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Hybrid systems with lead–acid battery and proton-exchange membrane fuel cell

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Abstract

Hybrid systems, based on a lead–acid battery and a proton-exchange membrane fuel cell (PEMFC) give the possibility to combine the advantages of both technologies. The benefits for different applications are discussed and the practical realisation of such systems is shown. Furthermore a numerical model for such a hybrid system is described and results are shown and discussed. The results show that the combination of lead–acid batteries and PEMFC shows advantages in case of applications with high peak power requirements (i.e. electric scooter) and applications where the fuel cell is used as auxiliary power supply to recharge the battery. The high efficiency of fuel cells at partial load operation results in a good fuel economy for recharging of lead–acid batteries with a fuel cell system.

Keywords: Hybrid system; PEMFC; Lead–acid battery; Modeling

1. Introduction

Within the last seven years many efforts have been made in the development of low temperature fuel cells. As a result fuel cells are now available as prototypes and first production models appear on the market. The most popular low temperature fuel cell is the proton-exchange membrane fuel cell (PEMFC) and this paper will concentrate on this fuel cell type. The PEMFC has not only advantages in comparison with batteries, but also some disadvantages, as lower efficiency in case of very low power, start-up delay, and up to now comparable high costs and low lifetime. Hybrid systems, based on a PEMFC and a lead–acid battery can combine the advantages of both technologies and avoid the disadvantages. Table 1 shows the advantages and disadvantages of batteries and fuel cells. The table shows that both systems complement one another.

Hybrid systems are of interest if a significant advantage can be achieved in comparison to pure battery or a pure fuel cell system.

The most important advantage of fuel cell systems is the decoupling of the energy storage (e.g. compressed hydrogen, metal-hydride, methanol) and the power converter (fuel cell). Therefore a large energy storage at relatively low cost is possible. If the fuel cell system is switched off the self-discharge is almost zero. Recharging, by refilling of the storage, can be done very fast. On the other hand fuel cell systems are still expensive and the power consumption of the periphery components is high, resulting in worse efficiencies in case of very low load operation.

Different possibilities for battery/fuel cell hybrid systems are possible, that basically differ in energy and power parameters from the fuel cell (i.e. continuous or block operation). The possible features of a fuel cell battery hybrid system depend also on the size of the fuel cell and the battery. Fig. 1 shows possible features and the general sizing of fuel cell and battery.

In case of high power load peaks, but much lower average power, hybrid systems are of special interest. A small battery

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Table 1
Comparison between fuel cell and battery

	Fuel cell	Battery
Energy content	Defined by the storage unit High specific energy is possible Independent from peak power	Specific energy: 25–200 Wh kg^{-1}
Power capability	Defined by the fuel cell stack Independent from energy content	Coupled with the battery size Discharge within a few minutes possible
Self-discharge	If switched off, self-discharge is 0	Approx. 1–10% per month
Efficiency		
<10% rated load	Worse (caused by periphery)	In most cases good efficiency
50% rated load	Medium	
Rated load	Medium	
Start-up characteristic	At RT about 50% of rated power	Immediately full power possible
Electrical rechargeable	Not possible (only in combination with a electrolyzer)	Possible
Charge time	Fuel refill/exchange is very fast	Charge time: 15 min–10 h
System technology	Complex	Simple
Costs	Up to now expensive, in general Power is expensive Periphery is expensive Energy is less expensive	In comparison to fuel cells low costs

with a high peak power capability is used for peak shaving. The battery can also support the start-up phase of the fuel cell. A typical power distribution between fuel cell and battery is shown in Fig. 2. Examples for hybrid systems with a special pulse power capability are given by Zhenhau et al. [1] and Gao et al. [2].

Other applications, where long periods with low power demands and also periods with medium or high power exist are also of interest. In this type of application the load is operated by the battery and the fuel cell is only used to recharge the battery if the state-of-charge is going below a minimum level. Another possibility is to guarantee a full recharge by use of an auxiliary energy source (here a fuel cell). This periodical recharge prevents sulphation. Typical applications are solar systems and SLI batteries. In case of solar systems it is assumed that a frequent full recharge can increase the typical battery lifetime [3].

