High Temperature PEM Fuel Cell System for Small Mobile Applications

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***Abstract*—This article presents a new system architecture, using a high temperature PEM fuel cell system for small mobile application. Due to the fact that such a fuel cell has a start-up time of several minutes and needs external heating for start up, the system is combined with a battery. The system control is realized using fuzzy logic. Based on a reference drive cycle conclusions are made on the system size and weight as well as the hydrogen consumption.**

I. INTRODUCTION

Due to the shortage of crude oil and the climate change, our mode of transport will change considerably during the next ten to twenty years [1]. For the moment cars are used as main mean of individual transport in most of the developed countries. Even though studies have shown that in Europe the mean driving distance per day is less than $40\,\mathrm{km}$ [2]. As those trips are mostly limited to one single user and a limited amount of charge, it would be possible to use smaller and lighter vehicles like scooters, which are more fuel efficient [3]. Furthermore, a hydrogen infrastructure might be an alternative to the existing crude oil infrastructure, as hydrogen can be produced from renewable sources [4]. Therefore, fuel cell systems are one solution to transform hydrogen into electricity that is used to drive the future vehicle [5].

For the moment mostly proton exchange membrane fuel cell systems (PEMFC) are used. They have the disadvantage of working at low temperatures of maximum $80\,^{\circ}\mathrm{C}$, thus imposing problems of system cooling and liquid water management [6]. Recent developments propose PEMFC systems working on higher temperatures up to $220\,^{\circ}\mathrm{C}$ using a polybenzimidazole-based membrane material [7]–[10]. As such a HTPEMFC has to be heated up to temperatures above $100\,^{\circ}\mathrm{C}$ before it can be used, the system used for transportation has to be hybridized with a secondary energy source. In this case a lithium ion battery system is used [11]. In the following the system is introduced and the power and energy demands are evaluated. Thereafter, the system architecture is introduced containing its structure, the basic elements, the system control using fuzzy logic and the system model. Simulation results based on a reference drive cycle are presented and conclusions are made on the system size and weight as well as the hydrogen consumption.

II. FUEL CELL HYBRID ELECTRIC SCOOTER

A. System architecture

The studies presented in this article are based on the characteristics on existing electric scooters. The main characteristics are:

- Mass (m): $200\,\mathrm{kg}$ (Scooter), $70\,\mathrm{kg}$ (Driver)
- Inertia or rotational mass (f): $5\,\%$
- Front surface (S): $1\,\mathrm{m}^2$
- Wheel diameter (r): $0.5\,\mathrm{m}$
- Drag coefficient: $\lambda = 0.9$
- Rolling resistance: $C_r = 0.01$

Furthermore, based on the bus voltages of existing electric vehicle systems the desired bus voltage is set to be $60\,\mathrm{V}$.

B. Drive Cycle

In Europe cars and scooters are evaluated using the European Drive Cycles. Those drive cycle are well adapted to evaluate comparative values of fuel consumption or pollutant formation, but they are not reflecting the real world behavior. The US city drive cycle is better adapted to represent a scooter drive including several acceleration and deceleration phases with a maximum speed of $55\,\mathrm{km\,h^{-1}}$, (Figure 1).

C. Power and Energy Demand

Based on the speed profile of the driving cycle and the system parameters the power profile of the vehicle as well as the energy consumed can be evaluated using the following equations.

