Hybrid Energy Storage System for Peak Shaving Application in Industries

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Abstract: Peak shaving of the electric power consumption has certain advantages for industries. For the provision of services like peak shaving, the integration of energy storage is the common option. Beside systems that use only one type of energy storage, hybrid systems combine the advantages of different energy storages to improve the overall service. In this work a combined system of a flywheel and a lithium-ion battery is suggested. The flywheel plays the role of the short-term energy storage unit, whereas the battery the role of the long term unit. The characteristic properties of both the storages are described. The power dispatch strategy between the units is implemented using a frequency dependent allocation and a short example is given. The surplus value that the flywheel adds to the hybrid system, arises from the reduced battery aging in comparison to a stand-alone battery system.

Keywords: Peak shaving, Energy storage, Kinetic energy, Flywheel, Lithium-ion battery

1 Introduction

The integration of renewable energies and the increasing market share of electric mobility set new challenges for the stability of the electricity grid. Industries were for long time considered as pure electricity consumers that could not actively contribute to the grid stability [1]. However, the integration of small generation units and the application of energy storage make the industries capable of accomplishing this goal [2]. Industries tend to create high power peaks during operation, for example due to the startup of machinery. Power peaks are inconvenient for the electricity network, since they impair the power quality as well as the grid stability. In order to cope with this issue, the energy operators introduce the so-called power price. The power price defines what an industry should pay for its maximum power demand within a fixed period. The power price should be paid additionally to the energy price. The industries can initiatively improve their electricity costs by reducing their power peaks, i.e. by applying peak shaving. Energy storage is a flexible option for industries to implement peak shaving, since no additional scheduling for their production and generation is needed. As long as the nominal capacity and power of the energy storage is appropriately dimensioned, it can compensate for the power peaks, keeping the industry around a predefined power limit [3].

In this work, a Hybrid Energy Storage System (HESS) capable to enable peak shaving application for small industries is presented. The HESS combines the advantages of a lithium-ion battery and a flywheel. The lithium-ion battery features a high energy density, while the flywheel features a high power density. Using the flywheel for the high and the battery for low dynamic part of the power peaks, among others, a reduced aging of the battery is achieved.

2 Description of the hybrid energy storage

The HESS developed and built by the Institute for Mechatronic Systems of TU Darmstadt within the framework of the “PHI-Factory” project is depicted in Figure 1. The main goal of PHI-Factory is to investigate whether production plants can contribute to the grid stability by means of managing their power flexibility [2]. Power flexibility in production plants could mean to be prepared to switch off consumers during peak periods, the so-called demand side management. Beside demand side management, production plants can play both the role of producer and consumer through the integration of generation and storage units. In this way contribution to the grid stability at peak periods is still possible, without the need to shut off consumers. A photovoltaic system together with combined heat and power engines are the generator units in PHI-Factory. Additionally, the HESS consisting of a flywheel and a lithium-ion battery plays the role of the storage unit.

The flywheel and the battery are connected to a common DC-Link, which is integrated to the mains though a grid-tie inverter. The flywheel is driven through a motor inverter, which is configured in speed control and follows acceleration and deceleration profiles. Similarly, a DC-DC-Converter is used to charge or discharge the battery. The power dispatch strategy for the HESS is implemented into a Programmable Logic Controller (PLC). Having access to power measurement devices, the PLC calculates the needed power for peak shaving and delivers the set values to the motor inverter of the flywheel and the DC-DC-converter of the battery.

Figure 1 Hybrid Energy Storage System 1: Flywheel, 2: Lithium-ion battery

2.1 Flywheel Description

Within the framework of a predecessor project named “ETA-Fabrik”, the Kinetic Energy Storage System (KESS) ETA290 is designed and built by the Institute for Mechatronic Systems as described in [4]. The main characteristics of ETA290 can be seen in Table 1.

Table 1 Main Characteristics of the KESS ETA290

Description	Value	Unit
Maximum power	120	kW
Capacity	1.4	kWh
Mass of rotor	150	kg
Outer diameter of rotor	430	mm
Inner diameter of rotor	290	mm
Length of rotor	600	mm
Usable speed range	7,500 – 15,000	rpm

The innovation of the flywheel lies in the highly integrated rotor design, which can be seen in Figure 2. The outer rotor design leads to a high energy density, since the active rotor components rotate with a high radius leading to an increased moment of inertia [4]. Fiber-reinforced plastic (FRP) is the material used on the outer surface of the hollow cylinder rotor, whereas metallic segmented parts are used on the inner surface. The use of FRP for flywheels has become a standard for high speed flywheels, since it can withstand higher tangential stress in comparison to metals. The metallic parts of the rotor are segmented and mounted in such a way that the tangential stresses are reduced.