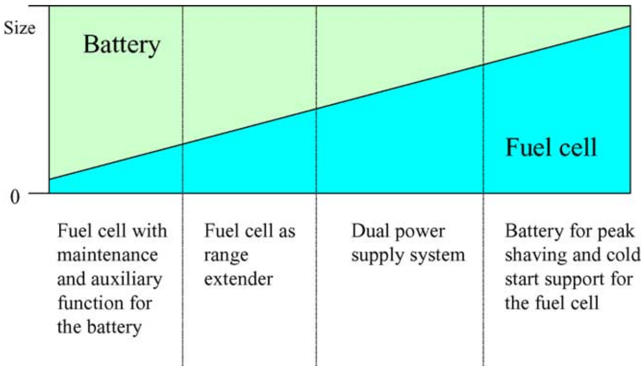

Fig. 1. Fuel cell and battery size in relation to different features of the hybrid system.

Different structures of hybrid systems are possible. In general an energy management system is necessary to control the energy flow between the energy generators, the storage system and the load. As the voltage range of a fuel cell is very high, a dc/dc converter is necessary to deliver a more stable output voltage. This dc/dc converter can also be used to control the charge process of the battery. Then no more power converters are necessary for a fuel cell/battery hybrid system. This structure is shown in Fig. 3. The dc-bus bar (line between battery, dc/dc converter and load) can also be used to add further energy converters or energy storage systems. For each further converter or storage system a separate power control device is necessary. In case of a hybrid fuel cell/battery/solar system, as is shown in Fig. 4, a solar generator is connected by a charge controller. It is possible, but not necessary, to control the charge controller by the energy management.

All our investigations were done with PEMFCs that are operated with air as oxidant. We use a cathode air circulation system to make the system as simple as possible. For hydrogen storage metal hydride or compressed hydrogen is used.

In hybrid systems diesel generators are often used. However the efficiency of a diesel generator is dramatically decreased in partial load condition. Therefore full recharging of lead–acid batteries with a diesel generator is done with a worse overall efficiency. One possibility to improve this characteristic could be the use of a hybrid system with battery, diesel generator and fuel cell. The diesel generator is then only used for charging the battery until the efficiency of the diesel generator is acceptable. The last charge phase is then done with a fuel cell system. In this case the fuel cell can be comparatively small.

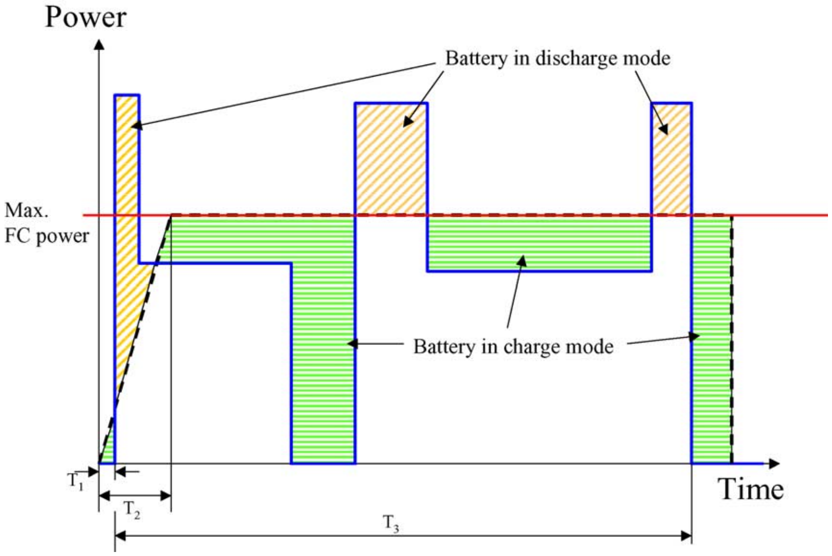

Fig. 2. Typical power profile of a PEMFC/battery hybrid system that is operated in a peak load mode.

