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Electric City Bus "Smart Wheels" – A Concept for Electric Mobility in Public Transportation

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Abstract

Within the Smart Wheels Project of the German Ministry of Economics and Technology (BMWi) a battery electric bus is developed, which is based on the Mercedes Sprinter City 65. The bus and its powertrain are designed with the help of detailed Matlab Simulink simulations for an operation in the very inner city center close to pedestrian areas and historical buildings. The bus has a length of 7.7 m and 25 seats for passengers and is equipped with a 120 kW electric machine. Besides the integration of a new electric drive system, the project is also focussing on a tailor made fast charging station that will be located at the end of the bus line. This offers the possibility of reducing the battery capacity, i. e. weight and costs. The DC charging system allows to recharge 20 kWh of electric energy within 20 minutes. First measurement results and experiences of operating the city bus are very promising. Several bus producers have already shown their interest in this project. It delivers many information for a possible serial production of this kind of buses.

Keywords: BEV (Battery Electric Vehicle); fast charge; public transport; regenerative braking

1 Introduction

Electrical powertrains are utilized in passenger cars almost as long as internal combustion engines. In 1881 a three wheel car, powered by an electric motor and a rechargeable battery, was introduced in Paris on the "International Electricity Exposition". At the beginning of the 20th century, electrically driven cars had a significant market share. Due to their short cruising range and to the introduction of the electric starter motor for internal combustion engines, electric powertrains have been forced out of the market during the following years. Up to now, vehicles powered by diesel or petrol engines control the market almost completely. Due to a rising common environmental sensitivity regarding pollution caused by combustion engines and changes in legislation, the development of alternative vehicle propulsion concepts came into focus and it has been attempted to utilize electric motors in vehicle propulsion systems. Motivated by the disadvantages of combustion engines in the ecological balance, an increasing scarcity of raw materials and therewith increasing fuel prices, great efforts are put into electric mobility. For example, the German government announced their target to have one million electric vehicles registered in Germany by 2020 and to make Germany the driving market for electric mobility. For this reason, the German Ministry of Economics and Technology (BMWi) founded the "ICT for electric mobility", a focal point of support and research. As a part of this, the pilot project "Smart Wheels" develops business models and Information and Communications Technology (ICT)-services to increase electric mobility in the model area Aachen (Germany) by integration into intelligent power networks and the infrastructure of the municipal energy supplier. Results of this project should also give answers to the usability of battery electric vehicles in daily life. Therefore a fleet of 20 electric scooters and 16 electric cars were purchased, equipped with data loggers and handed over to a group of probands (see Fig. 1).

Figure. 1: Vehicle fleet in the Smart Wheels Project

Due to short operating ranges in urban areas, the electrification of vehicle propulsion systems can be used as a reasonable measure to reduce noise emissions and pollution. Since the operating profile of city buses offers frequent stops, which allow recovering braking energy, the utilization of electric powertrains in city buses seems ecologically worthwhile. Another advantage of city buses is the predefined route, so that the necessary amount of energy can be calculated in advance. For this reason the development of a city bus with an electric drivetrain and a capacity of 30 passengers was started during this project.

2 Analysis of Possible Operational Scenarios

There are already different buses with battery electric propulsion available on the market that have a capacity of round about 30 passengers and a maximum range between 80 and 160 km under perfect conditions.

2.1 Demands concerning the electric propulsion system

Table 1 shows a list of four competitor vehicles and the specifications for the target vehicle [1]. The main points for not choosing an available bus were the limited power of all vehicles and the long charging time of at least 6 hours. Both criteria reduce the availability of the vehicle compared to a diesel or hybrid bus. Thus two main criteria were specified for the battery system and the electric drivetrain:

- A maximum discharging power of 100 kW for 30 sec is required
- A quick charging ability is required, which is loading 50 % of the nominal energy content into the battery within 20 minutes

Table 1: Available electric buses and specifications for target vehicle

		Competitor A	Competitor B	Competitor C	Competitor D	Target vehicle
Vehicle gross weight	kg	3700	3560	4300	3026	<4000
passenger capacity	Pers.	23	31	32	15 (seaters)	25
Power E-motor	kW	35	27	30	90	>100
Battery type		Lithium-Polymer	Natrium-Nickel chloride	Lithium-Polymer	Lithium-Iron phosphate	Lithium-Ion
Energy content	kWh	90	42	57.6	40	45-50
Charging time	h	8	8	<10	6-8	<0,5
Top Speed	km/h	50	33	45	80	60
max. range	km	120	130	120	up to 160	at least 50

In cooperation with the local transportation authorities in Aachen (ASEAG) different scenarios and routes for a smaller electric bus were discussed. The advantage of emission free and silent transportation of persons offers the opportunity to operate this bus in the very inner city center close to pedestrian areas and historical buildings.

