# High Speed Flywheels for Vehicular Applications

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***Abstract*—This article analyzes two business cases using flywheels in vehicles. Firstly, a diesel based car ferry, in Gothenburg, performing 102 5 minute long journeys per day. Secondly, a diesel based city bus. A theoretical analysis of the benefits, technical and economical, of electrifying these vehicles using flywheels is performed.**

**As basis for the analysis is a constructed high-speed flywheel, designed to store up to 870 W h at a rotational speed of 30 000 rpm. The rotor of the flywheel is constructed from a permanent magnet machine surrounded by a shell of composite material. The flywheel is optimized for low loss as well as low cost.**

**The economical analysis of the two business cases show great potential for cost reduction by either utilizing a flywheel as temporary energy storage for capturing regenerative braking energy or replacing the diesel generator completely as main energy storage.**

**The main material cost of the constructed flywheel pertains to the position sensors and the permanent magnet material used in the magnetic bearing.**

## I. INTRODUCTION

One of the big challenges for the electric vehicle is finding a technology able to store large amounts of energy, while at the same time being capable of handle high, bidirectional flows of energy. The total amount of available energy limits the reach of the vehicle. The maximum power not only determines the acceleration of the vehicle, but also how much of the braking energy that can be reused. As none of the methods of energy storage (batteries, fuel cells, petroleum based generators) presently fulfills both these requirements optimally, it would be of benefit to separate the main energy storage from the power capabilities of the driveline. This could be achieved by an energy buffer, capable of high power but at the same time able to store a moderate amount of energy. Flywheels have been identified as a promising technology for such a buffer.

One of the first implementations of a flywheel for vehicular applications was as main energy storage in the *Gyrobus*, first appearing in public in Switzerland in 1950. The steel rotor of the flywheel in the Gyrobus had a weight of 1500 kg and a diameter of 1.6 m. The maximum rotational speed was 3000 rpm corresponding to approximately 6.6 kW h. Energy flux to and from the rotor was achieved through a three-phase, 52 kW, asynchronous machine [1], [2].

An implementation of the concept of the modern flywheel for vehicular applications with composite material and magnetic bearings was realized at the University of Austin, Texas in 1999 [3], [4]. The unit stored 2 kW h of energy and was able to deliver 150 kW of continuous power. Additionally, a theoretical investigation on the concept of low-speed flywheels for a bus was completed, prompted by the high cost of the high-speed prototype [5].

In 2007 the company *Flybrid Systems* developed a completely mechanical system for energy storage in vehicles called *KERS*, kinetic energy recovery system [6]. The unit was made specifically for the purpose of meeting the 2009 Formula One regulations. The KERS was capable of storing up to 111 W h of usable energy, utilizing a 5 kg rotor. The system was rated at 60 kW with a maximum rotational speed of 60 000 rpm. In 2011, Volvo Car Corporation announced their intention of building flywheel hybrid cars for mass production using a similar concept to that of Flybrid Systems [7]. A prototype of such a car was finished in 2013, and is presently being tested.

In 2012, an *Audi R18 e-tron quattro* won the 24 Hours of Le Mans race, the worlds oldest competition in endurance racing, as well as the six hours of Silverstone race. The car was equipped with a flywheel accumulator system from *Williams Hybrid Power*, recently purchased by the British company *GKN*. The system comprised magnetically loaded composite material and ceramic bearings. Two pressure chambers, separated by a turbo-molecular pump, ensured low pressure around the flywheel, while the bearings operated at a slightly higher pressure. The system was able to store 140 W h of usable energy with a power-rating of 150 kW [8]. Later the same year, Williams Hybrid Power announced a joint cooperation with the *Go-Ahead Group* of producing six prototype buses with flywheel systems. These are presently being tested, and initial results show fuel savings with up to 30 %.

## II. STUDIED APPLICATIONS

Flywheels are very well suited for applications where the number of charge/discharge cycles as well as the peak power is high, but the demand on specific energy storage is low to moderate. *City buses* and *near shore ferries* are two applications that match these specifications.