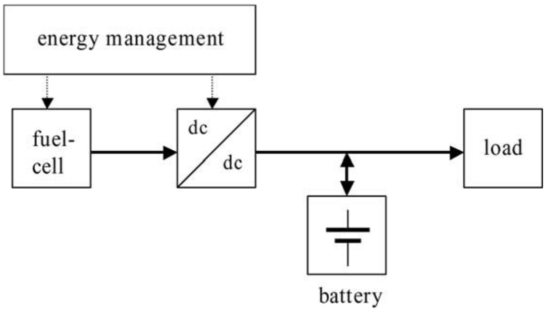

Fig. 3. Structure of the hybrid fuel cell/battery system that is discussed in this paper.

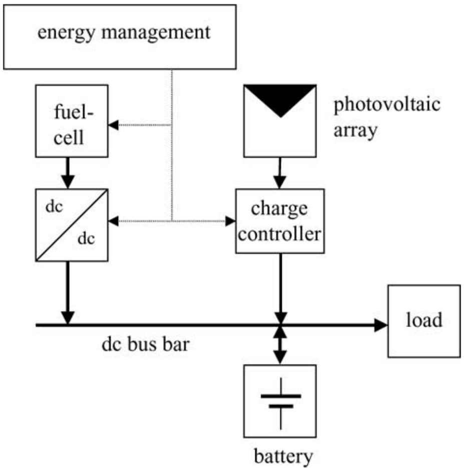

Fig. 4. Structure of the hybrid fuel cell/battery/solar system that is discussed in this paper.

2. Numerical simulation

To analyse the characteristics of a hybrid system, for example the overall fuel consumption as a function to different sizing and operation parameters, numerical simulation is used. We have used models for the fuel cell and the lead–acid battery as they are known from the literature.

2.1. The fuel cell model

There exist a couple of different models for PEMFCs. On the one hand there exist mechanistic models that are based on fundamental principles, such as mass transport, thermodynamic behaviour and other physical and chemical principles. Amphlett et al. [4] have developed such a model. The main disadvantages of mechanistic models are the complexity and the large number of parameters that must be determined. Empirical models are simpler, the number of parameters is smaller and the determination of the parameters is often simpler. Within this investigation we have used the model of Kim et al. [5] to describe the voltage/current characteristic. A simple equation with five parameters is used:

$$U = U_o - b \log i - Ri - m \exp(ni) \quad (1)$$

This equation described the fuel cell voltage U as a function of the current density i. U_o, b, R, m and n are parameters and depend on the fuel cell type, the fuel (oxygen or air), the temperature and the pressure. The logarithmic part describes the activation losses at small current densities and the exponential part describes the diffusion losses at high current densities. The linear part describes the ohmic losses that are responsible for the curve linearity at middle current densities.

The ZSW PEMFC system used is based on a cathode air recirculation system and has a dead end (whole H_2 is used) arrangement for the hydrogen. The system works at ambient pressure. For an operation temperature of 40 °C the parameters of Eq. (1) are as given in Table 2.Fig. 5 shows the measured (dots) and simulated voltage current curve for a single cell and the calculated output power of the fuel cell stack.

Table 2
Fuel cell parameters for a 300 W system

Parameter	Value
Active cell area	130 cm^2
Number of cells	20
Open circuit voltage, U_o	874 mV
b	65 mV per decade
R	0.58 Ω cm^{-2}
m	2.9 mV
n	9.3 cm^2 A^{-1}

The losses of the fuel cell are given by voltage losses, periphery losses and fuel utilisation losses. A detailed study is given by Thorstensen [6].

Periphery power losses are assumed to be linear. The total power losses are described by:

$$P_{\text{loss}} = P_0 + cP_{\text{el}} + (1.25V - U)I + (1 - d)1.25VI \qquad (2)$$

with P_0 the stand-by losses of the periphery; P_{el} the actual output power of the fuel cell; U the fuel cell voltage; I the fuel cell current; c the parameter for the power-related losses of the periphery; d the utilisation of fuel (typically 0.9–0.999).

