Operation Experience with Magnetodynamic Flywheel Storage Systems in Public Transport Buses

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1 Introduction

Flywheel energy storage devices in the power supply of hybrid electric buses save energy, reduce environment pollution and feature further system advantages.

Since 1988 flywheel energy storage systems "Magnetodynamic Storage" MDS (2 kWh/150 kW) have been applied in electric urban transport buses in several European cities. In these applications the MDS is part of either a diesel-electric or a trolley-electric drive system, leveling the power peaks of the drive and recovering the brake energy. As a result, energy consumption and pollution are decreased significantly.

The MDS is a compact flywheel system developed by Magnet-Motor GmbH (MM). The rotor is a hollow cylinder and is primarily made of carbon fiber compound. To make the system very compact, the motor/generator (M/G) unit is integrated concentrically in the cylindrical rotor. Figure 1 left-hand side presents a principle sketch of the MDS.

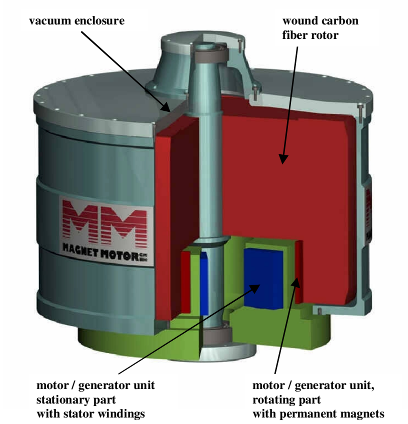

Figure 1: Principle sketch of an MDS

MDS K3 for bus application in its cardanic frame

The system stores energy when the M/G unit works as a motor and increases the speed of the rotor. The system delivers energy when the M/G-unit is switched to generator mode, thus reducing the rotor speed. The M/G unit is a permanent magnet excited machine, powered by compact, high performance IGBT-inverters and is especially developed for the application in flywheels. The machine is optimized for both very low no-load losses and a very high efficiency of 91-95 %, included the efficiency of the inverters.

The only system interface to the outside is the electrical connections of the M/G-unit. No rotating parts have to be directed outside the unit. By integrating the complete flywheel in a vacuum housing, the losses due to air friction are very low. The vacuum is maintained by a small pump, which needs to operate only temporarily.

Losses through friction on the mechanical roller bearings are minimized by magnetic supporting of the rotor. The cooling of the stator and of the inverters is performed by a closed loop liquid circuit, which means that no dust can penetrate into the system. A standard liquid/air heat exchanger transmits the heat to the surroundings.

For the application in vehicles the vertical arrangement of the rotor axle is an essential condition to minimize gyroscopic forces. Additionally the MDS is mounted in a cardanic frame (see Figure 1 right-hand side).

Of course, the application in buses implements an official safety certification including a crash test at a shock amplitude of 6g. The complete storage unit continued its normal operation even during these crash tests.

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A very important feature for the application in urban transport buses is the capability of an extreme high number of charge/discharge cycles. An average cycle duration of 2-3 minutes in a city bus means about 20 - 25 cycles per hour or up to about 180,000 cycles per year. The life time of the MDS is expected up to 10^7 cycles and thus it meets the requirements very well.

The next generation of MDS is presently on the test stand and will soon be applied in buses, tramways and city rails. Main data are given in Table 1 below. Data of the standard MDS for buses (MDS K3) are given in the first column:

		MDS K3 Bus Application	MDS K6 Prototype 2000	MDS M1 Prototype 1999	
Stored Energy	E=	7.2	21.6	32.4	MJ
Max. Power	P=	150	450	900	kW
Operating Speed	n=	12,000	21,000	18,000	min^{-1}
Diameter	d=	0.66	0.66	0.78	m
Height	h=	0.64	0.64	0.75	m
Mass	m=	400	400	600	kg
Specific energy	E/m	18	55	55	MJ/t
Specific power	P/m	0.38	1.13	1.50	MW/t

Table 1: Main technical data of present Magnetodynamic Storage devices

2 Application of MDS in Urban transport buses

2.1 Technical Concept of the Diesel-Electric-Storage Buses

Figure 2 gives at the left side an exemplary overview of the implementation of the Magnet-Motor-drive system and the MDS in one of the diesel-electric-storage buses, the Neoplan N4114DES:

Two MM motors mounted directly on the drive wheels power the rear wheels via a single stage planetary transmission. The drive motors do not only to propel the vehicle, they also serve as electric brakes. The MM generator is mounted directly on the flywheel of the internal combustion engine. It has a power rating of approx. 90 kW. The MM Magnetodynamic Storage (MDS) unit is mounted in the rear side of the bus. The electric drive motors, the generator and the MDS unit are controlled electronically by power electronic units (current inverters) with IGBT power modules. On the right side of Figure 2 a block diagram is shown.

