Model based design of a controller for fuel cell systems

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Abstract

The control of a proton exchange membrane fuel cell system (PEM FC) for domestic heat and power supply requires extensive control measures to handle the complicated process. The objective is to design, implement and commission a controller for the entire fuel cell system. The fuel cell process and the control system are engineered simultaneously, therefore there is no access to the process hardware during the control system development. Therefore the method of choice was a model based design approach, following the rapid control prototyping (RCP) methodology.

The gas generator and the PEM FC are simulated using a fuel cell library which contains a generic set of thermodynamic models of process components. In the course of the development the process model is continuously adapted to the real system. The controller application is designed and developed in parallel and thereby tested and verified against the process model.

The process model and the controller application are implemented in Simulink using Mathworks` Real Time Workshop (RTW) and the xPC development suite for MiL (model-in-the-loop) and HiL (hardware-in-the-loop) testing.

It is possible to completely develop, verify and validate the controller application without depending on the real fuel cell system, which is not available for testing during the development process. The fuel cell system can be immediately taken into operation after connecting the controller to the process.

Introduction

Compliance with the Kyoto Protocol requires substantial improvements in energy efficiency. One way to accomplish this goal is to combine the generation of electricity in power plants with household heat generation. The combined and decentralized generation of heat and power will ultimately lead to a significant increase in thermal efficiency and a corresponding reduction of greenhouse gas emissions.

Proton exchange membrane fuel cells (PEM-FC) are a very promising technology. The basic principle of a PEM-FC system is very simple: it is the reverse reaction of the well known electrolysis. By recombining hydrogen and oxygen at the cathode an electric current is induced and heat is generated simultaneously. In Figure 1 the four basic elements of a PEM-FC are depicted:

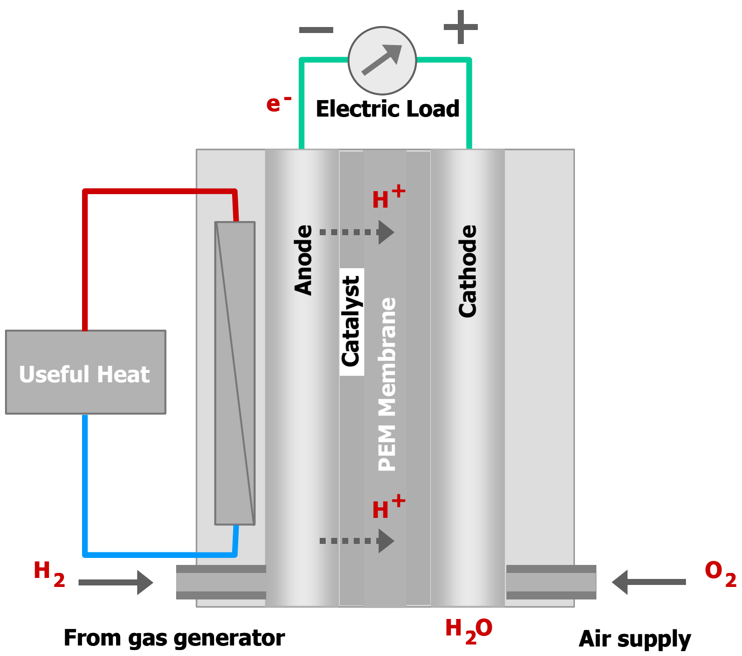

Figure 1: The parts of a PEM fuel cell [1]

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- The *anode,* the negative post of the fuel cell, conducts the electrons to an external circuit. It has channels etched into it that disperse the hydrogen gas equally over the surface of the catalyst.
- At the *cathode*, the positive post of the fuel cell, the oxygen is distributed to the surface of the catalyst. The cathode conducts the electrons back from the external circuit to the catalyst, where they recombine with the hydrogen ions and oxygen to form water.
- The electrolyte is the *proton exchange membrane*. This specially treated material only conducts positively charged ions and blocks electrons.
- The *catalyst* is a special material that reduces the activation energy of the reaction of oxygen and hydrogen. The catalyst is porous so that the maximum surface area can be exposed to the hydrogen or oxygen. The coated side of the catalyst faces the membrane.