2.2 Results of the Simulation Model

The ika has built up a Simulink® based simulation model for longitudinal dynamics to estimate the energy and power demand of the electric bus [2], [3]. An estimation of the driving range and the drivetrain behaviour has been made based on different driving cycles including two possible city lines in the center of Aachen. The following vehicle parameters have been used for simulation as shown in Table. 2.

Table 2: Vehicle parameters used in simulation

Vehicle parameters	
Vehicle type	Mercedes-Benz Sprinter City 65
Seats	12
Standing places	10 - 15
Length	7.700 mm
Width	1.993 mm
Height	2.845 mm
Wheel base	4.325 mm
Maximum weight	5.650 kg
Motor power	120 kW
Max. motor torque	300 Nm
Overall ratio	21.3
Battery nominal voltage	360 V
Battery nominal capacity	45 kWh
Maximum charging power	60 kW

The drivetrain of this virtual vehicle has been built-up completely in a Matlab Simulink® model. This model can be used to calculate the energy demand in different cycles and to analyse the behaviour of each drivetrain component. A list of the used cycles is shown in Fig. 2.

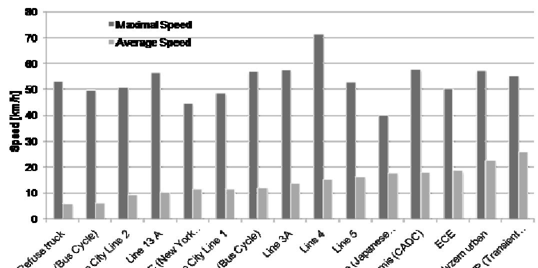

Figure 2: Cycles used in simulation

Only city cycles with an average speed of less than 30 km/h have been selected to represent a common use of urban buses. Each cycle has been simulated in a best case and a worst case regarding the energy consumption. The best case is a simulation with an additional load of just 300 kg and an average power demand of 400 W for the auxiliaries, the worst case is a simulation with the maximum weight of 5650 kg and an average power demand of 3000 W for the auxiliaries. The calculated maximum range with a usage of 80 % of the battery capacity is shown in Fig. 3.

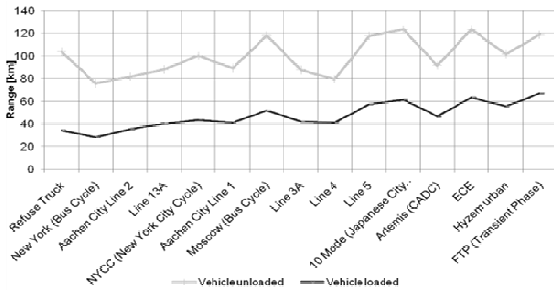

Figure 3: Calculated maximum range for a worst and best case scenario

So the bandwidth of the maximum driving range is between 30 km for the very worst case and 120 km for the best case scenario. Regarding the fact that city buses are usually not operated at their full passenger capacity, the simulations show that an average driving range of 50 km between two battery charging phases can be guaranteed.

3 Modifications of the Basic Vehicle

The Sprinter City 65 produced by Mercedes Benz Minibus uses the chassis of the 5.5t Sprinter platform truck. While being converted into a bus, the original rear ladder frame is removed and exchanged with a tubular steel frame covered with a body made of glass-fiber reinforced plastic as shown in Fig. 4.

