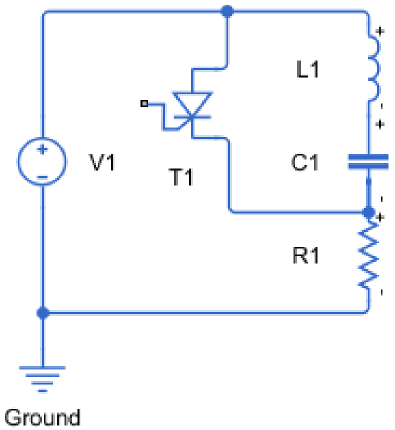

Fig. 3: Circuit of class B configuration

Let's assume the capacitor is initially charged with the upper plate positive. When the thyristor is turned on, an addition of two currents flows through the thyristor. The current from the source plus the discharging current from the capacitor. When the capacitor is fully discharged, it will be charged from the opposite direction. When the capacitor is maximally charged, it causes a reversed polarity and a commutating current that is the opposite of the flow direction of the thyristor. The thyristor will turn off, and the capacitor discharges through the resistor, and charges again due to the supply. (11)

Class B is also a quite simple configuration, only now the LC part doesn't carry the load current. This type is used in chopper circuits most of the times (12).

Class C The class C configuration uses two thyristors, two resistors and a capacitor. The circuit can be seen in Figure 4.

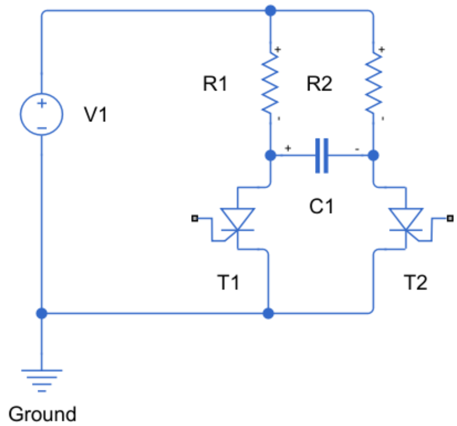

Fig. 4: Circuit of class C configuration

When T1 is turned on, the current flows in two directions. The first one is from the supply to the R1 to T1 back to the negative terminal of the supply. The second flow goes to R2, then through the capacitor, charging it, and the same route through T1 back to the negative side of the supply. To turn off T1, T2 is turned on. The voltage stored in the capacitor is in the same magnitude as the supply voltage, this causes that T1 is turned into reverse bias as T2 turns on, and therefore turned off. To turn off T2, T1 is turned on, and this process will work in the same way. (13)

Class C commutation is less simple as the class A and B configurations. However, because an extra thyristor is used, the commutation timing is not dependent on the LC oscillation, but can be chosen with the timing of the gate pulse. This type of commutation is useful at frequencies below 1000Hz (10).

Class D The class D configuration, using impulse commutation, is another forced commutation topology. The circuit can be seen in Figure 5.

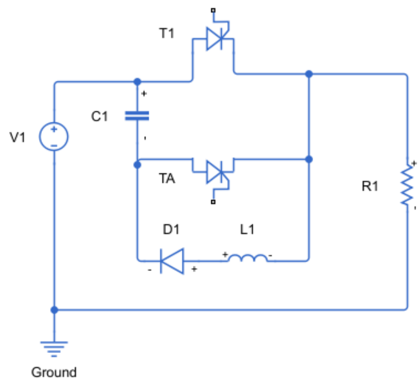

Fig. 5: Circuit of class D configuration

Assume that the capacitor is initially charged. When T1 is turned on, two currents start to flow: from the source through T1 and the load, and from the capacitor through T1, the inductor, the diode and ending at the negative side of the capacitor. The second flow is caused by the discharging capacitor. After the capacitor is fully discharged, it will be charged with reverse polarity because of the energy from the inductor. When then the auxiliary thyristor is turned on, T1 experiences the charges of the capacitor and therefore gets in reversed polarity and turns off. The current now flows from the supply voltage through the capacitor, TA, the load and back to the negative terminal of the source. When the capacitor is fully charged to the level of the supply voltage there is no potential difference anymore in the circuit. Therefore no current flows anymore and T2 is turned off. (14) (15)

Class D commutation can adjust the timing significantly, because of the auxiliary thyristor. The length of the conduction time is also easily adapted with the gate pulses. A great benefit is that the flow eventually stops completely and both thyristors can be turned off, unlike class C. In addition, the energy used to commutate the thyristor flows through the load. This makes that a higher efficiency is possible (10).

Class E The last commutation technique that will be discussed is the external pulse commutation, shown in Figure 6.

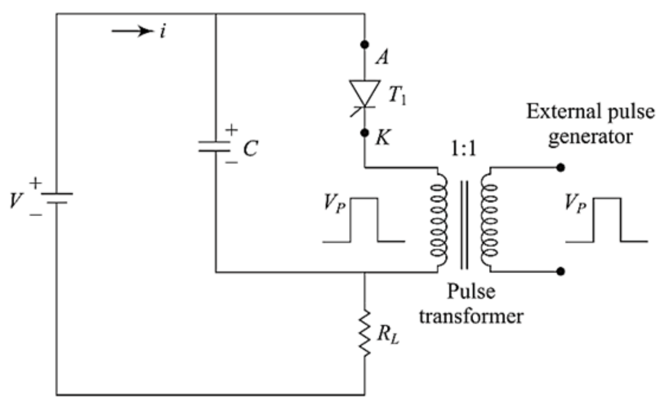

Fig. 6: Circuit of class E configuration (14)

