A bi-powered electric flywheel scooter

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***Abstract*—Mobility is omnipresent in the daily routine of the people. Every day people use different means of transportation. Even in urban area the density is quite high. Electric vehicles can make a contribution to decrease the stress through noise or air pollution for the citizens. However they have the same challenge to drive at jammed streets or parking. A solution is to switch to electric two-wheelers because they small, maneuverable and dynamically. In the urban area the launching and breaking parts in the driving situations for every vehicle are high. In these parts the demand of power at the energy storage is exacting. One attractive approach for energy storage is the flywheel energy storage. The storage has the capability to handle high power flow and to serve as a smart support for the battery. These ideas and first results are discussed in the following article. The test-bed for this dual storage concept is a scooter which has access to both storages.**

Keywords— Flywheel Energy Storage, Electric Scooter, Energy Storage Concept, Energy management

I. Introduction

E-mobility is closely associated with huge cities and urban regions. A challenge of huge cities is the limitation of space. All movements execute in a smaller available space like habitations, mobility and infrastructure. So the mobility concepts have to be adjusted. One implication of the limited space for the mobility is to use smaller and maneuverable vehicles. A vehicle class that corresponds to these requirements are two-wheelers. These vehicles have a lower complexity because they can renounce of high voltage levels. At the same time the power demand is on a moderate level as a result of overall weight. So the two-wheelers can carry compact energy storage and achieve acceptable driving range for urban usage. An exponent for this class is the scooter, which is discovered in a high amount in cities. The popularity of electrically operated scooters is growing. The reasons are for example restrictions of gasoline motorcycles in populous cities [1], [2].

II. Principles of Flywheel Storages

Flywheel energy storage is a battery for kinetic energy. It is a mechanical storage that uses the behavior of rotor and its moment of inertia to maintain their rotational condition. For changing this condition the flywheel has to be influenced by a torque. An applied torque changes the speed of the flywheel and influences the charge condition of the storage.

The storable energy content can be affected through material, geometrical and rotational aspects. Commonly there are two different directions to achieve high energy rates. That can be simple identified and derived from a basic mechanical relation. The kinetic energy E_{kin} depends on the moment of inertia Θ and the angular velocity ω of the flywheel.

$$E_{kin} = \tfrac{1}{2}\, \Theta\, \omega^2 \qquad (1)$$

Now, one design parameter is to increase the speed of the flywheel. But this loads the flywheel and the bearings. The consequence for the flywheel is to use material with a high strength. So storages with very high flywheel rotational speeds build with composite materials, mostly CFK.

The other direction to obtain high values of energy is to increase the rotor mass and radius of the rotor. The evidence yields the principle that a moment of inertia can also be described through inertia radius i and equivalent concentrated mass m [3].

$$\Theta = m\, i^2 \qquad (2)$$

Thereby the stress for the flywheel can be holding on a level that allows the use of common materials and manufacturing process. This means that material cost can be hold on an acceptable level by utilization steal to made the flywheel. The cause is that the material cost refers to the mass is 30 times higher than for steal. Under functional view the ratio between a part made by steal and CFK is by one sixth [4], [5].

III. Flywheel storage in mobile applications

The capability of flywheel energy storages (FES) were already recognized for automotive applications. There are different opportunities to integrate the FES in the vehicle. So the flywheel can be connected mechanically, electrically or also hydraulically. Factors for the decision can be power supply and packaging. For electric vehicles that allows only a limitation of changes in architecture of the vehicle an electric connection is a solution for integration.

In past there were activities for flywheel storages for mobile applications, see Table I. The projects differ about storage usage and the type of propulsion for the flywheel.

Table I. Overview about mobile applications [6]-[17]

Automotive Applications			
Project	***Publication***	***Flywheel function***	***Propulsion***
Gyrobus	1970th	Energy storage	Electric
Chrysler Patriot	1994	Energy storage	-
AutoTram	2005	Energy storage	Electric
Porsche 997 GT3 R Hybrid	2010	Energy storage	Electric
Flybus	2011	Energy storage	Mechanic
Audi R18 e-tron	2012	Energy storage	Electric
Volvo KERS	2011,2014*	Energy storage	Mechanic
Two-wheeler Applications			
Project	***Publication***	***Flywheel function***	***Propulsion***
Schilowski Gyrocar	1914	Stabilization	Electric
Ford Gyron	1961	Stabilization	-
Gyro-X car	1967	Stabilization	Hydraulic
Gyrobike	2007	Stabilization	Mechanic
Lit Motors C-1	2011	Stabilization	Electric

The flywheel is thereby used in two different ways, to store energy or to stabilize the horizontal moving direction of the vehicle. It shows that two-wheelers use the flywheel mainly for stabilization.

