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MODELLING ASSISTED TESTING AND QUALITY CONTROL OF FUEL CELLS

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ABSTRACT

Proton Exchange Membrane Fuel Cells (PEMFC) are dynamically and multi-dimensionally modelled within MATLAB-Simulink. Cells (stacks) are modelled 3-dimensionally. In case of system simulations a 1-D model is preferred to reduce computation time. Emphasis is given to critical operation conditions, e.g. the change of the membrane resistance as a function of the water content during fast load changes. Such investigations are expected to provide information about the pre-stage of degradation in PEMFCs. The model has been verified by experiments with a water cooled stack.
Modelling assisted testing allows well directed control and improvement of fuel cell components and systems and facilitates production control. Set-up of a hardware-in-the-loop (HIL) system enables real time interaction between the selected hardware and the model. This tool allows to investigate the behaviour of the real components in a virtual environment. Speeding up the design and assembly of the FC system, facilitating the control of fuel cell operation and acting as a tool for quality/production control are the main advantages of this method.
Keywords: Fuel cell, dynamic modelling, simulation, HIL, diagnostics, quality control

1. INTRODUCTION

In the recent years there has been a rapidly growing interest in fuel cell technology. In particular the Proton Exchange Membrane Fuel Cell (PEMFC) has reached a high development status. This development was mostly advanced by the automotive industry, because fuel cells help to substitute the fossil fuels and also provide environment-friendly propulsion. But there is also a growing market for stationary fuel cell applications e.g. for cogeneration of heat and power (CHP) and for replacement of batteries in portable devices, e.g., laptops.
Despite of the progress made in fuel cell vehicle fleets and CHP units there is still lot of work to bring fuel cells to the market. The reduction of still high costs and the build up of the hydrogen infrastructure have highest priority. Furthermore the durability and reliability of conventional systems has to be reached.
In particular for automotive and portable applications the knowledge of dynamic behaviour is of vital importance. The PEM fuel cell model presented in this work is capable of predicting the dynamic fuel cell behaviour at the different operating conditions and is thus especially apt for investigations of hard to follow time-dependent changes during fuel cell operation, notably changes at borderline conditions. Modelling-assisted testing and quality control of fuel cells is another important application. In the

following we concentrate on the latter topic, a detailed description of the former will be given elsewhere [6].
The use of test benches, which can be combined with the mathematical models of the components that are not available, open up fully new possibilities in the development of fuel cell systems. The test benches, which are represented in this work disposes a Hardware-in-the-Loop (HIL) interface that provides the fast data exchange between the test system with the available and the virtual hardware given by the model.

2. FUEL CELL STACK MODEL

The fuel cell model applied in this work is described in more detail in [1,2,5]. In order to reduce computation time the 1D-version of the model, preferable for the description of complete systems, has been used. The following section gives an overview of the basic model features and incorporated dependencies. The different layers of the fuel cell are implemented in the one-dimensional model with their respective physical and electrochemical characteristics (Fig. 1). In the gas diffusion and catalyst layer the different transport mechanisms of hydrogen, nitrogen, oxygen, water vapour and liquid water are included. The water transport through the membrane incorporates the effects of concentration gradients and the electro-osmotic drag. The nitrogen and hydrogen transport through the membrane is also included. Note that the properties of each layer are taken as location-independent in the 1D-model.