The possibility to shut the fuel cell down is an important characteristic, as the power losses are going down to 0, resulting in a storage system without self-discharge. On the other hand small loads result in a comparatively worse efficiency, as the stand-by losses of the periphery cannot be neglected. The data are based on the net calorific value of hydrogen (3.00 kWh (N m^{-1})). By use of this efficiency characteristic the hydrogen consumption is calculated in the simulation model. The overall efficiency of the fuel cell is shown in Fig. 6. The highest efficiency is reached at 70 W output power.

To analyse the influence of the fuel cell size, the active area is scaled according to the required nominal output power and the periphery losses are linear scaled with the nominal output power.

2.2. Power converter

The power converter between fuel cell and dc bus bar is a controllable dc/dc step-up converter with the following characteristic:

$$P_{\text{out}} = P_{\text{in}}\eta_{\text{dc–dc}} \qquad (3)$$

The energy management can control the output power, the output current and/or the output voltage. The efficiency of a dc/dc converter ($\eta_{\text{dc–dc}}$) depends on the output power, the voltage and the current in a non-linear way.

The power losses of the converter can be described by the following simplified equation:

$$P_{\text{loss}} = \alpha_0 + \alpha_1 I_{\text{out}} + \alpha_2 I_{\text{out}}^2 \qquad (4)$$

Within this equation α_0 describes the power consumption of the control electronics, $\alpha_1 I_{\text{out}}$ describes the linear part, caused by forward voltages of semiconductors, and $\alpha_2 I_{\text{out}}^2$ describes the square part, caused by ohmic losses.

Assuming constant output voltage, it is possible to calculate the efficiency only by the output power:

$$P_{\text{loss}} = \beta_0 + \beta_1 P_{\text{out}} + \beta_2 P_{\text{out}}^2 \qquad (5)$$

The efficiency is then given by:

$$\eta_{\text{dc–dc}} = \frac{P_{\text{out}}}{\beta_0 + P_{\text{out}}(1 + \beta_1) + P_{\text{out}}^2\beta_2} \qquad (6)$$

Fig. 7 shows the efficiency of the dc/dc converter versus the relative output power.

The dc/dc converter must be adapted to the fuel cell size. In case of other output power the parameters are scaled as follows: $\beta_0' = \beta_0 P_{\max}' P_{\max}^{-1}$; $\beta_1' = \beta_1$; $\beta_2' = \beta_2 P_{\max} P_{\max}'$.

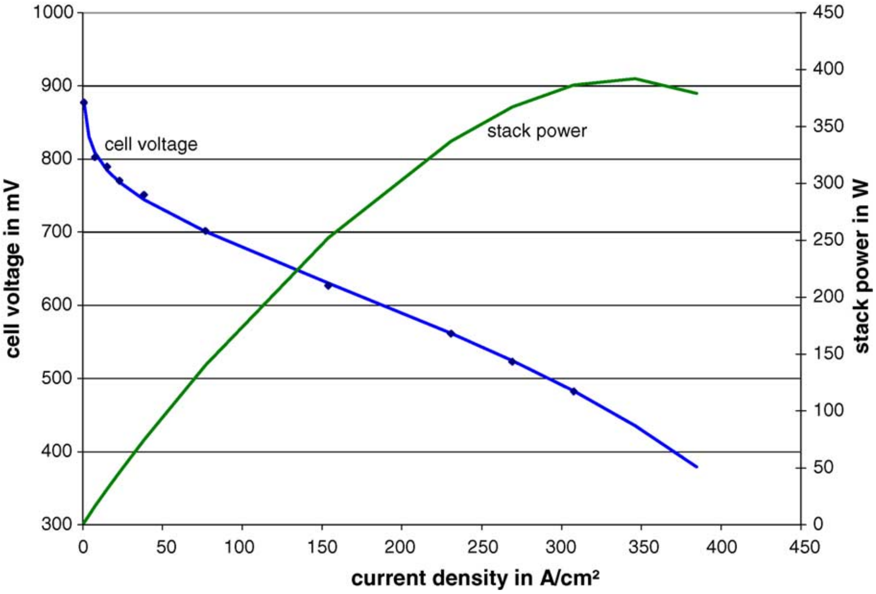

Fig. 5. Current–voltage curve for a single cell and output power for a stack with 20 cells (dots: measured, lines: simulated).