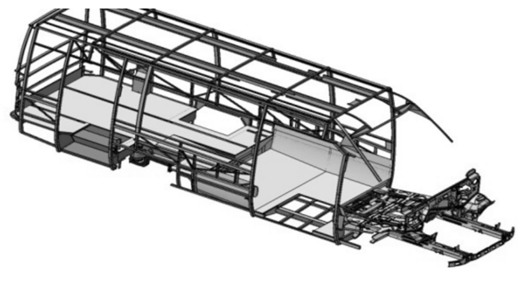

Figure 4: Rear tubular frame of the Sprinter City 65

Due to this design, the bus features a low-floor area at the front entrance. Therefore the original drivetrain is equipped with a custom made Z-formed gearbox mounted at the output flange of the automatic transmission which allows a routing of the cardan shaft even below the low-floor area on its way to the retarder. The rigid axle of this

Sprinter and the output of the retarder are connected with a very short additional cardan shaft.

3.1 Electrical and Mechanical Modificatons

While being converted into a battery electric vehicle, different system components of the diesel propelled Sprinter have to be removed or modified whereas other new components of the electric drivetrain are integrated. Table 3 gives an overview of the major modifications which have been implemented in this prototype vehicle.

Table 3: List of modifications

Removed Components	Modified Components	New Components
Combustion Engine	Frame for Battery Integration	High Voltage Batteries
Automatic Transmission	Instrument Cluster	Electric Motor
Z-formed Gearbox	Steering Rack	Planetary Gearbox
Cardan Shaft	Software Adjustment of ABS, ESP	AC/DC Converter
Retarder	Cooling Circuits	DC/DC Converter
Exhaust System	Heating Circuit	Power Distribution Unit
Large Fuel Tank	Radiators	230V-Charger
Engine Control Unit	Cable Harness	Electro Hydraulic Power Steering
Transmission Control Unit		HV Quick Charging Socket
		3 additional Control Units
		Information Display

The structure of the system architecture can be concluded from Figure 5. The propulsion unit consisting of the electric motor and the planetary gearbox is attached to the frame of the vehicle with four elastic engine mounts at the position of the former retarder.

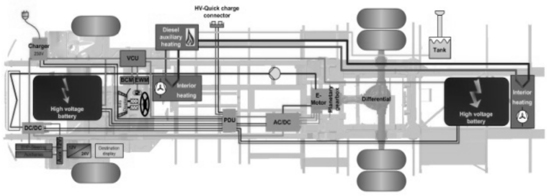

Figure 5: System structure of the Sprinter City 65 E-Cell

By choosing this position, the (second) cardan shaft, connecting the drive unit with the rigid axle could be taken from the basic vehicle. The AC/DC-converter is mounted at the underside of the chassis close to the motor in order to limit electromagnetical radiation emitted from the three AC-cables to a minimum. All electric HV-components are connected in one central power distribution unit (PDU) which houses the fuses and realizes an active discharge of the intermediate DC-circuit during power-off situations. The front HV-battery is mounted in the former automatic gearbox area, the rear battery is fixed to the tubular frame behind the rear axle. Figure 6 shows the connection of the front (left side) and rear battery bay (right side) to the existing structures of the chassis.

Larger effort has been invested in FEM-calculations of these structures to ensure the long term operational stability and to guarantee a high level of damage resistance in different crash configurations [4].

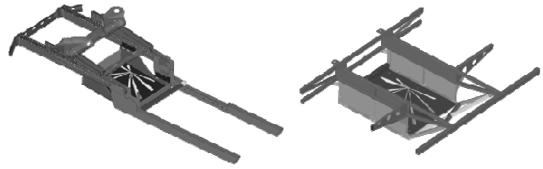

Fig. 6: Front and rear battery bay

To fix auxiliary components like the DC/DC-converter, the 230V-charger, the electric vacuum pump and a HV-PTC-heater, a rig carrying these components has been integrated in the former engine bay. Apart from these mechanical modifications an even larger part of work was invested in the development of a suitable topography of control units, CAN-structures and cable harnesses including reprogramming of existing control units and the creation of an operational strategy.

3.2 Modifications of the Topography of Control Units

Since taking out the entire engine including its sensors has a major influence on the behaviour of the different control units, several adaptations have to be made to the CAN-bus structure. Before the conversion, the CAN structure consisted of a class C high speed Vehicle CAN and a class B Interior CAN as shown in Fig. 7. Based on the knowledge of the CAN network and its senders and recipients, the influence of the conversion on the different control units was analysed and identified. Fig. 8 shows the modified CAN network.