This circuit works rather simple: an external pulse is applied to the T1. This creates a reverse polarity to the thyristor, turning it off. The capacitor is there to protect the circuit form voltage spikes. (16)

In class E commutation only an external pulse generator is used to generate the commutation pulse. As in the previous classes this pulse was generated with capacitors and thyristors, which doesn't need a pulse of the size that the external generator creates. Also this type of commutation was neglected by designers for the designing of power circuits (10).

b) Comparison in commutation classes

Since our end goal is delivering energy back to the AC grid, our inverter should be designed in such a way. Most AC grids on the world operate at a frequency of 50Hz (17). As mentioned earlier, class A commutation is more suitable for frequencies above around 1kHz. Class B is mostly used in chopper circuits, which is not our application. Class C is used in inverters, and also with operating frequencies below 1kHz. However, it is not very efficient, because the configuration consists of two thyristors and two resistors. This means that if both the thyristors are used for the bridge configuration, they need two different loads as well. Using only one of the thyristors of the commutation circuit for the bridge configuration leads to wasting a lot of energy through the other resistor. The class D topology is an efficient and versatile one, and therefore suitable for our application as well. Class E is a reliable configuration, but needs an external source and therefore adds complexity. In Table II the complexity in terms of the number components for different commutation configurations is shown, and the general application of each of them.

c) Simulation of thyristor inverter

After considering the different commutation techniques, it was chosen to use the class D commutation circuit. First a single class D commutation circuit was simulated, with the same circuit as in Figure 5. The following values were chosen: V1=100V, C1=10μF, L1=10μF, R=5Ω. The gate threshold voltage is 0.6V. The capacitor is initially charged. In the real application, the voltage level would be higher. Also, in this research the AC is considered single phase, so that the inverters can be single phase inverters as well.

	Class A	**Class B**	**Class C**	**Class D**	**Class E**
Number of components	2	2	3	4	2
Application	f >1000Hz	Choppers	f <1000Hz	Versatile	Not used

TABLE II: Characteristics of Different Commutation Classes

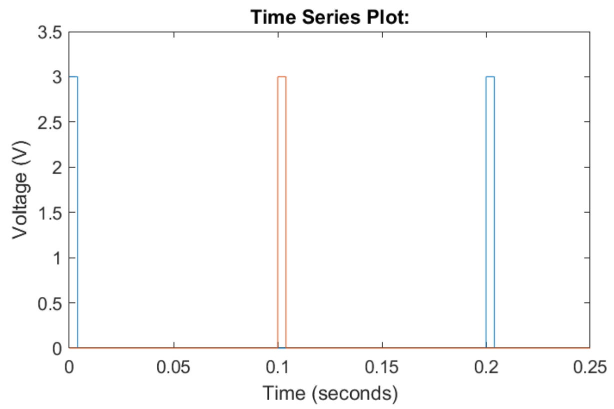

Fig. 7: Gate pulses applied to the thyristors, blue is applied to thyristor 1 and orange is applied to the auxiliary thyristor

Every 0.2 seconds T1 gets a gate pulse of 3V, well above the threshold voltage. After 0.1 seconds the auxiliary thyristor TA is turned on with a pulse. This timing ensures that the main thyristor conducts one half cycle of 50Hz, which is the target frequency in the inverter.

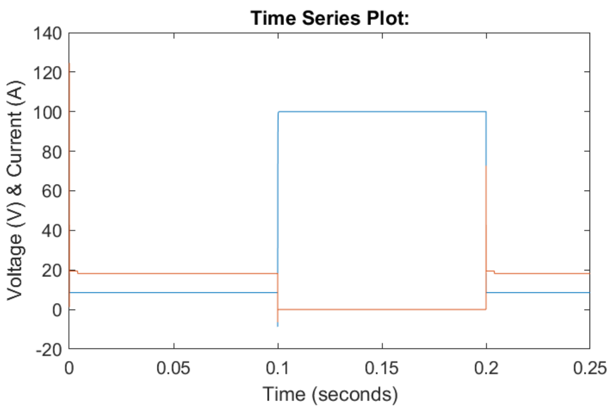

Fig. 8: The voltage and current of thyristor 1

In Figure 7 is shown that the voltage is 100V when the main thyristor is off, which makes sense as it doesn't conduct. The voltage is 8.6V when the thyristor does conduct. Ideally this should be zero, but this thyristor model has some internal resistance, causing it to be higher. The current is 18.2A in on-state, which is lower than the expected 20A (100V/5Ω). This is again caused by the internal resistance that is present. The negative and positive peaks in the current are from the charging and discharging of the capacitor respectively.

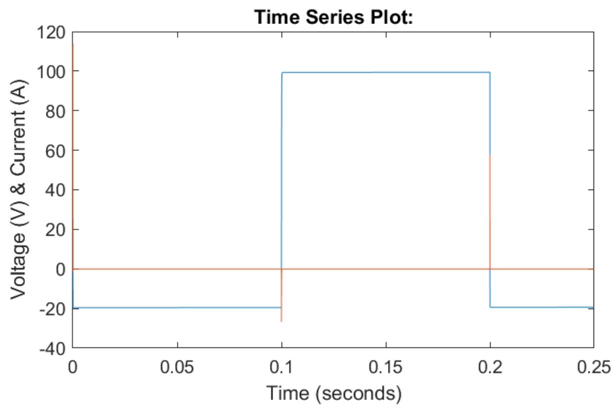

Fig. 9: The voltage and current of the capacitor

The capacitor voltage reaches from about -20V to 100V. The 100V makes senses as it is charged up till the supply voltage. According to the theory (18) it then should go to -100V. This is most likely caused by the component values of the capacitor and the inductor, because $I_C = V_1 * \sqrt{\frac{C}{L}}$ (10), and therefore also the voltage is dependent on the component values.

