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Hybridization and Control of Direct Methanol Fuel Cell Systems for Material Handling Applications

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1 Introduction

In the last few years several systems for light traction applications with a DMFC have been set up at Forschungszentrum Jülich GmbH (IEF-3) [1] [2]. A current project with industrial partners deals with a horizontal order picker as shown in Figure 1. Aim of this project is to replace the original traction battery by a DMFC system, which has several advantages:

- longer operating times
- no recharging of the batteries
- no need for spare batteries
- easy handling and unproblematic refuelling

A horizontal order picker is a small fork-lift truck, which is used in large warehouses for material handling applications. The typical operation of this vehicle can be described by a characteristic driving cycle, as shown in Figure 1. Table 1 gives an overview of the different power values of the characteristic driving cycle. Although the maximum peak power is exceeding 6 kW, the average power of the driving cycle is only 800 W. The maximum driving power, where the vehicle is running at its maximum speed, is 2.4 kW.

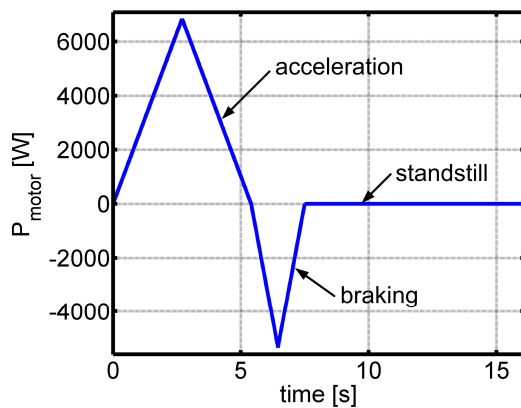


Figure 1: Characteristic driving cycle (left) of a horizontal order picker (right).

Table 1: Accelerating, braking and driving power.

| | |
|--------------------------------|---------|
| Accelerating power | 6800 W |
| Braking power | -5300 W |
| Average power of driving cycle | 800 W |
| Maximum driving power | 2400 W |

2 Hybridization Concept

The electric subsystem connecting the DMFC stack to the driving motor is set up as a hybrid system. There are several reasons for hybridizing a fuel cell:

- limited dynamic behaviour of the fuel cell [3]
- need for energy recovery during braking [4]
- dimensions of the fuel cell can be reduced [5]
- start-up of the fuel cell system [6]

Several configurations for the hybridization are possible. Basically series hybrid systems can be divided into two groups: active and passive hybrids [7]. Passive hybrids represent a direct coupling between the fuel cell (FC) and the energy storage (ES). Whereas in active hybrids they are coupled via converters. For a hybrid with one fuel cell and one energy storage device there are according to [8] four basic concepts (see Figure 2).

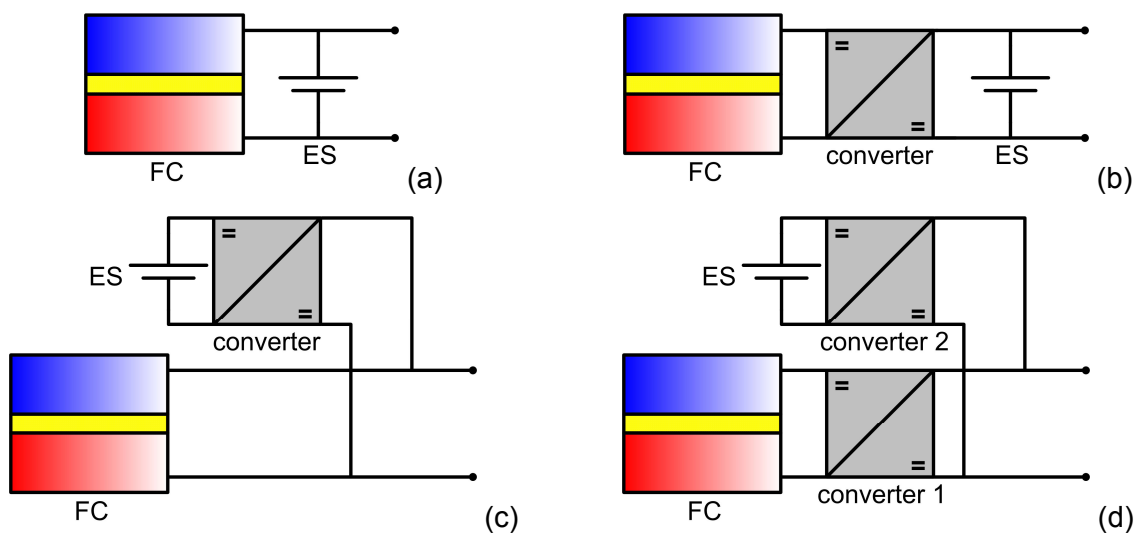


Figure 2: Basic concepts.