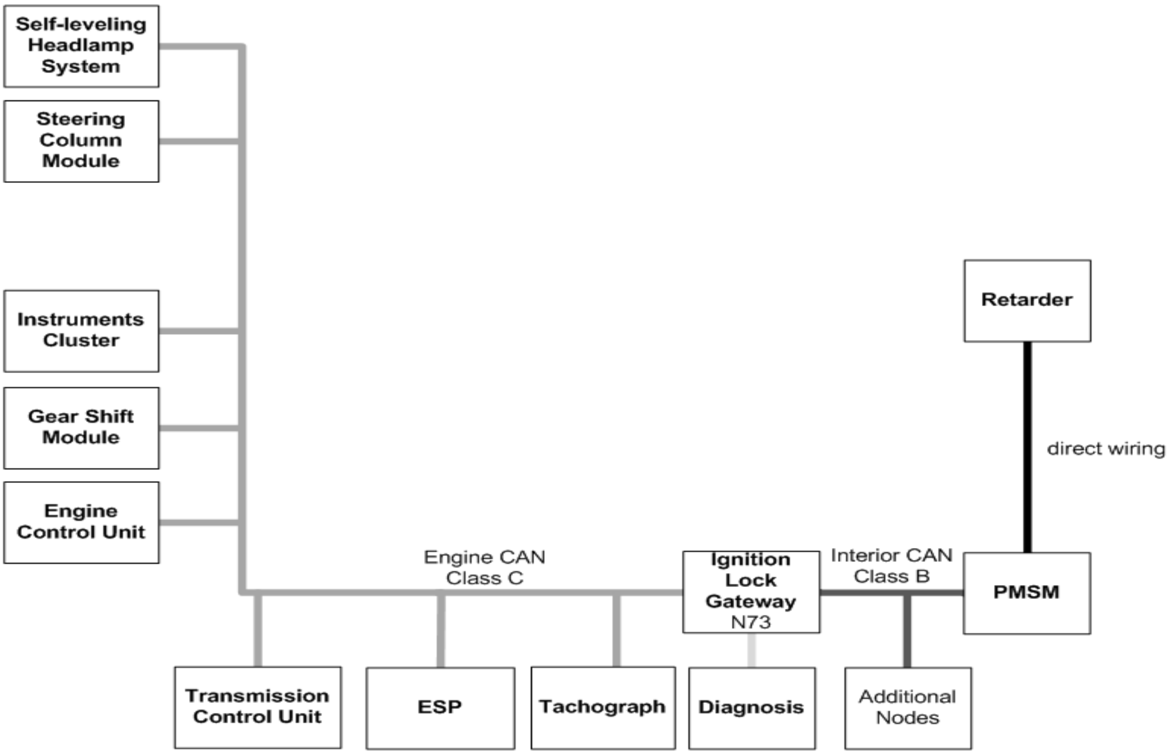

Figure 7: Control unit topography basic vehicle

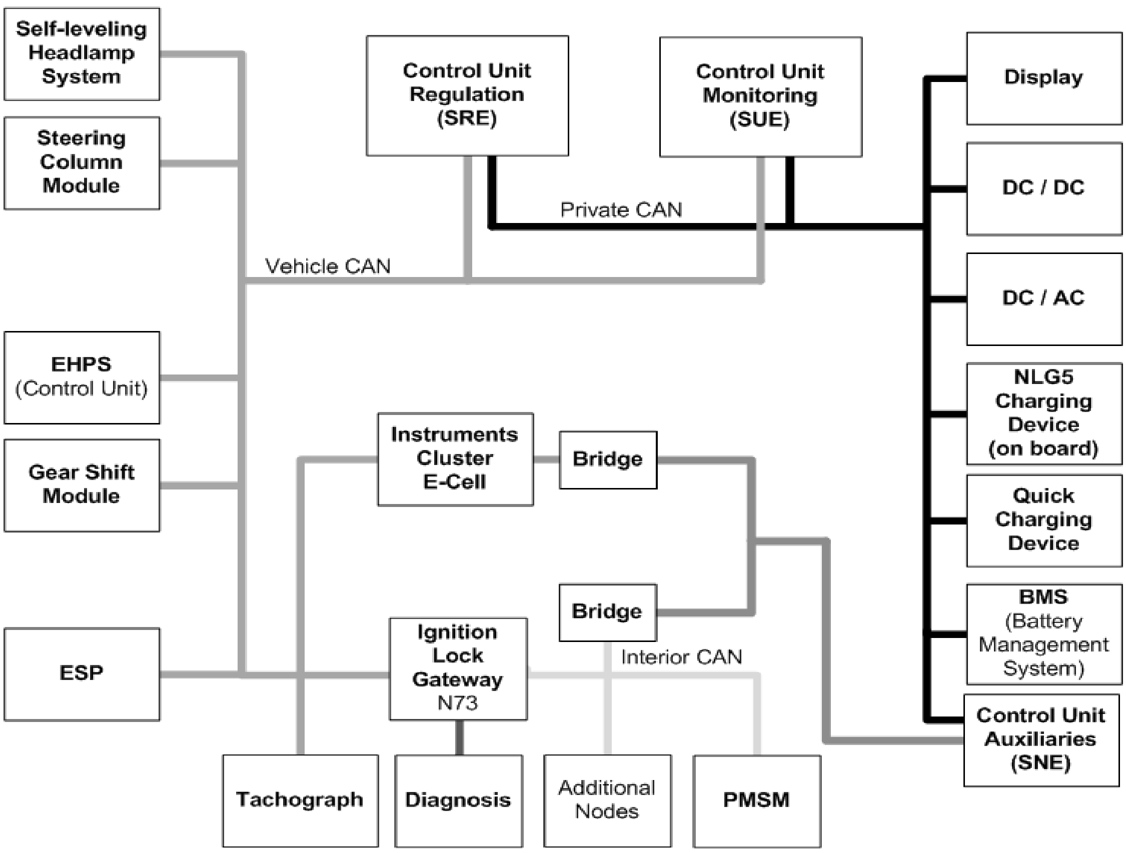

Figure 8: Control unit topography sprinter City 65 E-Cell

For example taking out the gearbox makes the use of the transmission control unit unnecessary. However, just leaving out this component causes a lot of trouble since there are other control units that expect messages from the transmission control unit.

These now missing messages must be simulated by a separate control unit, which has to be connected to the existing network. Therefore a third separate network (Private CAN) was established which interconnects the electrical components added to the vehicle. Two additional control units (SRE und SUE) were integrated and serve as gateways between Vehicle CAN and Private CAN. Also the entire operating strategy is implemented here using Matlab Simulink. An additional control unit (SNE) also gates the Private CAN to the Interior CAN using bridges since the two networks have different bus speeds.

The operating strategy itself is split into functional groups. The control system for the electric drivetrain is implemented on the SRE control unit, since the watchdog function is implemented on the SUE control unit. So the two control units interact directly and verify/check each other. The SNE controls all auxiliary systems, such as vacuum pump, water pumps, heater and fans.

The source code is generated by a tool chain, which is provided with the control units. It generates executable code directly from the ika's Matlab Simulink® models of the operation strategy.