The purpose of the flywheel may be to absorb high-power charge/discharge peaks, leaving the main energy storage with the task of providing a smooth and low-power current going solely in the discharge direction. This reduces the losses in the main energy storage and – in case it consists of a battery – extends its lifetime. The amount of batteries may thereby be reduced as batteries with high energy density, but low power density, can be used [9].

In addition, such a system may equally well be used for storing regenerative braking energy in a drivline based around an internal combustion engine. Another possible application is as load leveling in drivelines based around fuel cells.

In some cases, the flywheel may even be even be used as the main energy storage itself. These are cases where recharging of the flywheel is readily available, and can be performed frequently enough to limit the required amount of stored energy.

This paper investigates two business cases using flywheels in originally diesel based vehicles, one passenger ferry and one city bus. These two applications have some similarities in that they both mean long working days, a harsh environment and high cost for any unplanned down-time. They are also characterized by frequent starts and stops, making the flywheel's fast-charging capabilities and long cycle life valuable.

In this article two cases are studied for each application; one where the flywheel is inserted between the diesel engine and the traction motor, enabling regenerative braking. And one where the diesel engine is completely replaced by a flywheel system. These two cases are then compared with a reference case using the standard diesel engine alone.

### *A. City bus*

A city bus is characterized by frequent accelerations and decelerations with resulting bidirectional power flows. The demand on the energy storage is although high. It has to withstand numerous short but heavy charge and discharge currents in a harsh environment during long working days. It has to be able to operate within a wide range of ambient temperature. And on top every hour of unplanned down-time is expensive and highly undesirable. ICE buses have been around for a century and their advantages and disadvantages are well known. Hybrid and all-electric buses are beginning to intrude the market, with batteries as the predominant electric energy storage. They show significantly higher energy efficiency but batteries are not well-suited for all the requirements.

However, these requirements make a hybrid or all-electric city bus a good application for a flywheel as a power handling device. A typical city bus weighs 10 t and handles about 150 kW–200 kW of maximum power in both directions. With an average power demand of 30 kW–40 kW the difference between the average and maximum power ranges between four and seven times. Furthermore the average power demand is in only one direction while the instantaneous power naturally goes in both directions.

### *B. Ferry*

Recent interest in electrification of boats and ferries have materialized in several successful projects, see [10] and [11].

Flywheels have several advantages in marine applications with periodic start and stop cycles. They can be rapidly charged each time the ferry reaches shore. Batteries are typically only charged once overnight. The energy storage capacity required for the flywheel is then much smaller than for the battery, opening up for possibly lighter and more economical systems.

One-time charging at night or continuous charging at each stop have been evaluated for a commuter shuttle called *Älvskytteln* in Gothenburg (Sweden) [12]. The shuttle transports vehicles between the villages Lindholmen and Rosenlund, a distance of 900 m. The drive cycle, which can be seen in Figure 1, is repeated 102 times per day. Using a flywheel with high speed on-shore charging requires an energy storage of approximately 1 % of the total energy used in one day.

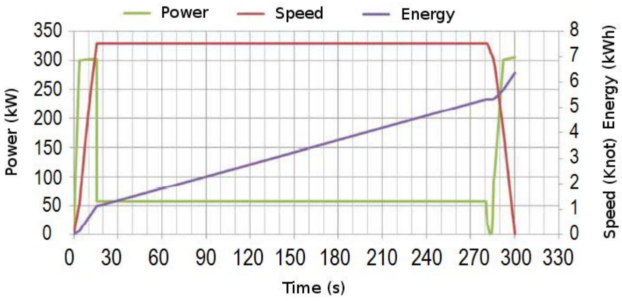

Figure 1. Power, energy and speed of a commuter shuttle in Gothenburg, Sweden, during a day without wind. Picture from [12]

Maintenance is also favorable to the flywheel; battery users have reported problems in off shore applications due to harsh environment. Flywheels design can suppress the gyroscopic effect, but in marine applications the gyroscopic effect can be an advantage. A flywheel system that stabilizes small size boats has been reported [13].

## III. INNER AND OUTER LOSSES

Inner losses are all losses occurring inside the drivetrain and thus affected by the vehicle. They consist of losses in the power electronics, in the mechanical parts of the drivetrain, in the energy storage and so on. Outer losses are the losses occurring outside the drivetrain and thus affected by the drive cycle.

