CONTINOUS SIMULATION SUPPORT DURING THE DEVELOPMENT PROCESS OF A FUEL CELL SYSTEM ON BOARD OF CONVENTIONAL AIRCRAFT

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Abstract

The growing importance of fuel cell technology for industrial as well as for private applications is obvious. In the last couple of years, mobile fuel cell system applications were driven by the automotive industry. Advantages of the fuel cell technology onboard an aircraft are seen in the replacement of the conventional auxiliary power unit (APU) and the ram air turbine (RAT). E.g., Boeing considers a solid oxide fuel cell (SOFC) as an APU alternative [1, 2].

Within the 3rd national research program (LUFO 3) Airbus launched the advanced power and water generation system project (APAWAGS). The scope of this project is to determine the power and water generation of a fuel cell system onboard an aircraft.

Because of economical reasons the continuous simulation during the entire development process is reasonable [4]. Scope of this paper is a concept for the application of simulation throughout the system development, from the concept phase to the commercial product. In addition the need of a technical realization for a distributed, multidisciplinary simulation will be discussed by means of a complex water and power generating fuel cell system.

1 General Introduction

The principals of direct conversion of chemical into electrical energy without combustion have been known since 1839 when W. Grove invented the first fuel cell. The first fuel cell application was installed onboard a space craft in the middle of the last century [4]. Currently, the development and simulation of fuel cell systems are driven by numerous research projects [5, 6]. First studies show a promising potential for the energy supply of commercial aircrafts.

This is the reason for the governmental subsidisation of fuel cell system application for future passenger planes as e.g. the APAWAGS project. Up to the time being, the pneumatic and hydraulic energy for board systems and cabin air conditioning are provided by the main engines [7]. In a more electrical aircraft environment these supplies could be replaced by fuel cell powered units.

The hydrogen for the fuel cell system is provided by a kerosene reforming process. In addition to the electrical power generation the fuel cell also produces water. The water feedback into the board system results in a weight decrease. Another advantage is the noise and emission reduction.

To prove the potential of the fuel cell technology onboard an aircraft and to address the problem a ground demonstrator is currently under construction. In addition to the demonstrator the EADS Corporate Research Centre (CRC) is assigned to establish a fuel cell system simulation. The simulation model will be verified by demonstrator measurements. Another task of the simulation is the virtual integration of the electrical aircraft loads and the onboard water generation to derive an efficient fuel cell application.

Because of security issues and possible hardware damaging it is not possible to run the fuel cell demonstrator under critical system conditions. Thus simulation is used to analyse over-load cases and damage scenarios, etc. For a fuel cell system onboard application it is essential to consider the aircraft environmental condition, which could easily be integrated in a simulation model. The simulation model will be used throughout the entire system development process. Therefore it will be adapted during all process steps.

2 Simulation in the Development Process

Today simulation is used in nearly all technical domains. The most important arguments for simulation are the increase in decision quality and –security. Currently system simulation assists in making critical decisions in the early development phases. From an economic point of view, it is advisable to use simulation throughout the entire development process. The more complex a system is the more legitimated is the use of simulation [8].

Specialised simulation tools are available for nearly all technical domains. Up to now, the reusability of the models is constricted because the simulation models are developed for a unique specific purpose [9]. Furthermore, the complexity level of the simulation increases, and multidisciplinary coherences must be feasible. These requirements can not be satisfied by specialised simulation tools. For this reason various simulation software manufacturer provide interfaces to different simulation tools so that strengths of each tool can be combined.

Over the past years a new faction of simulation tools accrues, the so-called multidisciplinary simulation tools. These tools are not limited to one physical domain and allow the modeling and simulation of heterogeneous physical systems [10].

