

# **A Fuel Cell Driven Aircraft Baggage Tractor**

S. van Sterkenburg, A. van Rijs, H. Hupkens

This document appeared in

Detlef Stolten, Thomas Grube (Eds.):

18th World Hydrogen Energy Conference 2010 - WHEC 2010

Parallel Sessions Book 5: Strategic Analyses / Safety Issues / Existing and Emerging Markets

Proceedings of the WHEC, May 16.-21. 2010, Essen

Schriften des Forschungszentrums Jülich / Energy & Environment, Vol. 78-5

Institute of Energy Research - Fuel Cells (IEF-3)

Forschungszentrum Jülich GmbH, Zentralbibliothek, Verlag, 2010

ISBN: 978-3-89336-655-2

# A Fuel Cell Driven Aircraft Baggage Tractor

**Stefan van Sterkenburg**, HAN University of Applied Sciences, The Netherlands

**Aart van Rijs, Huib Hupkens**, Silent Motor Company, The Netherlands

## Abstract

Silent Motor Company and the HAN University of Applied Science collaborate in the development of an aircraft baggage tractor. The baggage tractor is equipped with an 8kW fuel cell stack connected to a 26kWh battery-pack.

The control system implemented minimizes the start-up time of the fuel cell system, protects the fuel cell against overload and underload and controls the State of Charge (SOC) of the battery to its optimum value. A practical SOC-determination method is implemented which does not need detailed knowledge about the batteries applied.

This paper presents a description of the fuel cell system, its energy management system and SOC-determination method and the results of first test measurements.

## 1 Introduction

Schiphol Group has formulated a strategy to improve air quality and reduce CO<sub>2</sub> emissions in its Sustainable Mobility Concept and Energy Blueprint. One of the cornerstones is to implement sustainable and green innovative technologies. Ground transport at Schiphol airport is responsible for 30% of all emissions and thus may contribute significantly to the objectives.

One of the current projects related to this is the testing of a fuel cell hybrid aircraft baggage tractor. Hybrid baggage tractors are used to transport baggage on the platforms outside as well as inside the cargo halls. The advantages a fuel cell system compared to the commonly used diesel generator are that a fuel cell system does not emit any exhaust fumes other than water, causes less noise, may be more efficient and doesn't have to be switched off when driving into the cargo halls. Figure 1 shows the baggage tractor under test.



**Figure 1:** Hybrid aircraft baggage tractor equipped with a fuel cell system.

## 2 System Description

The aircraft baggage tractor is a 3.3 ton hybrid Volk tow tractor, with a towing capacity of 8.5kW. It is equipped with a 12kW electric motor and 80V lead-acid battery-pack with a capacity of 320Ah.

The original diesel generator is replaced by an 8kW fuel cell system. The fuel cell system is constructed in such a way that it takes up the same space as the original diesel pack. Therefore, modifications to the tow tractor were limited.

The fuel cell system is composed of the following components:

