Applications for energy storage flywheels in vehicles of Deutsche Bahn AG

Introduction

It is necessary to introduce effective energy saving measures in the operation of rail vehicles for economic and environmental reasons. It has for a long time been possible with electrically propelled vehicles to feed the vehicle’s kinetic energy occurring during braking back into the network by using regenerative braking. This form of energy feedback is not possible with diesel-propelled vehicles. In order to be able to recover the kinetic energy on diesel-propelled vehicles and use it again, energy storage systems have to be used. At present, energy storage systems based on accumulators and flywheel storage have the best prospects of being cost effective for rail vehicles in the immediate future. The use of flywheel storage is currently being investigated in the Research and Technology Centre of Deutsche Bahn AG. Comprehensive theoretical studies and simulations have already been carried out and now, in conjunction with Alstom LHB, Deutsche Bahn AG plans to test in service a system with storage flywheels on the LIREX® test carrier for the first time.

Objectives of the introduction of storage flywheels

The use of storage flywheels should firstly reduce the costs (LCC) of operating diesel-propelled vehicles, and secondly it should further improve the environmental compatibility of these vehicles. Both targets are achieved by the reduced consumption of diesel fuel: the emission of pollutants and CO₂ is reduced. In addition the diesel engine can be operated in the optimum areas for emissions by using a storage flywheel.

Technology of the storage flywheel

The WTZ storage flywheels installed in the LIREX® test carrier have a disc-shaped rotor which runs in a vacuum and is mounted on a common shaft with the electric machine. The electric machine is used both as a generator and motor and is excited by permanent magnets.

The rotor of the storage flywheel is made of carbon fibre, which is bound in an epoxide matrix. The fibres run around the circumference in a tangential direction. To control the radial stresses which occur in service, the rotor is made up of several rings pressed into one another. This construction provides for a defined prestress of the rings in the radial direction.

The rotor runs in an evacuated housing. This prevents the rotating parts becoming unacceptably hot due to air friction.

In order to rule out the danger to people, the housing of the storage flywheel is so designed that if the rotor is damaged no part can penetrate outside the housing.
All the parts necessary for the storage flywheel system are assembled on a common frame. These are the storage flywheel, the inverter, the vacuum pump, the cooling group and the brake resistors for emergency shutdown. The principle technical details for the storage flywheel system are given in Table 1.

**Figure 1: Schematic cut through the flywheel, which is used in the LIREX ®**

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Wissenschaftlich Technisches Zentrum (Scientific Technical Centre) (WTZ), Rosslau</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy content</td>
<td>6 kWh</td>
</tr>
<tr>
<td>Maximum power:</td>
<td>350 kW</td>
</tr>
<tr>
<td>Duration of the complete charging cycle</td>
<td>for 350kW, 40sec from $n_{\text{min}}$</td>
</tr>
<tr>
<td>Efficiency including frequency converter (charging/discharging)</td>
<td>&gt;90 %</td>
</tr>
<tr>
<td>Idling losses</td>
<td>2.5 - 7 kW</td>
</tr>
<tr>
<td>Voltage [V]</td>
<td>550V - 750V</td>
</tr>
<tr>
<td>Rotor material</td>
<td>Carbon fibre / epoxy resin</td>
</tr>
<tr>
<td>Diameter of the rotor</td>
<td>700 mm</td>
</tr>
<tr>
<td>Maximum speed</td>
<td>25,000 r/min</td>
</tr>
<tr>
<td>Minimum speed ($n_{\text{min}}$)</td>
<td>12,500 r/min</td>
</tr>
<tr>
<td>Type of bearings</td>
<td>Precision ball bearings with lubricating oil circuit</td>
</tr>
<tr>
<td>Type of motor</td>
<td>Synchronous motor, permanent excitation</td>
</tr>
<tr>
<td>Life</td>
<td>20 years</td>
</tr>
<tr>
<td>Suspension of storage flywheel</td>
<td>resilient mountings</td>
</tr>
<tr>
<td>Working temperature range</td>
<td>from -40°C to 60°C</td>
</tr>
<tr>
<td>Dimensions of the complete system (L x B x H)</td>
<td>1900 x 1625 x 1080 mm³</td>
</tr>
<tr>
<td>Mass including the carrying frame</td>
<td>1300 kg</td>
</tr>
</tbody>
</table>

Table 1: Technical data of the storage flywheel
LIREX® test carrier

LIREX® is a six-segment, diesel-electric multiple unit (MU). It consists of two half-trains with technically identical drive systems. There are two power packs in each half trainset (diesel generator units), which passively feed an intermediate circuit. The traction inverter, the auxiliary equipment regulator, the brake chopper and the storage flywheel are supplied from this intermediate circuit. Six of the total of eight axles of LIREX® are powered.

LIREX® is equipped with two energy storage flywheels each with a rating of 350 kW and an energy storage of 6 kWh. The rotating speed of the storage flywheels is a maximum of 25,000 r/min.

