2 Electric Car Operation and Flywheel Energy Storage

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Abstract: Since 2009 Heilbronn University has been investigating the specific needs of individual and commuter traffic for electric car operation in urban-regional areas. The plug-in battery-powered university research car has 26 lithium-based batteries, each with a capacity of 160 Ah and a voltage of 3.2 V. From approx. 11000 km of test drives with measurements and recordings of state variables like motor current or regenerative braking current it becomes clear that the available range allows reliable operation not only in urban, but also in mixed urban-regional areas. However, range remains an issue so that further research was started on additional flywheel range-extending systems. The paper reports first results of the flywheel system investigations. With a flywheel operation speed of 40 000 rpm basic effects of energy regeneration are investigated. Also, first results of the investigations concerning flywheel dynamics on the vehicle dynamics are presented.

Keywords: Electro mobility, Flywheel Energy Storage, Battery Electric Vehicle Operation

2.1 Introduction

The regional confederation Heilbronn-Franken is typical for a large number of mixed urban-regional districts in Germany and also in Europe, too. Typical for the Heilbronn-Franken area close to the southwest metropolitan area of Stuttgart is a slightly hilly landscape as seen in Figure 1.

Electro mobility in the understanding of battery-powered road vehicles promotes pollution reduction and energy saving in transportation. Heilbronn University was supported in 2009 by the ZIP (future investment program) program of the Baden-Württemberg state to investigate electrically powered passenger car impacts on mixed urban-regional transportation (initial project funding).

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Figure 1: Typical landscape view of South-west regional district of Heilbronn-Franken [1] and University Electric car during winter overnight charging

Intense discussions with electric car manufacturers in 2009 led to the procurement of a CITYSAX vehicle [2]. In close discussions with the manufacturer and the local service partner Auto Neff Heilbronn this Chevrolet Matiz conversion vehicle was supplemented by measurement and recording equipment. Figure 2 shows 8 of 26 traction batteries located in the space of the former engine cooling unit. The asynchronous electric motor with a permanent power of 16 kW and a peak power of 26 kW is adapted to the 5-speed gearbox clutch that is adopted from the gasoline-driven model. On top of the front traction battery unit and the electric motor a platform holds the 220 V DC to AC charging device, the AC to DC motor converter equipment and the 83.2 V DC to low voltage 12 V DC converter.

Further batteries are located in the former spare wheel compartment of the vehicle, battery charging and overall control units are located in the inner

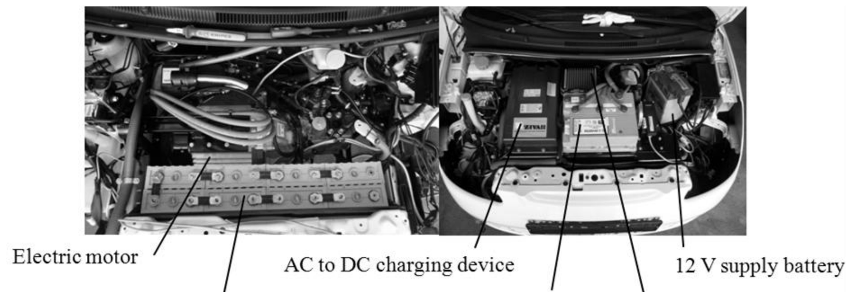

Figure 2: Electric car and components, front car view

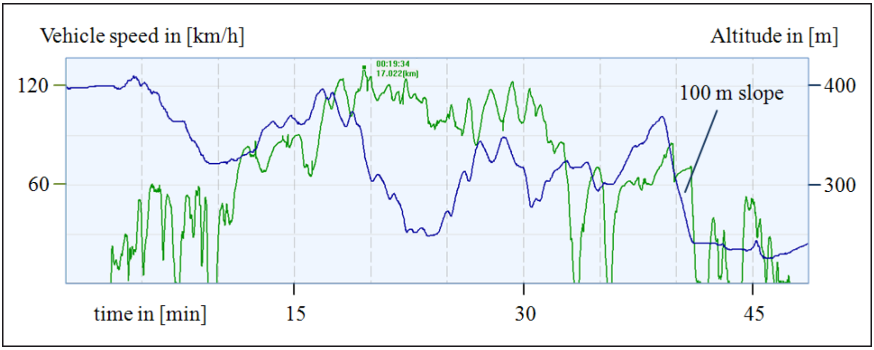

Figure 3: Vehicle speed and GPS logging of topographic profile of electric vehicle in 50 km driving cycle

compartment of the vehicle. The rear cargo volume provides space for additional equipment like fast charging or future range-extending prototype devices.