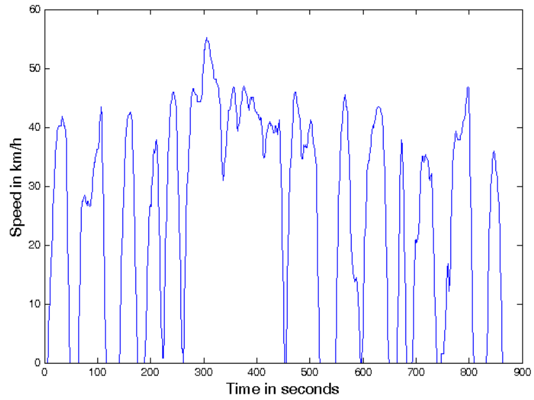


Figure 1. US City drive cycle II

$$P = \sum F \cdot v \tag{1}$$

$$E = \int P\mathrm{d}t \tag{2}$$

$$\sum F = F_{\mathrm{a+i}} + F_{\mathrm{roll}} + F_{\mathrm{aero}} \tag{3}$$

$$F_{\mathrm{a+i}} = m(1+f)\frac{\mathrm{d}v}{\mathrm{d}t} \tag{4}$$

$$F_{\mathrm{roll}} = m \cdot g \cdot C_r \tag{5}$$

$$F_{\mathrm{aero}} = 0.5 \cdot \rho \cdot \lambda \cdot S \cdot v^2 \tag{6}$$

The sum of forces contains the three different main forces. Firstly, the forces related to acceleration and inertia $F_{\mathrm{a+i}}$ in N (eq. 4). Secondly, the rolling resistance F_{roll} in N (eq. 5), is calculated using the acceleration due to gravity $g = 9.81\,\mathrm{m\ s^{-2}}$. Thirdly, the aerodynamic drag force F_{aero} in N (eq. 6) is taken into account using the air density $\rho = 1.2\,\mathrm{kg\,m^{-2}}$. The hill climbing force is neglected in this case. The power demand of the scooter can be seen (Figure 2).

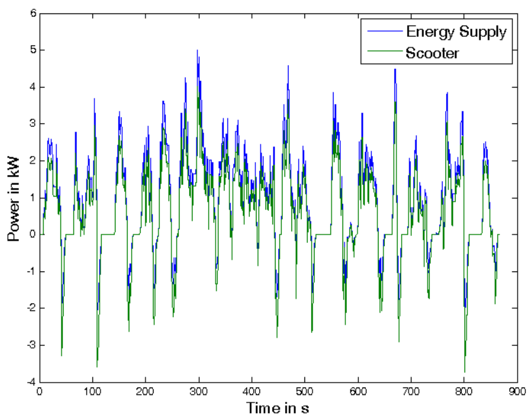


Figure 2. Power demand during drive cycle

It shows positive powers during acceleration and negative powers during breaking. For acceleration a system efficiency of 80 % is taken into account and for energy recuperation 60 % efficiency are considered. This leads to a mean power demand of 920 W with positive power peaks up to 5 kW and energy recuperation peaks of 4 kW. The energy demand during the cycle is 3.2 A h at 60 V.

III. System Architecture

A. Structure of system

The studied system consists of a lithium ion battery system that is directly connected to the bus. The HTPEM fuel cell system is connected to the bus via a boost converter. A resistive heater is connected to the fuel cell system to heat it up to 100 °C in order to be able to start it safely (Figure 3). The

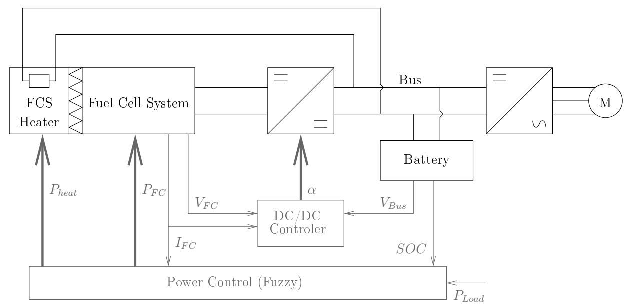


Figure 3. System Architecture

system is controlled using a proportional controller for the boost converter and a power control system using fuzzy logic. The main elements of the system are presented in more detail in the following.

B. Fuel Cell

High Temperature Proton Exchange Membrane (HTPEM) fuel cell systems are based on a polybenzimidazole (PBI) membrane with phosphoric acid as ionic conductor. They show good conductivity at temperatures of 120 °C up to 200 °C [8] and give thus advantageous features when operated on reformed hydrogen gas [10]. Furthermore, due to the absence of liquid water no humidification system has to be foreseen. However, liquid water deactivates the membrane and the HTPEM fuel cell system has thus to be preheated at temperatures of over 100 °C before start-up.
One commercially available HTPEMFC fuel cell system is the Serenergy[1] 166 Air C system with its dimensions of $(178x159x523)\mathrm{mm}$ and an approximative system weight of 7 kg. This fuel cell stack containing 65 cells is taken as example for the system modeling (Figure 4).