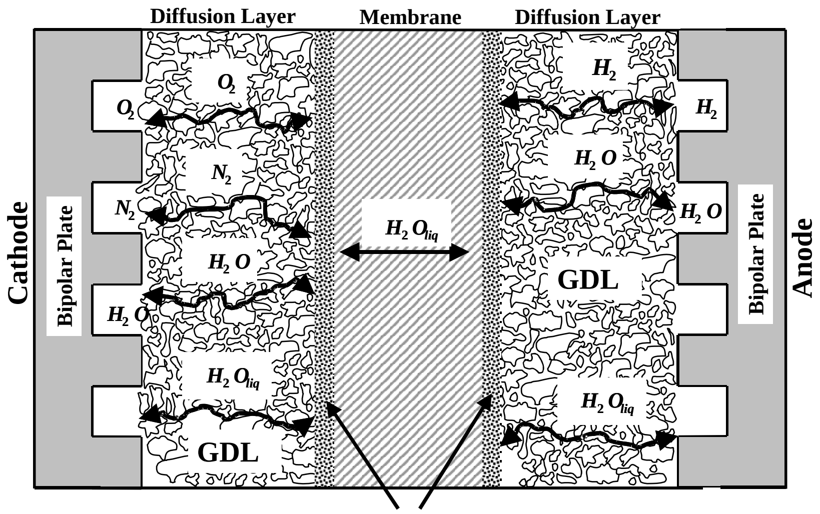

Figure 1. 1D- Fuel Cell Model

After calculation of partial pressures of the gaseous species, the water amount in the different layers, the polarisation losses at anode and cathode and the membrane voltage loss are calculated. The polarisation losses are calculated under consideration of the double layer capacitance at the electrodes. The outcome of the model is the stack voltage and the electrical power. The thermal power, the stack temperature and the rejected heat are computed under the condition that the temperature of all cells is uniform. The existing gas volumes in the stack have a big influence on the performance especially for dynamic loads, varying gas supply or gas humidifying.

The general dependencies of modelled values are given as follows:

Cell voltage: $U_{Cell} = f\,(T, p_i, \lambda, y_{H2,An}, y_{O2,Ka}, y_{H2,Ka}, y_{O2,An}, j, A_{Cell}, C_D)$

Cell temperature: $T = f\,(P_{Th}, T_{cool,in}, V_{cool}, c_{cool}, m_{cell}, \textit{stack size}, T_{Air})$

Gas transport within the diffusion media: $N_{i,GDL} = f\,(T, p_i, y_{i,FF}, y_{i,GDL}, j, A_{Cell}, \varepsilon_i)$
Herein ε is a function of the amount of water in the according media.

Water transport within the membrane: $N_{H2O,Mem} = f\,(T, p_i, y_{H2O,Ca}, y_{H2O,An}, j, A_{Cell}, \delta_{Mem})$

Oxygen transport within the membrane: $N_{O2,Mem} = f\,(T, p_i, y_{O2,Ca}, y_{O2,An}, j, A_{Cell}, \delta_{Mem})$

Hydrogen transport within the membrane: $N_{H2,Mem} = f\,(T, p_i, y_{H2,Ca}, y_{H2,An}, j, A_{Cell}, \delta_{Mem})$

Nitrogen transport within the Membrane: $N_{N2,Mem} = f\,(T, p_i, y_{N2,Ca}, y_{N2,An}, j, A_{Cell}, \delta_{Mem})$

For a detailed model description and the parameter values used in the simulations see Refs [1] and [5].

3. HIL SIMULATION

For the development of fuel cell stacks or fuel cell systems, there is an increasing need in suitable test benches. The MAGNUM company has been one of the first suppliers of fuel cell test benches and, in particular, of HIL capable test benches. The big advantage of using HIL test stands is that in early stage of development testing of whole systems can be performed, even if all the hardware is not available [3].
In conventional test benches whole fuel cell system can only be tested if all sub-systems and units are installed. Fig. 2 shows the test bench configuration with integrated HIL simulation replacing certain hardware with their simulation models.