Now, the Heilbronn University team has tested more than 11000 km with the CITYSAX electric car in autumn, winter and spring conditions, see [3]. Even in cold winter conditions of 2012 (including partially overnight parking with no weather protection) an operation was reliable, due to the gasoline-driven parking heater the internal compartment heating had no effects on range. It was decided to choose a set of realistic urban-regional driving cycles divided into ranges of 5, 12, 25, 50 and 75 km. The 50 km driving cycle is a one-way driving scenario, the reverse direction of 50 km is passed after recharging the car. Figure 3 shows the topographic profile and the vehicle speed in the 50 km cycle from Stuttgart to Heilbronn, Figure 4 shows the velocity and the power consumption from data loggings in the reverse direction.

It is remarkable that a peak power of 26 kW is sufficient to compete in today's high-speed motorway traffic. Also, Figure 4 shows the energy regeneration advantage by braking indicated by negative power consumption values.

The Heilbronn University team is convinced that electric car operation in mixed urban – regional areas is feasible for commuter traffic today. However, range is an issue for electric car operation today and in the future. Therefore range-extending techniques were investigated immediately and in close relation to the test driving cycles.

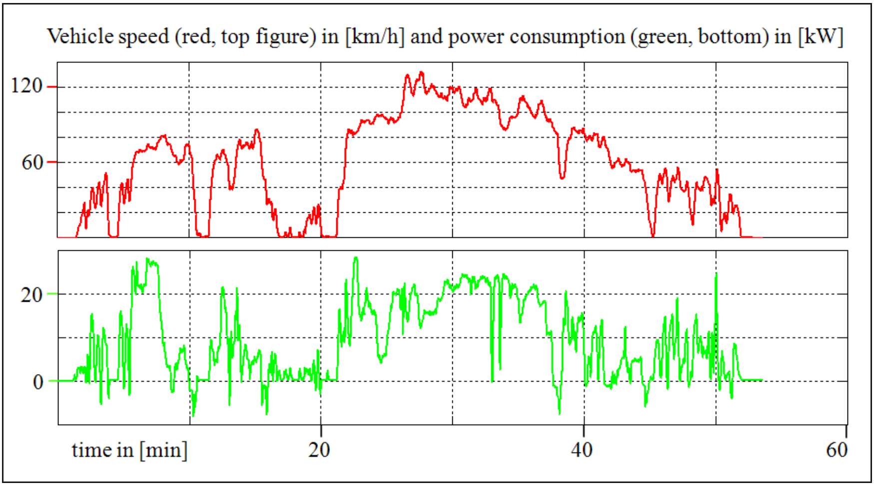

Figure 4: Vehicle speed and power consumption in 50 km cycle, opposite direction

2.2 Flywheel range extending approach

Range-extending techniques for electric vehicles are in lively discussion today. One of the first-ever series plug-in hybrid cars available today is the Chevrolet Volt unveiled in 2007 by the General Motors Company. The Chevrolet Volt and the similar model Opel Ampera or Vauxhall is called a plug-in hybrid electric vehicle that can be operated as a purely battery electric vehicle. When its battery capacity reaches a defined discharge state, its gasoline combustion piston engine powers an electric generator to extend the vehicle's range, see e.g. [4]. Further range-extending approaches are based on the Wankel rotary engine or on super-capacitors. The range-extending scenario described here is based on the flywheel energy storage system principle. Flywheel energy storage and propulsion systems have been investigated in some industrial applications, primarily for stationary emergency energy supply or for the delivery of high energy rates within a short time period. Figure 5 shows the Gyrobus as an automotive application that was built and operated 1953 in Switzerland. Its flywheel had a weight of 1.5 tons and revolved with a maximum speed of 3000 1/min, see [5].