Figure 2: Schematic illustration and block diagram of the diesel-electric drive system with MDS unit in the Neoplan 4114 DES.

With the Magnet-Motor system, the diesel engine will only have to deliver the average time power, using a generator that produces electric power. The actual drive system is either one single electric motor driving a conventional rear axle or two separate electric motors each mounted to a drive wheel of the bus.

Peak power necessary to get the bus moving and for acceleration is provided by the Magnetodynamic Storage system, again as electric power. The MDS is recharged during the braking phase and, if necessary, during the cruising speed phase with excess power from the generator. The bus will therefore have precisely the same performance functions as a conventional bus, but it will have decisive advantages:

- a smaller diesel engine will do the job
- energy savings through recovery of brake energy

- additional energy savings, significantly reduced emissions and less noise as a result of the special operating mode of the diesel engine.

Further bus integration possibilities are given in Figure 3 which show the diesel-electric-storage buses of Munich and Bremen respectively.

Figure 3: Diesel-Electric-Storage buses for public service in Munich (left) and Bremen (right)

2.2 Technical Concept of the Trolley Buses

The trolley buses are equipped with 4 wheel drive units. Prime energy is supported via the catenary with a power rating of maximal 100 kW. The MDS serves as a 150 kW peak power source and recovers the brake energy. A photograph of the first one of 12 Trolley buses, which operates since 1993 in Basel, Switzerland is presented in Figure 4.

Figure 4: Basel trolley bus equipped with Magnetodynamic Storage system MDS K3

3 Energy Saving Results and Discussion

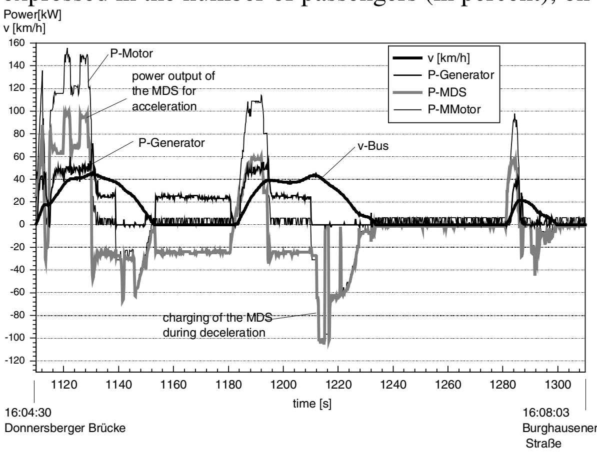
3.1 Diesel-Electric-Storage Buses

Typical results of recordings of the internal electric energy flow in a diesel-electric-storage bus are presented in Figure 5. The diagram on the right-hand side shows the energy produced by the generator as well as the energy consumed by the wheel motors to power the vehicle together with the energy contents of the MDS. A route segment was selected in which the MDS has approximately the same energy content at the beginning and at the end. It can be seen that 2,02 kWh, i.e. an equivalent of 35 % of the energy consumed to actually power the vehicle (MM motors) does not come from the generator, but results from recovered energy during the braking phases.

These measurements demonstrate the effect of brake energy recovery. The total energy consumption of the vehicle, however, is influenced by several additional factors so that the typical over all energy saving effect results in a smaller percentage.

In order to evaluate fuel consumption savings flow meter instruments were installed in the fuel supply line to the engine of two diesel-electric-storage buses as well as in one conventional diesel bus for comparison. The recording obtained from the flow meter delivered large amounts of data. Vehicle No. 2 for example covered a total distance of approximately 46,000 km.

As an examplary result of these measurements the influence of the weight of the vehicle (vehicle plus payload), expressed in the number of passengers (in percent), on the fuel consumption is presented. Figure 6 illustrates this.