The current is most of the times zero. Only when T1 or TA is turned on, peaks occur. These are the same peaks that were visible in the T1 current, coming from the charging and discharging of the capacitor. When the capacitor is reversely charged to -20V, voltage commutation doesn't work, however since the current peak from discharging the capacitor is bigger than the current through the thyristor, current commutation does work, and therefore the thyristor still turns off.

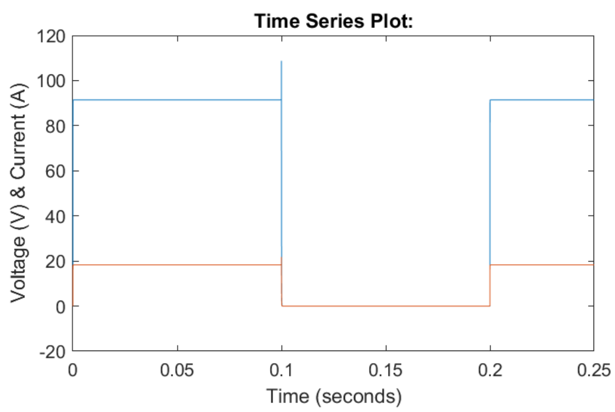

Fig. 10: The voltage and current of the load

The output curves show that T1 conducts for half a cycle and therefore have a current and a voltage at the load. The peak at t=0.1s in the current and therefore also in the voltage is coming from the discharging capacitor. This is not problematic, as in the final application of a bridge, there is a output filter to make a sine wave out of the square wave.

The circuit for the full thyristor bridge can be seen in Figure 11. It resembles the circuit in Figure 1, only now a commutation circuit is added to each thyristor.

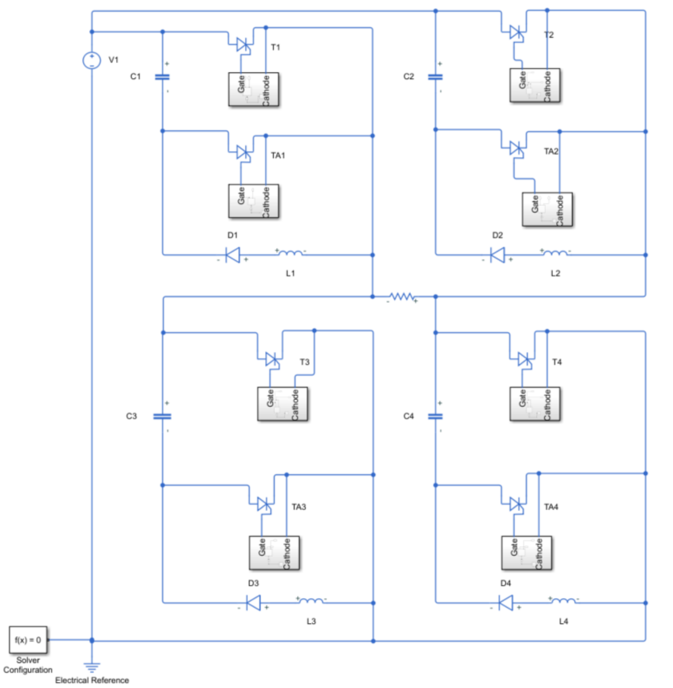

Fig. 11: The bridge configuration as simulated in Simulink

The subcircuits driving the gate consists of a pulse generator connected to a gate driver. The 'source' port of the gate driver is connected to the anode, as the the gate voltage needs to be the voltage from gate to cathode.

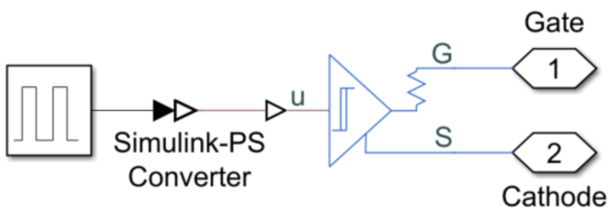

Fig. 12: The content of the subcircuits of Figure 11 driving the gate of the thyristors

With four commutation circuits in the full bridge some dead time had to be added, to ensure all thyristors turn off when they are supposed to. The output voltage and current are shown in Figure 13. The peak at the end of the conduction time of each thyristor is there as discussed with the single class D circuit. The voltage level is (-)84.1V at the load when the pairs conduct. The voltage drop is now approximately doubled compared to the single class D commutation circuit. The current is 16.8A, which is a fifth of the voltage, because of the load resistance of 5Ω.

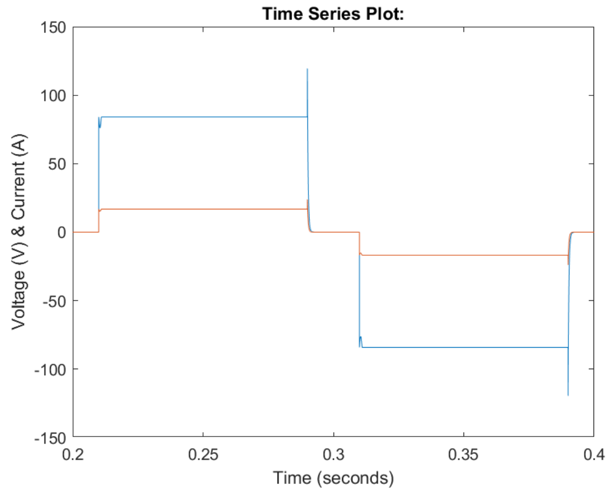

Fig. 13: Voltage (blue) and current (orange) waveform of the load

2) IGBT inverter

The IGBT is the main component in this inverter. It basically combines the bipolar transistor and the MOSFET; the collector and emitter from the bipolar transistor and the gate of the MOSFET. This component is, like the thyristor, suitable for high voltage and current applications. Unlike the thyristor, the IGBT turns off when the gate voltage is removed. This is one of the reasons why the IGBT has a higher switching frequency.

