The use of energy storage devices in suburban railway networks for more efficient utilisation of primary energy

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Abstract – **Energy storage devices are a useful extension to the electrical infrastructure in suburban railway networks. Their characteristic feature - to decouple the energy output from the energy absorption with respect to time - allows energy to be saved and load peaks to smoothed out. Compared to the possible alternatives, investment and operating costs can be saved through the use of a storage device. At the same time, on the whole a more uniform electrical loading of all components is achieved in the DC voltage network, which in turn has a positive effect on the operational reliability and service life of these components. Two basic objectives can be followed by the use of energy storage devices: firstly the saving of primary energy by efficient use of recovered braking energy and secondly voltage stabilisation at weak points in the DC voltage network. In the second case, the storage device is a cost-effective alternative to measures for reinforcing the power supply, which would otherwise be necessary, for example the construction of a new substation. The following article introduces a flywheel storage device that is already being used for this objective. The improvements that can be achieved by this storage device are revealed with the aid of actual applications and simulations.**

Introduction

Thanks to the use of modern vehicles with AC drive technology, recovered braking energy is available in DC railway networks, which in the optimum case is absorbed by accelerating vehicles in the immediate vicinity and thus leads to a lower energy demand from the substations. If, during braking, no consumer is available, the voltage at the contact wire increases since the energy cannot flow back into the upstream medium-voltage network via the rectifiers of the substations. If a certain voltage value is exceeded, the vehicle switches the current path from the contact wire to a braking resistor. The braking energy is then converted in resistors into heat and is not longer available as useful energy. If a storage device is placed in the vicinity of the braking vehicle, then this device absorbs the superfluous braking energy and then gives up the energy again when a consumer is in the vicinity. For example, if a vehicle approaches a stopping point, the storage device in the vicinity of the stop absorbs the braking energy and gives it up again if , the vehicle again needs energy when accelerating away from the stop. In this case the behaviour of the storage device can be very simply controlled via the voltage at the contact wire: the voltage rises when the vehicle brakes, the no-load voltage of the next substation is exceeded by a certain value, so this is the sign for the storage device to absorb energy. Conversely, the voltage at the contact wire drops as soon as a vehicle accelerates. If, in the course of this the voltage falls below a specific level, this means that the storage unit should give up energy. Therefore in this case the decoupling between energy absorption and energy output is used for efficient utilisation of the energy present in the network. All in all, the substations therefore draw considerably less primary energy.

Another very interesting way of saving costs through the use of energy storage devices is the application of peak load cover. The following is an example of this. The last substation feeding the end section, 3 km from the end of the line, is located at a deceleration section of the Hanover suburban railway.

At this section, üstra, the railway operating company in Hanover, had problems with maintaining the voltage at the contact wire. The shortening of journey times and the use of higher-capacity trains had necessitated the building of a new substation. Where only one train ran in the track section between substation and track end prior to the changeover, two trains ran simultaneously after the conversion. This allowed the voltage at the contact wire to fall until the trains were switched off and the track switches in the substation tripped up to 15 times a day because a supposed short-circuit was recorded.

The expensive new construction of a substation was avoided and the voltage reliably supported by the use of two Powerbridge type flywheel energy storage devices.

Energy storage device Piller Powerbridge

The POWERBRIDGE flywheel system was used to store energy in the traction power supply for DC railways. The basic circuit of the POWERBRIDGE system is shown in Fig. Figure 1.