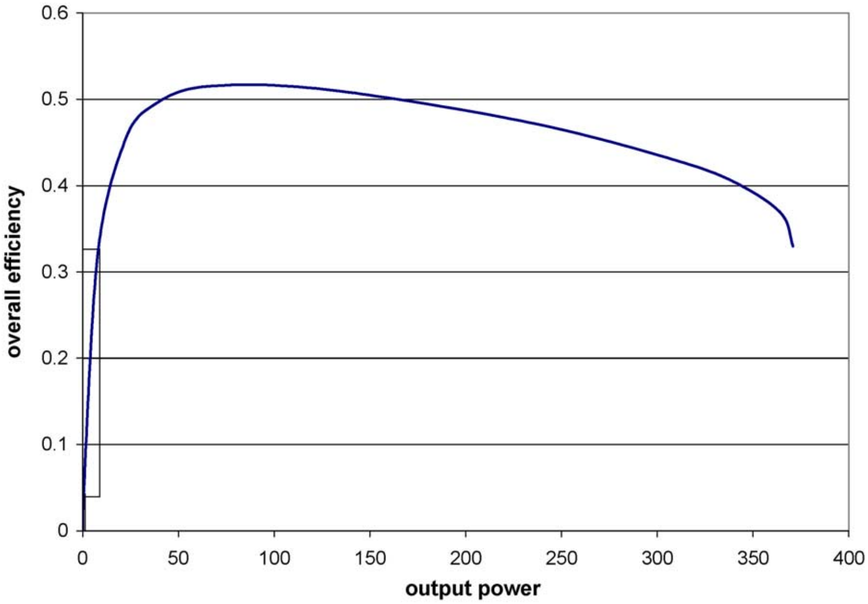

Fig. 6. Efficiency of the fuel cell system taking voltage losses, hydrogen utilisation and periphery losses into account.

2.3. The battery model

Depending on the application, different battery types were used. If the battery is operated in a high power mode, we use EnerSys Cyclon Batteries. In the case of low power cycling operation we use pasted plate vented type lead–acid batteries. The battery model is based on the Shepherd model [7]. To take charge losses into account, a model for describing the gassing characteristic is used. Fig. 8 shows the battery model.

U_{00} gives the equilibrium voltage in the discharged state and the capacitor C_a describes the linear relationship between the equilibrium voltage and the state-of-charge. C_d and R_p

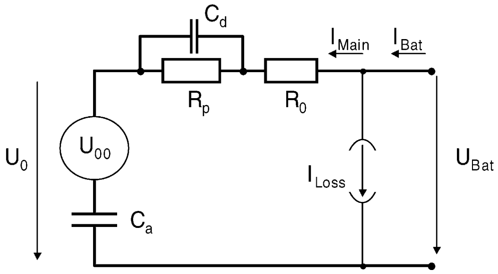

Fig. 8. Battery model.

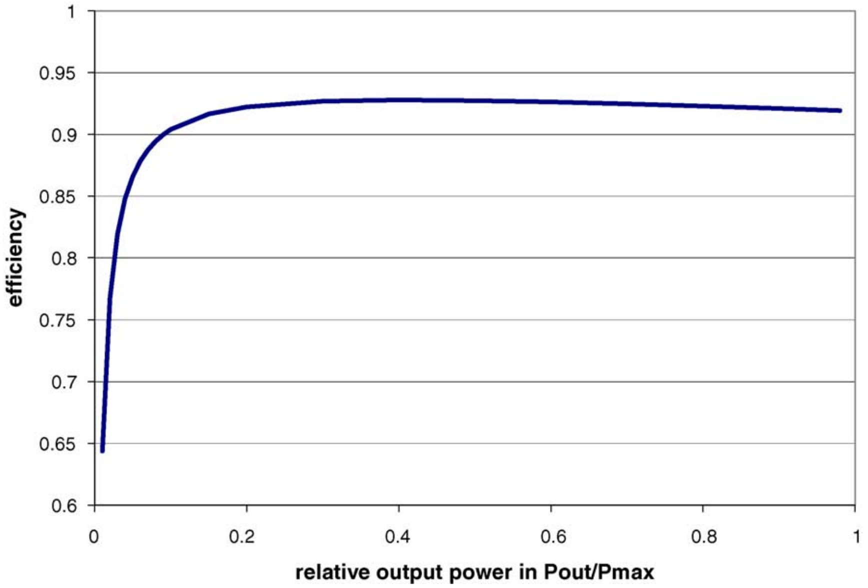

Fig. 7. Efficiency of a 300 W dc/dc converter ($P_{max} = 300$ W, $\beta_0 = 1.5$ W, $\beta_1 = 0.0533$, $\beta_2 = 1 \times 10^{-4}$ W^{-1}).