The IGBT is used in the same H-bridge configuration as the thyristor. Again two pairs alternately conduct, forcing the current to go through the resistor. Since the IGBT can handle a higher switching frequency, the gates are driven with a pulse width modulation (PWM) signal, as this is in the end better in the filtering process, compared with a square wave.

a) Simulation of IGBT inverter

In Figure 14, the IGBT inverter can be seen. The PWM subcircuits are shown in Figure 15.

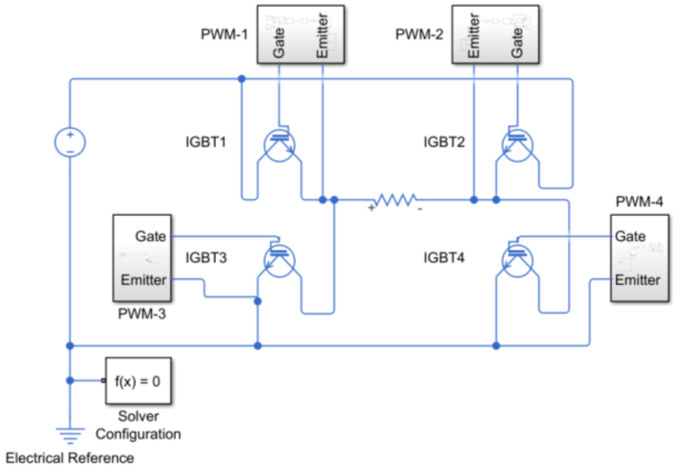

Fig. 14: The IGBT inverter in Simulink

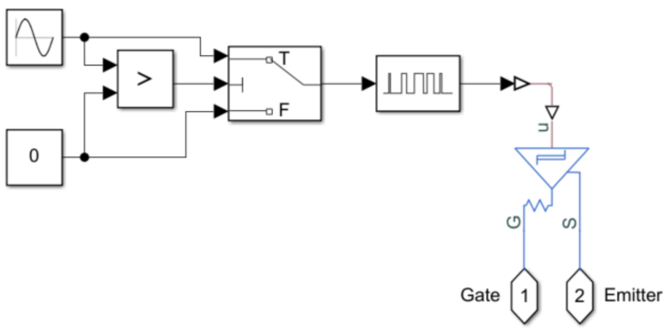

Fig. 15: The PWM subcircuits from Figure 14

The switch combined with the relational operator are there to make sure that every IGBT gets a PWM signal for half a period, with positive gate pulses, with a voltage greater than the threshold voltage. The gate driver is also connected to the emitter, since the threshold voltage concerns the voltage between the gate and emitter. The PWM frequency is set to 5kHz.

The load voltage and current are shown in Figure 16. The output voltage reaches from 0 to 100V and 0 to -100V for the negative half in the pulses of the modulation The load resistance is assumed to be equal to 5Ω. Therefore the current pulses reach from 0 to 20A. To supply to the grid, a sine wave has to be made from the PWM signal. A filter should be applied to obtain this sine wave. The filtering in not done in this thesis, as it is not the goal of this research.

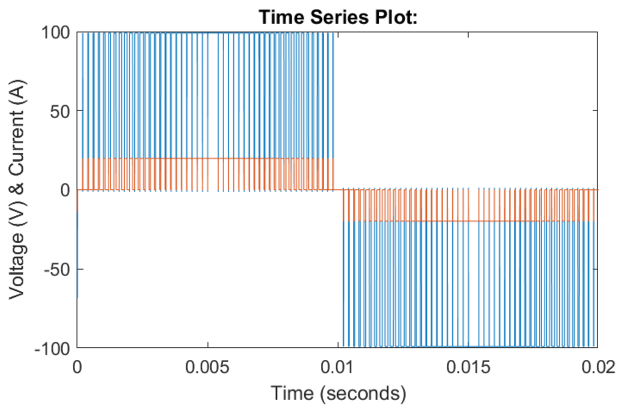

Fig. 16: Load voltage (blue) and current (orange) of the IGBT inverter

3) *Thyristor vs. IGBT inverter*

The thyristor inverter is more complex, because of the additional commutation circuitry. In the contrary, the IGBT inverter is more simple, as it turns off without a gate pulse, although there are still some calculations needed to create the PWM signal. Another significant difference is the power rating. IGBT's can handle less voltage and current than thyristors, as the maximum ratings of IGBT's are 3kV and 1kA compared to 7kV+ and 2.2kA+ for thyristors (19). However, as mentioned earlier the switching frequency of IGBT is between 1k-100kHz, compared to a maximum of 100Hz for thyristors (19). This makes IGBT based inverters more efficient, as PWM can be used and therefore less energy has to be wasted in the filtering process.On the other hand, thyristor inverters are generally less expensive than IGBT inverters (4) (20).
So, thyristor inverters can handle a higher power and are cheaper, but their efficiency is lower and they are more complex. IGBT inverter are more expensive, with a lower power rating, but are more efficient and less complex.

C. *Energy analysis*

To measure the impact of the discussed energy storages and the reversible substation, an energy analysis was conducted. This was done for two train stations: one busy one, Utrecht Centraal, and one more calm one, Deventer. One hour was taken on the 11th of July 2024, from 12:00 to 12:59 (21) (22). The amount of trains arriving and leaving at every minute was noted. At Utrecht Centraal station, there were 53 arriving trains and 55 leaving, at Deventer station there were 14 arriving and 14 leaving trains as well. A figure of the mapping of this is in Appendix A.