IV. Differences of Mobile Energy Storages

The flywheel energy storage has the capability to handle high power flows. This enhance a short time storing of power like recuperation and boosting flows seen in motorsports which is an ideal addition to batteries. Batteries balance the priorities of high power or energy capacities (Figure 1).

The cause is the different structure of the basic battery cell. They go in different directions for battery for high power or energy storing applications [18].

Today the batteries achieve high values of energy capacities and flywheel storages are able to deal with high power flows. The combination is a possible solution for range extending.

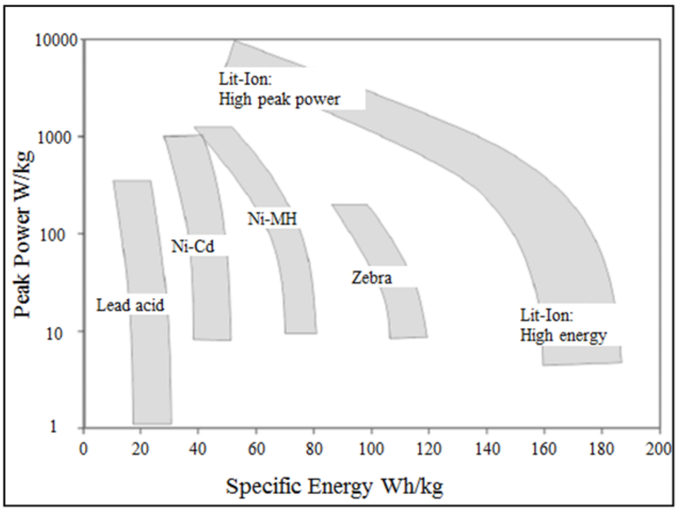

Figure 1: Ragone diagram of different battery types [19]

The flywheel is competing with the supercap. Both storage principles allow to handle high power flows. But the flywheel is in wide range temperature-insensitive and achieves high values of charge and discharge cycles by using suitable bearing and adjusted flywheel speeds.

V. Bi-powered Scooter

A. Approach

The research activities focus on an electric battery in combination with small flywheel energy storage for an electric scooter application. Both storages will be operated with respect to their specific advantage. For that purpose the storage concept and the vehicle need a smart and efficient driving and operating strategy. Besides this, a new flywheel storage unit has to be developed and designed for this vehicle class. The flywheel units is used as a small size secondary energy source for an eScooter as a first vehicle application and to extend flywheel applications later to small subcompact cars and light commercial vehicles, see Figure 2 and [20].