Outer losses can be categorized in two sub-groups. The first group, including air drag and rolling resistance, are called *definite losses* since they are not possible to recover in any way. The second group, including acceleration loss and slope resistance loss, is more interesting from an energy saving point of view. They are definitive losses in a traditional ICE drivetrain but not in an electric drivetrain that provides regenerative braking. Therefore, they are called *recoverable losses*.

Practically, not all of the recoverable outer losses can be recovered. First there are cases where the recoverable losses to some or full extent are used to even out the definitive losses to obtain the wanted speed of the vehicle. For example this happens when the vehicle is accelerating and/or going in a downhill.

## IV. SIMULATION SET-UP

A model of both a city bus in urban traffic, and the ferry Älvskytteln were modeled in an in-house simulation code (Matlab) used to evaluate drivelines.

The city bus in the simulation had a frontal area of $4.8\,\mathrm{m}^2$ and an air resistance coefficient of 0.8. Its maximum acceleration was set to $2.5\,\mathrm{m}^2$. Every trip included 20 stops and took 30 minutes to fulfill. Around five of these minutes consisted of recharging at an end stop.

The bus was assumed to run for 18 hours a day, i.e. 36 trips a day. Ten drive cycles were randomized and simulated, each with 20 stops where the bus stops for 30 s each. The road was built up by 100 parts, each one with the length randomized from a one-sided normal distribution with a mean of 100 m and a standard deviation of 50 m. The gradient of the road for every part was set by a two-sided normal distribution with a mean of 0 degrees and a standard deviation of 0.5°. The speed limit of the road was set to 50 km/h.

The simulation set-up for the ferry application was aimed at the specific case of the commuter shuttle described above. The mass of the ferry was 200 t, the maximum motor power was set to 300 kW and the number of trips per day was 102. For a complete description of the input parameters to the simulation software, see Table I.

Table I
PARAMETERS USED IN SIMULATION

| | City bus | Ferry |
|---|---|---|
| Mass [t] | 10 | 200 |
| Max motor power [kW] | 170 | 300 |
| Max braking power [kW] | 250 | 300 |
| Energy content in diesel [kW h/L] | 9.8 | |
| Average diesel motor efficiency | 25 % | |
| Optimal diesel motor efficiency | 30 % | |
| Electric drivetrain efficiency | 80 % | |
| Regenerative braking roundtrip efficiency | 75 % | |
| Energy stored in flywheel available for use | 75 % | |
| Safety margin for energy storage in flywheel [-] | 1.3 | |
| Diesel price (Sweden, excl. VAT) [€/L] | 1.22 | |
| Electricity price (Sweden, excl. VAT) [€/kWh] | 0.09 | |
| Trips per day [-] | 36 | 102 |
| Running days per year [-] | 300 | |
| Max power of flywheel [kW] | 170 | 300 |
| Discount rate [per year] | 5 % | |

## V. RESULTS OF SIMULATION

The maximum size of the flywheel for the two cases is calculated as the kinetic energy of the vehicle at top speed (50 km/h for the bus and 14 km/h for the ferry) plus the potential energy of the vehicle of the total altitude span of the drive cycle.

Further, the flywheel is assumed to have an operating window between 50 % and 100 % of its speed, which means that 75 % of the actual energy stored in the flywheel is available for use. Upon that a safety margin of 1.3 is added. Results of the simulations can be found in Table II.

### A. *Flywheel as energy buffer*

An average total flywheel size of 1.1 kW h for the bus and 0.72 kW h for the ferry was found to be required for the cases the flywheel acts as energy buffer. In both cases, significant savings in diesel cost was found.