The power profile of the arriving and leaving trains is shown in Figure 17. In the Netherlands the most common trains have maximum power ratings reaching from 1260kW to 2412kW (23) (24). Therefore the maximum is assumed to be 1500kW for this analysis. The total braking energy of one train is around 38% of the traction energy of one train, this is also a percentage that is measured in real experiments (25).

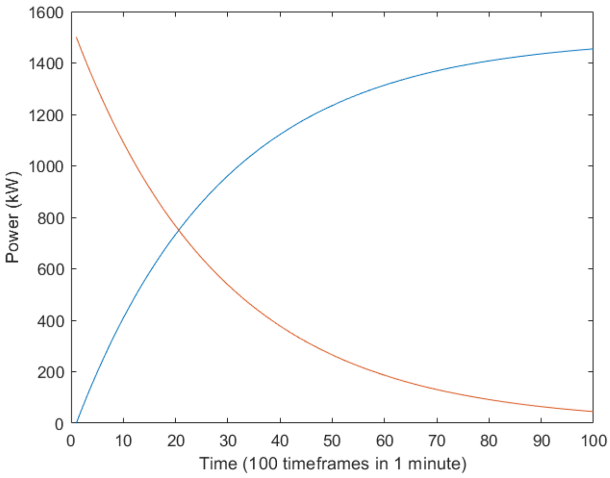

Fig. 17: The power arriving (orange) and leaving (blue) trains deliver

These braking and traction curves are now summed each time step within the hour. From this power curves the energy in kWh is calculated by multiplying the power at that instant with $1/6000$, as there are 100 timesteps in one minute of the hour. The energy and power flows are monitored so that it is known where the brake energy and power go, and where the traction energy and power is coming from. To avoid complexity it is assumed that the catenary is not able to store any energy.

The simulation is performed in a Matlab script. There are two main cases defined. If the total brake energy is higher than the required traction energy, the excess energy is stored or converted (to the AC grid). If the traction energy is higher than the braking energy, extra energy is obtained from the supply. Within these two cases there are also restrictions placed, such that the power always stays under the maximum allowed power of the systems, and the energy that is charged and discharged to and from the storage stays within the energy capacity boundaries. An overview of the maximum ratings and efficiencies is shown in Table III. The decision of the maximum ratings was based on real examples that already exist in the world, listed in (3). For the batteries most of the systems are several hundred kWh in energy and around 2 MW power. Therefore a system of 400 kWh and 2 MW was chosen. Most flywheel systems that are operating have an energy capacity below 10kWh. The one with a capacity of 8.2kWh has the highest power rating of 2MW, so these ratings are chosen. The supercapacitor storages have generally around 10kWh energy capacity. There is one system that scores best and was chosen for this simulation: 16.2kWh and 4.5MW. This system has a efficiency of 94%. The power ratings of the IGBT inverters are mostly around 1.5MW with an efficiency of 98%. The thyristor power rating are somewhat higher, i.e. 2.5MW, although with a slightly lower efficiency of 96%. The efficiencies of the batteries and flywheels were not mentioned in this article, and are therefore chosen based on (1), as in Table I.

The maximum energy for the thyristor and IGBT inverter is assumed to be infinity, as a lot of energy can be disposed in the grid. The efficiency is multiplied with the brake energy to account for those losses. Another assumption is that the energy storages initially are empty.

The simulation are thus executed for Utrecht Centraal and Deventer station, with the different recovery systems. It is executed looking at the energy streams and additionally, looking at the power usage. These simulations are done for the efficiencies listed in Table III, but also for a less ideal case, where the efficiencies are multiplied with 0.9.

IV. Results

The energy flows are displayed as a part of the total energy in the system and displayed in donut graphs. Please note that the time resolution is only one hour, for all the results.

The donut graph of the energy at Utrecht Centraal while using a battery is shown in Figure 18. It can be seen how the traction energy is composed and what part of the energy is wasted. The battery is responsible for 22% of supplying the traction energy, 11% is directly used as a train is arriving at the same time one is leaving, 65% is still needed from the power source as the braking energy can't account for all the traction energy. Then there is 2% waste, consisting of loss from the inefficiency. The state of charge of the battery is 31.7 kWh at most, which is equal to 8% of the full energy capacity.

Recovery system	**Efficiency (%)**	**Max Power (kW)**	**Max Energy (kWh)**
Battery	95	2000	400
Flywheel	92.5	2000	8.2
Supercapacitors	94	4500	16.1
Thyristor	96	2500	∞
IGBT	98	1500	∞

TABLE III: Efficiencies, Maximum Power and Energy of Components

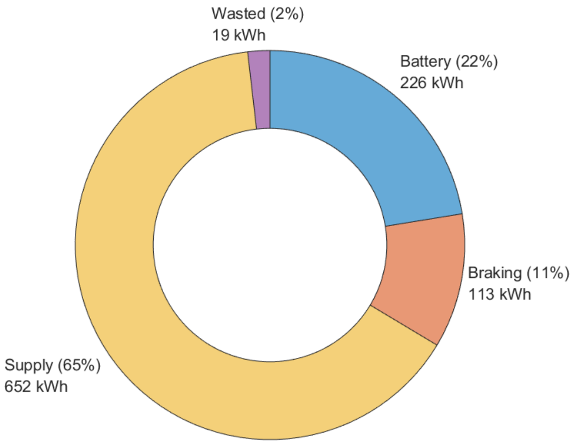

Fig. 18: Donut graph of the energy flows at Utrecht Centraal using a battery

In Figure 19 the donut graph is shown for the same conditions as Figure 18, only now at Deventer station, with a lower traffic density. Compared to Utrecht Centraal, a large part of the directly used braking energy flow has moved to the battery. The additional supplied energy and the waste are the same portion of the total as at Utrecht Centraal, but of course with a smaller absolute amount. Now the maximum state of charge that is reached is 14.7 kWh.