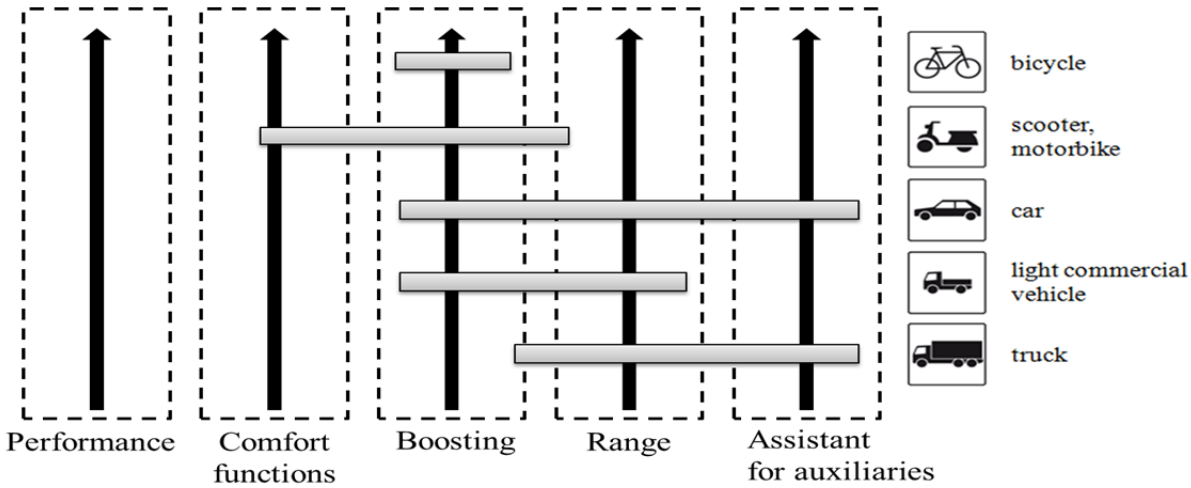

Figure 2: Application of the flywheel ordered by vehicle classes

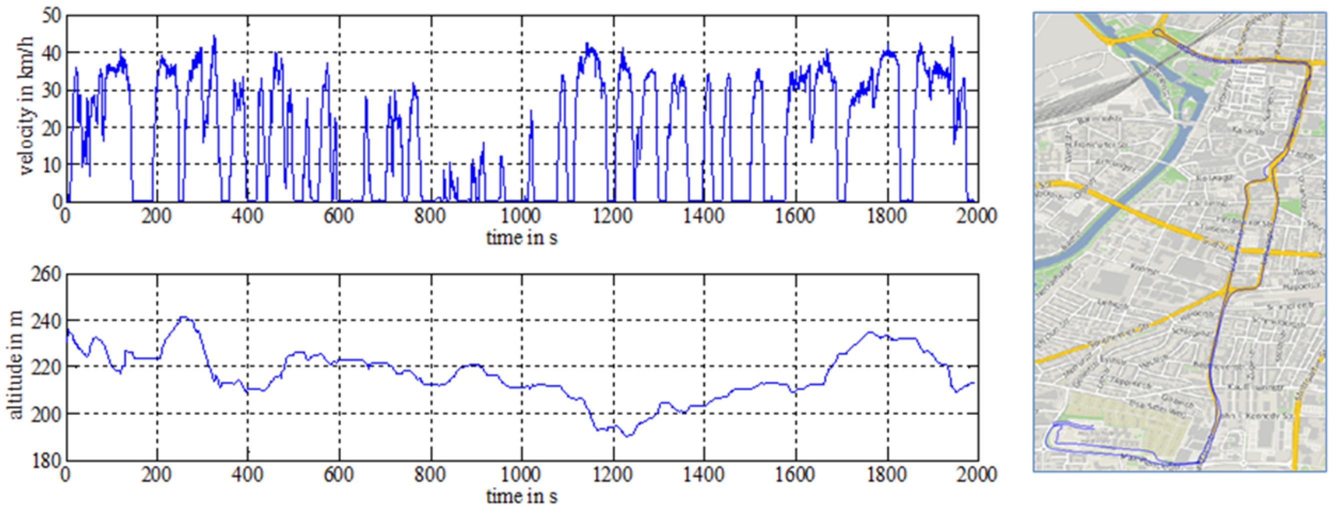

Figure 3: Real driving cycle

In all cases, additional advantages of the flywheel like stabilization of ride comfort and driving excitement issues are to be considered as well. In contrast to the using of flywheel systems in performance orientated applications like in motorsports, the focus of this project is to achieve an ecological benefit.

The approach is to use both storages to get a dual storage system. The propulsion unit of the scooter accesses to the storages in different situations. So the scooter has two different sources to get energy as well as power and so the scooter is "bi-powered". The research concentrated not only of one function, but use the storage for stabilization and as short time energy storage. This crucial point differs to research efforts in the past (Table I). The flywheel energy storage (FES) used in eScooters has special requirements in design and dimensioning. The main topic of the flywheel in this case is the support of the primary energy storage in terms of an electric battery. The job of the flywheel storage is to reduce the high electric power load which occurs in acceleration and braking phases during a ride of the scooter. So the purpose of the flywheel storage in the scooters is to handle the power in recuperation and boosting conditions.

B. *Introduction of the flywheel storage*

The descripted flywheel storage for the scooters is developed for the scooter application. The methods for the dimensioning and development of this flywheel energy storage are based on simulations, practical tests and measurements with the vehicle. For the estimation of the energy content according to real driving scenarios a recorded driving profile will be used, see Figure 3.