2.1 Aircraft Development Process

System development in the aircraft industry is structured by the means of the V-Model [11]. It provides a standardised method for the development of complex systems. The development process is divided into two main phases, the specification and disassembling on the left V-Model leg and the implementation and integration on the right leg (see Fig. 1) [12]. Within the scope of the system specification the higher-level requirements are sophisticated. This iterative process is repeated until the technical specification for a single system component or equipment is reached. This means that the system is divided into subsystems which are then developed independently. In the implementation and integration phase the development steps are passed through in inverse order (bottom up).

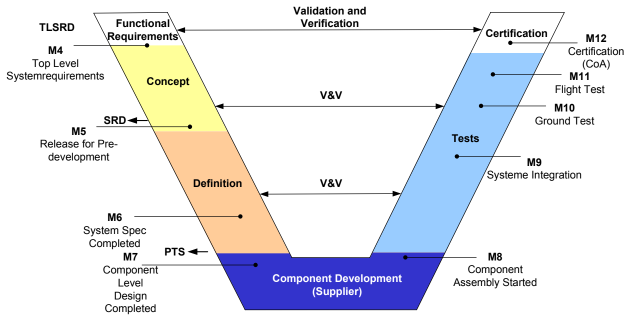

Fig. 1 V-Model Aircraft System Development

In Figure 1 the V-Model for the aircraft development process and the main milestones (M) are shown. The objectives of the V-Model procedure are:

- Minimisation of development risks
- Improvement of quality
- Decrease of development costs
- Improvement of communication

The main focus of the V-Model procedure is the validation and verification (V&V) in every single step of the development. However, the integration of all system components is not achieved until the final implementation (M11 Flight Test). Thus system incapabilities are detected in a late development stage and result in a time consuming and expensive retrace.

2.1.1 Simulation in System Development

To obtain an overview of the simulation potential regarding the aircraft system development process it is important to compare the advantages and disadvantages of simulation use (see Tab. 1).

Advantages	Disadvantages
• Improvement in decision quality • Cost-effective system analyses • Safe analyses of critical boundary conditions • Quick parameter variation • Flexible use as analytical model	• Time consuming modelling • Problem of simulation model V&V • Guarantee of optimised solution not possible

Tab. 1 Simulation Use [13]

Beside the advantages of the simulation there are also some disadvantages. In principle, simulation should only be used with according expert know how, accurate planning and at the right time. Classical development processes are distinguished by the use of simulation in the late development phases. In the early phases, the development is based on empirical knowledge. Thus new system developments have a high risk potential because of the leak of knowledge. The use of simulation is not considered in classical development processes [14].

Development time, - costs and quality are closely connected. E.g., a shorter development period often results in a decrease of quality. 5% of the entire development process are produced in the early phases, in contrast to the fact that 70% of the development costs are defined in this phases. First, the use of simulation increases the effort but, in the middle-term, simulation reduces the iteration steps, increases the system know how and reduces development time and – costs.

The point in time for simulation use is crucial. As can be derived from Fig. 2, the impact of simulation use in the early development process is huge while the costs for the simulation are low. Thus it is advisable to use simulation in the early stages [15]. In addition to this, a continuous simulation during the whole development process is reasonable [3].

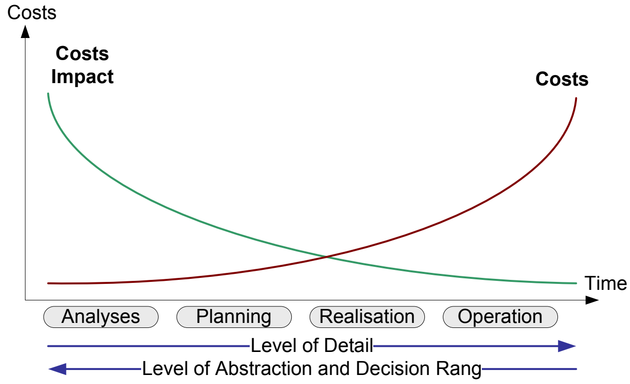

Fig. 2 Impact of Simulation Use Regarding the Development Costs

The use of simulation in the Airbus development process is described in numerous Airbus procedures. However, it is just recommended to use simulation but there is no standardised process of how simulation should assist in system development.