Table II
RESULTS OF SIMULATION

| | City bus | Ferry |
|---|---|---|
| Total energy [kW h] | 15.4(0.28) | 6.37 |
| Total braking energy [kW h] | 4.06(0.02) | 1.01 |
| Total distance travelled [km] | 11.2(0.33) | 1.10 |
| Total running time [s] | 1534(24) | 300 |
| Diesel only | City bus | Ferry |
| Diesel consumption per trip [L] | 6.27(0.11) | 2.60 |
| Diesel cost per year [k€] | 82.6(1.50) | 97.1 |
| Diesel + flywheel | City bus | Ferry |
| Diesel consumption per trip [L] | 4.19(0.10) | 1.91 |
| Diesel cost per year [k€] | 55.2(1.28) | 71.3 |
| Yearly savings [k€] | 27.4(0.23) | 25.8 |
| Required size of flywheel [kW h] | 1.10(0.19) | 0.72 |
| Present value of savings (20 years) [k€] | 341(11.5) | 322 |
| Flywheel only | City bus | Ferry |
| Electricity consumption per trip [kW h] | 15.4(0.36) | 7.0 |
| Electricity cost per year [k€] | 15.0(0.35) | 19.3 |
| Yearly savings [k€] | 67.6(1.16) | 77.7 |
| Required size of flywheel [kW h] | 19.6(0.50) | 8.0 |
| Present value of savings (20 years) [k€] | 843(14.4) | 969 |

In the case of the city bus, the yearly savings from the reduction of fuel by almost 35 % amounted to 27.4 k€, or 341 k€ in present value over 20 years.

The corresponding numbers for the ferry application was a fuel reduction of 25 % corresponding to 25.8 k€ annually, or 322 k€ in present value.

Assuming a total cost of 100 k€ for power electronics (AC/DC/AC to and from the flywheel), the upper estimate of the cost per stored kW h for the city-bus application becomes 220 k€/kWh and 310 k€/kWh for the ferry.

### B. *Flywheel as main energy storage*

An average total flywheel size of 19.6 kW h for the bus and 8.0 kW h for the ferry was found to be required in case the flywheel should act as main energy source.

In the case of the city bus, the yearly savings from replacing the diesel fuel with electricity amounted to 67.6 k€, or an estimated 843 k€ in present value for a system life of 20 years.

The corresponding number for the ferry application was 77.7 k€ annually, or an estimated 969 k€ in present value. These quite large savings stem primarily from the higher efficiency of the electric driveline, and the lower price of electric energy, compared with the diesel based driveline.

Assuming also here a total cost of 100 k€ for power electronics yields an upper estimate on the specific cost of 38 k€/kWh for the city bus, and 110 k€/kWh for the ferry application.

Note that in this calculation, only the fuel savings are included, not the significant cost reduction resulting from removing the now obsolete diesel driveline. Also not included in the estimation is the fact that in some cases (most likely the case of the ferry) the local grid is not strong enough to provide the power required to charge the energy storage. Then, a secondary energy buffer is required at each charging station, or the grid connection has to be improved.

## VI. CONSTRUCTED FLYWHEEL

In order to gain experience with the costs associated with the construction of a flywheel energy storage, a flywheel aimed at functioning as an energy buffer in an electric bus was designed and constructed, see [14]. The design limit of kinetic energy in the system was 0.87 kW h at a rotational speed of 30 000 rpm.

A composite shell was used to obtain the targeted amount of stored energy within a compact form-factor. The shell was constructed from two layers of unidirectional composite material, an inner layer of glass fiber surrounded by an outer layer of carbon fiber. The use of an inner rim of glass fiber, as well as producing the shell in one curing, resulted in a significant cost reduction.

A permanent magnet rotor was enclosed within the composite shell. The magnets were positioned in a cylindrical Halbach structure within a high-strength aluminum cylinder. The flux-path was closed through an inner concentric steel cylinder. The stator was constructed using Litz wire and fixated to a non-conductive plastic structure in order to reduce eddy current losses.

The rotor was suspended with the help of magnetic bearings in order to decrease stand-by losses and vibrations, and increse lifetime. Passive thrust magnets levitated the rotor axially. An active magnetic bearing (AMB) comprising eight actively controlled heteropolar electromagnetic actuators fixated the remaining four degrees of freedom.