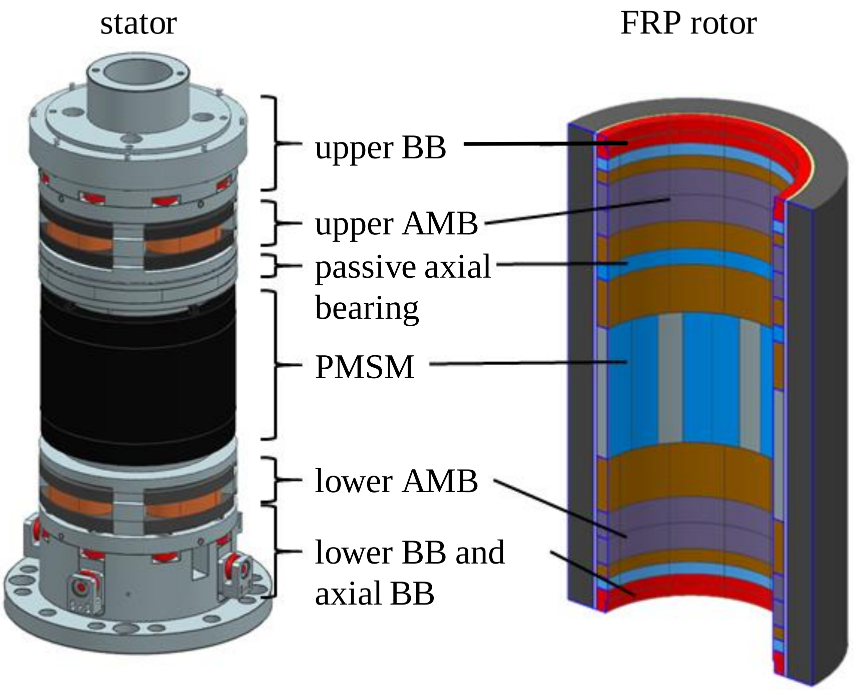


Figure 2 CAD model of the flywheel. Left: Stationary part, Right: Rotating part [5]

In order to operate a flywheel at high speeds, low friction losses are of significant importance. For this reason, the KESS is enclosed in a containment that is evacuated using a turbomolecular vacuum pump. Active magnetic bearings (AMB) are used for the radial suspension of the rotor, while the rotor is levitated axially by a passive magnetic bearing. Using a passive magnetic bearing, no additional energy is needed to support the static weight of the rotor [6]. In case of a magnetic bearings failure or any other type of failure that leads to loss of the rotor suspension, backup bearings (BB) are implemented on the stator to support a safe rotor run down.

The flywheel should be often kept spinning on a constant speed in order to be ready to deliver a deceleration profile. Therefore, low motor power losses are of significant importance. A permanent magnet synchronous machine (PMSM) is selected as the flywheel drive, mainly because of its high conversion efficiency and low losses in the rotor. Keeping the losses low in the rotor is important, since for a levitated rotor in vacuum heat transfer is only possible by radiation. The power losses of the PMSM were investigated in [7].

2.2 Battery Description

The Battery Energy Storage System (BESS) comprises four identical and parallel-connected battery subsystems. The properties of each subsystem can be seen in Table 2. The energetic capacity of each system amounts to 30.6 kWh, so that the complete BESS has an energetic capacity of 122.4 kWh. The nominal power of the four modules is 308 kW, which is equivalent to a charging/discharging rate of 2C. However, the BESS is dimensioned using the nominal power of the DC-DC-Converter, which is 120 kW. In this way, the battery cannot be charged faster than a rate of 1C. The lithium-ion-cells have the shape of the so-called Coffee-Bag-Cells, which is distinguished for its low thickness of only 12 mm. The lithium-ion-cell type is Nickel-Mangan-Cobalt (NMC).