3.3 Battery System

Considering the daily driving range of the average inner city bus, the capacity of a battery for a full electric vehicle would have to be at least 120 kWh. This would lead to a battery weight of more than 1100 kg and a volume of 850 l. As already stated before, it was therefore decided to build up a smaller battery of only 45 kWh which can be fast charged with a power up to 60 kW.

3.3.1 Layout

The battery is divided into two identically sized parallel packs consisting of 98 Kokam 60 Ah pouch bag cells in series, leading to a voltage range from 264 to 412 V. The battery type has been chosen due to the ratio of power density needed for fast charge and the relatively high energy density that goes along with pouch cells. The two battery packs are controlled by a common battery management system (BMS) consisting of a Master BMS and 14 Slave BMS. Therefore, each Slave BMS controls a module consisting of 14 cells. Each module is housed in a separate compartment that gives mechanical stability to the relatively soft pouch cells as it can be seen in Figure 9.

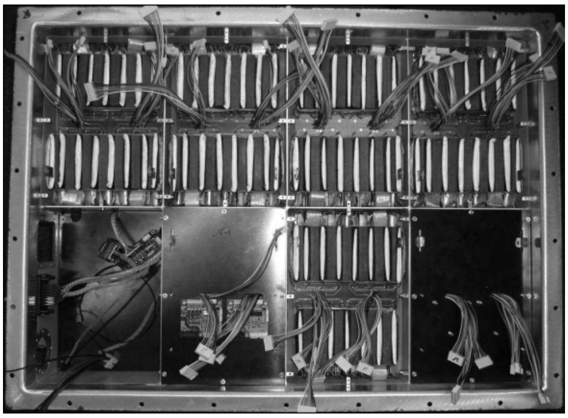

Figure 9: Battery layout consisting of 7 modules with 14 pouch bag cells each

Moreover the cells are fixed in the position with a cover on which the Slave BMS is mounted. To avoid the danger of an electric shock the modules are fully insulated against direct contact with the housing. Moreover, the insulation resistance of the whole high voltage circuit is monitored within the battery. The remaining free compartment is used as switch box and houses the high voltage and communication plugs.