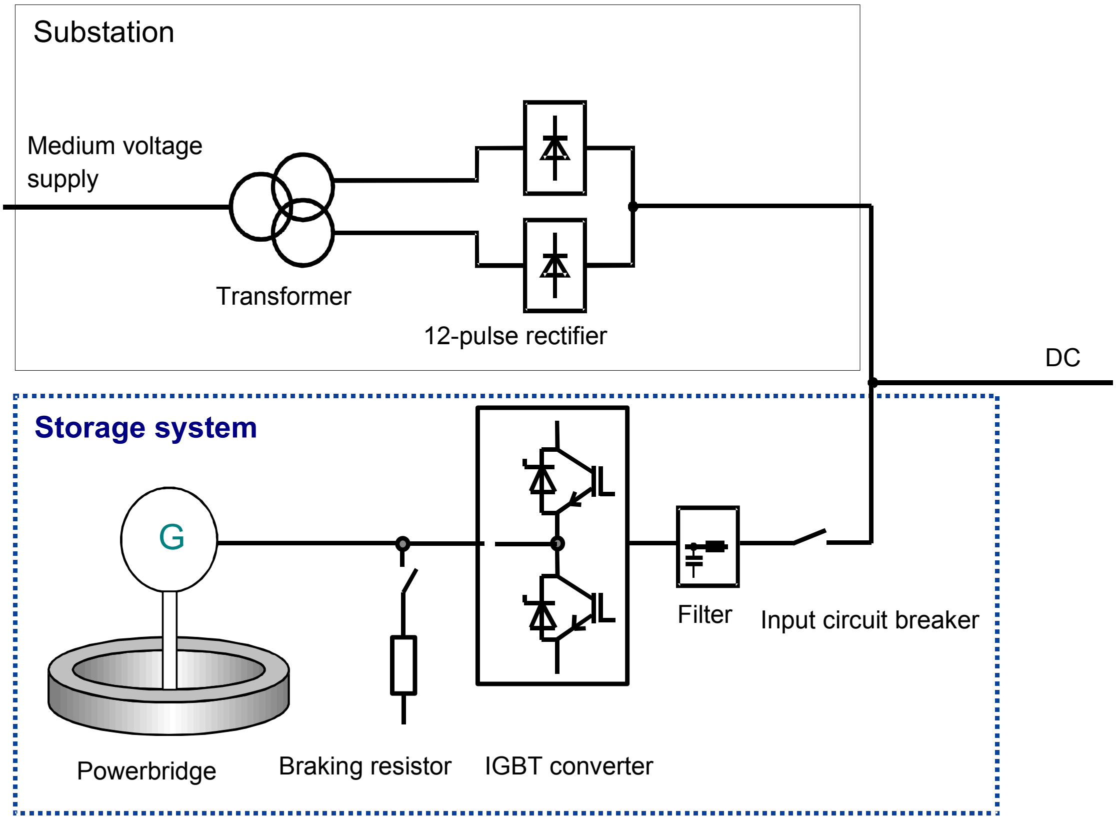

Figure 1: Powerbridge storage system

Normally the traction power is supplied by an uncontrolled twelve-pulse rectifier in the substation, which is fed via a transformer from the medium-voltage network. While the flywheel storage device is directly installed in the rectifier station and is used to store braking energy, the storage system is directly connected in parallel with the contact wire infeed. The storage system can, however, be directly connected to the contact wire at any point within the supplied network if it replaces an additional rectifier station used for voltage support in the supply network.

The Powerbridge storage system comprises the flywheel itself and a braking resistor which transfers the stored energy into heat if the PB has to be stopped immediately. E.g. the connection to the DC net has been interrupted and the PB has to be stopped. The IGBT converter is used for charging and discharging the PB and also to start the PB from standstill. The filter turned out to be necessary because the voltage at the overhead line is far from being a real DC voltage. A DC circuit breaker is the interface to the overhead line.

The storage system has only a connection to the DC line and it is not necessary to connect it to medium voltage. This is very important on the one hand because it is often very expensive to provide a substation with medium voltage: earth moving is necessary, a cable has to be drawn, a medium voltage switchgear has to be installed. And on the other hand without a connection to medium voltage the system can be installed very easily and quickly with little efforts and the installation location can be chosen very flexible.

Piller's rotating storage device is designed to replace batteries in premium power uninterruptible power supply systems, because batteries show many drawbacks like size, insufficient reliability for some applications, maintenance efforts and so on. Depending on the capacity of present-day large systems, an electrical power of 1100 kW is available for a bridging time of 15 s, which is used to supply the load during transient interruptions and enables a Diesel to be started.

In an in-house study Piller evaluated alternatives to batteries. The aim was to offer customers an energy storage device that has higher reliability, smaller size and much less maintenance effort than battery systems. Superconductive coils, supercaps and high speed flywheels were assessed but due to different reasons found not suitable at least for use in UPS applications. So Piller decided to go the way of what we think is the most reliable technology for energy storage devices today: a low speed steel flywheel. ("Low speed" means still a speed between 1800 rpm and 3600 rpm).

A vertically mounted cylindrical steel flywheel mass was chosen for the storage device. Since the speed versus the stored energy is a quadratic relationship, and the mass is therefore only linear, a relatively large flywheel mass is required. Due to the low speed of the periphery of the flywheel, operation in a vacuum is not necessary. A partial vacuum or a special gas filling makes it possible to obtain a considerable reduction in frictional losses.