Table 2 Properties of the battery module: AKASOL AKASYSTEM 15 AKM

Description	**Value**	**Unit**
Nominal Power	77	kW
Capacity	46	Ah
Energetic Capacity	30.6	kWh
Maximum Voltage	756	V
Minimum Voltage	486	V
Mass	372	kg

The battery is water cooled, so that an average cell temperature of 25 °C can be achieved even in case of high ambient temperatures. The BESS is controlled through an Electronic Control Unit (ECU), which has the task to monitor the temperature, current and voltage of each battery module and disconnect it in case of a failure.

3 Simulation of Peak Shaving

Although the HESS is already built and the provision of peak shaving has been proven, it is more convenient to show the capabilities and behavior of the system through a simulation. In that way a power profile that allows a high utilization of the system can be applied and a long-time simulation to investigate the battery aging becomes possible.

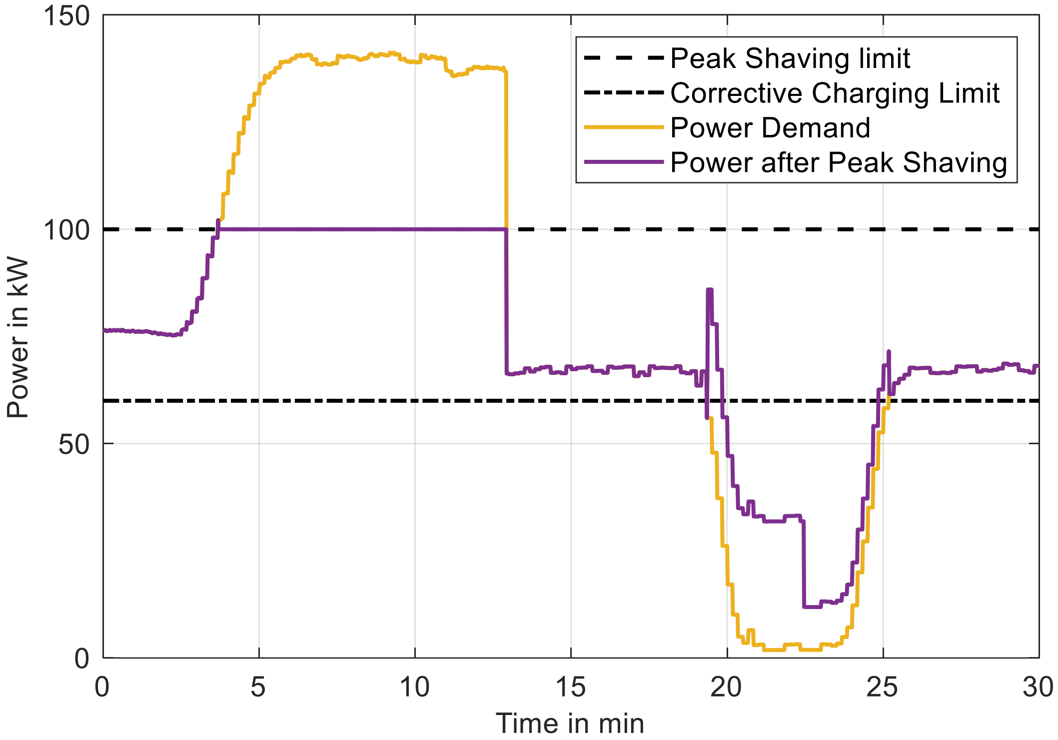
Energy management strategies of hybrid energy storages have gained increasing interest over the last years, as the integration of renewable energy to the grid increased. In [8, 9] an overview of energy management concepts for the control and energy management of hybrid energy storages is given. A frequency decoupling control strategy for a HESS consisting of a flywheel and a lithium-ion battery aiming to support a residential microgrid has been already explored in [10]. In the same work a method to dimension the power and capacity of both the battery and the flywheel as well as an economic assessment is discussed.

Because of its simplicity and already proven good performance, a power dispatch strategy using a frequency dependent allocation is also applied for the peak shaving application. Using the frequency dependent allocation, the BESS compensates the low dynamic part, while the KESS reacts to the remaining high dynamic part of the power peaks.

In order to give a better insight to the power dispatch strategy, a simulation of power peak compensation through the HESS is presented in Figure 3. The power demand was generated using a randomized power profile. The power profile combines consumers like machine tools, cleaning machines and ovens, which are typically used in an industrial production plant. The peak shaving limit was freely set to 100 kW and the corrective charging limit to 60 kW. That is, if the power demand rises over 100 kW the energy storages will compensate for the additional power needed. Furthermore, when the power demand falls under 60 kW the energy storages can be recharged. For a power demand between 60 kW and 100 kW, the energy storages are used neither for peak shaving nor for corrective charging.