Additionally to the normally open main relays each pack is secured with fuses at both poles. To be able to detect an error in the pack as soon as possible and to avoid further damage that can be caused by a thermal runaway, the temperature and voltage of each cell is measured. The temperature sensors are installed in between two cells so that each sensor is influenced by the two neighbouring cells. One damaged sensor therefore doesn't necessarily lead to the shutdown of the pack.

There still might be a driving situation, like for example an overtaking, in which an emergency shutdown of the battery is even more dangerous for the driver as a failure in the battery. Therefore a major point of safety is to be able to drive on with one battery. This is guaranteed by supplying the Master BMS externally by the 12 V-circuit and installing the insulation monitoring device at the intermediate circuit side of the switches. As there is only one inverter for both packs a reconnection of the packs during driving is not possible due to the high balancing current between the two packs. Therefore, the packs would have to be balanced during charging before being able to operate the vehicle in the normal mode again. This indicates that even though it is possible, the emergency shutdown of one pack should be limited to only few cases and the safety of the battery has to be ensured by avoiding these battery states beforehand by the battery management system.

3.3.2 Thermal Management

By using a quick charge system and having a high packing density, thermal management needs to be addressed as one central point of system layout. Therefore the thermal behaviour of a single cell was measured as shown in Fig. 10. At six spots temperature sensors were attached to the cell to cover the vertical and horizontal temperature distribution at the surface.
To shield the cell against outer influences it was isolated in styrofoam and then charged and discharged. This approximates the conditions in an uncooled battery pack.

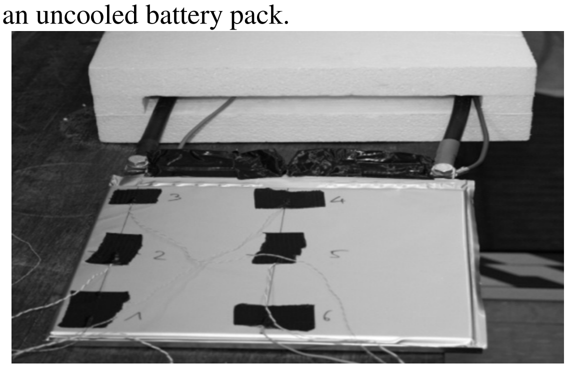

Figure 10: Measuring setup for
the temperature distribution of the cell

The charge and discharge current is set to 90 A and the shutdown temperature is 50°C. To simulate a summer day, the worst case regarding cooling, the cell is preconditioned to 35°C. As expected, the hottest spot of the cell is in the middle directly below the contacts where the temperature is measured by sensor 4. Therefore, in the following only the temperature at this point is addressed. After not even one discharge-and-charge cycle the temperature exceeds 50°C and the experiment is interrupted (see Fig.11). The experiment shows that a cooling system is mandatory. Therefore, a cooling system is implemented consisting of a liquid cooling plate in between the cells. The aluminium plate is attached to one of the cells by a silicone layer and covers the whole surface.