A picture of the constructed prototype, as well as some of its main parameters, can be found in Fig. 2.

| Parameter | Unit | Value |
|---|---|---|
| Total mass | [kg] | 73.0 |
| Rotor mass | [kg] | 46.6 |
| Total height | [mm] | 535 |
| Rotor outer diameter | [mm] | 350 |
| Thickness of shell | [mm] | 76.4 |
| Moment of inertia | [kg·m$^2$] | 0.636 |
| Max rotational velocity | [rpm] | 30000 |
| Max kinetic energy | [W h] | 871.8 |
| LP RMS phase-voltage | [V] | 116 |
| HP RMS phase-voltage | [V] | 269 |
| Continuous LP power | [kW] | 2.0 |
| Continuous HP power | [kW] | 4.7 |

Figure 2. A magnetically levitated flywheel with composite shell has been designed and constructed. Picture from [15]

### A. Rotor construction

At the core of the constructed rotor there is an aluminum cylinder (22), see Figure 3. A shaft (18) is mounted in the central hole of the aluminum cylinder. Also found on the main shaft is an aluminum cup (20), a steel cylinder (21) and a plastic cup (19) (containing the axial bearing magnets). A similar plastic cup can be found on the opposite side of the structure (24), carrying the other half of the axial bearing magnets.

Inside the aluminum cylinder there is a plastic matrix (26), containing the main rotor magnets of the machine (25). Lastly the whole core is inserted into a thick composite shell (23), which both acts as energy storage by increasing the systems moment of inertia, and as structural support by preventing the core from expanding as the rotational speed is increased.

The composite shell consists of both a glass-fiber inner layer and a carbon fiber outer layer, with a ratio of around 50/50 between the two composites.

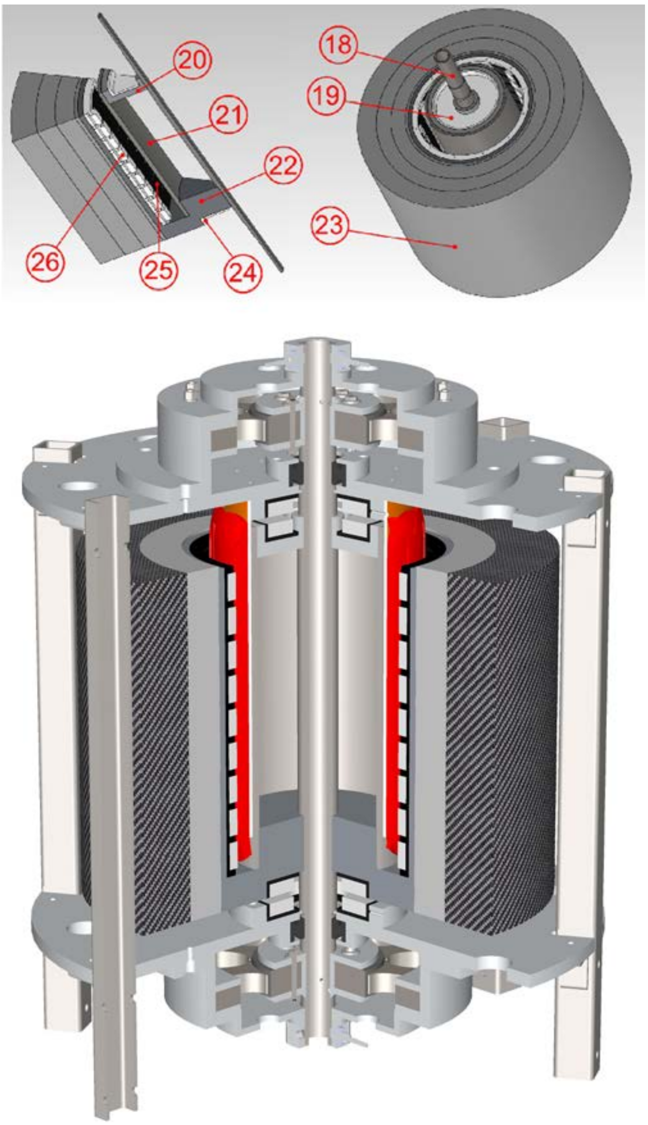

Figure 3. Cut view of CAD design for the constructed flywheel. Top: Rotor assembly. Bottom: Overview of complete flywheel.

### B. Magnetic bearing construction

Eight laminated actuators and two targets were constructed from sheets of non-oriented electrical steel, approximately one square meter in size. The legs of the actuators, and the inside of the guiding plates holding the laminates together, were covered with electrically insulating but thermally conducting tape. Each individual electromagnet was thereafter manually wound with 1 mm enamelled copper wire. Each actuator was wound with 400 turns resulting in a filling factor of 45 %.