In order to evaluate the fuel cell voltage as function of the cell current, the empiric temperature dependant approach presented by Korsgaard [8] is used (eq. 7).

[1] www.serenergy.dk

Figure 4. Serenergy 166 Air C HTPEM fuel cell System

$$V_{\mathrm{FC}} = U_0 - \frac{RT}{4\alpha F}\ln\left(\frac{i+i_0}{i_0}\right) \quad -R_{\mathrm{ohmic}}\cdot i - \frac{R_{\mathrm{conc}}\cdot i}{\lambda - 1} \tag{7}$$

$$\begin{aligned}
\alpha &= a_0 + b_0 \\
i_0 &= a_3 \exp\left(-b_3 \cdot T\right) \\
R_{\mathrm{ohmic}} &= a_1 T + b_1 \\
R_{\mathrm{conc}} &= a_2 T + b_2 \\
a_0 &= 2.761 \cdot 10^{-3} & b_0 &= -0.9453 \\
a_1 &= -1.667 \cdot 10^{-4} & b_1 &= 0.2289 \\
a_2 &= -8.203 \cdot 10^{-4} & b_2 &= 0.4306 \\
a_3 &= 33.3 \cdot 10^{3} & b_3 &= -0.04368 \\
U_0 &= 0.95
\end{aligned}$$

Fuel cells have, in most cases, to be supplied with hydrogen [12]. In order to be able to supply the HTPEM fuel cell inside the scooter with hydrogen different means of storage can be used [13]:

- **Liquid hydrogen** is stored at temperatures of around $20\,\mathrm{K}$ and pressures around $8 - 10\,\mathrm{bar}$.
- **Pressurized hydrogen** is stored at pressures of $350 - 700\,\mathrm{bar}$ in composit containers.
- **Metal hydrides** are able to store up to 5 wt% of hydrogen inside their metal matrix.

All technologies have proven their viability and currently undergo improvements with regard to weight, volume and costs. At the same time questions of refueling and hydrogen infrastructure have to be solved.

C. Battery

For this system a Lithium Ion (Li Ion) battery is used. Li Ion batteries offer high specific energy and high specific power. Due to the use of the rare metal lithium the cost of such a battery is high in comparison with other battery technologies. The main application for the moment is for portable application but they also become more and more used in mobile application.

The Li Ion battery is modeled with a simplified version of the approach presented by Erdinc [11]. Therefore, the open circuit voltage of the battery is calculated depending on the state of charge (SOC) using (eq. 8). The SOC is expressed using (eq. 9) with SOC_{init} the initial state of charge, i the current delivered to or taken from the battery in A and C the usable battery capacity in $\mathrm{W\,h^{-1}}$. The internal resistance of a battery is considered to be constant $2\,\mathrm{m\Omega}$.

The question of hydrogen fueling for scooters has been discussed in [13].

$$\begin{aligned}
V_{\mathrm{OC}}\left(SOC\right) = &-1.031 \cdot \exp\left(-35\, SOC\right) + 3.685 \\
&+ 0.2156 \cdot SOC - 0.1178 \cdot SOC^2 \\
&+ 0.321 \cdot SOC^3
\end{aligned} \tag{8}$$

$$SOC = SOC_{\mathrm{init}} - \int (i/C) \tag{9}$$

For the studied system it is foreseen to use two packs of 18 Li Ion batteries in parallel. As each cell has a nominal open circuit voltage of $3.6\,\mathrm{V}$ the battery package will have a nominal open circuit voltage of $70\,\mathrm{V}$. The energy density needed for the system is $6\,\mathrm{Ah}$, thus leading to an approximative battery size of $0.3\,\mathrm{L}$ and an battery weight of $0.3\,\mathrm{kg}$. It has to be taken into consideration, that the battery is an energy buffer, the main energy source is the HTPEM fuel cell system. A pure battery driven electric scooter with comparable performance with a Nickel Hybrid battery has a battery with a capacity of $3.7\,\mathrm{kW\,h}$ and thus ten times bigger [14].