For the decision which concept is the best for the considered application the following three criteria were analyzed with simulations and experiments:

- system efficiency
- needed fuel cell power
- dynamic behaviour of the fuel cell

Simulations show that basic concept (a) has the best system efficiency (29.2 %) and needs the least fuel cell power (1.2 kW) [8]. The second best concept is basic concept (b) with 26.3 % system efficiency and 1.3 kW needed fuel cell power [8]. As they represent the two groups active and passive hybrid the dynamic behaviour of the fuel cell was analyzed. Simulations and experiments show that the amplitudes within the dynamic behaviour of the fuel cell are smaller for basic concept (b) as the converter decouples the fuel cell from the highly fluctuating driving profile [8]. So for this application basic concept (b) was chosen, resulting in the hybrid system setup in Figure 3.

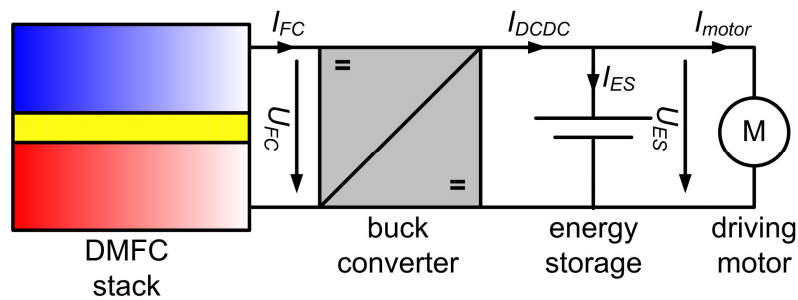


Figure 3: DMFC hybrid system.

3 Dimensioning of DMFC Stack and Energy Storage

3.1 Dimensioning of the DMFC stack

The main goal of the control strategy (see chapter 4) is to maintain the state of charge (SOC) of the energy storage on a constant level. So the useable electric power from the DMFC stack should be equal to the average driving power of the motor plus system losses from the buck converter (DCDC) and the energy storage (ES). Furthermore the power consumption of the peripheral components must be covered. With the energy flow diagram in Figure 4 the needed DMFC stack power is 1.3 kW as described in chapter 2.

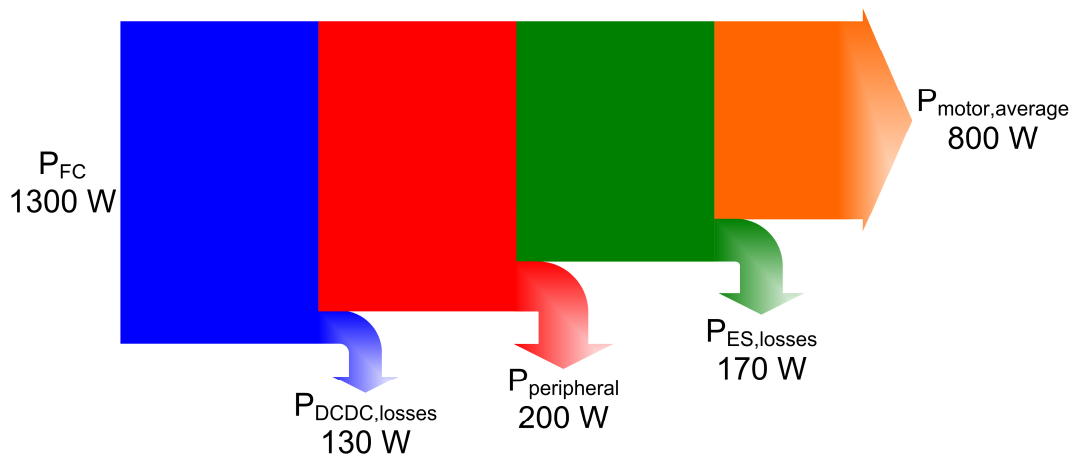


Figure 4: Energy flow diagram.