Since pure hydrogen is not readily available for domestic and stationary power generation, natural gas (CH_4) is the preferred fuel, especially since many houses are already connected to natural gas supplies by pipeline. Natural gas is first converted to hydrogen by steam reformation. After passing a shift reactor and a methanizer in which CO is removed, the anode gas mainly consists of H_2, CO_2, H_2O with traces of CH_4 and CO. It enters the fuel cell on the anode side. The main components of the system are the gas generator, the fuel cell stack and the inverter (c.f. Figure 2)

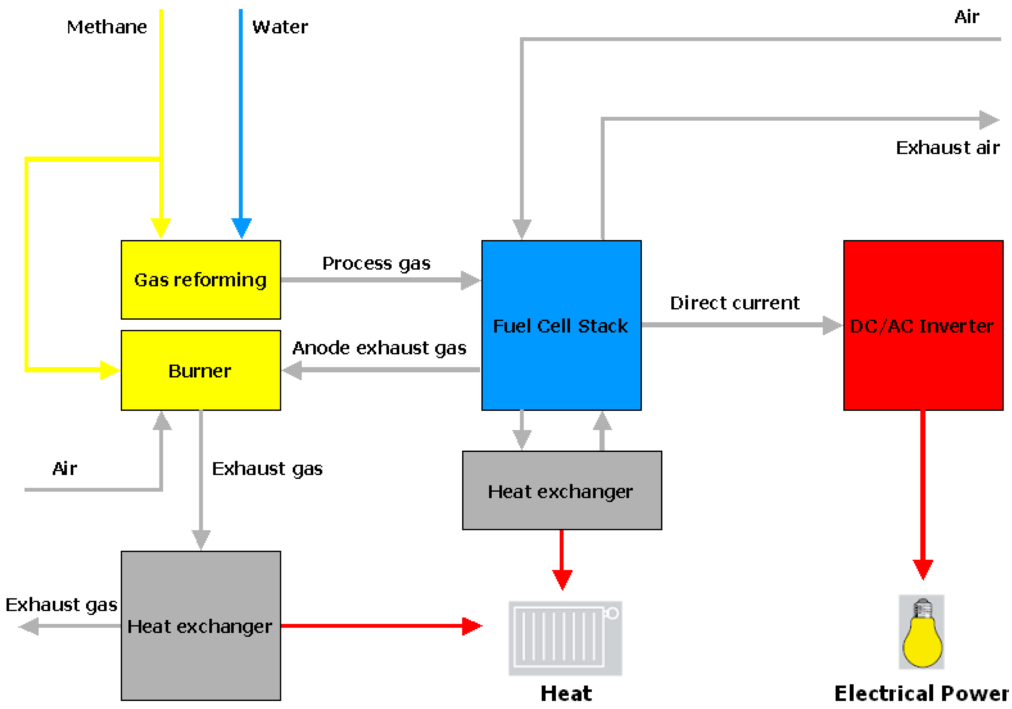

Figure 2: The schematic of a PEM fuel cell *system* for domestic heat and power generation [1]

When an H_2 molecule comes in contact with the catalyst, it splits into two H^+ ions and two electrons (e^-). The electrons are conducted through the anode, where they make their way through the external circuit (doing useful work) and return to the cathode side. On the cathode side of the fuel cell, the oxygen (O_2) molecule flows through the catalyst, where it forms two oxygen atoms with a strong negative charge. This negative charge attracts the two H^+ ions through the membrane, where they combine with an oxygen atom and two of the electrons from the external circuit to form a water molecule (H_2O).

Anode side $2\,H_2 \Rightarrow 4\,H^+ + 4\,e^-$

Cathode side $O_2 + 4\,H^+ + 4\,e^- \Rightarrow 2\,H_2O$

Overall $2\,H_2 + O_2 \Rightarrow 2\,H_2O$

In a single cell this reaction will produce only about 0.7 V [2]. To increase this voltage to a reasonable level, many separate fuel cells are combined to form a fuel-cell stack. The current is determined by the contact surface between the gas, the electrode, the electrolyte and the distance between the two electrodes. PEM-FCs operate at a fairly low temperature (ca. 80 °C).

The overall characteristics of a fuel cell stack are best described with the help of the so-called polarization curve (Figure 3).