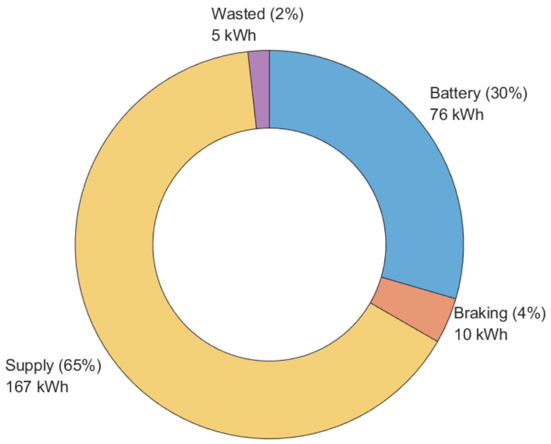

Fig. 19: Donut graph of the energy flows at Deventer using a battery

The IGBT and thyristor donut graphs are very similar to the one of the battery. As they both are assumed to have a energy capacity of infinity, and the battery never reaches its maximum capacity.

Note that the energy recovered through the reversible substation is not captured like in the energy storages, but they are displayed in the same manner as the energy storages in the donut graphs. Only now that IGBT/thyristor slice in the donut graph represent the part that was originally recovered by the reversible station. However, in real life it is just supplied from the rectifier as the other supply segment in the graph.

A small difference is that the IGBT and thyristor inverter have a slightly higher efficiency, leading to a couple kWh's more recovered energy and less waste. Another difference that only is seen at Utrecht Centraal, is that the thyristor inverter has a slightly higher (2%) recovered amount of energy than both the battery and the IGBT inverter.

In Figure 20 the total amount of power, that consist of the different sources and the wasted power, can be seen when a thyristor inverter is used. Comparing this with the same conditions, in the case of an IGBT inverter, shown in Figure 21, the thyristor inverter can provide 4% more power than the IGBT, 2% more than the battery (this data is displayed in Appendix A). These couple percentages higher are divided over the storage/reversible substation segment and the (direct) braking segment.

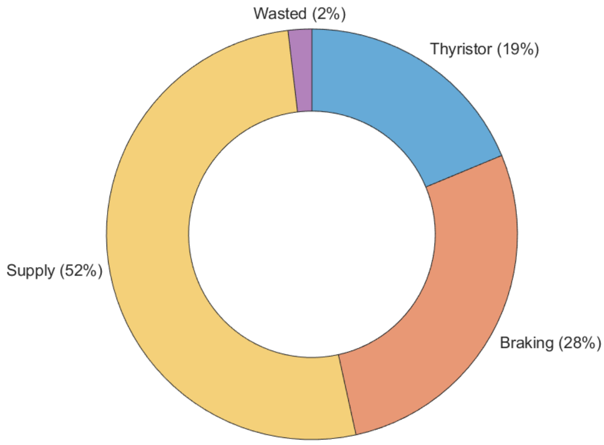

Fig. 20: Donut graph of the total power at Utrecht Centraal using a thyristor inverter

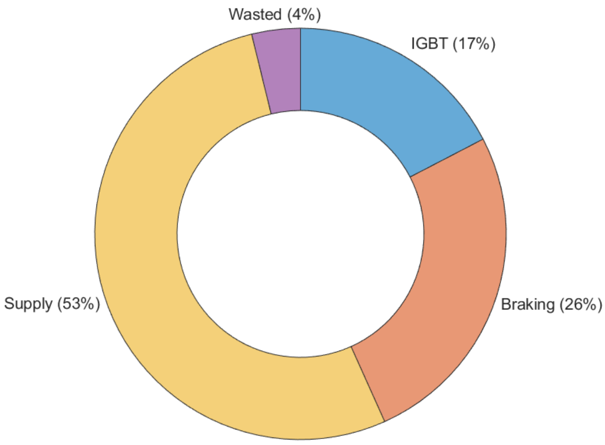

Fig. 21: Donut graph of the total power at Utrecht Centraal using a IGBT inverter

The energy donut graph of the flywheel used at Utrecht Centraal is shown in Figure 22. A lot more energy is wasted when using a flywheel. The energy stored and directly used are significantly less than in the energy donut graphs we saw before. The same difference in behaviour between Utrecht Centraal as before is seen with the usage of flywheel; An increase in the use of the energy storage and a decrease in the directly used braking energy. The values for Deventer are: Flywheel (20%) 57 kWh, Braking (3%) 10 kWh, Supply (67%) 186 kWh and wasted (9%) 26 kWh. So there is also a relative decrease in wasted energy.

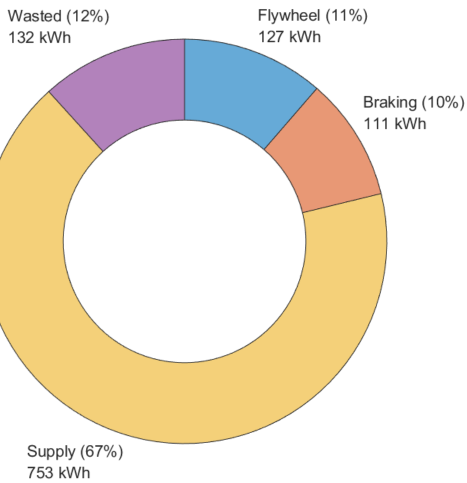

Fig. 22: Donut graph of the energy flows at Utrecht Centraal using a flywheel

In Figure 23 the energy donut graph of Utrecht Centraal is shown, with the use of supercapacitors as energy storage. It can be seen that there is around 7% waste. Comparing this to the battery from Figure 18, this greater amount of wasted energy is mostly energy that is stored in the case of a battery.