3.2 Dimensioning of the energy storage

Dimensioning parameters for the energy storage are the maximum energy content and the maximum power (charge and discharge), which are influenced by the operating states of the application (see Table 2):

- State 1: heating-up of the DMFC stack
- State 2: normal operation with average driving power (see Table 1)
- State 3: abnormal operation with maximum driving power (see Table 1)

Table 2: Operating states and their influence on the dimensioning.

| State | P_{FC} | Driving power from ... | Influence on ... | |
|-------|----------|------------------------|------------------|------------------------|
| | | | energy content | charge/discharge power |
| 1 | = 0 | ES | Yes | Yes |
| 2 | ≠ 0 | FC + ES | No | Yes |
| 3 | ≠ 0 | FC + ES | Yes | No |

During heating-up the DMFC stack delivers no electric power, so the driving power only comes from the energy storage (ES). Whereas during normal and abnormal operation the DMFC stack delivers an average power according to chapter 3.1. Here the driving is done with the fuel cell (FC) and the energy storage (ES). During normal operation the energy storage will stay on a fixed state of charge (see chapter 4). So this has no influence on the needed energy content. When the vehicle is only driven by the energy storage (State 1) the energy storage will be discharged, resulting in a needed energy content. If the driving power is higher than the average driving power (State 3) the energy storage will also be discharged. The main task of the energy storage is to be discharged during acceleration and to be charged during braking. So during heating-up and normal operation the maximum charge and discharge power can be taken from Table 1. As there is no acceleration and braking during abnormal operation this has no influence on the maximum power.

As the space for the complete DMFC system is limited by the original battery box in this case for the energy storage only 20 l are left. The minimum values for energy density and power density of the energy storage can thus be calculated according to Table 3. For the decision which kind of energy storage will be suitable a Ragone chart is used [8]. The Ragone chart with the performance limits according to Table 3 can be seen in Figure 5. It becomes clear that the energy density of super capacitors is too small. So a battery, in this case a lithium-ion-battery, was chosen [8].

Table 3: Performance limits for energy storage.

| | |
|-----------------------|---------|
| Energy density | 65 Wh/l |
| Power density | 350 W/l |

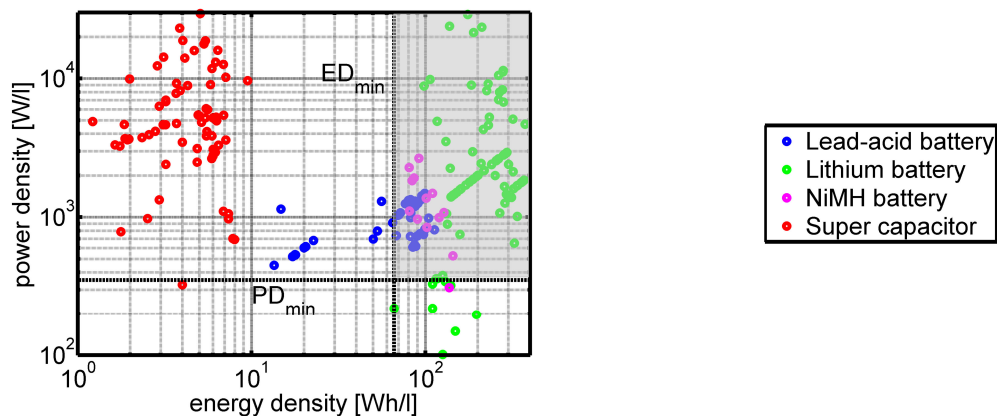


Figure 5: Ragone chart with performance limits.

4 Control Strategy

To control the power flow between the DMFC stack and the energy storage (here: battery) in such an active series hybrid a control strategy is needed. Figure 6 illustrates the main structure of the control system, consisting of three controllers. The different currents and voltages can be taken from Figure 3. The main goal of the control strategy is to maintain the state of charge of the energy storage on a constant level. A possible control value, which is shown in Figure 6, is the actual energy storage voltage $U_{ES,a}$. With this control variable “controller 1” calculates the desired DMFC stack voltage $U_{FC,d}$, which is limited to a minimum value depending on the actual fuel cell temperature $T_{FC,a}$. This limitation has the aim of avoiding aging of the fuel cell caused by catalyst corrosion [9]. The deviation from the actual fuel cell voltage $U_{FC,a}$ is the input for “controller 2”. The output of this controller is the desired current $I_{DCDC,d}$ at the output of the buck converter. The described limitation block has the aim of avoiding aging of the fuel cell. The aim of the “map control” is also related to aging and deals with the identification of an aging process. A characteristic map is implemented, which describes the behaviour of an unaged fuel cell. From this a theoretical fuel cell current is calculated, which is compared with the actual fuel cell current $I_{FC,a}$. The result of this comparison is a correction factor, which is used to adjust the methanol mass flow \dot{m}_{MeOH} and the air volume flow \dot{V}_{air} compared to their standard values for the unaged fuel cell [10].