It is an urban cycle with a distance of nearly 9.5 km and represents a circular track between two locations of the Heilbronn University. The mean velocity is in the area of 26.6 km/h. The used electric scooter has a maximal driving velocity of 45 km/h. Through the deceleration values of the vehicle and the expected recuperation energies an energy content of approximately 2 Wh is determined. After the predefinition of the energy content of the vehicle the flywheel is shaped and the design process started for the integration of the electric propulsion unit of the FES. The simulation results lead to a flywheel with a weight of nearly 4 kg up to a speed of 10.000 rpm. Due to achieve a compact energy storage for the scooter the flywheel is shaped as external rotor, which allows to integrate the propulsion unit in the flywheel (Figure 4).

Figure 4: New flywheel energy storage design

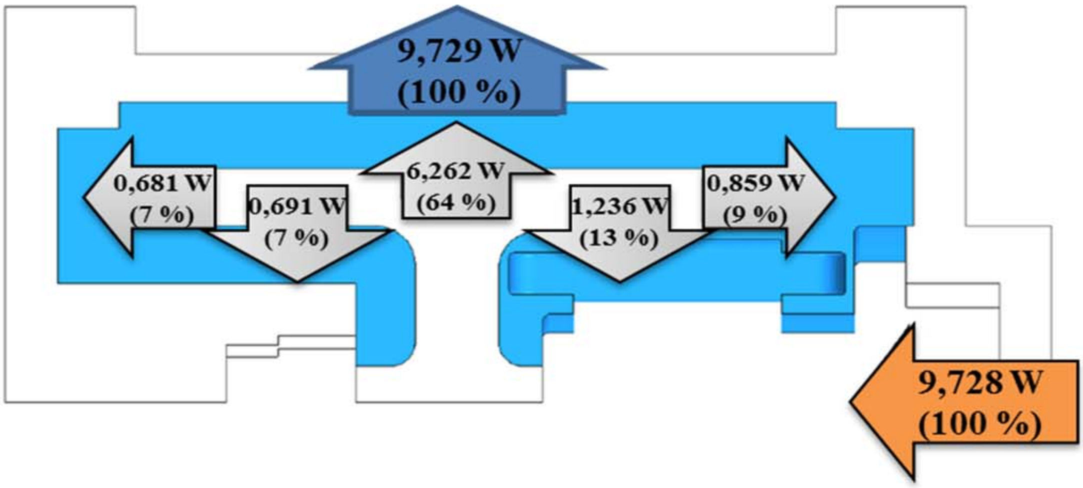

Figure 6: Cross-section of the storage and the estimated power losses from the CFD-Simulation

The shape of the flywheel is cylindrical and is made of steel. Flywheel energy storages have a high ratio of self-discharging, due to losses in the bearings and the air resistance. So the first prototype is equipped with hybrid bearings to reduce the friction loss. For limitation the air friction it is reasonable to reduce the air pressure in the housing of the storage.

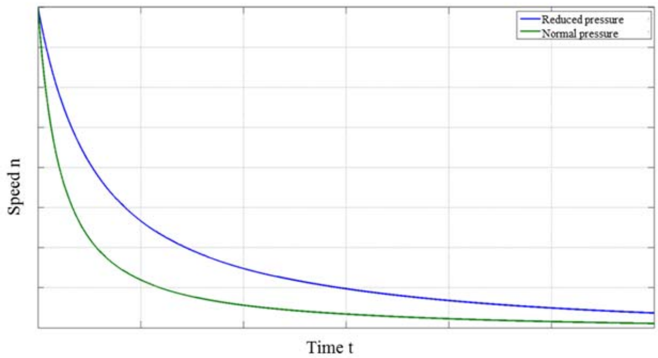

Figure 5: Behavior of the flywheel energy storage through pressure variation

The reduction of the pressure effects that the gradient decrease and so the flywheel slows down by high speed less (Figure 5). For estimation of the losses a CFD – simulation under normal pressure has been performed. Figure 6 shows the estimated losses referred to area of appearance. The air resistance has an increased influence in the spacing between housing and rotor as well as in the area of the stator. The energy storage of the scooter is provided to work under low pressure to reduce the losses and the self-discharge.

The flywheel storage is electrically connected to the power unit of the vehicle. The flywheel energy storage is powered by an electric synchronous motor. The motor generates losses that dissipate as heat. The result is that the storage warms up. The heat can achieve critical values for the bearings and the motor winding. Another CFD simulation proves the temperature behavior of storage. In Figure 7 the stress cycle is illustrated, which is linked to the information about the produced heat through the electric motor. The solution is pictured in Figure 8 and Figure 9.