LIREX® has an energy management system that controls the charging and discharging of the storage flywheels as well as setting the target values for the power packs depending on the operating mode and the energy requirement.

Figure 2: Test vehicle LIREX®

Operating modes of the storage flywheels

In order to be able to consider the advantages of storage flywheel systems for different applications, six different operating modes were defined. These operating modes and the targets that can be achieved with them are given in Table 2.
The different operating modes will be investigated during the testing of the LIREX ®. In this investigation, the achievable gains for each operational mode are to be quantified and the simulations that have already been done are to be confirmed. The effect of the ambient parameters will also be investigated to see to what extent, for example, the distance between stations, the line properties (gradients etc.) and auxiliary power consumers, affect the advantages that can be achieved.

<table>
<thead>
<tr>
<th>No.</th>
<th>Operating modes</th>
<th>Cost saving</th>
<th>Improvement of the environmental compatibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Reduction of the fuel consumption by recovering the braking energy</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>2</td>
<td>Increased power during acceleration (booster operation)</td>
<td>x&lt;sup&gt;(1)&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Noise reduction during starting in stations</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>4</td>
<td>Emission-free operation on short sections of line (e.g. tunnel stations)</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>5</td>
<td>Auxiliary supply when standing with the diesel engine stopped</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>6</td>
<td>Reduction of the fuel consumption by operation of the diesel units in low-consumption operating areas</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

<sup>(1)</sup> Smaller power packs can be fitted.

Table 2: Operating modes of the storage flywheel

Control strategies for the energy flows

Various control strategies are used in the different operating modes to achieve the main objective. The control strategies described refer primarily to the Lirex ® test carrier, but can also be used generally on other vehicles.

Operating mode 1: Recovering braking energy

During braking, the energy generated is fed into the intermediate circuit. Initially, only the auxiliary power consumers and storage flywheel are supplied through the intermediate circuit when braking. As soon as more energy is fed in than the auxiliary power consumers require, the storage flywheel is charged. When the storage flywheel is fully charged, the excess energy is converted into heat in the braking resistors. When the vehicle requires more energy than the dynamic brake supplies, the energy of the storage flywheel is used first. Only when the storage flywheel approaches its discharged limit or the load requirement exceeds the capacity of the storage flywheel are the diesel engines again cut in to produce power.

Operating mode 2: Increased power during acceleration (booster operation)

This control strategy is basically similar to operating mode 1. The only difference is that the available power is not limited by the control system. Consequently, the sum of the power output of the storage flywheels and the diesel engines is available during the acceleration phase.
This strategy can only be used if the power electronics and the traction motors have been designed for this increased power. This cannot always be assumed to be the case if equipment is to be retrofitted to existing vehicles.

The Lirex® test vehicle allows unrestricted booster operation.

**Operating mode 3: Noise reduction during starting in stations**

An ideal control system for noise reduction in stations would be to arrange for a storage flywheel charge before the vehicle entered the station that was just sufficient and to shut down the diesel engines for the duration of the time the train was in the station and the subsequent departure. During deceleration and acceleration outside stations, the control system should behave the same as in operating mode 1 or 2.

The main difference between operating mode 3 and operating modes 1 and 2 is that for operating mode 3 a control algorithm has to be used that looks ahead. Only with knowledge of the positions of stations can the control system arrange at the right time (looking ahead) for the storage flywheel to get sufficient charge.

A “sufficient charge“ must ensure there is sufficient energy available for the following consumers:

- The supply for the auxiliary consumers when the train is standing still.
- The supply for the traction equipment and the auxiliary consumers until the train has left the station.

The quantity of energy required in the storage flywheel depends on several factors. The most important of these are:

- The duration of the time stopped in the station
- The energy requirement of the auxiliary consumers (note: this energy requirement can of course be reduced in an optimised control system, e.g. the air-conditioning equipment can be temporarily switched off when the train is standing in a station)
- The length, or duration of the period when the train is departing from the station
- The acceleration required when leaving the station
- The gradient of the track at the entry to and exit from the station
- The line resistance of the station tracks
- The losses in the storage flywheels

**Operating mode 4: Emission-free operation on short sections of line**

Like operating mode 3, operating mode 4 requires a control algorithm that looks ahead. In this case as well, the information on the emission-free section of line that has to be run through can be supplied either by an automatic system or by data input by the train driver to the control algorithm.

Just as operating mode 3, initially an automatic system will not be fitted for operating mode 4. The control system can arrange, after activating operating mode 4, to immediately charge the storage flywheels to 100% of the available capacity and then shutdown the diesel engines.

The train driver must, therefore, know where the section of line which must be run through without emissions begins and approximately how long it takes to charge the storage flywheels to 100%.
Operating mode 5: Supplying the auxiliary equipment when the train is standing with the diesel engines shut down

When the train is stationary, only a comparatively small proportion of the available power of the diesel engines is required to supply the auxiliary consumers. In this operating situation, the fuel consumption of the diesel engine for the power required is generally comparatively high. The control strategy does not need in this case to look ahead. Essentially, operating mode 1 is used. As soon as the vehicle comes to a standstill, the state of charge of the storage flywheels is checked and, if necessary, brought back to almost 100% by means of the diesel engines. Then the diesel engines are shut down.