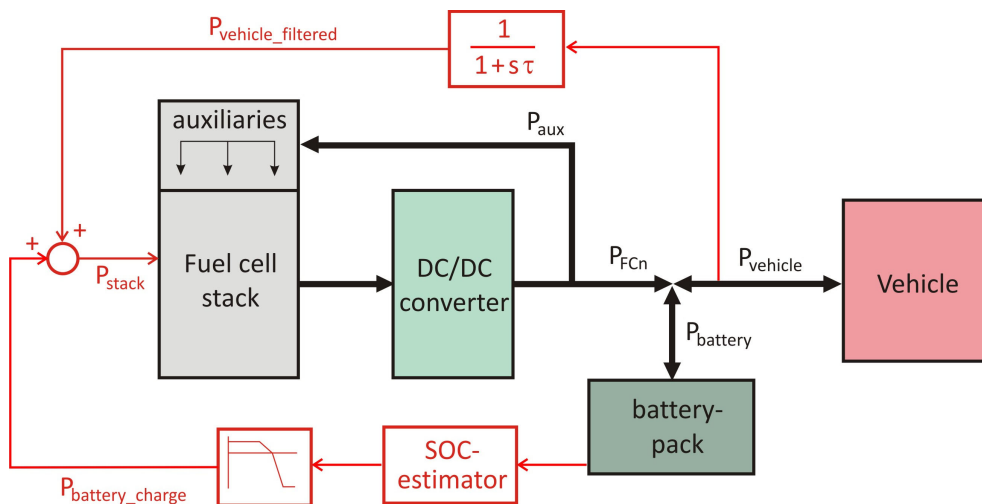
- The fuel cell stack. The stack is produced by NedStack. It consists of 64 cells in series with a rated power of 8 kW and current of 250A.
- A 74 liter 350 bar hydrogen tank. A completely filled tank at ambient temperature contains 1.8kg of hydrogen, which represents a free Gibbs energy of 60kWh.
- A step-up DC/DC-converter which converts the fuel cell stack voltage to the 80V battery voltage. The converter is equipped with an input current control.
- Auxiliary equipment. This includes all hardware to make the fuel cell system operate such as equipment for the cooling system, air pump, pressure valves, extended safety facilities and the fuel cell control unit. The power consumption of all auxiliary hardware depends on the power delivered by the stack and varies from about 400W to 800W.
- The control unit. This unit controls all auxiliary equipment and the DC/DC-converter. An extended safety strategy and energy management system is implemented. Software is written in Matlab / Simulink and code is generated by the automatic code generation tool of Simulink.

## 3 Energy Management System

The main task of the energy management system (EMS) is to determine the power supplied by the fuel cell. In order to do so, a set of three control systems are implemented, which are active depending on the operational mode of the fuel cell.

At power up, a temperature based control strategy is followed. The current supplied by the fuel cell is adjusted to its maximum value, which depends on the temperature of the stack. This causes fast warming up of the stack and thus minimizes the starting up time of the fuel cell.

After starting up, the fuel cell system enters its operational mode. In this mode, the energy management strategy is based on a load following strategy combined with a SOC-maintaining strategy. This strategy is illustrated in figure 2.



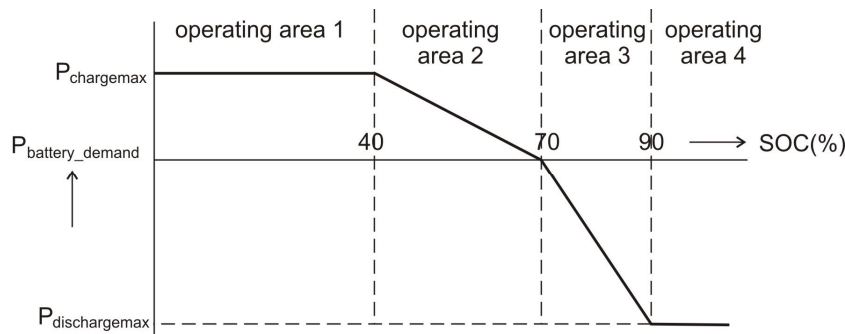
**Figure 2: Outline propulsion system with SOC maintaining EMS.**

The adjusted stack power is controlled to the following value:

$$P_{stack} = P_{vehicle\_filtered} + P_{battery\_demand}$$

The vehicle demand  $P_{vehicle\_filtered}$  is determined by filtering the power consumed by the baggage tractor with a first order low-pass filter with a time constant of 10 seconds.

The battery demand of the battery  $P_{battery\_demand}$  depends on the SOC of the battery and differentiates between four operating areas (see figure 3).



**Figure 3: Curve of power demand of battery-pack.**

Operating area 1:  $SOC < 40\%$ . In this operating area, the SOC is relative low, which is undesirable for reasons of increased deteriorating of the battery and the lack of sufficient buffer capacity in times of high power needs. To shorten the duration in this operating area,  $P_{battery\_demand}$  is set to its maximum value. This value is determined by the maximum allowable charge current of the battery which is set to a C/3-rate charge current.