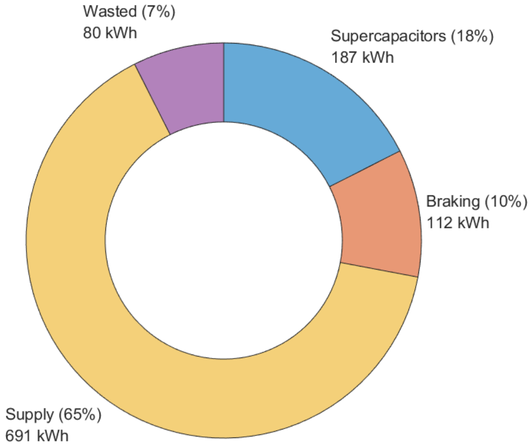

Fig. 23: Donut graph of the energy flows at Utrecht Centraal using supercapacitors

For the utilization of supercapacitors at Deventer station, the energy graph ends up to have the same rounded percentages as the battery in Deventer, shown in Figure 19.

The power results for the supercapacitors, shown in Figure 24, have little wasted power, only 2%. The supercapacitors account for 15% of the power consumption, 28% comes directly from braking energy and the remaining 56% is delivered by the normal supply.

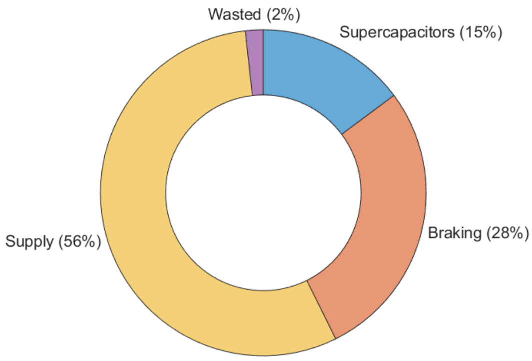

Fig. 24: Donut graph of the total power at Utrecht Centraal using supercapacitors

The simulations were also done for a less ideal case, where the efficiencies were multiplied by 0.9. In Figure 25 the energy donut graph for Utrecht Centraal is shown. Comparing this graph with Figure 18, the wasted energy increased. The energy from the battery decreased and the similarly the directly used braking did. To compensate for the bigger losses, the energy from the supply increased. This behaviour was the same for the other recovery systems.

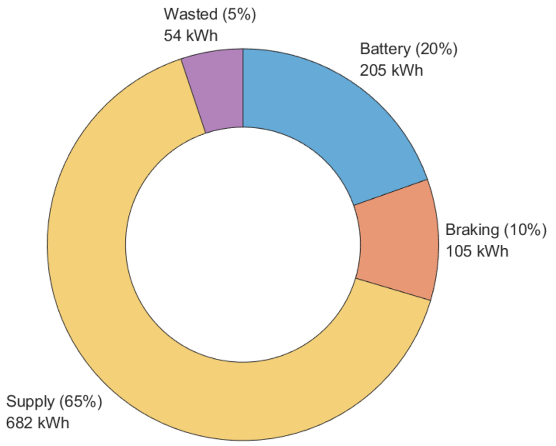

Fig. 25: Donut graph of the energy flows at Utrecht Centraal using a battery with lowered efficiencies

V. Discussion

There a couple of differences in the results between the stations Utrecht Centraal and Deventer. The higher traffic density, over 100 trains, at Utrecht Centraal, compared to almost 30, at Deventer, leads to a higher braking and traction energy. As there a more trains, the chance of a train leaving while another train is arriving, is a lot bigger. This makes the percentage of the directly used braking energy bigger at Utrecht Centraal. Conversely, the percentage used by the storage is significantly bigger at Deventer. However, the energy that is temporarily stored is in absolute ratings still higher at Utrecht Centraal

Another remarkable result is that at Utrecht Centraal, in the end the thyristor inverter recovers more energy than the IGBT inverter, despite of having a lower efficiency. This is caused by the higher power capability of the thyristor inverter. At Utrecht there are more trains arriving at the same time more often than at Deventer. This gives the thyristor inverter an advantage at high traffic density stations, since it can handle the higher braking power of the trains better.

The flywheel is the storage system which has the lowest energy capacity. This leads to it being the result with the highest waste, because when multiple trains arrive the storage is full to quick, leaving the rest of the braking energy unusable.

Supercapacitors also have a relative low energy capacity, which is visible in Figure 23 as there is a waste of 7%. However, for Deventer the supercapacitors are sufficient, as they perform equally to the battery. The supercapacitors have the highest power rating of all compared systems. It is equal to the thyristor in the power bar charts, as it only has 2% power waste. The reason that is is not higher is because of the efficiency of 94%, which causes more power loss in that way than the thyristor.

In general, the energy analysis is strongly dependent on the assumptions of the maximum ratings. The difference between the power ratings is smaller than difference between the energy ratings. This causes that the difference in waste in the power bar charts is not that versatile. Especially the assumed energy capacities of the flywheel and supercapacitors stand out, if in reality they would be higher, they would peform better.