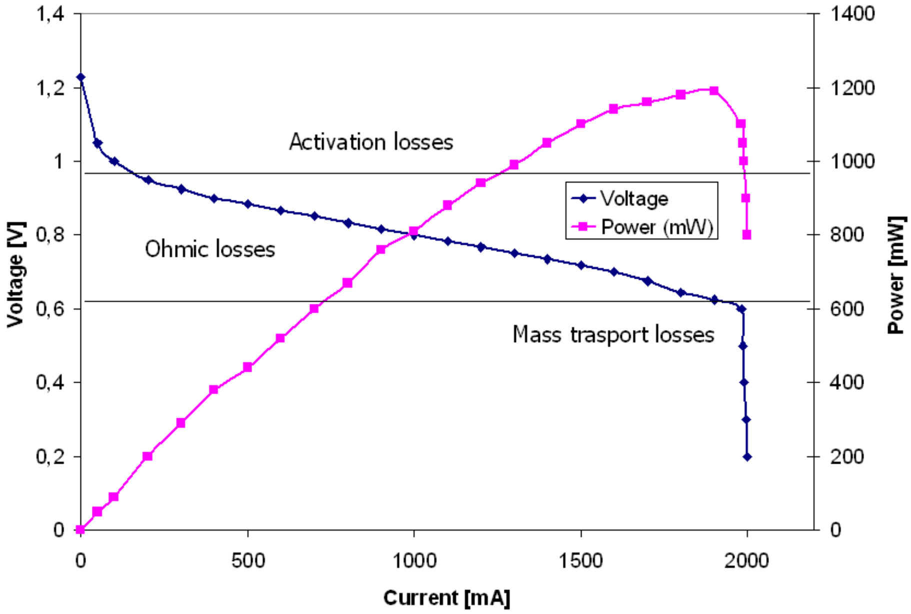

Figure 3: Polarization curve describing the effect of discharge current on cell voltage and power for a single cell

Details on the polarization behaviour of fuel cells can be found in e.g. [3]. Usually, it will be the objective to operate a fuel cell stack at its maximum cell power, thereby approaching its point of instability. The overall process as well as the various sub-processes must be controlled in narrow limits.

Rapid Control Prototyping

Before explaining the specifics of the control design for the fuel cell system, a brief introduction to the methodology of rapid control prototyping is given.

Modern control system development relies heavily on modeling, simulation, and real-time testing for both the control system and the process. In rapid control prototyping a process model or plant model is used for evaluation and optimization purposes, while the control model is used to design and/or adapt the control system. Different combinations of the process and control part of the real world application and the simulation are possible.

Since the real process is not accessible for control development a physical model of the plant is designed against which the controller is developed. The first fundamental step is the model-in-the-loop (MiL) simulation (Figure 5a). Here the process and the controller are simulated within the same development environment. The objective is to design and test the system in its operational modes and functions without any risk. Operating conditions that are otherwise difficult to access can readily be simulated. Furthermore, the simulations allow intricate test sequences to be performed quickly and repeatedly at reasonable cost, since the simulation runs much faster than the process in real-time.

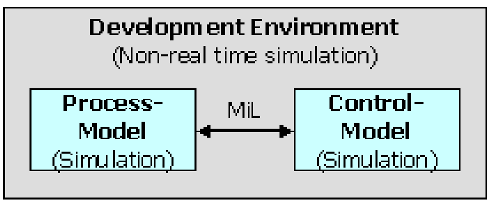

Figure 5a: Model-in-the-loop simulation as a part of rapid control prototyping

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Prototype hardware and control system software can be tested at the subsystem level using hardware-in-the-loop simulations (HiL) long before the real system becomes available for testing (Fig. 5b). The HiL simulation runs in real time and performs all the input/output operations with the system under test so that the test item “thinks” it is operating as part of the real system in its operational environment [4]. The system is tested under nominal conditions as well as at and beyond the specified operational boundaries including emergency situations. HiL simulation allows thorough testing very early in the development process and significantly reduces project risk compared to the classical approach of waiting until the real system is available before integration and testing.

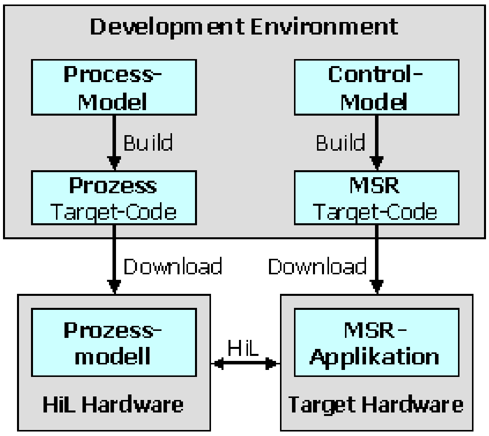

Figure 5b: Hardware-in-the-loop simulation as a part of rapid control prototyping

By combining the benefits of model based control system design using advanced simulation tools, automatic code generation tools and HiL simulation, the system development time can be reduced by almost fifty percent. A simulation of the fuel cell system (process) is developed in the simulation environment of Simulink using the fuel cell components library FClib [5]. Within the control system model, the supervisory logic is modeled by a state-machine coded in Stateflow.