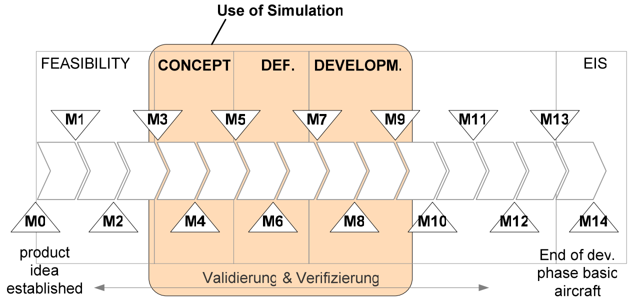

Fig. 3 Simulation within the Airbus Development Process

In Fig. 3 the Airbus milestone plan is shown. It is recommended to use simulation from the definition of the basic concept (M3) to the aircraft assembly (M9).

Recapitulating, it can be said that there is no standardised procedure for simulation within the aircraft system development. There are general development procedures which describe the process in principle but a concrete realisation for highly integrated systems is still missing.

2.2 Weaknesses of the Development Process

In chapter 2.1, weaknesses in the current development process were identified. The described process is distinguished by three main deficits. First of all, a continuous simulation support throughout the entire development process does not exist. Thus, simulation is not used in the early development phases (concept definition) where it would highly influence the development costs and – time. Furthermore, there are many delays in the process because of discontinuities. And finally, system with multidisciplinary interaction are not considered, so that interoperability, mainly discovered in late integration phases, results in expensive and time consuming iteration steps. By analysing the system development process the following main problems were identified.

Deficit 1: Inadequate simulation activities in the early process phases

- No decision support by simulation results in the concept phase
- Early concept decision only based on previous developments
- Small level of innovation in the concept phase
- No concept optimisation

At present, simulation models are hardly not exchanged between different departments. Thus the reuse of existing models is restricted and models are developed several times in different departments.

Deficit 2: Process delays because of missing cooperation

- Delays because of missing input
- Inadequate model exchange

The development of an aircraft system is a domain-overlapping process with interaction to numerous systems. Currently, the system interaction does not take place in the specification and disassembling phases (see chapter 2.1). Unique simulations for single isolated applications are used, so that systems are simulated independently. The system capability is checked in the integration test. An overall system simulation does not exist at present.

Deficit 3: System interactions are not considered

- Check of system interaction in late process phases
- Cost and time consuming iterative loops

For the accomplishment of continuous simulation support a data management is indispensable. At the moment, many different data management systems are in use. The administrative effort to maintain transparency and up-to-dateness and to avoid redundancies is enormous.

Deficit 4: Inadequate exchange of data, models and information

- Use of estimates
- Inadequate communication of simulation data (know-how loss)
- Isolated application (department internal development)
- Reuse of models is restricted
- Information quality
- Inconsistency of models and data

Deficit 5: No system overlapping organisation and communication of data

- Inordinate data exchange
- Many different data bases and management systems
- Different access rights
- Duty of acquisition

So it can be said that there is no standard process for the simulation support in the aircraft development process.

2.3 Concept for the Continuous Simulation Support during the Development Process

The requirements for a continuous simulation support are evident from the deficit analyses. The use of simulation throughout the development process depends on the information management. Thus, the requirements for the concept are divided into two parts (see Tab. 2).

Process	**Information management**
1. Simulation support in the concept phase 2. Parallelisation of activities 3. Examination of system interactions	4. Increase of data exchange 5. Increase of model exchange 6. System overlapping organization of the information management
7. Warranty of realisation	

Tab. 2 Concept Requirements

Simulation support in the concept phase 1
As described in chapter 2.1.1, the impact of the simulation use in the early phases is huge. Thus, concept failure can be identified early so that cost and time consuming iteration steps can be avoided.