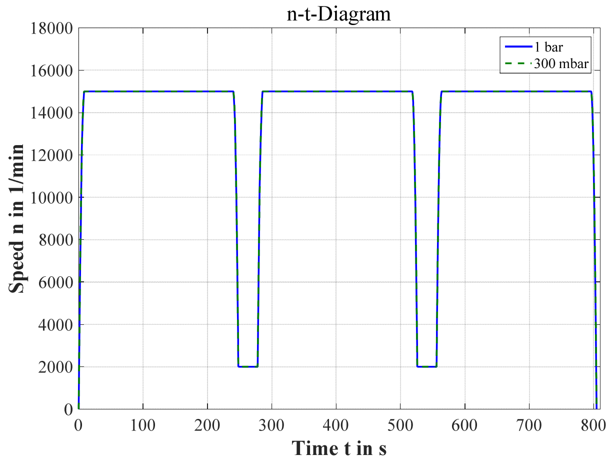

Figure 7: Stress cycle used in CFD Model

Thereby the temperate pathway differs due to varying air pressure.

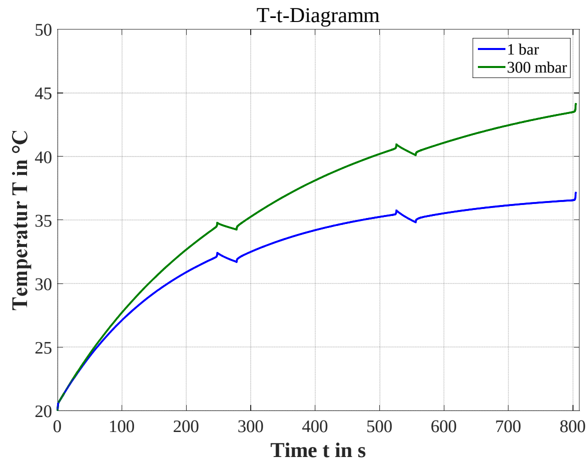

Figure 8: Warm up process based of the CFD simulation

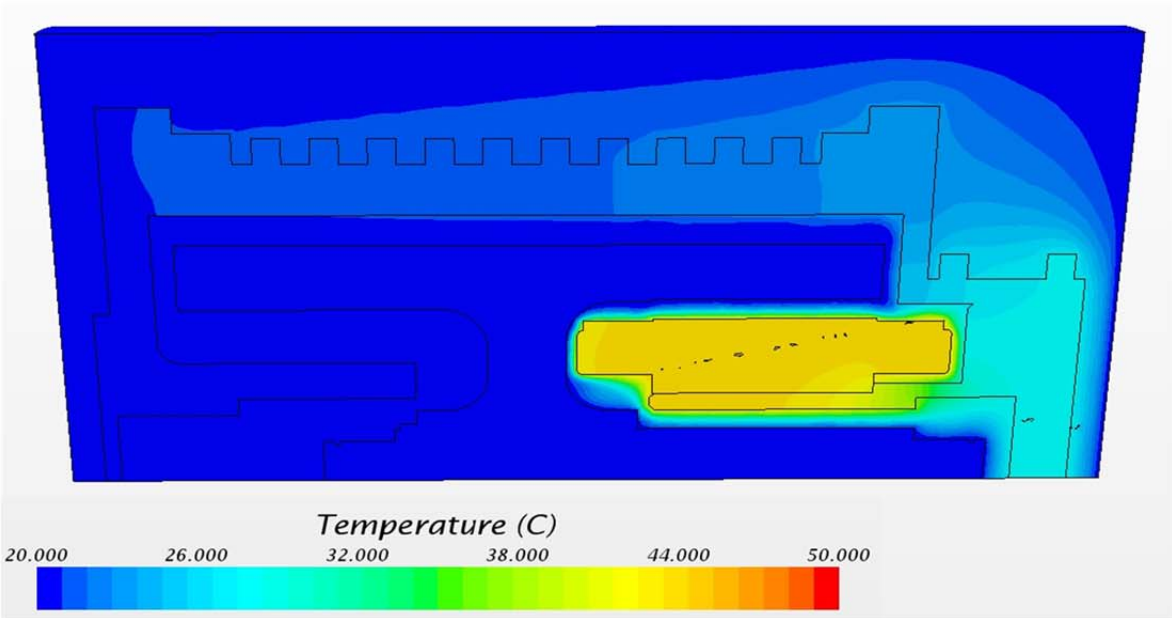

Figure 9: Temperature distribution after 805 s by 300 mbar

Under low pressure the temperature achieves values in the area of 40 °C. The expected losses of the high efficient motor pose no threat for the storage parts. Nevertheless to support the thermal management the storage prototype will be equipped with additional “heatpipes” for transporting the heat.