As can be observed in Figure 3, when the peak is over 100 kW for the first time at around 3.5 min, the KESS instantly compensates the power, while the BESS slowly starts supplying the remaining power. Shortly before 8 min the capacity of the KESS is exhausted and the BESS takes over the remaining peak power. When the power consumptions fall under the predefined limit for corrective charging, which happens at around 19 min, the energy storage units are charged. The KESS is charged with 20 kW, while the BESS with 10 kW.

Apparently, the capacity of the KESS is not high enough to stay active for the complete peak duration of 10 min. A solution to this problematic would be to adjust the frequency allocation, so that the flywheel is loaded smoother. However, this would on the same time increase the intensity that the battery is loaded. Furthermore, it would not have any effect to the energy flow through the battery. Therefore, a better solution would be to increase the energetic capacity of the flywheel, so that the latter covers a larger proportion of the peak energy.



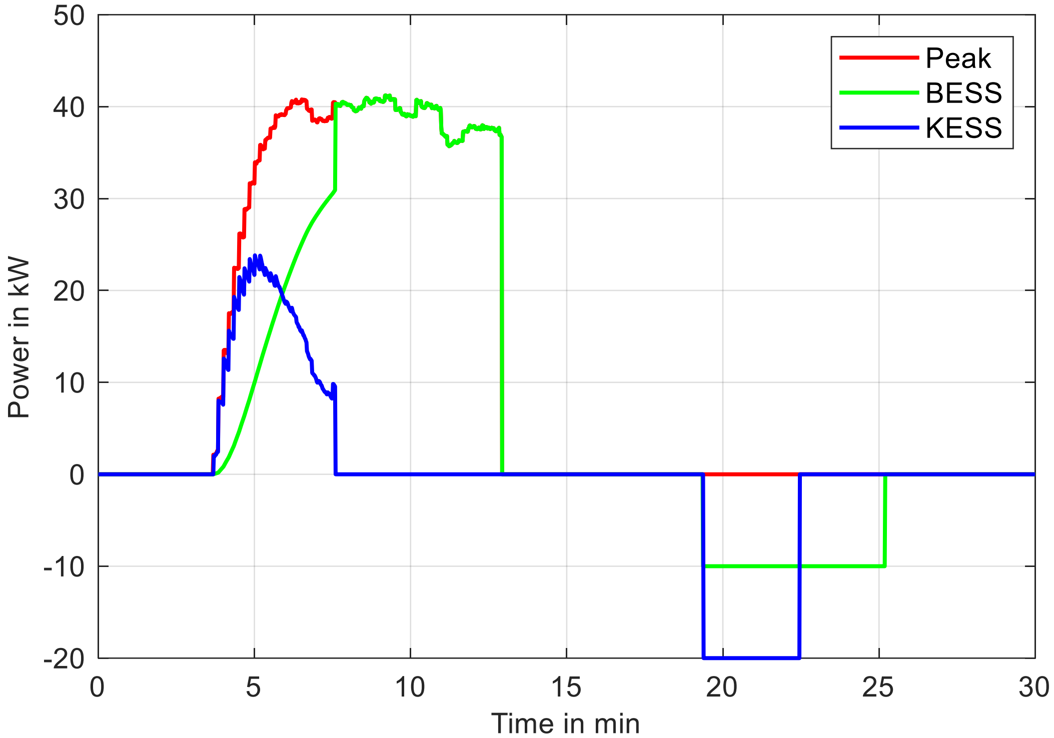


Figure 3 Application of peak shaving on a randomized industrial power profile using a hybrid energy storage system

4 Battery aging over the years

In order to evaluate the additional value that the flywheel offers to the hybrid system a simulation for several years of peak shaving provision was conducted. The HESS provided peak shaving eight hours per day for every weekday, which means 260 days per year. The battery aging was calculated separating the cyclic from the calendric aging, an approach that is commonly used [11, 12]. The model for the cyclic and calendric aging follows the equations used in [12], adjusted to the lithium-ion cells used in the system at hand. A rainflow counting algorithm that is often used for fatigue analysis, is applied to count the charge flowing through the cells and divide it to separate ranges [13]. The range classification of the rainflow algorithm directly corresponds to the Depth of Discharge (DoD) of the lithium-ion cells. Using the rainflow algorithm to count the charge flow and the adjusted aging model the capacity deprivation of the battery can be estimated.