D. Power Converter

As the battery is directly linked to the bus, the bus voltage is determined by the battery voltage. The bus voltage is thus not stable but depending on the current delivered by the battery and has a nominal voltage of $70\,\mathrm{V}$. The introduced HTPEM fuel cell stack has a nominal voltage of $55\,\mathrm{V}$. A boost converter is thus used in order to increase the fuel cell stack voltage to the bus voltage level [15]. The boost converter imposes the current that has to be delivered by the fuel cell, depending on the fuel cell power demand imposed by the system control, and evaluates the duty cycle.

The boost converter is controlled using a proportional controller to evaluate the duty cycle, the fuel cell power command is directly imposed into the fuel cell model.

E. System Control

The power control of a combined HTPEM fuel cell system with a Li Ion battery system to supply an electric scooter is a complex problem. Taking into account the need of fuel cell preheating it leads to a system with the following in and outputs:

- Input:
  - P_{load}: the power demanded by the system to meet the demanded speed profile;
  - T_{FC}: the temperature of the fuel cell stack;
  - SOC: the state of charge of the Li Ion battery.
- Output:
  - P_{FC}: the power that has to be supplied by the fuel cell stack;

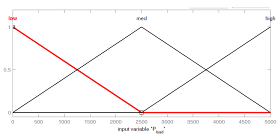
– P_{heat}: the power needed to preheat the fuel cell stack.

As the system contains several inputs and several outputs all from different domains a classical control approach might be rather complex. Furthermore, the main aspects of the system are known by experience. This is why a rule based control design approach as it is proposed by fuzzy logic is well adapted for this problem.

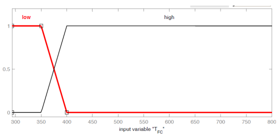
Fuzzy logic is a technique to embody human-like thinking into a control system. A fuzzy controller can be designed to emulate human deductive thinking and may thus lead to a faster development and implementation of control cycles . The fuzzy control was first introduced by Lotfi Zadeh in 1965 and was soon implemented in different systems. The fuzzy control is based on heuristic rules, which is a logical implication of the form:

If ⟨ condition ⟩ then ⟨ action ⟩.

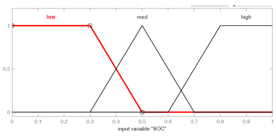
They are characterized by linguistic variables with values like *low* and *high* representing qualitative concepts about the state of a system. Those linguistic variables are converted into numeric values using membership functions. Each value can be associated to different membership functions. As the membership functions are not discrete but fuzzy a value can be associated to different membership functions. The membership functions of the in- and outputs of the discussed system are presented in (Figure 5).



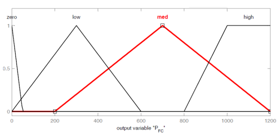
(a) P_{load}



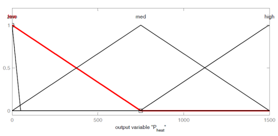
(b) T_{FC}



(c) *SOC*



(d) P_{FC}



(e) P_{heat}

Figure 5. Membership functions of in- and outputs of the studied system

The membership functions of inputs and outputs are connected to rules leading as presented in Table I. The rules used in this case are based on experience and take into consideration that the fuel cell cannot work as long as its temperature is below 100 °C, or that energy recuperation can only be effectuated by the battery. Those rules lead to a concrete system output which is traduced to the system output by defuzzification.

F. System Model

The system model is realized under Matlab/Simulink R2009b. The evaluation of the system power demand as a function of the scooter characteristics is done using the QSS toolbox developed by the ETHZ.

The model contains the following main elements which have already been introduced in more detail above:

- Lithium Ion Battery
- HTPEM fuel cell system
- Power Converter
- Fuzzy Controler

The schematic of the modeling can be seen in (Figure 6).