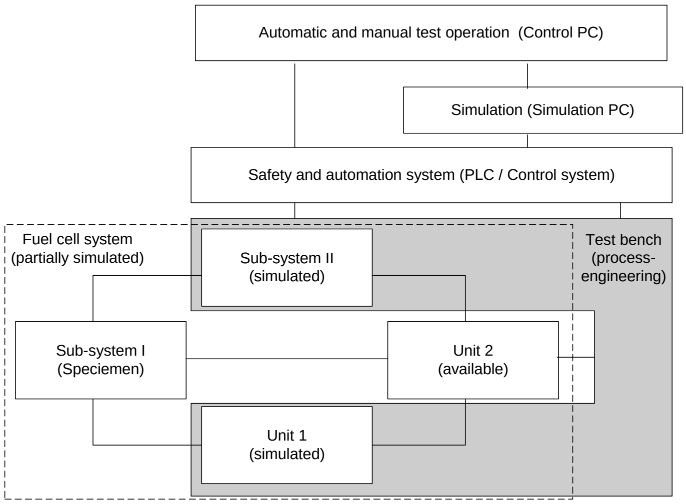

Figure 2. HIL capable test bench

One of the main aspects for the realisation of HIL test stands is safety [4], because of the possibility to operate the hardware together with safety control programmes based on the simulation models. The high safety standard is reached through the implementation of multistage switch off procedure on the PLC (Fig. 2). Further on, each of the set values for the controllers calculated in the model are checked by the PLC before being passed on to the hardware. The PLC will restrict the set values to reasonable limits and prevent dangerous operation conditions. This is especially important in case of, e.g., a mix of hydrogen and oxygen in the cell because of leakages.
Regarding automotive applications is the dynamic operation of the test bench is another important aspect. Therefore fast mass flow and pressure controllers are integrated and also fast data acquisition and data exchange between the PLC and control PC respectively simulation PC are realised.
For fast dynamic changes of the gas humidification in the test stand, model based control algorithms are implemented. Thermodynamic simulations have been integrated to set-up new control algorithms for temperature and moisture. These methods allow to determine the actual moisture with high accuracy, by measuring solely temperature and considering heat capacities of gases and equipment.

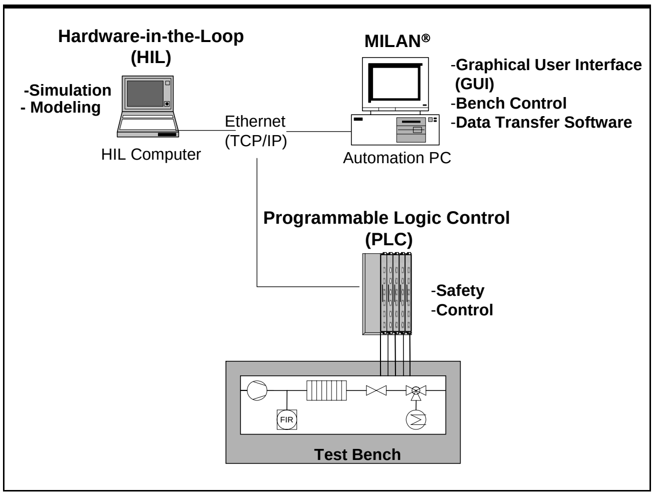

Figure 3. Automation and data transfer within HIL test bench

As shown in Fig. 3, the fast data transfer between the automation PC, HIL computer and the PLC is realised via ethernet connection. The HIL simulation can be started by the operator by choosing an adequate operation mode on the automation PC. The simulation model is running on the HIL PC in real time writing selected set values to the PLC and simultaneously reading actual values from PLC.

4. SUMMARY

A MATLAB-Simulink based dynamical model, capable of describing PEM fuel cell systems with sufficient accuracy in real time, has been developed. In addition to the calculation of cell voltage, this model also allows the calculation of time dependent stack temperature and partial pressure changes of the gaseous/humidified fuel and oxidant.

The setup of HIL capable test benches has been designed and the special requirements for using these test benches for fuel cell testing are described. The use of the model assisted HIL test benches and the resulting advantages for the development of fuel cell systems is demonstrated for systems with high dynamic needs, notably automotive applications.

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List of Symbols

C_{cool}:	Heat capacity [J/(kg*K)]
j :	Current density [A/ cm^2]
m_{cell}:	Cell mass [kg]
$N_{i,GDL}$:	Molar flow gas diffusion layer [mol/s]
$N_{i,Mem}$:	Molar flow in membrane [mol/s]
p_i:	Partial pressure of component i [pa]
P_{Th}:	Thermal power [W]
$y_{i,\,Ca}$:	Component i in the catalytic layer cathode [mol/ m^3]
$y_{i,\,An}$:	Component i in the catalytic layer anode [mol/ m^3]
$y_{i,\,FF}$:	Component i in the flowfields [mol/ m^3]
T:	Cell Temperature [K]
$T_{cool,\,in}$:	Temperature of coolant [K]
V_{cool}:	Cool medium Flow [m^3/s]
U_{cell}:	Cell voltage [V]
$y_{i,\,GDL}$:	Component i in diffusion layers [mol/ m^3]
ε_i:	Porosity of medium i [ ]
λ:	Stoichiometry of gas supply [ ]
δ_{Mem}:	Swelling factor of the membrane [ ]