The State of Health (SoH) of the battery corresponds in our case directly to the capacity deprivation of the lithium-ion-cells. This approach is common in the literature, and is for example applied in [14]. The influencing parameters taken into consideration in the battery aging model are: the State of Charge (SoC), the Depth of Discharge, the charging/discharging rate and the cell temperature. A high temperature or charging/discharging rate accelerates the aging of the lithium-ion cells. Temperatures over 40 °C can deteriorate the battery lifetime severely. For this reason, lithium-ion cells are often actively cooled to a lower temperature. Deep discharging of the battery as well as charging close to the maximum SoC also deteriorates the battery lifetime. It is though advantageous to operate the battery to a SoC range close to 50 %. For the same reason a DoD over 80 % should be avoided.

In Figure 4 the aging of the lithium-ion-cells for a 15-year-simulation is presented. The battery is used only for peak shaving and therefore the SoC is kept at a high level between 70 % and 90 %, which at the same time means a low DoD of 20 %. The charging/discharging rate of the battery is also kept for most of the cycles relatively low at about 40 %. It is assumed that the cell temperature is held through active cooling at about 25 °C. Under these apparently advantageous circumstances a moderate to low aging of the battery is expected. It can be seen that after 11.6 years the SoH of the cells reaches 80 %, which typically means for most of the applications the battery End of Life (EoL). At this point the calendrical aging is responsible for 33 % of the total aging and the cyclic aging for the remaining 67 %.

Two additional simulations for the 15-year provision of peak shaving were conducted. In the first simulation a KESS with 1 kWh additional energetic capacity was used. For the second simulation the BESS should cover the peaks alone without the help of the KESS. Thus, a different cycling aging characteristic is expected. In Figure 5 a comparison of the total aging of the initial HESS, the HESS with an increased capacity KESS and the stand-alone BESS can be observed. As already shown, the lithium-ion-cells of the HESS will exhaust their designated lifetime after 11.6 years, whereas the cells of the stand-alone BESS will reach 80 % SoH already at 10 years. The lithium-ion-cells for the HESS with an increased capacity KESS will reach EoL at 12.3 years. Summarizing, the use of the KESS offers a 16 % longer lifetime to the lithium-ion-cells. Using a KESS with 1 kWh more capacity leads to 23 % improved battery lifetime.