The control system was centered around a programmable automation controller (PAC) from National Instruments, the CompactRIO (C-RIO). Contactless position sensors were used to measure the position of the rotor shaft accurately and with high bandwidth. The position of the shaft was translated into a required current in an outer control loop in the PAC.

Further, sensors using the Hall effect measured current through each electromagnet. The values of current were fed to an inner control loop in the PAC, which forced the current to the desired value by varying the duty cycle of the MOSFETs.

All circuits were encapsulated in aluminum boxes, and connected with shielded cables to minimize electro-magnetic interference, see Figure 4. For a more detailed description of the test set-up, see [15].

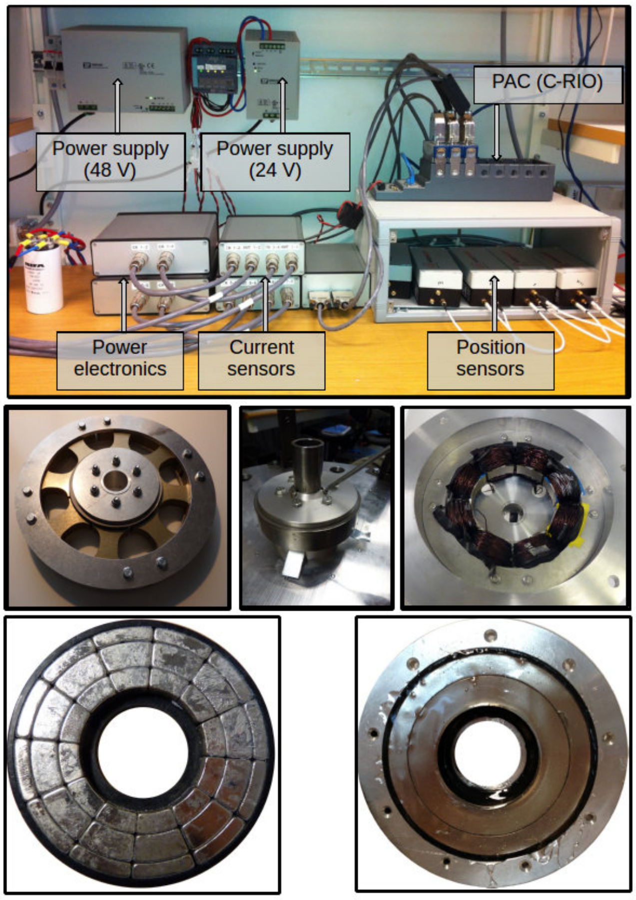

Figure 4. Magnetic bearing. Top: Power electronics with current control for radial active magnetic bearings. Middle: Constructed active magnetic bearing actuators. Bottom: Constructed passive axial thrust magnets.

A first test of the magnetically levitated system can be seen in Figure 5. The test compares the spin-down loss of the rotor, in air, with a previous flywheel of similar size with mechanical bearings. Note that power loss associated with generation of the bias current (approximately 40 W) is not included.