The embedded software for the control system is directly generated from Simulink as a C language source using the automatic code generation tools Real Time Workshop and Stateflow Coder. The C code is compiled and deployed in the real-time environment using the xPC Target suite. The target hardware is the PC-compatible xPC Target Box. The communication between the control system and process is via CAN-Bus, reducing cabling efforts to a minimum. Figure 6 shows the final set-up of the Hil environment and highlights some details.

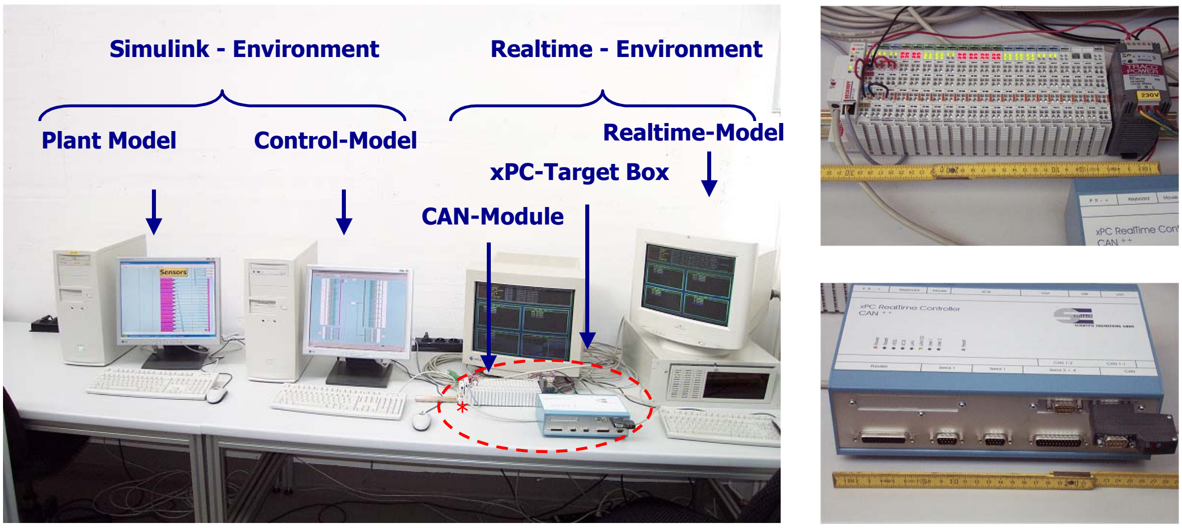

Figure 6: Hil Simulation setup using xPC Target (main figure). Inset figure above right, CAN bus terminal, inset below right, xPC Target Box

Process Model

The model of the entire fuel cell system contains dozens of components at the systems level: burner(s), steam reformer, shift reactor, methanizer, fuel cell stack, mixers, heat exchangers, pumps, fans, valves and sensors. Since the plant model is also used for evaluation and optimization purposes the physical conservation principles are considered and an extensive thermodynamic balancing functionality is included. Some elaborations are necessary as this is not a straightforward task for Simulink. In order to avoid a tedious repetitive modeling procedure, the model was set up with the help of the Simulink based fuel cell library “FClib”. The structure of FClib is shown in Figure 7 below. Note that FClib is fully compatible with the xPC Target suite and thus readily supports HiL simulations.