Figure 5: Gyrobus [5]

New flywheel materials like carbon fiber and further progress in high speed power electronics led to a renaissance of the flywheel approach. Recent deployments of flywheel storage systems are described in Porsche race technology applications, see [6]. Here the flywheel which is connected to an electric drive system rotates with a maximum speed of 40000 1/min. Also the Volvo Motor company announces an additional flywheel storage system with a maximum speed of 60000 1/min, see [7] and Figure 6.

There are several advantages in a flywheel energy storage system. On the one hand, its basically mechanical assembly allows multiple discharges and recharges that are not possible for modern lithium batteries. Also the short-term delivery of high energy rates is not compatible with a long duration of battery life. On the other hand, high speed flywheels need additional devices for the reduction of air and bearing friction that enlarges self-discharge. Also, the installation within a mobile platform may cause vibrations and may need appropriate suspension devices, see [8].

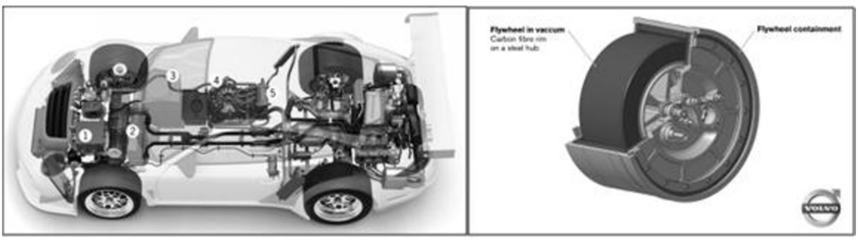

Figure 6: Porsche (left) and Volvo (right) flywheel energy storage application descriptions from [6] and [7]

In the scope of this research project two basic scenarios of preview range extending and fast recharging are considered that differ from today's range-extending strategies.

Preview range extending

In this case the Range extension via flywheel energy storage is supposed to be done before starting a car ride for which more energy is needed. For this purpose, the flywheel range extender is charged on demand and its energy is consumed at the beginning of the ride. During this phase the flywheel range extender saves traction battery energy. This also takes into account of the fact that the flywheel energy may be needed for trip specific compartment heating, compartment cooling, peak acceleration or extreme uphill slope requirements. This preview operation mode takes into account that nowadays an average continuous battery electric car ride does not exceed 1-2 hours. It is designed to prevent flywheel power demands in the case of disadvantageous self-discharge conditions.

Fast recharging

In this operation mode range, extension via flywheel energy storage is supposed to be available when an unexpected recharge due to trip conditions is necessary. Here, the flywheel principle is advantageous since fast charging reduces the lifespan of today's lithium-type batteries. A mid-term goal is an emergency recharging suitable for an additional 20 min or 20 km electric car trip.

For both cases it has to be decided if energy regeneration via braking is transformed into the flywheel or the traction battery capacity. Further flywheel energy storage applications may include emergency power supply for a vehicle's electric network balance or even for stabilizing the ride comfort.

From initial discussions of the research scenarios it became clear that research activities are advantageously decoupled. One research subtopic comprises questions about energy conversion between flywheel and electric motor/generator unit including power electronics devices. All results from simulations and experiments for this subtopic were generated in the Master study project and thesis [9]. Another important research subtopic is the dynamic interaction between the flywheel and the supporting mobile platform. All results from simulations and experiments for this subtopic were elaborated during the master study project and thesis [10] and will be explained in the next chapter.

2.3 Flywheel and mobile platform interaction

After theoretical prestudies on flywheels, see e.g. [11] it was decided to establish a simulation model for mobile platforms close to the University Electric Vehicle design. Therefore, the mobile platform simulation model is provided with an integrated flywheel unit with a maximum of two revolving disks. All model setups and simulations were performed with the computer simulation tools MATLAB/ Simulink and SIMPACK. A proper validation of the simulation model and its results was an important goal of the project. Initial validation plans for a new smaller scale laboratory mobile flywheel design and manufacturing were discussed and abandoned due to project time and costs. Instead of this, the research project team decided to follow the practical idea described in [10]. Here, the mobile platform testbed is simulated by the programmable movements of an articulated industrial robot available in the Heilbronn University robot laboratory. It allows the indication and reproduction of typical yaw and move motions to a versatile adapter that connects with a smaller scale flywheel device. The connector itself includes a torque and force measurement unit to identify the internal forces and torques applied during the enforced robot motion. Finally, a commercial camera flywheel stabilizing device from Keynon company [12] was chosen and mounted to the connector, see Figure 7.