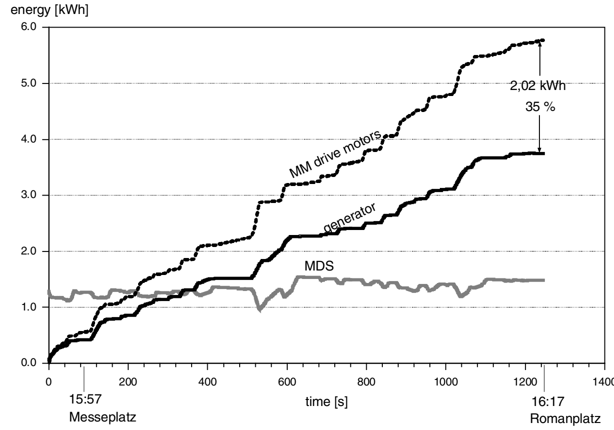


Figure 5: Recording of the internal electric energy flow (left) and (right) schematic of the system's internal energy balance on a typical run in Munich (regular line service). Only about 65% of the energy required to power the bus is produced by the diesel engine/generator unit. The remaining 35% result from recovered braking energy.

The figure (lower graph) shows no significant weight dependence of the fuel consumption. This is in contrast to the fuel consumption values for a comparable conventional buses (upper graph), in which can be observed an increase in the fuel consumption directly proportional to the increase in weight.

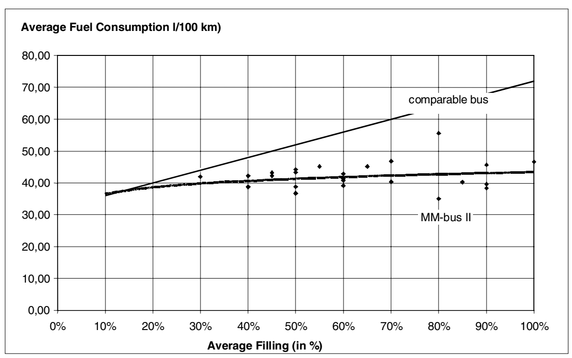


Figure 6: Average fuel consumption and vehicle weight

In total the measurements of energy consumption show that the potential for energy savings of the diesel-electric drive system with MDS is particularly high compared to a conventional diesel engine drive system if the following operating conditions prevail:

- if possible, very high passenger numbers
- short distances between bus stops and marked acceleration and braking phases
- mid-range average speeds.

These conditions are typical for a bus doing line service in cities, but this does not apply for all lines and at all hours of operation. The following example will serve for the evaluation of energy savings under normal conditions in line service.

The mileage of a standard, conventional urban service bus in Munich is approx. 60.000 km annually, and it will consume approx. 25.000 liters of diesel fuel for this distance. The average fuel consumption is approx. 42 l/100 km. The daily running time is normally 16 hours. This is roughly the time span between 6:00 a.m. and 10:00 p.m. Within this time span you normally have two rush hours (6:30 to 8:30 a.m. and 4:00 to 6:30 p.m.).

About 48 % of all the passengers ride the bus within these two rush hour times (the equivalent of approx. 10.7 % of the total daily traffic per hour), and the rest of the passengers share the remaining 11.5 hours (the equivalent of

approx. 4.5 % of the daily traffic per hour). During these rush hours, the average (high) passenger rate can be expected to be around 70 to 75 % and during other times, it can be expected to be approx. 15 %.
A standard, conventional urban service bus has a fuel consumption of 60 l/100 km during the rush hours, according to the correlations illustrated in Figure 6, while a bus used in the demonstration project would only consume approx. 42 l/100 km under the same operating and route conditions . This is the equivalent of a reduction in the fuel consumption of approx. 30 %. During the off-hours with low passenger rates, there is practically no difference in the fuel consumption between the two drive systems.

But since all available buses are deployed during the rush hours and the number of buses is usually reduced considerably during non-rush hours because there is less demand for transportation, it can be assumed that considerable fuel savings can be achieved if the drive system with MDS is implemented.

The following situation would result, assuming the situation in Munich, with approx. 550 urban buses in daily service and with an average of 250 days in operation per bus, per year:

	Standard bus	MMM bus	Change
Diesel consumption RH per day	22,300 liters	15,600 liters	- 30 %
Diesel consumption NRH per day	33,100 liters	33,000 liters	+/- 0 %
Diesel consumption per day	55,400 liters	48,600 liters	-12 %
Diesel consumption per year	13.9 million liters	12.2 million liters	-12 %
RH: Rush hour NRH: Non-rush hour			

Table 2: Comparison of fuel consumption

As a result, there could be fuel savings of approx. 1.7 million liters of diesel fuel annually in Munich, if the complete bus fleet were equipped with the technology described in this report.

