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Design of an Energy Storage System for a Hybrid Electric Fuel Cell Bus

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1 Introduction – Presentation of the H_2-Bus Project

A cooperation of the German companies Vossloh Kiepe and Hoppecke, the Dutch company Advanced Public Transport System BV (APTS), the Institute for Automation Engineering (IA) of the University of Applied Sciences Cologne and the Institute for Power Electronics and Electrical Drives (ISEA) of the RWTH Aachen University develops and constructs a total of four 18 m fuel cell driven articulated city buses with energy storage system. Starting in 2010, two of them are going to be exploited at regular line service in Cologne, the other two in Amsterdam. The project “H2-Bus” is promoted by the Netherlands and the German state of North-Rhine Westphalia (part of the “NRW Hydrogen HyWay” lead project).

The authors are responsible for the sizing of the fuel cell system and the energy storage system as well as the energy management systems as described in the following sections.

2 Characteristics and Requirements of the Fuel Cell Bus

The drive train is energized by a hydrogen fuel cell (FC) system. An energy storage system supports the FC and recovers braking energy. The following conditions and features are mandatory for sizing both systems:

- The traction power of at least 200 kW has to be ensured.
- In case of a fuel cell malfunction, the energy storage system has to provide a reserve of driving range of not less than 1 km.
- Due to the high costs and low life expectancy of fuel cells, the energy storage system has to cover dynamic power demand changes (accelerating, regenerative braking) and allow for stationary fuel cell exploitation.
- To achieve sufficient storage system lifetimes at affordable costs also hybrid storage systems with two different storage technologies are taken into account.
- Limitations to current and voltage due to the power electronics (DC/DC converter, traction inverter, DC-link)
- The average passenger load is assumed to approx. 3,5 tons
- Auxiliary consumers (air conditioning, steering assistance) have been analyzed and are assumed to (“average” scenario) continuously 19.5 kW plus fuel cell system consumers (pumps, heat dissipation,…). The “worst case” scenario is assumed to continuously 43 kW (in total).
- Weight and available installation space

3 Approach: Sizing of Fuel Cell System and Energy Storage System

A vehicle model in MATLAB/SIMULINK has been developed to calculate the energy and power demand. Figure 1 shows a schematic of the drive train. Each component is linked to the DC link via a DC/DC-converter to enable maximum flexibility in terms of energy and power flow. The latter is controlled by an energy management system (EMS). Hybrid storage systems, composed of two different storage devices, are considered, too ("Energy storage device 1" and "Energy storage device 2").

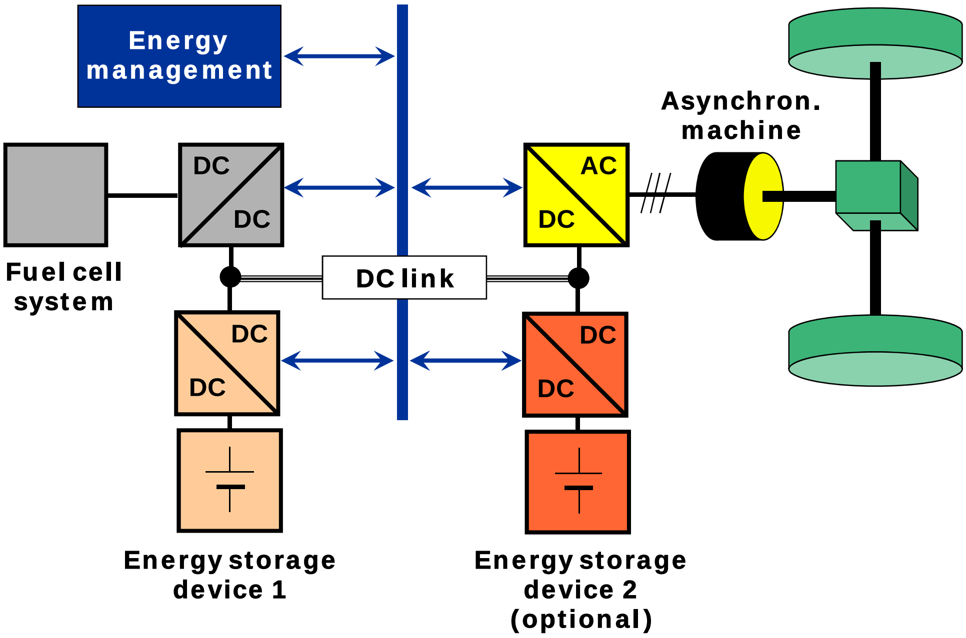

Figure 1: Schematic of the drive train.