C. *Operating behavior*

The FES for the eScooter is used as a short time buffer and for the power demand of the propulsion unit of the vehicle. Inside the dual energy storage concept the FES is responsible for the power supply and the battery for the range supply. The storage can achieve 75 % of the stored energy by reducing the speed to half (Figure 10).

The FES works in a low speed level area in comparison to other flywheel storage applications. Through the steel flywheel, a rotational speed up to 10.000 rpm and an aim energy content of 1 Wh it is classified as low-speed flywheel energy storage. Flywheel energy storages generally allow high frequency of charge and discharge cycles and so the storage for the eScooter is very dynamically used. In this connection the purpose is to consume the stored recuperation energy immediately in the next acceleration phase (Figure 11).

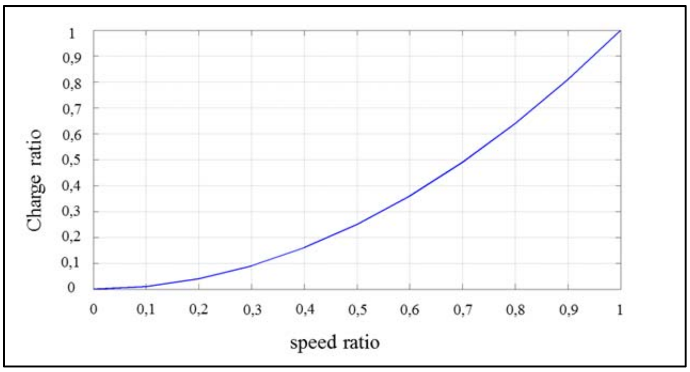

Figure 10: Charge and discharge behavior of a flywheel storage

Thereby it is possible to achieve short buffer times and affects like self-discharging through friction are limited. The impact of friction by the air and the bearings is explicitly shown in Figure 11 through the energy losses during idle or hold phases unless the next charge period begins.

Also it is illustrated that the flywheel of the FES has no kinetic energy stored in the beginning of the ride unless it has been charged externally. During the acceleration and braking phases of the vehicle the flywheel energy storage changes the level of its kinetic energy.

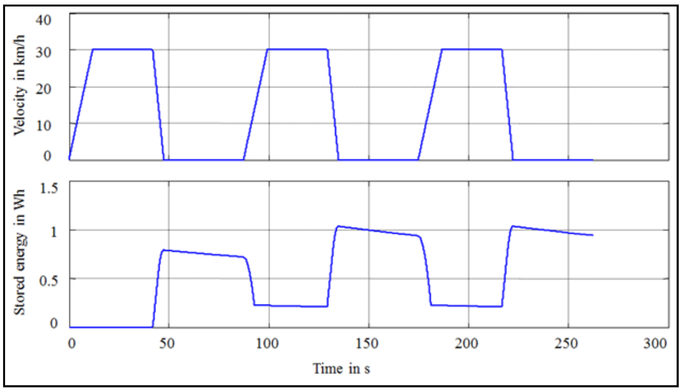

Figure 11: Drive cycle to support the dimensioning process

This FES operation reduces the impact of the gyroscopic moment caused by the rotating flywheel. Basically, this moment could hamper the driver during riding the eScooter. Through a particular suspension the impact can be limited. Currently it is investigated to use the moment to stabilize the scooter in stopping conditions. A stopping condition is for example waiting at the traffic lights. Therefore the storage is used for comfort. Under consideration of standard vehicle axis system the orientation of the FES and its axis of rotation is parallel to the y-axis of the vehicle, which is normal to vehicle longitudinal plane. A gyroscopic moment arises through the moment of inertia and the angular velocity of the flywheel as well as through a turning of the rotation axis of the FES.

In this case the yaw and roll moving of the vehicle are critical if the flywheel spins and the impact of the gyroscopic moment must be analyzed.

Through the low-speed flywheel design the impact shall be reduced. Due to identify the impact of the moment of the driving behavior a simulation model is currently created.