VI.Conclusion

To conclude, for a station with a high traffic density, the thyristor inverter seems to recover the most energy, but the IGBT inverter and battery are only slightly less efficient. The flywheel and supercapacitors are less suitable for a heavy traffic stations, as their energy capacity is very limited. For a station with low traffic density, the decision is less limited to maximum ratings, and therefore supercapacitors work also efficient there.

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APPENDIX

A. AI statement

During the work of this thesis the chatbot ChatGPT was used for a couple purposes:

- To obtain the right formulation of a sentence, after a sentence was put in. This sentence was afterwards checked such that it did not add new information, but just used the proper words to efficiently express what the author wanted to say.
- While building the simulation code was put in that did not work the way the author would like it to work, or did not work at all due to errors. The AI was then asked why this did not work, and what were possible solutions to make it work in the right way. The solutions were sometimes adopted, but never copied without knowing how the code works.
- While writing the report, the AI helped making the tables with nice aesthetics, with consistency, such that every table has the same lay-out.

B. Train mapping

In Figure 26 it can be seen how the train schedule was mapped to obtain the net arriving and leaving trains. This are only the first 20 minutes, but it was done the same way for the rest of the time of the hour, and also for the station of Deventer.

11-6-2024	Time	Arrival	Departure																		
Rail	12:00	12:01	12:02	12:03	12:04	12:05	12:06	12:07	12:08	12:09	12:10	12:11	12:12	12:13	12:14	12:15	12:16	12:17	12:18	12:19	12:20
1						1							-1						1		
2																					
3								-1													
4										1											
5								1		-1											1
6												1									
7						1							-1			1				-1	
8																			-1		
9														-1							
10																					
11				-1														1			
12			1					-1					1							-1	
13																					
14																	1		-1		
15												1			-1						
16																					
17																					
18		1		-1								1			-1				1		
19							1					-1									
20									1						-1				1		
21							1					-1				1					
Trains arriving	0	1	1	0	0	2	2	1	1	1	0	3	1	0	0	2	1	1	3	0	1
Trains leaving	0	0	0	2	0	0	0	2	0	1	0	2	2	1	3	0	0	0	2	2	0
Net	0	1	1	-2	0	2	2	-1	1	0	0	1	-1	-1	-3	2	1	1	1	-2	1
Total arriving	53																				
Total leaving	55																				

Fig. 26: The first 20 minutes of the mapping of the trains at Utrecht Centraal

C. Energy analysis data

In Table IV the relative and absolute values are displayed of the energy analysis of all recovery systems for both Utrecht Centraal and Deventer. As an example, an empty donut graph is depicted in Figure 27 to illustrate how this values would be displayed in the donut graph.

In Table V the data for the power distribution graph is shown for both the stations Utrecht Centraal and Deventer.

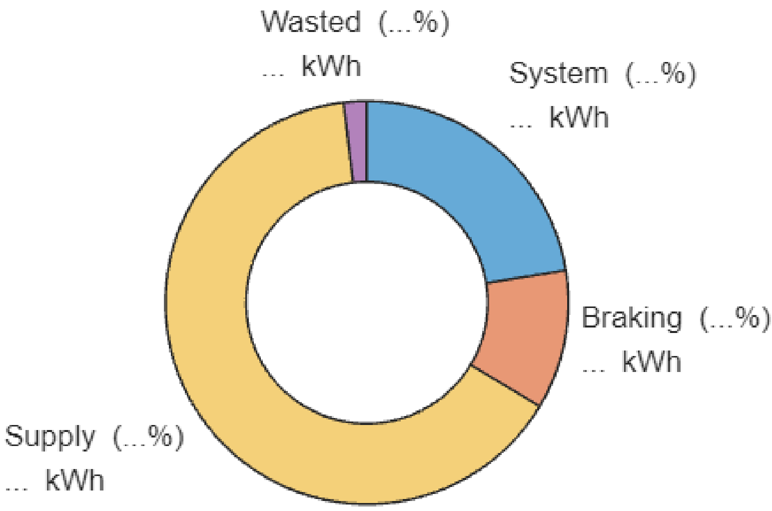

Fig. 27: Example donut where the percentages of Table IV can be visualised in

Station	Recovery system	System (%)	System (kWh)	Braking (%)	Braking (kWh)	Supply (%)	Supply (kWh)	Wasted (%)	Wasted (kWh)
Utrecht	Battery	22	226	11	113	65	652	2	19
Utrecht	Flywheel	11	127	10	111	67	753	12	132
Utrecht	Supercapacitors	18	187	10	112	65	691	7	80
Utrecht	Thyristor inverter	24	237	11	114	64	640	1	15
Utrecht	IGBT inverter	22	219	12	115	66	657	1	7
Deventer	Battery	30	76	4	10	65	167	2	5
Deventer	Flywheel	20	57	3	10	67	186	9	26
Deventer	Supercapacitors	29	76	4	10	65	167	2	5
Deventer	Thyristor inverter	30	77	4	10	65	165	1	4
Deventer	IGBT inverter	30	77	4	10	65	165	1	2

TABLE IV: Energy donut graph data for the stations Utrecht Centraal and Deventer

Station	Recovery system	System (%)	Braking (%)	Supply (%)	Wasted (%)
Utrecht	Battery	18	27	52	3
Utrecht	Flywheel	10	26	60	4
Utrecht	Supercapacitors	15	28	56	2
Utrecht	Thyristor inverter	19	28	52	2
Utrecht	IGBT inverter	17	26	53	4
Deventer	Battery	23	26	50	2
Deventer	Flywheel	17	25	56	2
Deventer	Supercapacitors	23	26	50	2
Deventer	Thyristor inverter	23	26	50	1
Deventer	IGBT inverter	23	26	50	1

TABLE V: Power distribution of all recovery systems for the stations Utrecht Centraal and Deventer