The flywheel device consists of two hinged flywheels with external power supply and a maximum speed of 20 000 1/min rotating in a helium-tight housing.

Comprehensive work was necessary on the set-up, calibration and validation of this approach. Since an internal design of the cardanic hinges and force elements of the flywheel device was not documented, intensive work including X-Ray video recordings was required to identify the flywheel device parameters

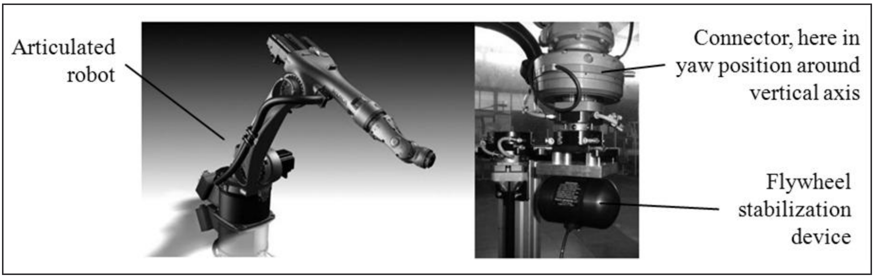

Figure 7: Mobile platform testbed with articulated robot, connector and flywheel device

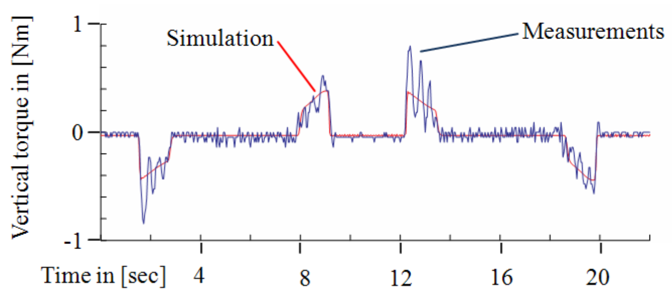

Figure 8: Vertical torque of flywheel stabilization device during yaw motion

itself. Figure 8 shows the vertical torque from measurements and simulations induced from a yaw movement with 24°/sec. Due to the internal elasticity of the force and torque sensor, all measurements were superimposed by vibrations.

After these preceeding investigations a validated simulation model was set up in Simulink and SIMPACK and finally ready for adaption and scaling to a mobile platform. This platform is a first approximation with the parameters of the subcompact electric vehicle. The simulation model now allows variable parameter and hinge design modifications as well as different flywheel speeds, orientations and moments of inertia, see Figure 9.

First simulations show the influence of flywheel hinging modifications on the vehicle movements including stabilizing effects. Further simulation and analysis work on the basis of this validated and scalable simulation model is planned.

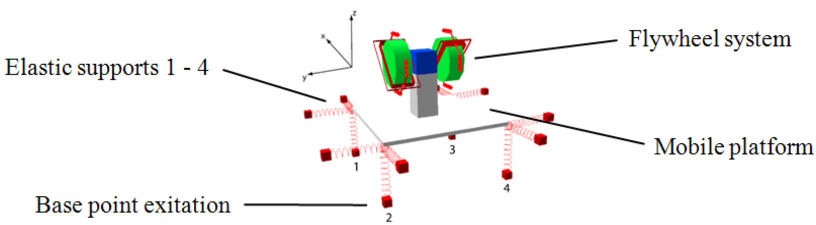

Figure 9: Simulation model of flywheel on mobile platform

2.4 Energy Dynamics

All basic work concerning the interaction between flywheel, power electronics and the electric motor/generator unit is comprised in the research study [9]. Together with the power electronics company ARADEX GmbH and the flywheel manufacturing company Rosetta GmbH a stationary flywheel system was simulated, designed, manufactured, installed and tested, see Figure 10. All simulations were done with MATLAB/Simulink.