describe the polarisation losses (mainly given by diffusion) and R_0 describes the ohmic resistance plus the voltage drop given by the charge transfer.

The polarisation resistance depends on the state-of-charge. During charging the following equation is used:

$$R_p = \frac{A_c}{B_c - \text{soc}} \tag{7}$$

where A_c and B_c are parameters and 'soc' is the state-of-charge (0–1). During discharging the equation changes to:

$$R_p = \frac{A_d}{B_d - \text{dod}} \tag{8}$$

where 'dod' is the depth of discharge (1–0). The losses depend on the voltage and the temperature by the following exponential characteristic [8]:

$$I_{\text{Loss}} = I_{\text{L0}} \exp\left(\frac{U_{\text{Bat}} - U_{\text{N}}}{k_1} + \frac{k_2(T - T_{\text{N}})}{TT_{\text{N}}}\right) \tag{9}$$

U_N and T_N are the nominal voltage and temperature of the battery (2.0 V per cell, 298 K) and I_{L0} is the loss current if the battery has the nominal voltage and the nominal temperature. k_1 and k_2 are parameters describing the relationship to the voltage and to the temperature.

The parameters shown in Table 3 where determined for a vented lead–acid battery.

Table 3
Parameters of the battery model

Parameter	Value
U_{00}	2.078 V
C_a	5.4×10^6 F
R_0	Discharge: 5.8 mΩ, charge 11.0 mΩ
A	Discharge: 1.3 mΩ, charge: 2.6 mΩ
B	1.005
I_{L0}	6 mA
k_1	85 mV
k_2	6500 K

2.4. Operation strategy

There are different operation strategies possible. The degree of freedom is mainly given by the possible usage of the storage (SOC range) and the sizing of the different components. For applications with lead–acid batteries auxiliary functions such as recharging and fully recharging are of most interest.

In a scenario in which we are interested, the system is operated by the battery and at normal condition the fuel cell is deactivated. If the battery state-of-charge goes below 20% the battery is recharged by the fuel cell to full state-of-charge (scenario 1) or alternatively up to 80% SOC (scenario 2). For recharging the fuel cell is operated close to the nominal operation power if the battery is able to accept this high charge power. The charge method is cc–cv (constant current/constant voltage) with a cell voltage of 2.35 V. It is assumed that there is no load active during the recharging phase. The following system size is assumed:

- *Battery*: 24 V, 150 Ah, vented type (parameters according to Table 3).
- *Fuelcell*: PEMFC 300 W.

3. Results

Fig. 9 shows the recharging of the battery according to scenario A1. The recharge starts with a state-of-charge of 20%.