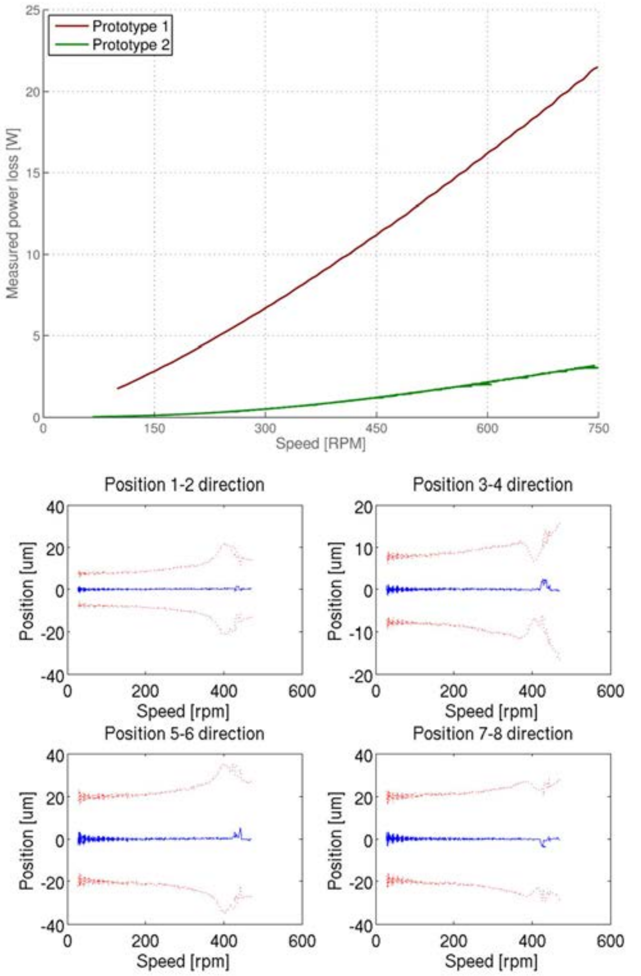

Figure 5. First spin down test of flywheel (note: in air). Top: comparison of the spin-down losses of the magnetically levitated flywheel (Prototype 2) with a previously constructed mechanically levitated flywheel (Prototype 1). Note: the power loss of the active magnetic bearings are not included. None of the two flywheels have been balanced. Bottom: Deviation of measured position from set position for the upper and lower radial active magnetic bearings during spin-down.

The flywheel operated stably until the designated top speed of 8000 rpm. The deviation from the set-point of both upper and lower bearing was always under 40 µm, although the rotor has not yet been balanced.

The difference between the intrinsic losses in a flywheel with mechanical bearings as apposed to one with magnetic bearings is clearly visible although the spin-down test was performed in air. At low speeds, where most of the loss in the mechanical flywheel comes from the friction of the rubber seals in the ball-bearings, the intrinsic loss in the magnetically levitated system is at least one order of magnitude smaller.

However, note that in this plot the power required to drive the bias current in the actuators (around 40 W) is not included.

### C. Material cost

Although a magnetically levitated flywheel may seem like an overly complicated and expensive solution to store energy, the actual hardware needed to build one is not that hard to come by, nor is it very expensive. Furthermore, the computational power needed to make the flywheel function is becoming cheaper by the year, thanks to the rapid development within the field of electronics and microcomputers. Today a single FPGA have enough computational power to levitate a fully-fledged flywheel, as demonstrated in the setup presented within this paper.

In the cost breakdown for the prototype, Table III, one can see that the most expensive parts, with good margin, was the inductive position sensors. Followed by the combined cost for all the neodymium magnets. Those two components stand for 8.4 k€ of the total 13 k€. The reason for the high price on the sensors is that they have a very high accuracy ($< 4\,\mu m$) and high bandwidth (20 kHz). This accuracy is not really needed to get the system to work, but is is advantageous to have in a prototype in order to get precise measurements.

Table III
MATERIAL COST OF FLYWHEEL

| Part | Cost [k€/kWh] | Fraction of total cost [%] |
|---|---|---|
| Rotor | | |
| Carbon fiber [Toray T700] | 0.6 | 3.1 |
| Glass fiber [Advantex] | 0.05 | 0.2 |
| Additional rotor structure | 0.6 | 3.1 |
| NeFeB magnets | 2.15 | 11.0 |
| Chamber | | |
| Support structure | 0.6 | 3.1 |
| Electromagnets | 0.35 | 1.8 |
| Stator | 0.35 | 1.8 |
| Vaccum System | 0.45 | 2.3 |
| Electronics | | |
| FPGA (CompactRIO) | 1.7 | 8.7 |
| 3-phase inverter | 1.1 | 5.6 |
| Current control circuit | 0.55 | 2.8 |
| Position sensors | 11.1 | 56.6 |
| Total | 19.6 | |

### D. Rotor Manufacturing

In order to reduce the manufacturing cost of the composite shell, and to allow for shorter manufacturing time, the shell is was wound and cured all in one cycle. The alternative being winding the composite in separate rings and curing them individually and then press-fitting them on top of each other. However, the downside with the single cure approach is that it induces radial tensions in the shell. In order to control these radial tensions and following strains special care has to be taken when winding the composite but also to the geometry of the rest of the machine.