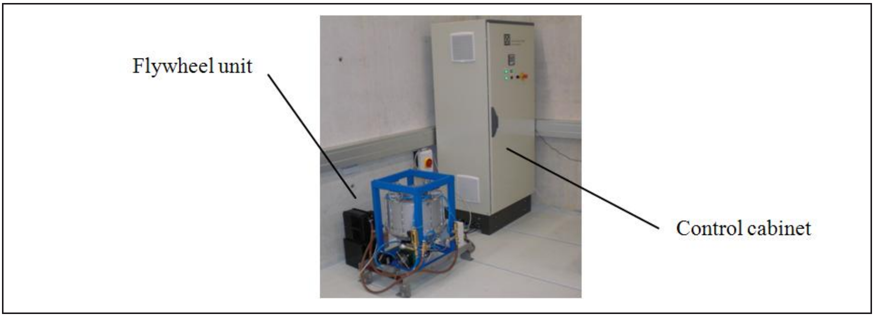

Figure 10: Stationary flywheel testbed with flywheel unit and control cabinet

The simplified laboratory flywheel prototype without carbon fibre wheel body has a maximum speed of approx. 40 000 1/min and an energy content of 70 kWs. To reduce complexity no vacuum was generated, the energy was consumed via electric recovery into the University electric supply network. The double-pole synchronous electric motor/generator unit has a peak power of 15 kW.

Parameters for the moments of inertia and especially for bearing friction were calculated and measured in close collaboration with the flywheel supplier. The characteristic curves for friction torque modeling are determined from deceleration tests. Comprehensive tests including high speed acceleration, constant speed runs and fast deceleration show a very good compliance between simulation model and measurements, see Figure 11.

This testbed is now designed for flywheel devices with a higher energy content and higher speed. It also became clear that self-discharge is one of the main optimization targets for flywheel energy storage systems. Based on the simulations and measurements, a flywheel model with an energy content of 1.5 kWh was simulated together with the University electric car and Heilbronn drive cycle parameters. A theoretical drive length of 8 min including the ascending slope of

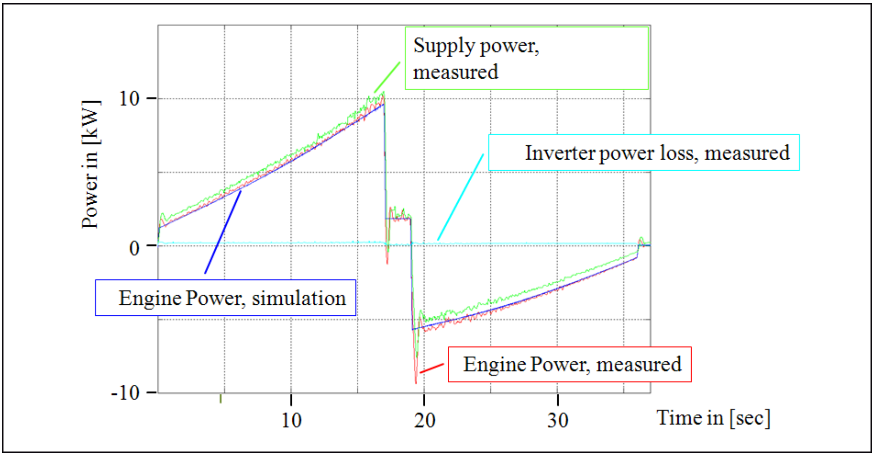

Figure 11: Flywheel power characteristics from fast acceleration and deceleration within 35 s

Figure 3 shows that further work must be done on the fly-wheel layout and especially on the bearing and air friction. In the next step the energy recovery into the University electric supply network will be replaced by a controllable resistance energy consumption.

2.5 Conclusion

From 11000 km test experience with a 26 kW powered electric car of 13 kWh range, the Heilbronn University team is convinced that electric car operation in mixed urban – regional areas is feasible today especially for commuter traffic. However, range is and will be an issue for all battery electric vehicles. In this paper, a fly-wheel range-extending approach is investigated by theoretical, simulation and laboratory research.

Therefore, two new basic operation strategies are proposed. A “preview range extending” strategy consumes the precharged flywheel energy content early at the beginning of a travel not only for traction but also for heating and cooling purposes. This strategy compensates the effects of flywheel energy losses due to friction. The “fast recharging” strategy holds if unexpected range extensions occur. Here, the flywheel capability of multiple fast charging without reduction of lifetime is utilized. During further initial work, two basic research tracks for

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