Parallelisation of activities 2
By detailing the phase model, it is possible to develop the test equipment parallel.

Examination of system interactions 3
The virtual examination of system overlapping interaction between milestones M4-M6 forwards the integration tests, so that huge iteration steps can be avoided.

Increase of data exchange 4
The process information should be contemporarily available. The communication of the actual data results in a decrease of misunderstandings.

Increase of model exchange 5
The reuse of existing models lowers the development costs. A requirement for the model exchange is a standardised interface.

System overlapping organization of the information management 6
It is essential that all involved participants can access the provided information. An information overhead should be avoided.

Finally the benefit of the concept should exculpate the effort (Warranty of realisation 7).

2.3.1 Process Support by the Use of Simulation

The process requirements (see Tab. 2) can be fulfilled by simulation. A continuous simulation support throughout the development process can be achieved via different model abstraction levels (see Fig. 1). In the concept phase, an approximate model is used. First system conclusions are made using this model. The model detailing level increases within the continuing process.

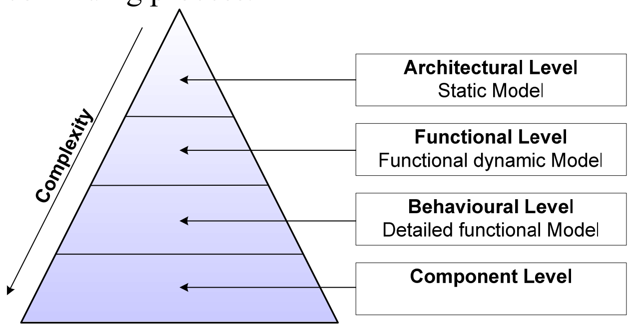

Fig. 4 Model Abstraction Level

It is important that different abstraction levels of a model are provided and can be used independently.

A combination of stand alone simulation and overlapping system interaction simulation allows an adequate procedure regarding the simulation benefits and the resources. The system departments run internal simulations, e.g., to verify the system concept. This allows the use of the most convenient software. In addition, system overlapping simulation is conducted e.g. at the end of the concept phase. The benefit of this approach is that incompatibilities are detected in an early process phase.

A system overlapping simulation can be divided into four categories (see Tab. 3).

	1 Model	numerous Models
1 Simulator	1. Type Modelling and Simulation in one Tool	2. Type Separate modelling, but coupled Simulation
numerous Simulatoren	(4. Type) (Modelseparation)	3. Type Simulation Coupling

Tab. 3 Categories of the system overlapping simulation [16]

1. Modeling and simulation with a multidisciplinary tool

In this case, a single simulation tool is used whereby a short computing time can be reached and the integration of sub-models is easy. A major disadvantage is that the tool selection is limited. This results in a decrease of simulation flexibility. In addition, all models must exist in the current tool modeling and simulation language.

2. Single modeling and overall simulation

The system in divided into several sub-systems which are then modeled independently. Afterwards, the models are imported into one simulation tool. A requirement for this kind of simulation is a standardised model exchange interface and the possibility of model integration of the overall simulation tool (Model import).

3. Simulation coupling

The co-simulation and the distributed simulation allow simulation coupling. Models can be developed with different simulation tools. These different simulation tools can than be coupled for an overlapping system simulation. One advantage is the use of existing models. Another one is tool flexibility, so that the most convenient tool can be used at all times.

2.3.2 Information Management

The root of the information management is not one single data base for all information (data, models, documents, etc.). In fact, the existing data management structures shall be used. The difference is that when information is stored into a data base a link is generated and deposited in the central information base. The link provides a central access to the corresponding information via information base. An individual user access avoids information overflow and informs the user when new information is stored in the system. The personal access rights and the information are monitored (for correctness, completeness, traceability, etc.) by a team. Existing models can be exchanged via information management. This allows the reuse of models in the following development phases (see Fig. 5):