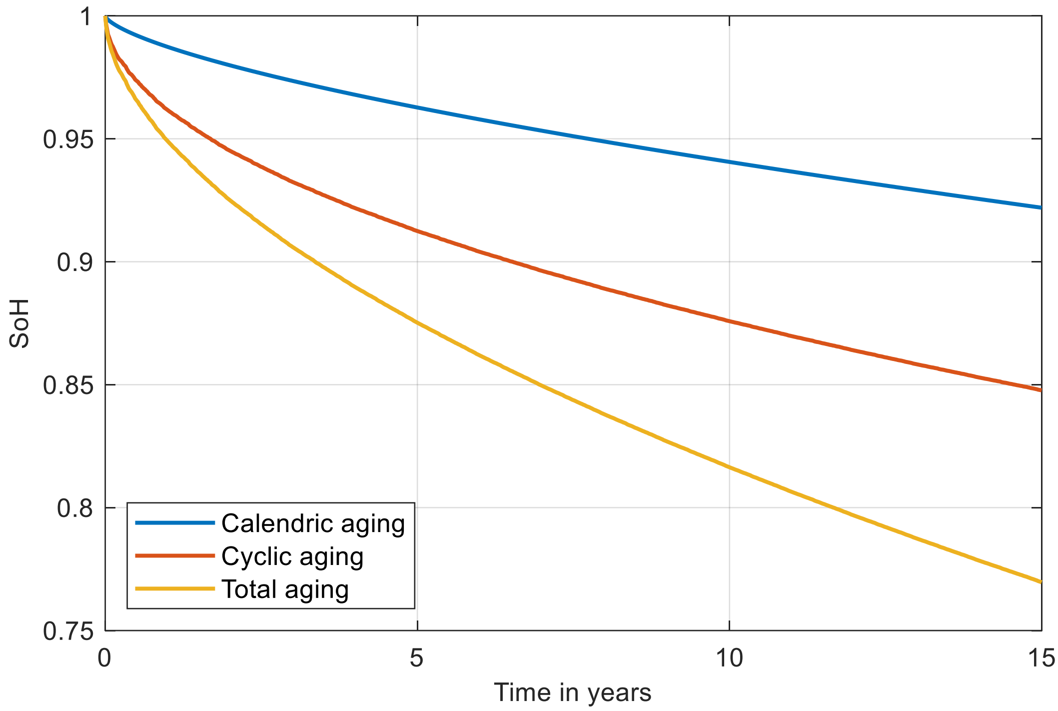


Figure 4 Cyclic, calendric and total aging of the lithium-ion battery cells of the initial hybrid energy storage used for the 15-year provision of peak shaving

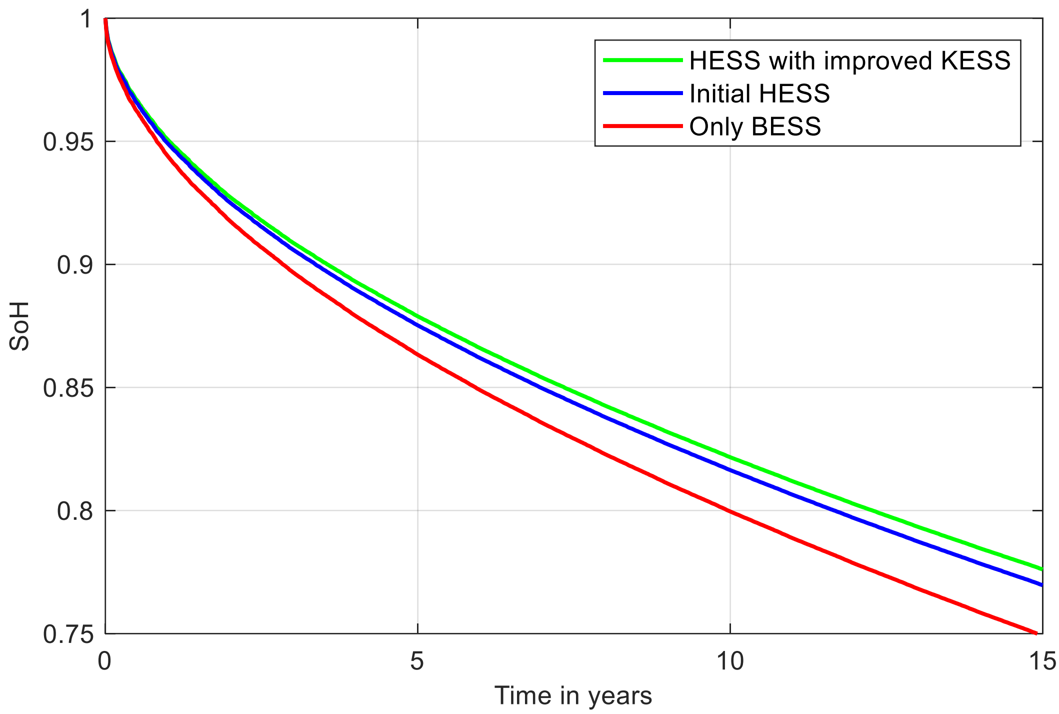


Figure 5 Comparison of total battery aging for the initial hybrid energy storage, a hybrid energy storage with improved flywheel capacity and a stand-alone battery for the 15-year provision of peak-shaving

5 Conclusion

Industries can reduce their electricity cost and improve their power quality applying peak shaving. Energy storage is a convenient way to apply peak shaving without disrupting the industrial production plans. Beside stand-alone energy storage solutions, hybrid energy storage is an interesting alternative. The presented HESS consisting of a flywheel and a lithium-ion battery enables peak shaving and improves at the same time the battery lifetime in comparison to a stand-alone battery. The power dispatch between the energy storage units is accomplished through a frequency dependent allocation, which targets to use the flywheel for the high dynamic power profile and the battery for the low dynamic one. A simulation showed that the relatively low energetic capacity of the KESS leads to an increased commitment of the battery, as the KESS often reaches its capacity limits. Therefore, an increased energetic capacity of the KESS is desirable, as this will directly lead to an increased battery lifetime.

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