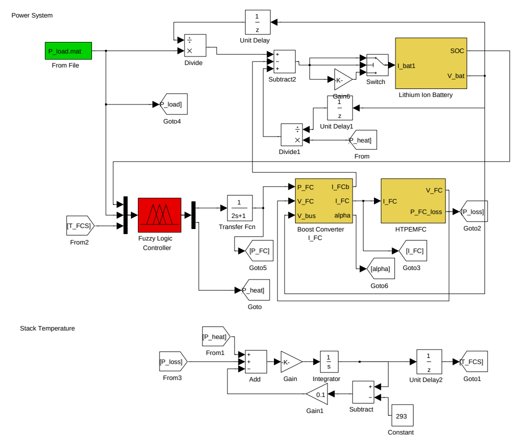


Figure 6. Transduction of the model into Simulink

IV. Simulation Results

First of all the different powers in the system are shown in (Figure 7). The power demanded by the load is represented by the solid blue line. The power delivered by the battery is presented by the dotted green line. It can be seen that the battery is used to deliver the power dynamics with power peaks between −4 kW and 5 kW. The battery is the only element that can recuperate energy. The HTPEM fuel cell can only deliver power after it has been warmed up to temperatures of more than 100 °C, this is why the delivery of power (red dashed dotted line) only starts 200 s after the beginning of the system, before the fuel cell can be switched off. It can be seen that the fuel cell power profile is rather smooth with a maximum value of 1 kW the nominal system output. It has to be noticed, that the smooth power profile is advantageous for the fuel cell system, which is sensitive to dynamic power steps [6]. Finally, it has to be noticed that a certain fraction of the battery power (dashed turquoise line) is used for the stack heating.

The voltages of battery (solid blue line) and fuel cell stack (dotted green line) can be seen in (Figure 8). As has been introduced above the battery is directly connected to the system bus and defines thus the bus voltage. It can be seen that the battery voltage evaluates between 40 V and 80 V which can still be acceptable for a system. In order to reduce the voltage drop of the battery a battery with higher capacity

Table I
FUZZY RULES OF THE SYSTEM

1	IF	T_{FC}	is	**high**					THEN	P_{heat}	is	**zero**				
2	IF	T_{FC}	is	**low**					THEN	P_{FC}	is	**zero**				
3	IF	SOC	is	**low**	and	T_{FC}	is	**low**	THEN	P_{FC}	is	**zero**	and	P_{heat}	is	**low**
4	IF	SOC	is	**med**	and	T_{FC}	is	**low**	THEN	P_{FC}	is	**zero**	and	P_{heat}	is	**low**
5	IF	SOC	is	**high**	and	T_{FC}	is	**low**	THEN	P_{FC}	is	**zero**	and	P_{heat}	is	**med**
6	IF	SOC	is	**low**	and	T_{FC}	is	**high**	THEN	P_{FC}	is	**high**	and	P_{heat}	is	**zero**
7	IF	SOC	is	**med**	and	T_{FC}	is	**high**	THEN	P_{FC}	is	**high**	and	P_{heat}	is	**zero**
8	IF	SOC	is	**high**	and	T_{FC}	is	**high**	THEN	P_{FC}	is	**zero**	and	P_{heat}	is	**zero**

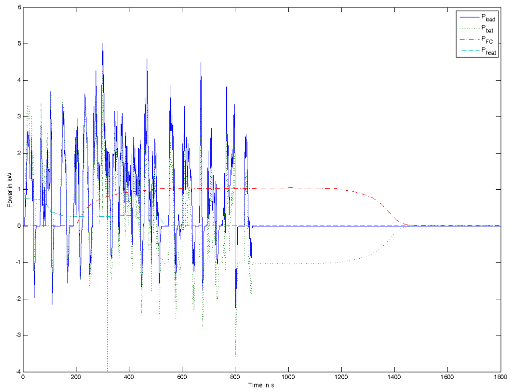


Figure 7. Different powers delivered by the system

can be used, but this will lead to higher system weight and volume. Furthermore it can be seen, that a considerable voltage drop occurs at 300 s due to an exceeded power demand. A limitation in power demand will solve this issue. It can be seen, that the fuel cell stack voltage is between 40 V and 60 V. The fuel cell stack is connected to the bus via a boost converter. As soon as the fuel cell stack is connected the battery voltage is superior to the fuel cell voltage and a boost converter is thus well adapted [15].