- Models from previews developments can be reused in the concept phase
- For the development of the test equipment, models from M4 to M6 can be reused
- For hardware in the loop (HIL), models from system departments and suppliers can be used

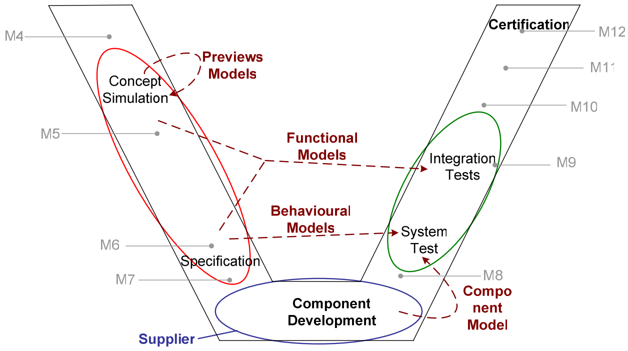

Fig. 5 Model Reuse

The advantages of this concept are the reuse of existing infrastructure and the central allocation of individual user-concerning information. In addition, it also enhances development transparency, communication and model exchange and - reuse. A disadvantage is that the implementation of such a system is time consuming.

2.3.3 Development Process Concept

The concepts for the process and the information management were derived in the last two chapters. The continuous simulation support is a combination of stand alone simulations and of overlapping system simulations at specific milestones. The information management concept includes a central information base. In the following, these concepts are combined to an integrated development process (see Fig. 6). Objectives are the improvement of quality and the concurrent reduction of iteration steps, hence the reduction of development time and costs.

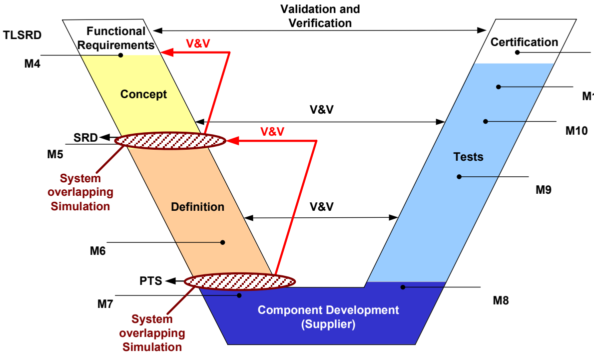

Fig. 6 Development Process Concept

As described in chapter 2.2, there is no adequate use of simulation in the concept phase. The virtual analyses of different concepts enhance the flexibility so that an optimised concept can be selected [17]. That is the reason why simulation in the early phases is recommended.

In the current process, verification of the system functionality is accomplished in a late development phase. This can result in time consuming iterative loops. Single functionalities are often affected by many different systems. The adjustment of these systems is the basis for the required functionality. This problem can be solved by means of overlapping system simulation. In addition, an overall simulation also detects system incompatibilities in the concept and specification phases. This decreases the integration tests and reduces the iterations in the late phases.

A disadvantage of such simulation is the additional effort for the implementation. That is the reason why the use of multidisciplinary simulation must be well considered. The end of the concept phase and the end of the definition phase are suitable for overlapping simulation (see Fig. 6). At the end of the concept phase the system architecture is defined and at the end of the definition phase the specification is handed over to the equipment supplier. Hence, changes of the system architecture as well as of the specification would result in substantial modifications.

In parallel to the equipment development, the suppliers should deliver simulation models of the components. These models can be used in the test and integration phases. With HIL-capable component models it is possible to e.g. analyse damage scenarios. The exchange and reuse of models via information basis allows an early development of the test equipment.

Recapitulating, it can be said that a continuous simulation support throughout the development process reduces development time and costs. The basis for a smooth use of the simulation is provided by an information management system.

3 Application: Fuel Cell Simulation

In Fig. 7 the principle design of a fuel cell APU for the power and water generation on board an aircraft is displayed.