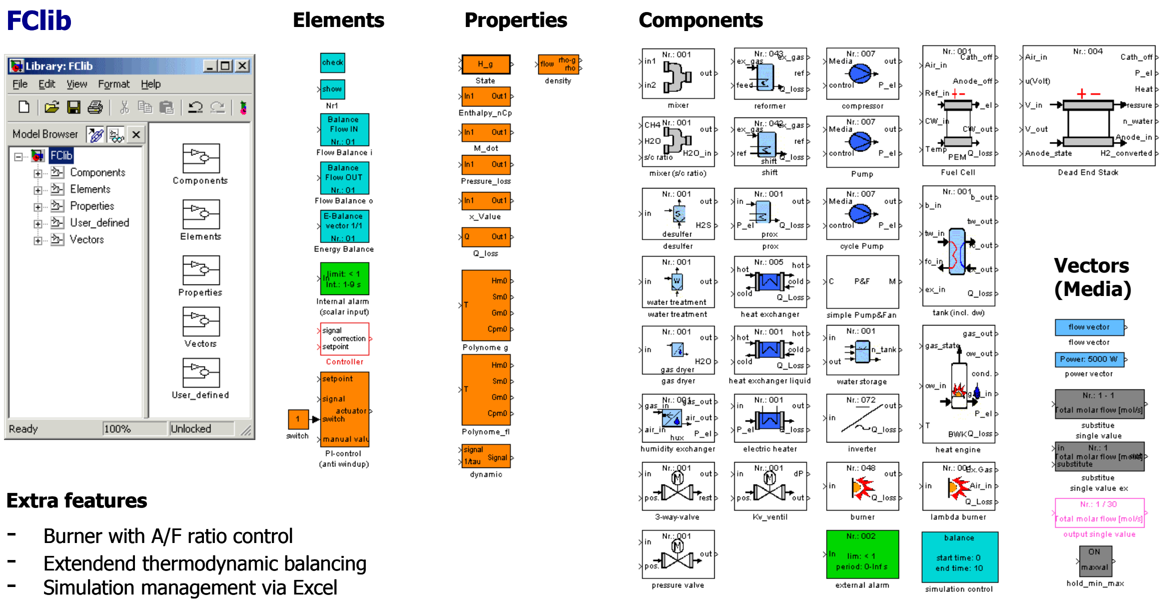

Figure 7: The Simulink based fuel cell library FClib [5]

The properties of the components used in the model correspond to those of the real plant. In operation, the model uses a step time short enough to capture the dynamic plant characteristics. The process model embedded into the model-in-the-loop setup is shown in Figure 8. The data conversion blocks transform the signal values of the CAN Bus to physical values and vice versa. This makes separation of the process model from the control system model straightforward and easy. The process model is completely designed in physical space.

In order to facilitate the development of the process model, the fuel cell system was functionally divided into subsystems:

- Burner
- Process media supply
- Steam reformation
- Gas clean-up
- Fuel cell stack
- Electrical system and converter
- Cooling cycle

The subsystems were built with the help of the components taken from the fuel cell library.