Figure 2 shows the speed profile used as simulation input and the resulting power demand of the traction drive. It can be seen that the fuel cell system, the most costly component, would have to be oversized (demand only for traction > 200 kW) and would have to cope with dynamic load changes in case no energy storage system is used. In addition, the energy highlighted as red areas would be wasted as braking energy cannot be recovered.

For this purpose, different battery technologies were compared. Unlike private cars, buses of the local public transport serve up to 6000 hours a year, resulting in high stress for the battery system. Lithium ion batteries show excellent performance data. Reasons for discarding them from consideration were safety issues, the demand for high mechanical robustness and the lack of experience in heavy duty automotive applications. There are safe, reliable or mechanically robust lithium ion batteries, but it is difficult to achieve all features at a time and, in consideration of the tight project schedule, availability is a key factor. Further, nickel metal hydride (NiMH) batteries and electrochemical double layer capacitors (DLC) were investigated. Both of them are frequently used in hybrid electric transportation applications (buses, trams, trains) already today.

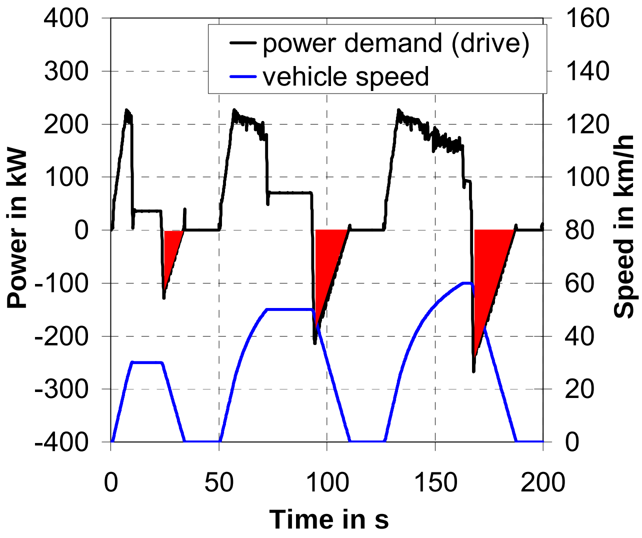

Figure 2: **Speed profile and resulting traction power demand, 0 % acclivity.**

Impedance-based models for the storage devices have been developed to be used in the vehicle model. Considering the requirements listed above, different storage system configurations among other were investigated by simulation in detail:

I. 450 NiMH cells (75 Ah, 1.2 V/cell)
II. 12 DLC modules (each module: 125 V rated voltage, 63 F nominal capacity)
III. 252 NiMH cells (75 Ah) and 6 DLC modules

For configuration III, 3 operating strategies were derived and compared, each having different advantages and disadvantages:

A) The NiMH battery is primarily used. Once it cannot provide any more requested power, the DLC covers the rest.
B) The DLC are used primarily. Once they are empty or cannot accept any more energy, the NiMH battery takes over the difference.
C) The state of charge (i.e. voltage) of the DLC system is controlled in function of the vehicle's speed to always being able to accept energy provided by regenerative braking. The NiMH battery covers the remaining dynamic power demand.

As benchmark, the following criteria were used:

- Load leveling to keep the fuel cell system in a stationary operation point
- Stress of respective energy storage device:
  Heat generation (NiMH & DLC) and depth of cycling (NiMH only)
- Overall system efficiency and H_2 consumption
- Uphill performance

4 Results

Table 1 shows an overview of the simulation results of the three configurations.