In contrast to high-speed rotating flywheels, a fully controlled magnetic bearing can be dispensed with. Magnetic load reduction of the conventional bearings reduces the losses, increases maintenance intervals and bearing life.

Advantages of the low-speed flywheel are rugged construction with proven components, high overall system reliability and simple power electronics. The service life of such a system is approximately 25 to 30 years, which is comparable to other electromagnetic devices. Compared to high-speed storage systems, weight and footprint are actually greater, but the simpler design results in lower costs for a system of this type.

A synchronous machine mounted on a shaft along with the flywheel enables energy to coupled in and out. The frequency of the main machine is of the order of 120 Hz. Variable machine excitation allows a simple converter design compared to permanently excited systems, and excitation shut-off totally eliminates hysteresis losses.

Fig. 2 shows the side view of the POWERBRIDGE mechanical storage device. The rotor of the main machine is mounted above the flywheel on the same shaft. The stator of this four-pole synchronous machine is shrink-fitted into the tapered housing, so that the winding and core losses can be dissipated via the outer wall. The synchronous machine is excited electrically and without slip rings via the exciter located at the upper end of the shaft. The rotating rectifier is positioned below the upper end.

The properties of all parts are well known because the Powerbridge uses the same technology than has been used for decades in generators of power stations and all sorts of power supplies. Therefore the whole system could be simulated and modelled in advance and the simulation proved to be very close to reality after test of the first prototypes.
Worldwide more than 400 Powerbridges are running in UPS applications. In railway applications up to now 4 Powerbridges are operated by uestra, transportation company of Hanover, Germany (since 1999).
It has been found that the Powerbridge is also well suitable for the use in DC railway systems:

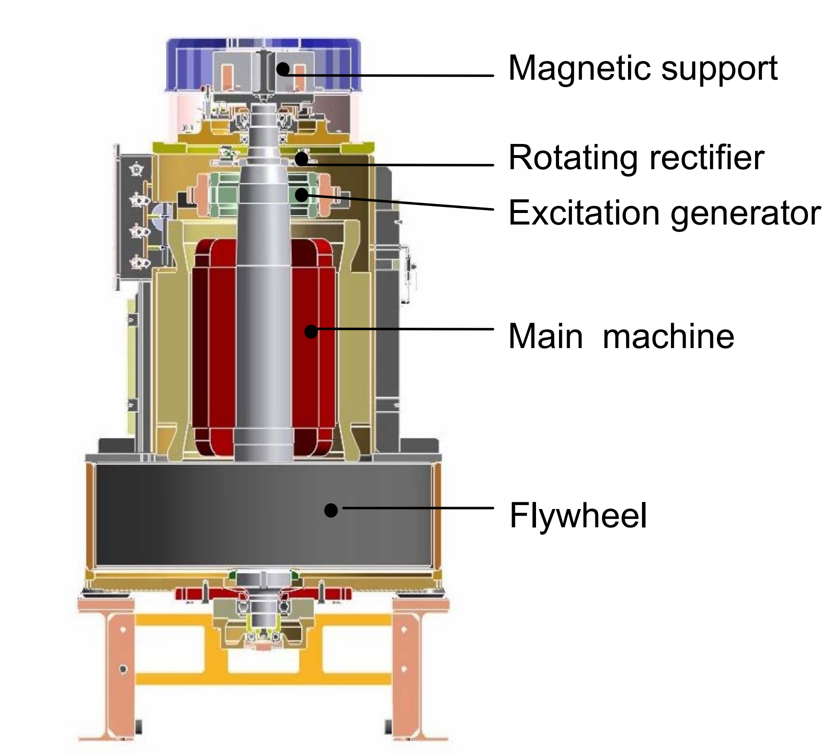

Figure 2: Cross section of PILLER Powerbridge

4.6 kWh of useable energy content and 1000 kW power are in the same range than the kinetic energy and power consumption of a DC railway vehicle. The system is well suitable for nearly all common DC voltages used in railway systems worldwide.