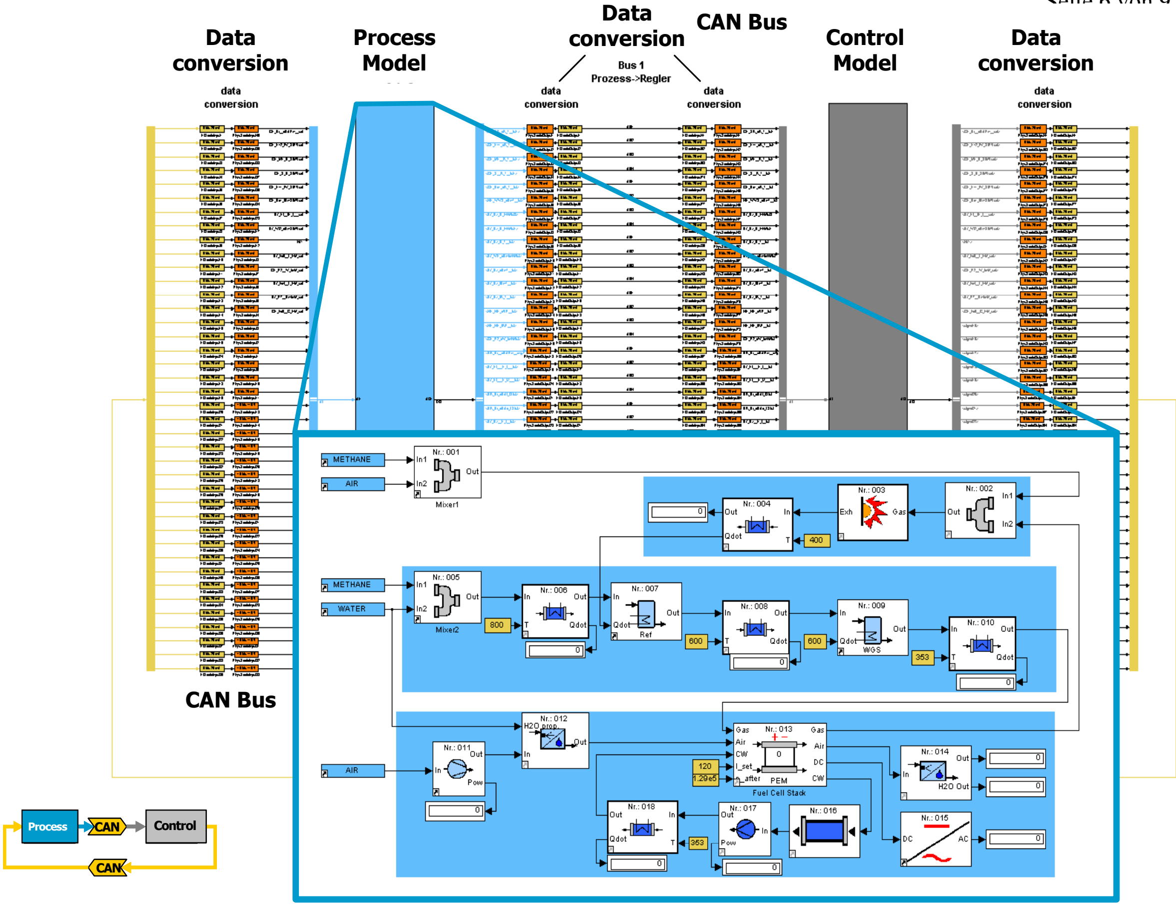

Figure 8: The process model (plant) as a part of the RCP model-in-the-loop setup (simplified)

Controller Design

Once the model of the fuel cell system described in the previous section has been set up, control system design begins. Since the fuel cell system is rather complex, the controller is developed in steps with the help of MiL Simulations. A Simulink library of the essential control elements is used to facilitate the programming task. The control system can be subdivided into following functional groups:

- State machine
- Closed loop controls
- Open loop controls
- Alarms
- Target scopes

The fuel cell system is very complex and exhibits a strong nonlinear and discontinuous behaviour. Therefore it is not possible to linearize the Simulink process model and use it directly to design the controller.

The fuel cell stack subsystem and the gas generator operate in many different states. These states depend on the working fluid (gas or steam), the load conditions, the operating modes (normal, start-up, shut-down, emergency) etc. The state machine is designed in Stateflow.

The MIMO control system is modelled as a collection of SISO systems. Cross coupling is prevalent but can be reduced by an adequate definition of states. The control parameters are adjusted for each state, thereby ensuring smooth transition. In most cases a standard, well tuned PI controller with anti wind-up is sufficient. Since the fuel cell stack exhibits a pronounced nonlinear behavior a MIMO scalar fuzzy controller is implemented relaxing the practical tuning requirements. The set-points of the actuators in open-loop are determined from state dependent mappings.

The alarms have a very important function. They not only handle the various emergency conditions but also ensure that the (prototype) fuel cell system is operated within safe limits under all circumstances: As some components are unique and difficult and time consuming to replace, damages must be avoided under all conditions. The alarms are later relaxed to the minimum as operational experience is gathered. In order to facilitate alarm management a generic alarm handling system was implemented, that allows the operator to enable, disable and parametrize alarm functions online. The application checks all available hardware and software signals and automatically generates an alarm definition table where all of the alarm conditions are stored. In real-time simulations the sensor and actuator signals can be displayed on the target monitor, by adding target scope blocks to the Simulink model. After downloading, these blocks create the scopes.

Finally, during validation the on-target system control is connected to the real process. Minor adjustments are made on-the-fly from within the Simulink model (running on the host PC) and downloading them to the target. A more user friendly possibility is to create a dedicated host file which uses the Simulink platform and connects to another, more comfortable monitoring & control software (in this case LabVIEW) via the xPC API interface.

The system control model embedded into the model-in-the-loop setup is shown in Figure 9.