Additionally, the inner parts of the rotor is intentionally made of weaker, heavier materials, like aluminum and pieces of sintered NdFeB magnets. So when system begins to rotate these relatively "weak and heavy" parts will begin pressing against the inner walls of the much stiffer composite, due to the centripetal forces. This in turn creates compressive radial forces in the composite, counteracting the radial tensile stresses left over from the manufacturing process.

The trade-off for these compressive radial stresses is an increase in the hoop stress of the composite. Note though, that in a unidirectional filament wound carbon-composite, which this rotor is, the hoop direction is by far the strongest direction of all, having tensile strengths many times that of even steel. This allows for much higher rotational speeds that those achievable by a pure metal flywheels of similar size.

In this prototype the composite shell has an total thickness of 74 mm. Any thicker and the radial stresses left over from manufacturing would delaminate the material. Although the thickness of the composite shell is maximized, the 50/50 composite ratio is not optimum from the point-of-view of stored energy per Euro. For this a ratio containing much more glass-fiber, up to around 80 %, would be better due to the lower cost of glass-fiber.

The reason for not using this 80/20 design is purely due to manufacturing limitations. When the composite shell is cured as a whole and as a mixture of different fibers, the different thermal expansion coefficients of the materials have to be taken into account as the curing occurs at around 120°. Here the carbon fiber have around 1/10:th the expansion of the glass-fiber. If the glass-fiber layer is too thick, buckling of the fibers occur, see Figure 6.

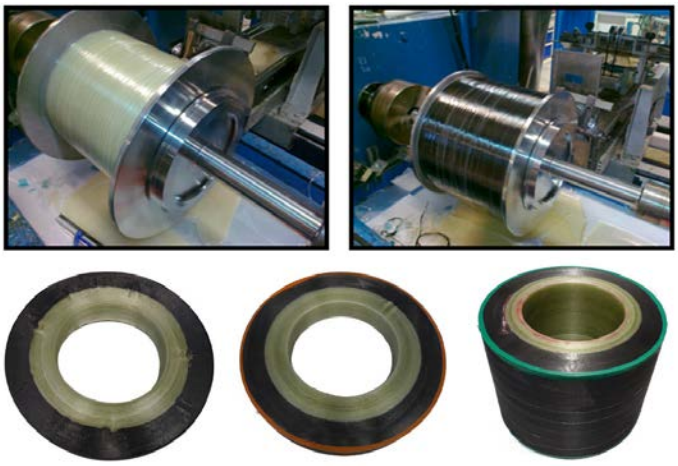

Figure 6. Manufacturing of composite shells. A layer of glass-fiber is wound unidirectionally on a mandrel, after which a layer of carbon fiber is added. The middle of the three constructed shells (bottom) shows buckling from thermal expansion of the glass fiber during curing.

## VII. DISCUSSION

An introduction of flywheels into the drive-train is profitable both for the ferry and for the city bus even though the ferry seems to be the most interesting business case. The ferry also has other advantages such as a higher tolerance to added mass and volume.

However, some investments have to be done. Except for the obvious investment in the flywheel itself also charging facilities have to be set up at the end stops (for bus) and on shore (for ferry). The bus has to be equipped with an electric traction motor. This is not needed on the ferry since it already is diesel-electric – like almost all ferries.

The magnitude of the C-rates required, especially for the hybrid case but also for the all-electric case, indicates that batteries is far from a good choice for this application. They would also very fast be worn-out by the high number of cycles per year.

The main material cost for the flywheel at the moment are the very expensive position sensors. Secondly, the cost of permanent magnetic material is very high. The material cost of the composite material is relatively low, especially since the shell is made partly of glass fiber composite.

The cost of manufacturing is significant, but difficult to estimate. The position sensors used in the set-up requires no additional manufacturing, except assembly. However, the composite shell requires winding and curing in specialized machinery. Depending on where and how this is done, the cost of production of the rotor may increase significantly.

The next step of the development of the flywheel is to balance it, optimize the control algorithm and make accurate models of the different loss mechanisms during operation.

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