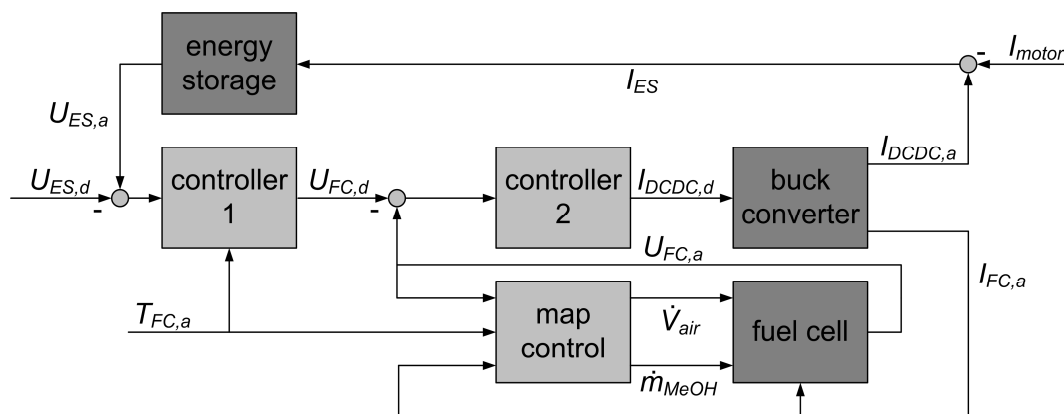


Figure 6: Structure of the control system.

5 Conclusions

There are several advantages in replacing the lead-acid battery, such as faster refuelling and extended operating time. Because of the highly fluctuating load profile, the DMFC stack has to be hybridized. In this case an active series hybrid is the best solution. The dimensioning of the DMFC stack and the energy storage has to be done in the run-up according to the requirements of the load profile. Requirements for the energy storage are a high energy density and a high power density. Therefore only batteries come into consideration. For the hybrid system it is important to have a control strategy. The control strategy presented has two aims regarding aging of the fuel cell: avoiding of aging and identification of aging.

References

- [1] H. Janßen, L. Blum, N. Kimiaie, A. Maintz, J. Mergel, M. Müller, D. Stolten: "Performance Characterization of a 4-Wheel DMFC Scooter" Proceedings "3rd European PEFC Forum", 04 - 08.07.2005, Lucerne, Switzerland
- [2] M. Nölke: "Entwicklung, Auslegung und Umsetzung eines DMFC-Systems der kW-Klasse" PhD Thesis, RWTH Aachen University, 2007
- [3] O. Garcia: "DC/DC-Wandler für die Leistungsverteilung in einem Elektrofahrzeug mit Brennstoffzellen und Superkondensatoren" PhD Thesis, ETH Zurich University, 2002
- [4] A. Di Napoli, F. Crescimbin, L. Solero, G. Pede, G. Lo Bianco, M. Pasquali: "Ultracapacitor and Battery Storage System Supporting Fuel-Cell Powered Vehicles" Proceedings "18th International Electric Vehicle Symposium (EVS 18)", 20 - 24.10.2001, Berlin, Germany
- [5] K. Seong Jeong, B. Soo Oh: "Fuel economy and life-cycle cost analysis of a fuel cell hybrid vehicle" Journal of Power Sources, Vol. 105, 2002, pp. 58 - 65
- [6] T. Markel, A. Pesaran: "Energy Storage System for Fuel Cell Hybrid Vehicles. Status Report" Proceedings "Joint VSATT and ESTT Meeting", 16.02.2006
- [7] M. J. Blackwelder, R. A. Dougal: "Power coordination in a fuel cell-battery hybrid power source using commercial power controller circuits" Journal of Power Sources, Vol. 134, 2004, pp. 139 - 147
- [8] J. Wilhelm: "Hybridisierung und Regelung eines mobilen Direktmethanol-Brennstoffzellen-Systems" 2010
- [9] R. Steinberger-Wilckens, J. Mergel, A. Glösen, K. Wippermann, I. C. Vinke, P. Batfalsky, M. J. Smith: "Performance degradation and failure mechanisms of fuel cell materials" Materials for fuel cells, October 2008, pp. 425 - 465
- [10] M. Müller, A. Maintz, J. Wilhelm, H. Janssen, D. Stolten: "Brennstoffzellensystem und Verfahren zur Regelung eines Brennstoffzellensystems" Patent application DE 10 2007 014 617 A1, 25.09.2008