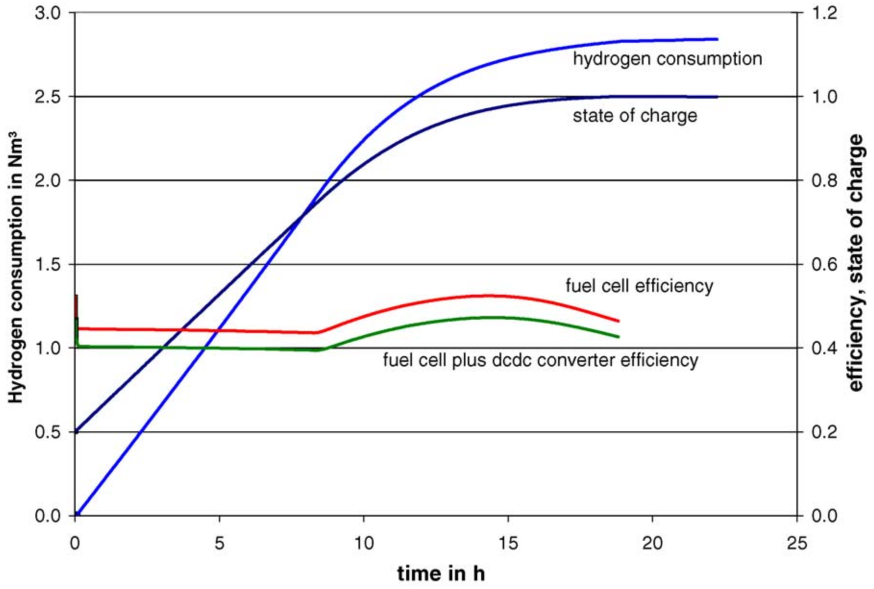

Fig. 9. State-of-charge, efficiency, and hydrogen consumption during recharging a vented lead–acid battery (24 V/150 Ah) with a 300 W fuel cell system.

The recharge is done with a constant current of 10 A and a voltage limit of 28.2 V. The first 8.5 h the battery is charged with constant current. In this phase the efficiency of the fuel cell is about 44% and including the dc/dc converter the efficiency (charge power to hydrogen consumption) is about 40%. At about 8.5 h the battery reaches the charge voltage of 8.2 V and the charge current is reduced to control the voltage. During this charge phase the fuel cell efficiency is going up to 52% (including dc/dc converter: 47%). The maximum is reached when the fuel cell reaches the point with maximum efficiency. With further decreasing charge power the efficiencies again decrease. At the end of the charge process the charge power is fallen to 21 W. The efficiencies at that point are 46% (fuel cell only) and 42.7% (including dc/dc converter). The fuel consumption is 2.83 m^3 of normal hydrogen which corresponds to 8490 Wh. The energy stored in the battery was increased by 3078 Wh resulting in an overall efficiency of 36.3%.

If scenario A2 is used (same as A1 but charging is terminated at 80% SOC) the charge time reduces to 9.26 h and 2.1 N m^3 of hydrogen are required. The energy stored in the battery was increased by 2296 Wh, resulting in an overall efficiency of 36.4%. This means that the lower efficiency of the fuel cell is compensated by the higher efficiency of the battery. This means that from an energy view/point recharging to full state-of-charge is as efficient as recharging to only 80% SOC.

However it must be taken into account that the periphery losses of the fuel cell have a strong influence on the results. Higher stand-by losses P_0 result in a reduced efficiency, especially if the fuel cell works with partial load as is typical for charging between 80 and 100% SOC. The periphery power consumption is therefore a key parameter for the system efficiency if battery recharging is required.

4. Conclusions

Hybrid systems show a couple of advantages in comparison to pure battery powered or pure fuel cell powered systems. In principle there are two categories of battery/fuel cell hybrid systems:

- Battery powered systems that use a small fuel cell to enable auxiliary functions such as periodic recharging to full state-of-charge.
- Fuel cell powered applications that use a battery for peak load shaving.

In the case of battery powered systems, the use of a fuel cell for auxiliary functions will increase the battery lifetime if lead–acid batteries are used. Solar powered systems can also result in a smaller PV generator and/or a lower loss of load probability.

The efficiency of recharging of lead–acid batteries with a fuel cell system depends strongly on the battery/fuel cell size and the stand-by losses of the fuel cell. For the system we have investigated recharging to full state-of-charge is as efficient as recharging to only 80% DOD. The reason is the increased efficiency of the fuel cell and the dc/dc converter at lower power that compensates the lowering of the charge efficiency of the battery at increasing state-of-charge. Therefore fuel cells are a good and efficient power source for lead–acid battery recharging and bring many advantages in comparison to diesel generators.

Fuel cell systems that use a battery for peak load shaving show higher peak power and it is possible to reduce the fuel cell size. The minimum fuel cell size that is possible is the average load power. This however can result in heavy cycling of the battery which reduces lifetime. Therefore, in most applications where the battery is used for peak power, other battery technologies than lead–acid are used.

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