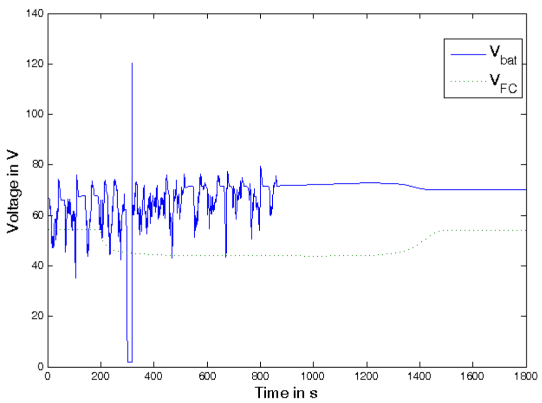


Figure 8. Battery and fuel cell stack voltages

The parameter to judge a battery pack is the state of charge (SOC) as which is presented in (Figure 9). The initial SOC is 75 % during the cycle it drops down to 35 % and at after the cycle the battery is recharged to 70 % SOC. Unfortunately, the power peak at 300 s is not represented by the SOC. Therefore and due to the fact that the SOC is difficult to evaluate for a real system it can be discussed if the SOC is the best parameter to describe the fitness of a battery or if other values might be used.

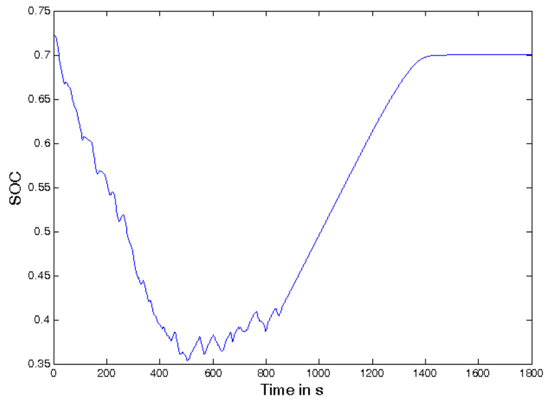


Figure 9. State of charge of the battery

As has been described above, the fuel cell stack has to be preheated to over 100 °C before it can be used. The temperature evaluation is shown in (Figure 10). It shows that the fuel cell stack is heated up to working temperatures after around 200 s. Afterwards the fuel cell can be used. Due to the internal power losses the stack heating continues up to 218 °C where it stabilizes.

The hydrogen consumption to fulfill a drive cycle including the following battery recharge is 8.5 mol, which is equivalent to 0.5 L of hydrogen compressed to 350 bar. The system efficiency during the entire cycle can hence be evaluated and is 39 %.

V. CONCLUSIONS AND PERSPECTIVES

This articles introduces an architecture based on a HTPEM fuel cell system combined with a lithium ion battery for small mobile applications. The simulations shows that this solution is valid using a battery pack with a nominal voltage of 70 V and a battery capacity of 6 A h. Still, it can be seen, that preheating

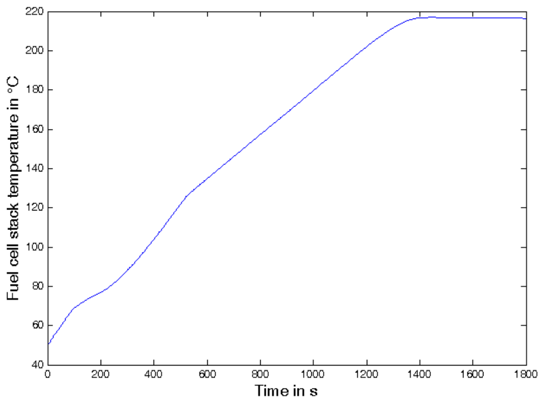


Figure 10. Fuel cell stack temperature

time of the HTPEM fuel cell stack of around 200 s is around 25 % of the drive cycle length. Due to those preheating times such a system will be more adapted for longer missions.