Simulation

The use of an energy storage device is preceded by a load flow calculation for the network section in which the storage device is provided. This network section includes, for example for use at a track end, possibly the section from the penultimate substation up to the track end. This type of simulation is a simple and reliable method for determining the achievable savings and improvements in the network by using one or more storage devices. Or, it can forecast the characteristics (energy content, maximum current) which a storage device needs to possess in order to obtain the desired voltage stabilisation.

Problem

In the network of a German transport company there are problems with the voltage stability at the contact wire at the end point of a line. It is to be determined with the aid of a simulation what effect a PILLER POWERBRIDGE energy storage device has on the voltage stability. For this, the conditions in the network without the device were first modelled, The simulations were then repeated with the storage device under otherwise identical boundary conditions. The objective is to maintain the switch current in the substations as near as possible at ≤ 1800 A (= starting current of two trains accelerating simultaneously.

Boundary conditions of the simulation

The modelling is done with the data available from the transport operating company. An equivalent electrical circuit diagram of the track was built (see Fig. 3), in which the vehicles were considered as moveable consumers. The stopping times of the trains which otherwise are moved according to the timetable and track data, are influenced by a random generator. The energy conditions in the network are recalculated every 50 ms. These calculations were carried out for a period of 60 minutes. For the simulation, the basic time between trains was 5 minutes. All calculations are made on the basis of the theoretical maximum loading, that is to say:

- Maximum wear of the contact line
- Maximum resistance of the contact line
- Maximum temperature of the contact line
- The weight of all trains close to the maximum permissible overall weight
- The virtual maximum loading by auxiliary loads (e.g. heating and full load)

The calculations were carried out both at the highest present-day braking voltage of 900 V and at the maximum braking voltage, 1000 V, that is provided for 750 V systems.

The length of the track from the "Moosweiher“ stop to the "Laßberg" stop is 9826 metres. In the calculation the "Moosweiher" stop is assigned to the track point "0", the "Laßberg" stop corresponds to the track point "9826". In the calculation with the storage device, the location of the device is taken as "0".

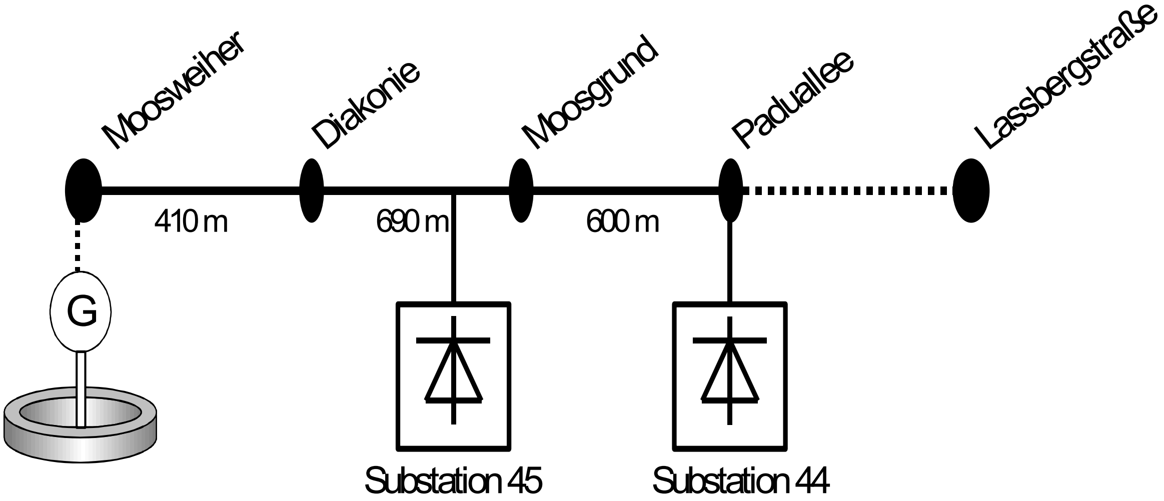

Figure 3: Track section under consideration, with locations of storage devices and substations

The basic technical data of the energy storage device are:

Voltage range	750 V (conforming to DIN EN 50163)
Energy contents	4.6 kWh (16.5 MWs)
Power	1 MW
Max. current	1500 A

The following variants were simulated:

1. Without storage device, braking voltage 900V
2. One device at the "Moosweiher" stop, braking voltage 900 V
3. One device at the "Moosweiher" stop, braking voltage 1000 V

Results

Table 1 below shows the substation currents, the currents at the track switches, the energy consumption and the 15-min peaks when no storage device is used (variant 1).
The maximum current from the rectifier substations is less than the maximum switch current, since current from the substation as well as current from the regenerative vehicles can flow via the switches.