The advantage lies in the fact that the diesel engines can be run in a more favourable operating range when charging the storage flywheels.

Operating mode 6: Reduction of the fuel consumption by operation of the diesel units in low-consumption operating areas

For this control system, it is first necessary to determine in which operating ranges the diesel engines have a comparatively low specific consumption. The control system then arranges that the diesel engines run as often as possible at the minimum consumption levels. If the diesel engines deliver a larger output than is instantaneously required, then the storage flywheels are charged. If the storage flywheels are fully charged and the load requirement is still far less than the power developed by the diesel engines, the diesel engines can be shut down. If several diesel engines are available on a vehicle, then the diesel engines can be successively shut down depending on the instantaneous power requirement.

Simulation of the operating modes

As part of a study, simulations have been carried out at Deutsche Bahn AG in order firstly to establish whether sufficient energy savings can be achieved with a storage flywheel and secondly to be able to specify the most important design parameters for a storage flywheel (storage capacity, power required etc.). The simulation of the originally planned test line Magdeburg - Halberstadt - Thale is described below, by way of an example.

The actual line data for curve and gradient resistances as well as the maximum speeds permitted on the line at the time of the simulation were used. The line has a total length of 87 km and 8 stations. The simulation was based on operating mode 1, reduction of the fuel consumption by recovering the braking energy. The vehicle parameters corresponded to those of LIREX ®. The simulations were carried out with Matlab/Simulink and allowed, among other things, for the power losses of the storage flywheel as well as the maximum available coefficient of adhesion between wheel and rail. The optimum method of driving was assumed.

Figure 1 shows the maximum permissible line speed and the cumulative energy requirement for a vehicle with and without storage flywheels.
This simulation showed an energy saving potential of about 11% for a vehicle with storage flywheels compared with a similar vehicle without storage flywheels. In general, the simulations showed, as expected, that the use of storage flywheels in vehicles produced the greatest advantage particularly on routes with relatively short distances between stations.

**Further optimisation**

In the operating modes described above, control algorithms that look ahead were not used for the planned test. A further improvement of the energy efficiency can probably be obtained by the use of control algorithms that look ahead. This applies especially when the applicable running time reserves are included in the control system as additional information.

A further idea is to operate the diesel engines using storage flywheels in emission-optimised load areas. Since conflict is likely between the aims of an emission-optimised and a fuel-consumption-optimised control system, such a control system should only be considered as an interim solution on the way to an efficient exhaust gas treatment system.

The use of storage flywheels in conjunction with a sequential deactivation of diesel engines could contribute to a further improvement in the energy balance.

The operating modes used for the test are for the moment only targeted towards one objective in each case - for example, mode 3 “noise reduction”. For an efficient application of storage flywheels, a compromise between the various targets can, depending on the operating situation, show a better solution.
In general, it is true to say the more information that is put into the control system and the more regulating variables that can be affected, the more efficiently can the primary energy be used. A precondition for such an optimisation is, of course, that a suitable control algorithm is available. Generally speaking, there is no ideal control system or ideal application of storage flywheels: It always depends on what objectives are to be achieved with this energy storage.

**Future outlook**

Storage flywheels will only be used in large quantities if they can save their costs in a comparatively short time. The savings can result from a reduction in fuel consumption, but can also come from the avoidance of other higher costs. An example of this is the emission-free operation of vehicles in tunnel stations. The most important factor, besides the technical reliability of storage flywheels, is therefore the cost of purchasing and maintaining them and - as a reference parameter - the cost of diesel fuel.

It can be assumed that the costs for storage flywheel systems would be considerably reduced if they were made in quantity. Since in the foreseeable future the cost of diesel fuel is more likely to rise than fall, the chances for the cost-effective use of storage flywheels can be confidently assessed.

**Summary**

Deutsche Bahn AG is for the first time testing a modern storage flywheel in the LIREX ® innovation vehicle. With the storage flywheel, the environmental compatibility is to be improved and the operating costs are to be reduced by lower diesel fuel consumption. After extensive simulations, different operating modes are being investigated in the tests: Recovery of the braking energy, emission-free operation on short sections of line, noise reduction, increase of power (booster operation) as well as the supply of the auxiliary equipment during standing and the reduction of diesel fuel consumption by the operation of the diesel engines in the operating areas that give the lowest fuel consumption.

**Source data, bibliography**


[2] Dr. Frank Täubner, Schwungrad-Energiespeicher - Stand der Technik, (Energy storage flywheels - state of the art) Paper to the Conference "Stadtbahnen ohne Fahrdraht“ (Urban services without contact wires), Kaiserslautern, 1999