The power control system based on fuzzy logic is well adapted for the introduced system. Experience based rules can be introduced easily leading to a low dynamic fuel cell management management.

Based on this work further evaluations of HTPEM fuel cell systems for mobile and stationary applications with or without fuzzy control can be made.

REFERENCES

[1] J. Barkenbus, "Our automotive future: Co2 savings through a disruptive technology," *Policy and Society*, vol. 27, pp. 399 – 410, 2009.

[2] L. A. De La Fuente LaYos, "Mobilitaet im personenverkehr in europa," 2007, (in german). [Online]. Available: http://www.eds-destatis.de/

[3] B.-O. Ducreux, "Powered two wheelers compared with cars: Driving dynamics, fuel consumption and exhaust emissions in daily use," ADEME, December 2008.

[4] B. Blunier and A. Miraoui, *20 Questions sur la Pile à Combustible*. Édition Technip, 2009, no. ISBN 978-2-7108-0928-9, (in french).

[5] R. K. Ahluwalia and X. Wang, "Fuel cell systems for transportation: Status and trends," *Journal of Power Soures*, vol. 177, pp. 167–176, 2008.

[6] F. Gao, B. Blunier, and A. Miraoui, "A multiphysic dynamic 1d model of a proton exchange membrane fuel cell stack for real time simulation," *IEEE Transactions on Industrial Electronics*, 2009, doi:10.1109/TIE.2009.2021177.

[7] A. R. Korsgaard, R. Refshauge, M. P. Nielsen, M. Bang, and S. K. Kaer, "Experimental characterization and modeling of commercial polybenzimidazole-based mea performance," *Journal of Power Sources*, vol. 162, no. 1, pp. 239–245, Nov. 2006.

[8] A. R. Korsgaard, M. P. Nielsen, and S. K. Kaer, "Part one: A novel model of htpem-based micro-combined heat and power fuel cell system," *International Journal of Hydrogen Energy*, vol. 33, pp. 1909–1920, 2008.

[9] ——, "Part two: Control of a novel htpem-based micro combined heat and power fuel cell system," *International Journal of Hydrogen Energy*, vol. 33, pp. 1921–1931, 2008.

[10] J. L. Jespersen, E. Schaltz, and S. K. Kaer, "Electrochemical characterization of a polybenzimidazole-based high temperature proton exchange membrane unit cell," *Journal of Power Sources*, vol. 191, no. 2, pp. 289–296, Jun. 2009.

[11] O. Erdinc, B. Vural, and M. Uzunoglu, "A dynamic lithium-ion battery model considering the effects of temperature and capacity fading," in *Clean Electrical Power, 2009 International Conference on*, 2009, pp. 383 – 386.

[12] D. Chrenko, D. Bouquain, and A. Miraoui, "Fuel cell electric scooter: Comparison between a hydrogen direct and a methanol hybrid architecture," in *IECON*. Porto, Portugal: IEEE, November 2009, best Paper Prize of the Power Electronics Technical Committee (PETC) of the IEEE Industrial Electronics Society (IES) among the papers presented at the 2009 IECON.

[13] D. Chrenko, M. Kabalo, F. Gao, B. Blunier, D. Bouquain, and A. Miraoui, "Fuel cell electric scooter: Considerations toward an optimized architecture," in *Vehicular Power and Propulsion Conference (VPPC)*, Lille, France, September 2010, (submitted).

[14] Vetrix, "Vetrix vx-1 characteristics," http://www.vectrix-paris.fr/catalogue.php, 07 2010.

[15] M. Kabalo, B. Blunier, D. Bouquain, and A. Miraoui, "State-of-the art of dc-dc converters for fuel cell vehicles," in *Vehicle Powwe and Propulsion Conference, 2010. VPPC '2010. IEEE*, 2010, (submitted).