Operating area 2:  $40\% \leq SOC < 70\%$ . In this operating area the battery demand decreases linear from its maximum value to zero. The upper limit of this operating area (70%) sets the SOC point of operation because on average  $P_{battery\_demenad}$  is zero in a steady state. A SOC

operating point of 70% is chosen because this value is the best compromise between the following contrary requirements:

- A relative high SOC is favourable for the lifetime of the battery and lasting high power needs
- A relative high SOC causes less efficient charging of the battery [1] and may lead to more on and off switching of the fuel cell during idle periods of the baggage tractor.

Operating area 3:  $70\% \leq \text{SOC} < 90\%$ : In this operating area,  $P_{\text{battery\_demand}}$  decreases further to its maximum discharge power. Its value is determined by the maximum allowable discharge current of the battery, which is set to 1C.

Operating area 4:  $\text{SOC} > 90\%$ : In this operating area,  $P_{\text{battery\_demand}}$  remains constant at its maximum discharge power.

A third control action is activated if the average cell voltage of the stack exceeds the operating range of 0.5V-0.8V per cell. In this case, a proportional-controller controls  $P_{\text{stack}}$  to the following value:

$$P_{\text{stack}} = P_0 + k_i * \Delta U$$

with:  $k_i$  = proportional constant (the value of  $k_i$  depends on sign of  $\Delta U$ )

$$\begin{aligned} \Delta U &= U_{\text{stack}} - n_{\text{stack}} * 0.5V && \text{if } U_{\text{stack}} < n_{\text{stack}} * 0.5V \\ \Delta U &= 0 && \text{if } n_{\text{stack}} * 0.5V < U_{\text{stack}} < n_{\text{stack}} * 0.8V \\ \Delta U &= U_{\text{stack}} - n_{\text{stack}} * 0.8V && \text{if } U_{\text{stack}} > n_{\text{stack}} * 0.8V \end{aligned}$$

$P_0$  = value of  $P_{\text{stack}}$  at the moment of activating this control action  
 $n_{\text{stack}}$  = number of cells of the stack)

The current control of the DC/DC-converter controls the stack current  $I_{\text{stack}}$  to a value of:

$$I_{\text{stack}} = P_{\text{stack}} / U_{\text{stack}}$$

#### 4 Determination of SOC

The SOC is an important parameter in the energy management system. To determine it, several methods have been proposed in literature [2]. Most of them are based on complex battery models which need detailed battery parameters which are not known of the batteries used in the baggage tractor. To overcome this problem, a simple SOC determination method is applied which uses a combination of SOC-estimation from the electromotive force (emf) and Coulomb counting.

The emf of the battery is estimated by using the Thevenin battery-model [3] shown in figure 4.

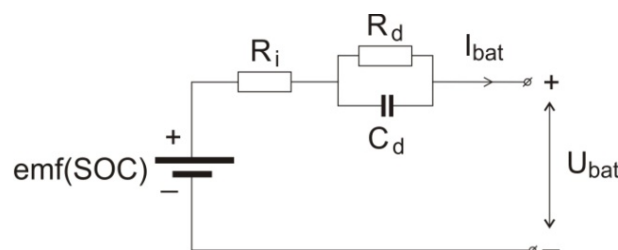


Figure 4: Thevenin battery model.

The internal resistance  $R_i$  in this model is determined real-time by the difference equation:

$$R_i[n] = 0.99 * R_i[n - 1] + 0.99 * \frac{-\Delta U_{bat}}{\Delta I_{bat}}$$

with  $\Delta U_{bat}(t_i) = U_{bat}(t_i+2s) - U_{bat}(t_i)$  and  $\Delta I_{bat}(t_i) = I_{bat}(t_i+2s) - I_{bat}(t_i)$

( $t_i$  is the time sampled at a rate of 20 samples per second)

The calculation of  $R_i[n]$  is only being executed when  $|\Delta I_{bat}|$  exceeds 50A in order to prevent small measurement inaccuracies causing large errors.