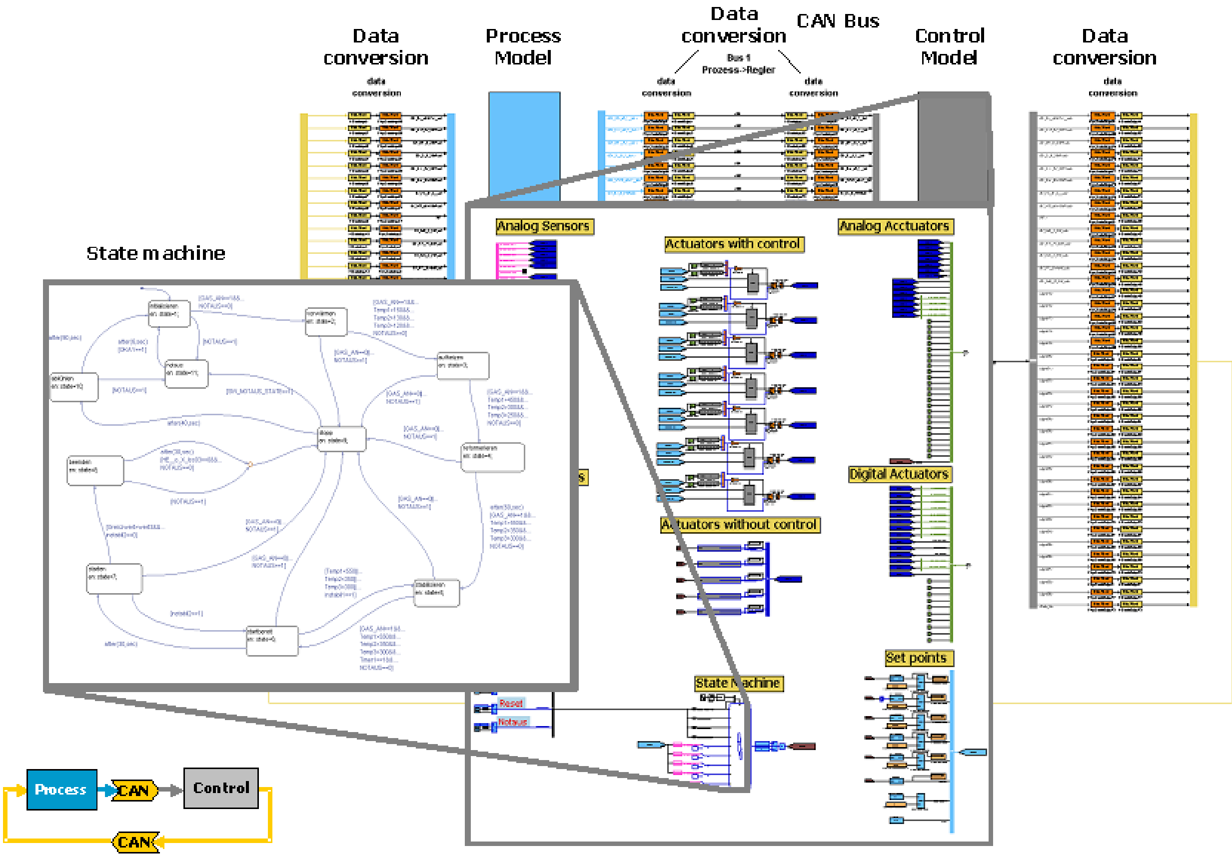

Figure 9: The control system model with state machine as a part of the RCP model-in-the-loop setup

Results

After the Simulink model of the fuel cell process and its control system are tested thoroughly the embedded software to implement the control system is generated. This is done by separating the contol system model from the process model along the I/O device. Each I/O signal is connected to an appropriate device driver. The xPC Target software suite provides automated embedded code generation, compilation and deployment using a provided real time kernel. The xPC Target environment operates while connected to a host for program downloading and testing purposes, or in a stand alone system. The I/O between the embedded processor and the process is across a CAN bus interface.

Following the build and installation of the executable program on the embedded system, the control software can be tested in a realistic environment. However, the real process is not yet available at the time the embedded code is ready for testing. Also, the risk of damaging the expensive prototype hardware with untested software is too high. The most realistic testing is therefore by means of HiL simulations. The HiL simulation uses the same I/O interfaces between the embedded system and the process simulation that the real process will use to interface with the processor.