Table 1 : Currents, energy consumption and 15-min. peaks without storage device

SubStn. Number	Pos.	Max. SubSt current [A]	Switch currents [A]				Consumption [kWh/h]	15-min peak [kW]
			Max. current ->Moosweiher	Rms current ->Moosweiher	Max. current -> Lassberg-straße	Rms current -> Lassberg-straße		
45	830	1120	1958	433	864	265	-181	196
44	1700	814	920	303	1076	300	-140	151
43	3000	1276	1108	301	1385	311	-191	209
42	4300	1322	1555	299	905	283	-188	197
41	5600	1303	1260	294	1201	331	-188	204
31	6981	1342	969	340	1463	313	-179	197
32	8001	1312	1436	262	1168	372	-185	206
33	9820	1633	1633	369	51	12	-186	200
Total consumption (over all substations)							-1438	

Table 2 shows the corresponding values when a storage device is used at the "Moosweiher" stop (location "0") (variant 2).

Table 2: Currents, energy consumption and 15-min peaks with storage device (variant 2)

SubStn. Number	Pos.	Max. SubSt current [A]	Switch currents [A]				Consumption [kWh/h]	15-min peak [kW]
			Max. current ->Moosweiher	Rms current ->Moosweiher	Max. current ->Lassberg-straße	Rms current -> Lassberg-straße		
45	830	1047	1389	338	823	276	-135	143
44	1700	708	851	271	1020	300	-126	137
43	3000	1174	1063	297	1384	311	-188	201
42	4300	1268	1456	299	992	289	-189	199
41	5600	1302	1293	296	1168	331	-189	203
31	6981	1342	981	336	1407	310	-181	198
32	8001	1321	1436	265	1107	372	-186	202
33	9820	1608	1608	369	51	12	-187	203
Total consumption (over all substations)							-1382	

Table 3 shows the corresponding values with storage device and a braking voltage of 1000 V (variant 3).

Table 3: Currents, energy consumption and 15-min. peaks with storage device (variant 3)

SubStn. Number .	Pos.	Max. SubSt current [A]	Switch currents [A]				Consump-tion [kWh/h]	15-min peak [kW]
			Max. current ->Moos-weiher	Rms current ->Moos-weiher	Max. current ->Lassberg-straße	Rms current ->Lassberg-straße		
45	830	1057	1412	357	853	320	-116	124
44	1700	708	1073	318	1022	348	-117	128
43	3000	1166	1288	336	1384	351	-180	193
42	4300	1271	1461	328	991	319	-185	196
41	5600	1310	1351	324	1185	356	-184	198
31	6981	1344	997	368	1372	345	-173	195
32	8001	1323	1452	311	1120	400	-177	199
33	9820	1609	1609	366	51	12	-183	199
Total consumption (over all substations)							-1317	

As the comparison of the tables shows, as expected only the section in the vicinity of the storage device is affected, that is to say, the loading of substation 45 is considerably reduced and the load on substation 44 is lower. The differences between the substations is basically due to the random effect in the simulation.

Whereas without storage devices the current at the switch of substation 45 rises above 1800 A, with storage devices in both variants a considerable reduction in the maximum current to around 1400 A is possible.

The energy absorption of the substations during the 60-minute simulation period is shown in the "Consumption" column. The "Total consumption" value therefore indicates the energy demand on the entire track, taking into account all losses, for example in the contact wire. All storage device losses are also indicated by the corresponding values in tables 2 and 3. This shows that with the use of a Powerbridge under the present conditions, more than 50 kWh per hour can be saved and - by increasing the braking voltage to 1000 V - even savings of more than 100 kWh/h are possible. This results in such high annual savings in energy costs, when only the workdays are taken into account (see table 4) that the storage device can be amortised via the savings in energy costs.

Table 4: Energy savings during workdays when using the storage device

	Annual saving (220 workdays/year, 15h/day, 6cts/kWh)	
	In kWh	In €
Comparison between variant 2 and variant 1	184 800	11 088
Comparison between variant 3 and variant 1	399 300	23 958

The following chart shows the current at the switch of substation 45 over time.