All transient processes (charge transfer kinetics and diffusion processes) are represented by a single parallel circuit  $R_d//C_d$ . The values of  $R_d$  and  $C_d$  are determined empirically by analyzing the recovery of  $U_{bat}$ .

Based on the model above the emf voltage is determined from measurements of  $U_{bat}$  and  $I_{bat}$ . From a lookup table, the SOC is then determined.

The accuracy of the SOC estimation from this method is rather limited at fast changing battery loads. This is caused by the simplified battery model that explains transients only with a first order approximation and inaccuracies in the determination of its parameters. Therefore, the SOC estimation of this model is filtered with a relatively large time constant of 300s to avoid fast fluctuations in the SOC caused by transient phenomena. The initial condition of the first order filter is set to 100% SOC. This prevents the battery to be overcharged at the start of a driving cycle when no accurate SOC estimation is available yet.

In order to determine the transient behavior of the SOC, also Coulomb counting is being applied. Coulomb counting is most effective to determine the changes in SOC in a short time interval. Deviations in current measurement and leak currents may cause drifting on the long term. For this reason, the SOC determined by Coulomb counting is filtered by a high pass filter. The same time constant is used as the low pass filter applied with the SOC-estimation from the emf. In this way both SOC-values can be added and a reliable value is obtained for both short term and long term.

## 5 First Test Results

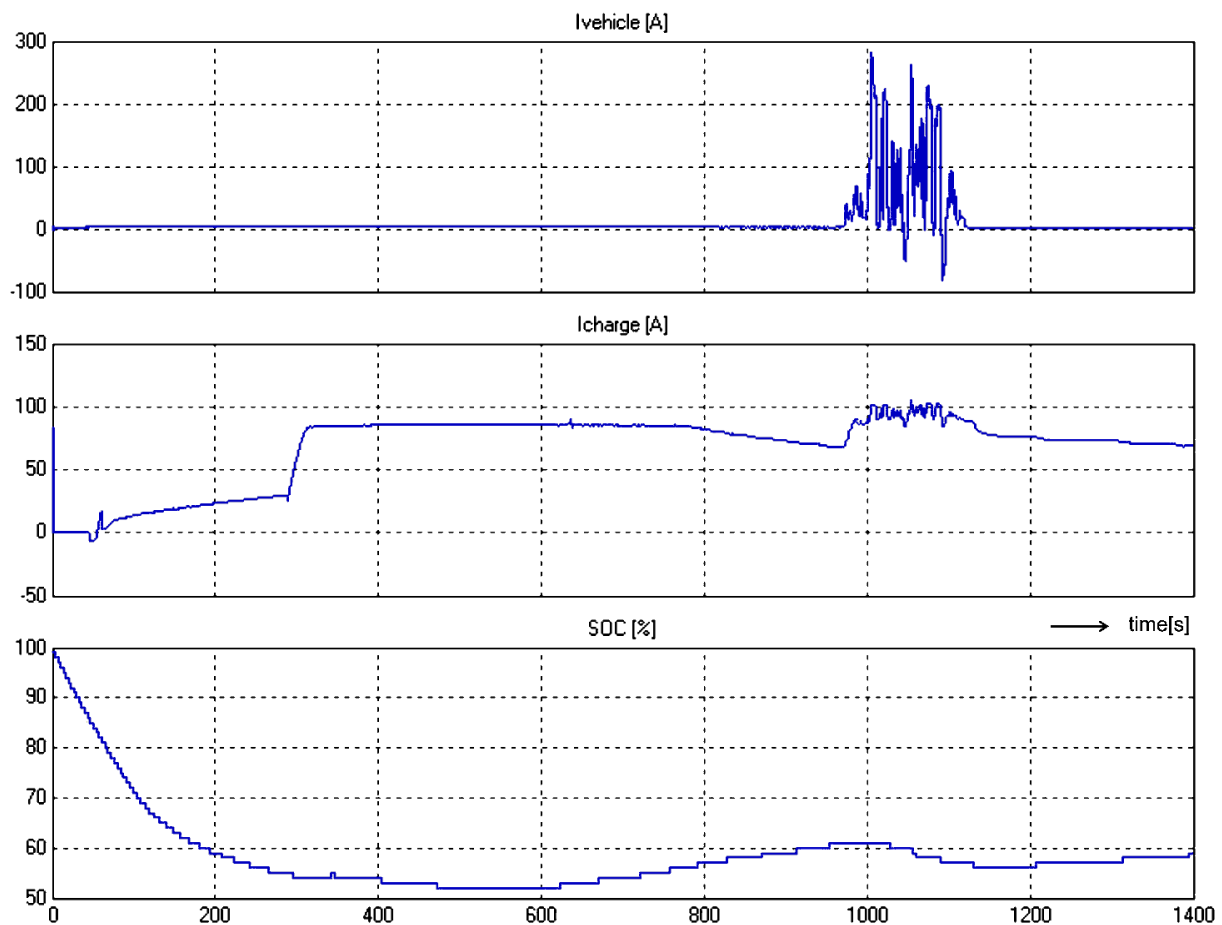
At the moment of writing, the fuel cell driven baggage tractor is tested at short driving cycles of only a few minutes. These tests are primary meant to test the general working of the fuel cell system, to adjust any possible shortcomings and to get realistic values for the vehicle power demand.