The average energy savings for such an electric urban bus is between 10% and 15%. If implemented on special lines, such as those with dedicated bus lanes that permit unhindered acceleration and braking processes, the energy savings can be expected to be approx. 25%.

3.2 Trolley Buses

The transportation authority in the Swiss city of Basel finds average energy savings of about 20 % to 25% for their trolley bus fleet with MDS support compared with conventional trolley buses on the same line. This value is comparable with the energy savings of the above described measurements with diesel-electric-storage buses.

4 Pollutant reductions

Pollutant emission tests had been carried out with the same type of buses. A summary of the most important results of the measurements, compared with a conventional bus are presented in extrapolated to the bus fleet of Munich:

This results in a CO_2 reduction of 12 % according to the reduction of average fuel consumption, a reduction of about 50 % of CO emission and a reduction of about 50 % of p.m. emission.

	Standard bus	MMM bus	Change	Change
Pollutant	tons/year	tons/year	tons/year	Delta in %
CO_2	33,000	29,000	- 4,000	- 12
CO	185	92	- 93	- 50
NO_x	560	560	+/- 0	+/- 0
Particulate	18.2	8.9	- 9.3	- 49

Table 3: Comparison of air pollutant emissions

5 Experiences, Maintenance and Repairs of MDS in 12 Basel Trolley Buses

The Basel Trolley Bus prototype was set into operation at the end of 1992. 11 additional buses were delivered during the year 1995. For these last buses 13 MDS units are available. For each of the MDS units the averaged operating hours are presently (01/09/2000) about 16,000 h. The operation hours of the MDS in the prototype bus are about

25,000. These add up to a total of about 233,000 h of MDS operation in the Basel buses. The total mileage of the buses is currently about 3 million kilometers.

The buses are up to 19 h/d in line service. Maintenance intervals for the MDS system in the buses are currently defined to 3500 operation hours. Based on the experiences especially with bearings and lubrication as well as on a proper optimization the intervals can be increased further. As we had even 6000 h operation without maintenance we are sure to increase regular maintenance intervals to more than 6000 hours in the near future. For the power electronic we have a statistical MBTF (mean time between failure) of more than 40,000 hours.

Currently the MDS has to be removed from the bus both, for repairs and for maintenance and has to be sent back to MM. Typical maintenance is to check the components as well as the system and to clean and lubricate or to exchange the bearings. This work usually needs about one working day.

In the first year of operation early failures occurred. These were on the one hand too low adjusted sensor levels for operation monitoring and on the other hand failures in the mechanical parts of the M/G-stators and in the cooling system. In the following years miscellaneous failures as well as failures of the bearings occurred. After having finished the last optimization of the bearing systems we had only one repair in 38,000 hours of operation. This is one repair in 8 month operation of 12 MDS units. The statistical situation of maintenance and repairs in the last 5 years is presented in Figure 7.

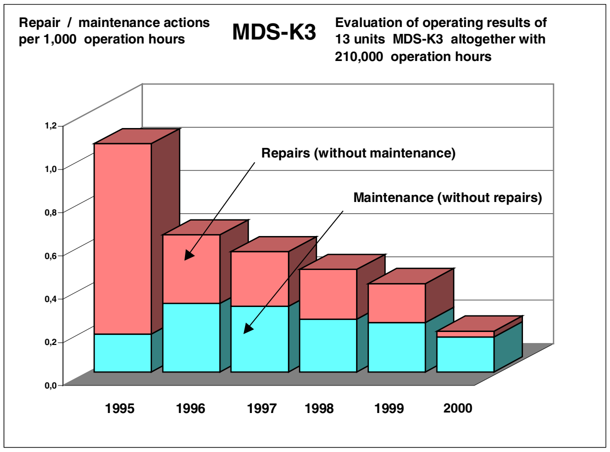


Figure 7: Repair and maintenance statistic of MDS units in 12 Basel Trolley buses

6 Conclusion and Outlook

It could clearly be shown that a reliable operation of MDS units in electric buses is possible. MDS and drive system has stood the test doing daily service over a couple of years. The electric drive system requires only 60% to 65% from the prime energy source due to the brake energy recovery of the MDS. This results in a reduction of prime energy consumption of the vehicle of about 10% to 25%. Electric diesel buses can reduce their pollution exhaust significantly, using an MDS.

MDS-technology is available up to 5MW in the laboratory. As a further application a prototype of a 800 kW MDS was installed in a transformer substation of the city rail in Cologne, Germany in spring 2000. First operation experiences of about 1500 hours were achieved.

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