Table 1: **Overview of energy storage configurations, 0 % acclivity, aux. scenario: "average", "stress" is given in terms of cycle depth and heat generation in the storage system.**

	FC operation	NiMH stress	DLC stress	Weight	Fuel consumption
NiMH config. I	σ_P: 7 kW	ΔSOC: 4.6 % $P_{loss,cell}$: 19.9 W	-	1.51 t	192 gH_2/km
DLC config. II	σ_P: 35 kW	-	$P_{loss,module}$: 150.5 W	0.86 t	183 gH_2/km
Hybrid system config. III					
Strat. A)	σ_P: 15 kW	ΔSOC: 9.4 % $P_{loss,cell}$: 58.6 W	$P_{loss,module}$: 85.9 W	1.36 t	216 gH_2/km
Strat. B)	σ_P: 10 kW	ΔSOC: 3.5 % $P_{loss,cell}$: 12.4 W	$P_{loss,module}$: 669.7 W	1.36 t	194 gH_2/km
Strat. C)	σ_P: 4 kW	ΔSOC: 3.8 % $P_{loss,cell}$: 14.3 W	$P_{loss,module}$: 334.7 W	1.36 t	186 gH_2/km

Using configurations I and III C), the fuel cell system can be operated with a standard deviation (σ_P) of roughly 7 kW and 4 kW respectively. Both values are considered to be acceptable. In contrast, configuration II shows 35 kW standard deviation, which is due to the low energy capacity of the DLC system, limiting the available fuel cell power support relatively soon. Figure 3 shows the used drive profile ("actual speed") and the resulting power behavior of the different components for configuration II. As soon as the DLC modules' power has to decrease, the fuel cell system operation point has to match the resulting dynamic difference to the power demand.

The stress of the energy storage components is deviating significantly depending on configuration and operating strategy. As depth of cycling (ΔSOC) has a major impact on aging of NiMH batteries, it was desired to stay below 5 % of the nominal capacity. The temperature is another major influencing factor of aging of both NiMH batteries and DLC. It is represented by the heat generation ($P_{loss,cell}$ and $P_{loss,module}$) caused by losses due to the inner resistances[1]. Configurations I, III B) and C) are considered to be acceptable for the NiMH battery. For the DLC modules, this is valid for configuration III C), only. According to manufacturer instructions of the DLC, roughly 400 W of losses per module will lead to a temperature increase of 15 K above ambient.

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[1] Heat generation due to gassing effects – as they occur in NiMH batteries – are not included in this calculation.

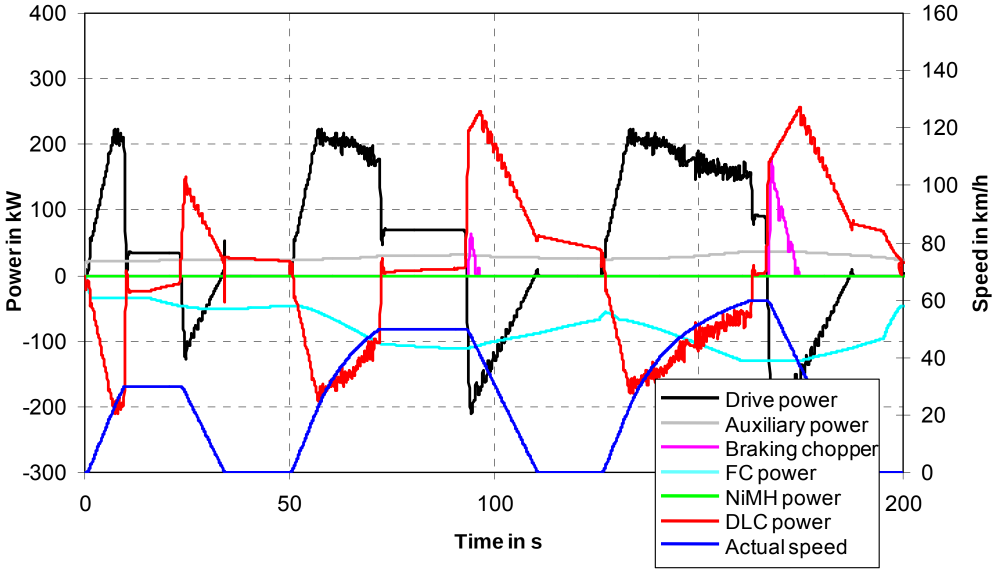

Figure 3: Simulation results, configuration II, aux. scenario: "average".