Figure 4 shows the measured values of the vehicle current and charge current (the output current of the DC/DC-converter) and the SOC-estimation of such a test. The test has been executed at an ambient temperature of 12°C. The SOC of the battery-pack was about 50% at the start of the test.

From this measurement the following can be observed:

- At  $t=55s$  the fuel cell stack is turned on. The temperature based control strategy is then followed. About 240s later, the fuel cell stack has reached its operating temperature and switches to a load following / SOC maintain control strategy.
- The SOC starts with its initial value of 100% and drops with a time constant of 300s to its real value.

- In the time interval from 240s to 970s the vehicle is standing still and the power of the stack is determined by the SOC. The DCDC-converter charges the battery with a slowly decreasing current in order to charge the battery to its preferable value of 70%.
- From  $t=970$ s to 1125s the vehicle starts driving. The vehicle current varies roughly between 300A at full power and -100A at regenerative braking. In this time interval, the current  $I_{charge}$  increases because of the load following strategy. The SOC-estimation shows a decreasing trend in this time interval. This must be explained by an inaccuracy of the SOC-estimation method.
- From  $t>1125$ s the vehicle is standing still again and the fuel cell stack further charges the battery to its preferable value of 70%.



**Figure 4:** The upper two graphs show the measured values of  $I_{vehicle}$  and  $I_{charge}$ . The lower graph shows the SOC-estimation.

## 6 Conclusion

This paper describes the design of a fuel cell driven baggage tractor. Three control strategies are followed in the EMS: a temperature based strategy is active at starting up and takes care for fast warming up. The stack is fully operational within 4 minutes at an ambient temperature of 12°C.

During normal operation, a load following / SOC maintaining strategy is followed. First test results demonstrate that this strategy works. The SOC-estimation method appears the most critical part of the strategy because of its inaccuracy.

The control strategy which adjusts the cell voltage within its operating area of 0.5V–0.8V is not tested yet.

### References

- [1] J. Manwell and J. McGowan, "Lead acid battery storage model for hybrid energy systems," *Solar Energy*, vol. 50, pp. 399–405, 1993.
- [2] "State-of-the-art of battery state-of-charge determination" by Pop, Bergveld, Notten en Regtien (*Meas. Sci. Technol.* 16 (2005) R93–R110)
- [3] "Dynamic model of a lead acid battery for use in a domestic fuel cell system", M. Dürr, A. Cruden, S. Gair, J.R. McDonald, *Journal of Power sources* 161 (2006), pp 1400-1411