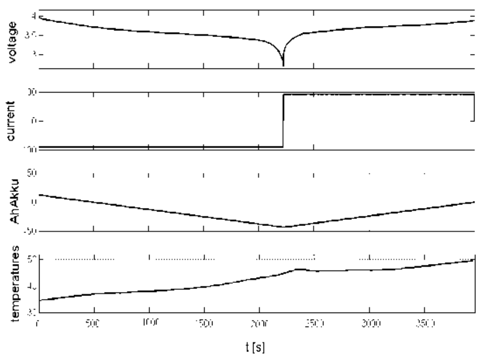

Figure 11: Cycling of a cell without cooling

The aluminium plate leads to a uniform cooling of the cell and is connected to the cooling plate at the bottom of the battery pack. As this would lead to big stray capacities within the battery pack, an additional electrical insulation in between the aluminium plate and the cooling plate is needed. The interface material has to fulfill several tasks: on the one hand it has to guarantee the electrical insulation and on the other hand the material has to have a good heat transfer coefficient so that the thermal connection of the cells to the cooling plate is ensured. Moreover, it should be soft enough to compensate surface roughness of the cooling plate.
For limiting the ageing and increasing the safety of the battery it is not only important to have an uniform cooling within one cell but all over the pack. The design of the cooling plate itself needs to be adjusted to a low pressure loss within the pack and a good and similar thermal connection of all cells. Therefore, simulations in COMSOL have been carried out to optimize the layout of the plate. Three different concepts have been taken into account. The easiest layout would be a meander channel in the cooling plate, which is not used due to the big dimension of the pack. Another option would be to build several meander in parallel which was not used because of the relatively low pressure capability of the used pump.
The finally chosen option, the bifilar cooling consists of circular channels within the cooling plate with always a hot and a cold channel next to each other as shown in Fig. 12. Simulations with different width of the channel and different velocities at the inlet show that the best cooling can be achieved with a width of 6 mm and a velocity of 0.7 m/s. According to simulations a temperature gradient below 3°C can be achieved throughout the pack.

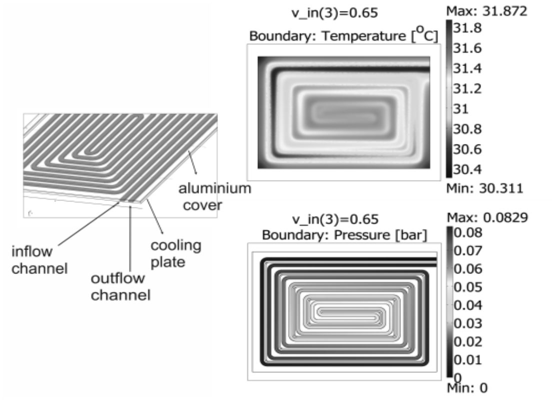

Figure 12: Cooling plate simulation results

3.4 DC Quick Charge System

To limit the battery capacity and the battery weight to an acceptable value a DC quick charge system is used which makes it possible to recharge around 20 kWh of electric energy in around 20 minutes. Thus, the battery capacity has not to be designed to supply a whole operation day but only around two to three hours of operation.

The quick charge system consists of the components “charging point” and “power electronics” (see Fig. 13). These two components are connected via a DC and signal connection cable including the charging plug and the user interface (Start/Stop button, emergency stop, display). The charging point, developed by the company Mennekes, can be placed outdoor and protects the charging plug and cable against humidity and vandalism. The power electronics consist of a control unit and two power modules of 30 kW output power each. The three-phase, 400 V AC voltage is firstly filtered and rectified and then distributed to the two power modules. These modules convert the DC voltage into a high-frequent AC voltage which is transformed by two transformers (galvanic isolation). The transformed AC voltage is then rectified and filtered on the secondary side. With an output relay and a decoupling diode the DC output voltage is directly used to charge the on-board battery of the electric bus. As the power electronics from the company Pintsch Bamag are normally used in railway technology they are protected against condensing humidity and can therefore be placed outside in a suitable cabinet. This is not possible with most conventional power electronics, They have to be installed in air-conditioned environments.

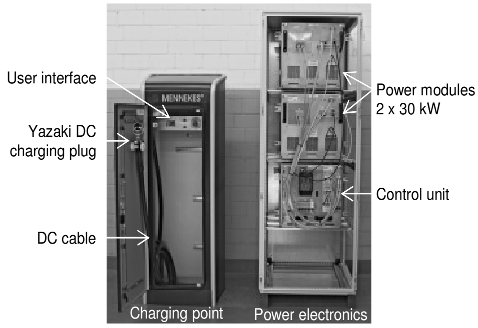

Figure 13: DC Quick Charge System: 265 V to 450 V DC Output Voltage, Max. 170 A DC Output Current, 60 kW DC Output Power

A simplified diagram of the start of the charging process is shown in Fig. 14. At first, the bus driver has to park the bus correctly and plug in the DC charging plug. Then the driver pushes the “Start charging” button located inside the charging point and the quick charging process begins according to the steps in Fig. 14. The charging process is monitored by the battery management system (BMS) attached to the electric bus battery. According to the state of the battery, the maximum possible charging power which does not violate the conditions for safe battery operation (e.g. cell voltage an temperature) is set. The charging power is controlled by setting the power electronics’ output voltage. This voltage is calculated by the BMS, the SRE transmits the set point value via CAN to the power electronics control unit. By locking the charging plug during the charging operation a safe charging process is guaranteed. In the case of failures in the communication or when the charging plug is removed (in the case of a failure in the locking mechanism), the output relays immediately shut down the DC voltage. This is realized by looping the relay control voltage through the charging plug.