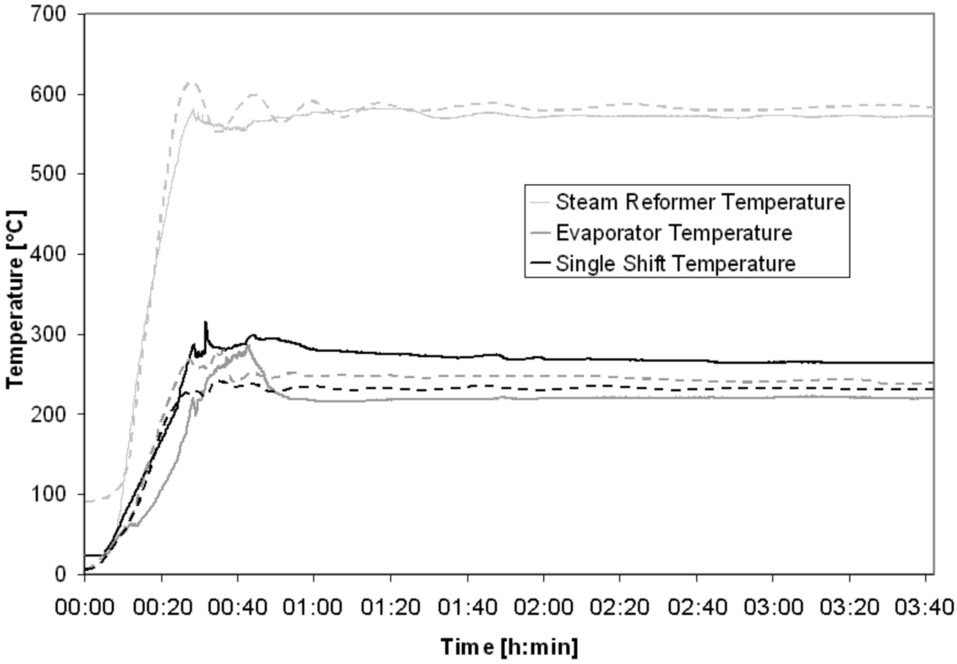

Figure 10: Important system temperatures during a warm up procedure

The process model must of course be sufficiently accurate to allow for realistic testing of the embedded software under all relevant modes of operation. Ideally, the control system's entire operational envelope is traversed under normal as well as under extreme conditions during HiL simulations. It should be noted, that test scripts can easily be implemented and executed automatically in batch runs, saving many hors of valuable development time.

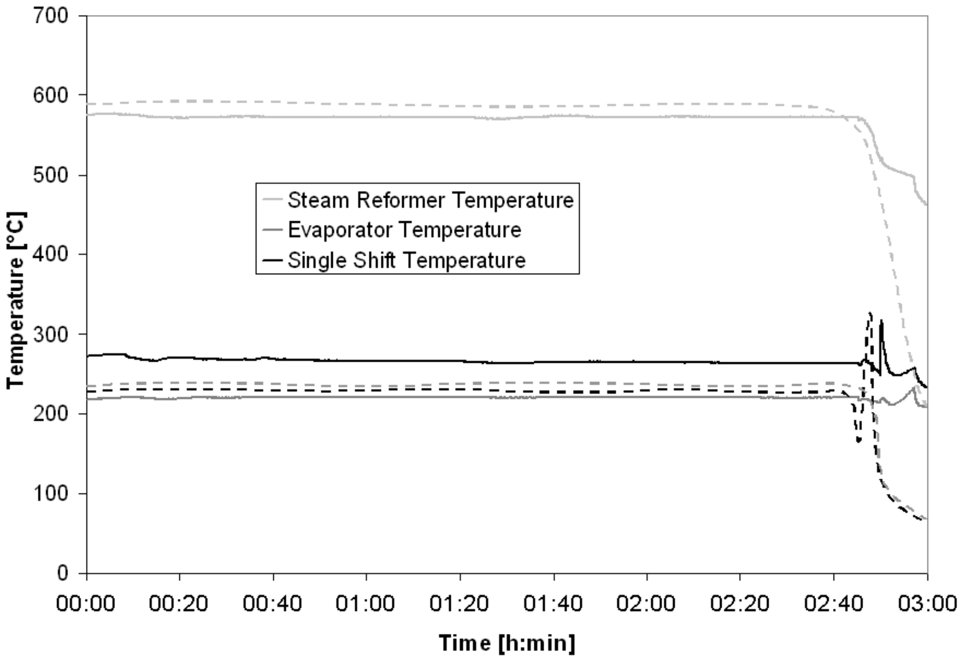

Figure 11: Important system temperatures during a cool down procedure

The simulated results (broken lines) of the particularly important system temperatures and their real values (solid lines) are depicted in Figures 10 and 11. Both Figures show that the measured and the simulated results are in good accordance.

Conclusion

The steps involved in the RCP design of a fuel cell system are outlined. Starting from a Simulink process model that is built with the help of a fuel cell library, FClib, a model based design of the control system is employed. The process and control models are then combined in Mil simulations. The automatically generated embedded code is extensively tested in HiL simulations. The result of this highly efficient design process is a significantly reduced time of development at reduced cost and improved quality.

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