The fuel consumption depends on many parameters. Except for weight, efficiencies of the components have an important influence. With the NiMH battery generally having a lower efficiency, NiMH-orientated configurations and strategies (configuration I and III A)) show a higher H_2 consumption. Furthermore, the components' efficiencies (energy storage devices and FC system) themselves depend on current rate and temperature. This correlation results in the fact that operating strategy C) consumes less hydrogen than B).

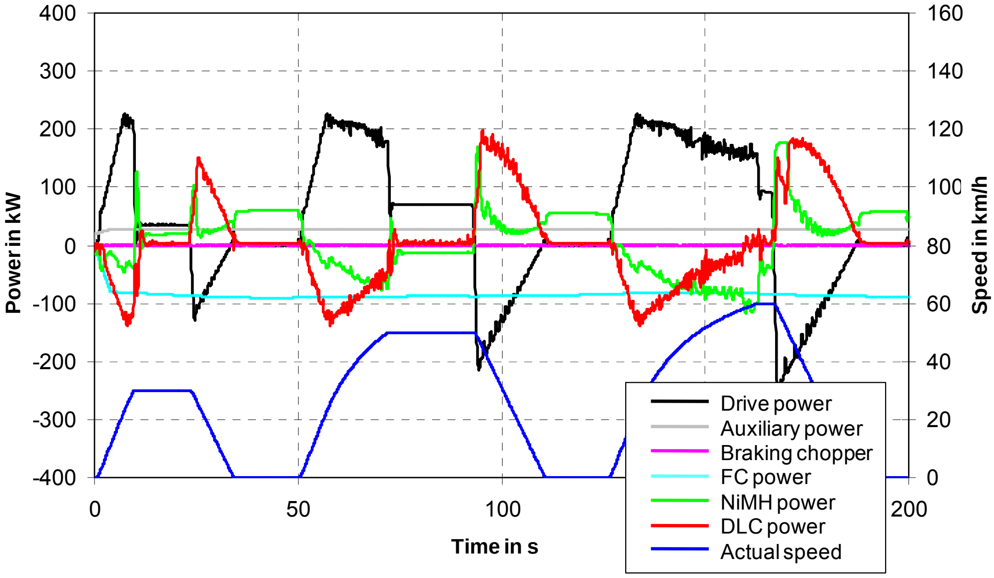

Figure 4: Simulation results, configuration III C), aux. scenario: "average".

Figure 4 shows the simulation results for configuration III C). The fuel cell system is operated at approximately 83 kW net power output. At the beginning of acceleration phases, the DLC modules provide the higher share of drive power. In the further course it is (partially) replaced by the NiMH battery's share. This behavior allows a good power distribution and keeps down stress of both components. At the very beginning of the braking phases the NiMH battery has to accept the main part of the recovered power. This is due to the fact that, according to the operating strategy, the DLC voltage is low at higher speed and thus limits the power capability.

5 Conclusions

The following conclusions can be drawn:

- Configuration II is not suited to sufficiently support the fuel cell system to achieve stationary operation. Furthermore, the low energy capacity is even more disadvantageous at uphill routes and, in case of a fuel cell system malfunction, allows for less than 0.8 km driving distance only.
- In general, configuration I seems to be suited for the given purpose.
- Using a hybrid storage system, the stress for the components and the fuel consumption can be reduced if the load is reasonably shared (strategy C)).

An H_2 consumption of 200 g/km (Table 1) results in an average power demand of roughly 85 kW. Further simulation results show that the necessary fuel cell net power varies from 80 kW to 120 kW on average. The latter is considered to be sufficient for the bus system.

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