Here again it can be clearly seen that the current peaks due to the storage device are considerably reduced and the RMS value is also reduced (see table 2). At the same time the voltage at the vehicle is stabilised and maintained at a constant level (see Fig. 5).

Figure 4: Switch current at substation 45 with and without Powerbridge

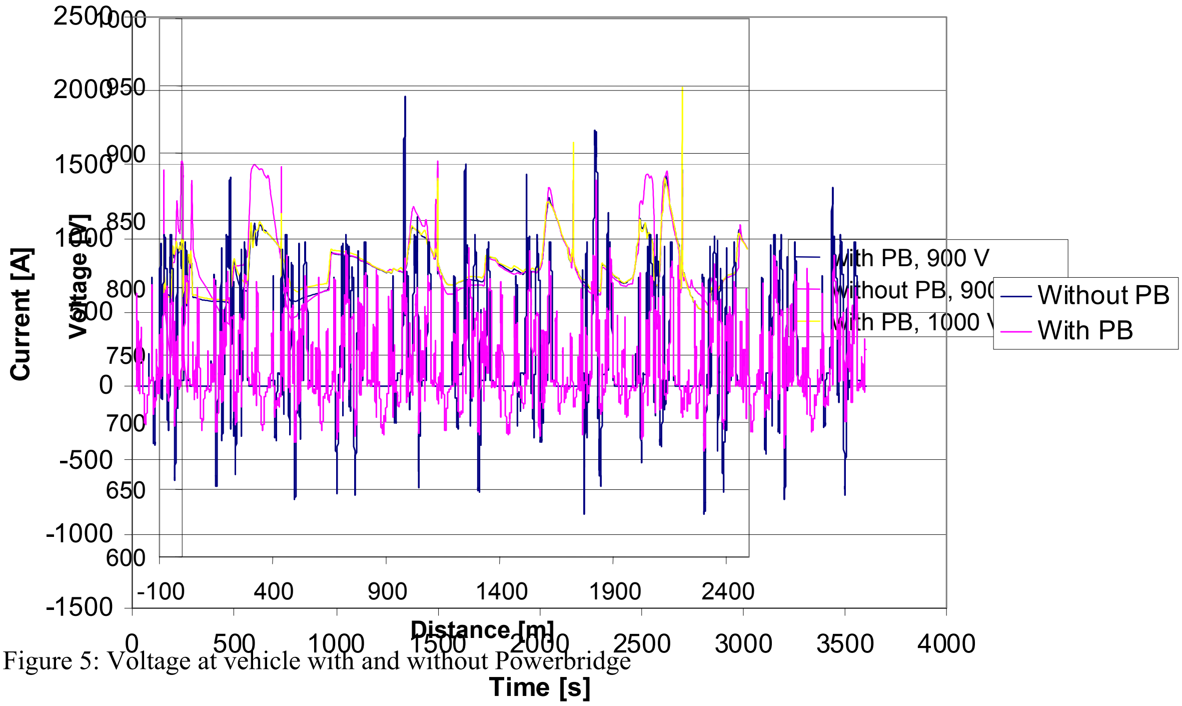

Figure 5: Voltage at vehicle with and without Powerbridge

Summary

The simulation shows that the problems in the "Landwasser" area are eliminated by the use of a PILLER POWERBRIDGE energy storage device. The switch currents are appreciably reduced to below the maximum permissible level. At the same time, energy savings which make a considerable contribution to the amortisation of the storage device are possible and at the same time, with an increase in the braking voltage, allow full amortisation of the storage device via the achievable savings.

An example was given for voltage stabilisation at the end of a track. It might also make sense to have a mobile power supply available to cope with problems that come up only from time to time. For instance if a substation has to be switched off for maintenance, if many vehicles draw energy from only one substation for instance after big events which took place in a stadium or similar premises.

If new, more powerful vehicles are introduced, energy demand in the grid is higher which might lead to energy shortages. These shortages can also be eliminated by the use of Powerbridge.

Energy cost can be reduced because of savings of braking energy. Due to the load leveling effects of the Powerbridge the overall efficiency of recuperation of energy from braking vehicles is increased and the disturbing feedback from the DC line to the medium voltage level is minimized.

To improve the quality of the power supply a renewal of the overhead lines is often considered. If this renewal is only to increase voltage stability along a track the Powerbridge is a cost-effective alternative.

In general it’s worth thinking about a storage device as soon as measures for improvement of the power supply have to be taken.