VI. Measured Power and Energy Demands

The information for the theoretic required energy content is generated through elementary sensor information. In the next step the scooter is equipped with a professional measurement system and sensors. The new and detailed information are required for driving strategy, controlling and dimensioning of the interface between the storages and the propulsion unit of the scooter. Now the first measurement solutions are shown.

The measurement system is able to take a detailed statement about the power and energy demands during the real driving cycle. Thereby central information is the battery voltage. This parameter provides first information about the range and the content of the battery (Figure 12).

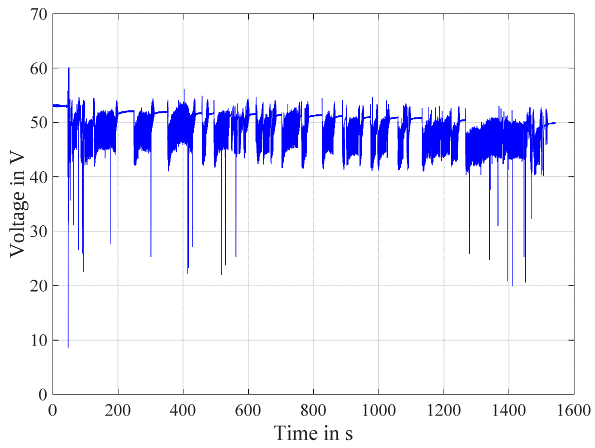

Figure 12: Battery voltage during real driving cycle

The Figure 12 shows that the open circuit voltage decreases during the ride. At the beginning is has a voltage of 53 V and at the end 50 V. The measured signal has noise, which is under investigation and is caused by electromagnetic compatibility problems. The battery voltage and the current are used to get information about the electric power demand (Figure 13).

The power demand increases if the vehicle is accelerating. Through the new approach of using a flywheel storage it is expected that the peaks of the power demand are decreased. Thereby the battery is preserved and the range will be improved.

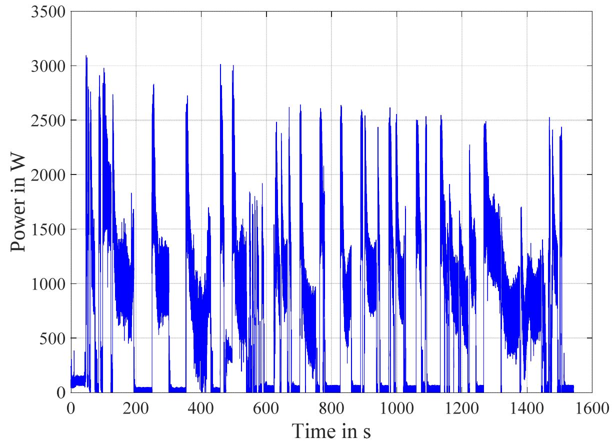

Figure 13: Power demand during real driving cycle

The required electric energy for the cycle can be deduced from the power demand. It results an energy consumption of 283 Wh. This calculated value is put into proportion to the charged energy value after driving. It results a degree of efficiency of 71 %. The aim of the bi-powered approach is to increase the efficiency and the range.

VII. Conclusion

In this contribution the concept of two special energy storages for “bi-powering” a scooter are presented. Thereby the scooter will be equipped and powered with a combination of battery and flywheel energy storage. The flywheel energy storage is self-developed. For the dimensioning of the energy content of the mechanical accumulator several measurements of a real driving cycle and simulation results are used. With this information the design of the flywheel leads to an energy content of around 1 Wh by a rotor speed of 10.000 rpm. The required electric motor for rotation and storing is directly integrated in the flywheel and is a permanent magnet synchronous motor. The measurement system is extended and so the quality of the analyses is improved. The first solution of the measured data shows, that the propulsion systems has a degree of efficiency in the area of 71 %. The aim of the utilization of a flywheel energy storage is to preserve the battery and increase the efficiency.

This work serves as a basis for the general usability of flywheel energy storage for mobile applications as an alternative or supplement to purely battery-powered systems. The project team is convinced that a flywheel approach with its advantages like a high number of charging and discharging cycles, the ability of deep discharge and a large recyclability ratio can contribute to an ecological future vehicle design.

The further project steps comprise a comprehensive simulation about the longitudinal and lateral dynamics of the eScooter in order to evaluate the effect of the gyroscopic moment and the range extending potential.

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