The quick charge process is stopped by pressing the “Stop charging” button at the charging point. The display shows important information about the charging process like the amount of charged energy or possible error states of the charging station.

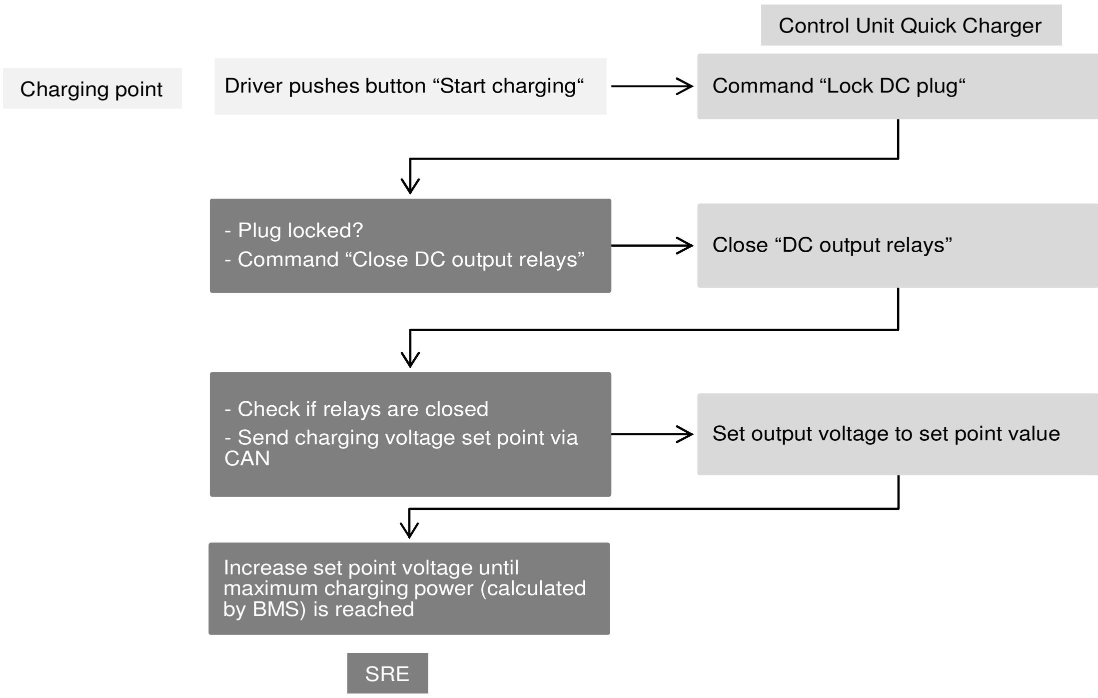

Figure 14: Start of the quick charging process

4 First Results of Test Drives

The bus has been tested in an early stage of the initial operation phase on ika's own testing facilities to prove the energy demand calculated in the simulations. The test drives have shown that the energy demand out of the high voltage batteries is between 35 and 70 kWh/100 km depending on the vehicle load and the driving behaviour. These results correlate with the simulation. Another interesting result of the first test drives is the fact that for a dynamic driving profile the recuperated energy into the battery is almost one third of the amount that is needed to propel the vehicle and to supply the auxiliaries.

Acknowledgment

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Acronyms, Abbreviations

CAN – Controller Area Network
BMS – Battery Management System
FEM – Finite Element Method
HV – High Voltage
ICT – Information and Communications Technology
PDU – Power Distribution Unit
PTC – Positive Temperature Coefficient
SRE – Electronic Control Unit for the Operational Strategy
SUE – Electronic Control Unit for parts of the Operational Strategy and Watchdog
SNE – Electronic Control Unit for the Control of Auxiliaries

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