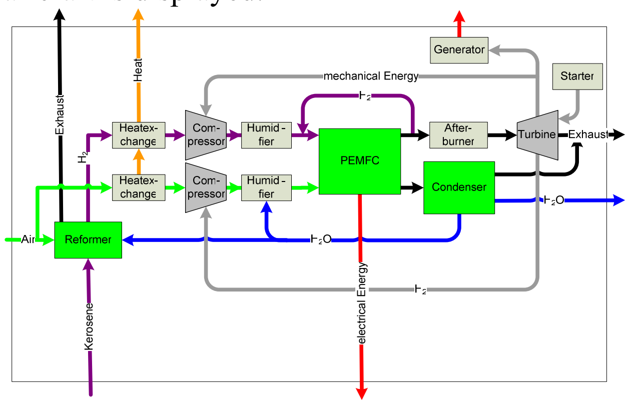

Fig. 7 Fuel cell APU onboard an aircraft

The hydrogen is generated from desulphurised kerosene with the aid of an auto-thermal reforming process. Thermal energy is fed into the auto thermal reformer till the operational temperature is reached. At this temperature an equilibrium of the endothermal and exothermal reaction is reached. For the operation of a proton exchange membrane fuel cell (PEMFC) the anode and cathode gases need to be humidified. The fuel cell converts chemical energy into electrical energy. This oxidation process of hydrogen generates water. For the condensation of the steam a part of the electrical energy is used.

For the simulation of the fuel cell system a multidisciplinary simulation environment is needed. E.g. in the reformer, chemical and thermal reactions as well as fluid mechanics have to be considered. For the modelling of the fuel cell, electrical and thermal procedures and fluid mechanics have to be regarded. And for the turbine start-up and the operation of the compressor, mechanical simulation models are necessary.

3.1 Distributed Fuel Cell System Simulation

As described in chapter 2.3.1 distributed simulation can be used for the simulation of multidisciplinary systems (see Fig 8).

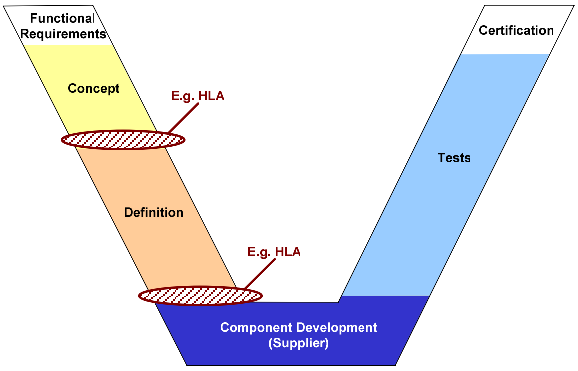

Fig. 8 Overlapping Simulation with the HLA

The high level architecture (HLA) was used to develop a distributed fuel cell simulation. Advantages of the HLA are the detailed time management and the independence of an operational system. In case of simulation parameter variation existing federates (simulation participants in the HLA) can be easily adapted. This results in a high reusability of the HLA models. The entire communication of the federation (simulation coupling of federates) is controlled by the runtime infrastructure (RTI). Thus, federates communicate with the RTI through the RTI-ambassador and in return via federate-ambassador (see Fig. 9).

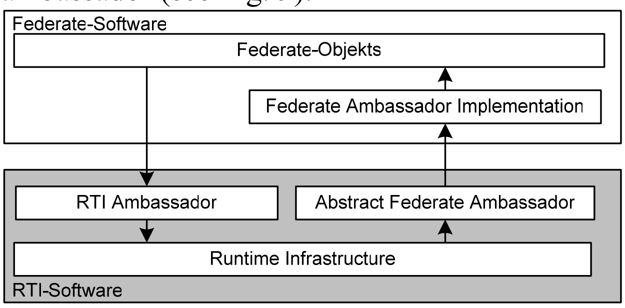

Fig. 9 Ambassador Concept

The possibility of the areal separation of the distributed simulation via TCP/IP transmission and the reduction of computing by logical simulation model separation are additional benefits.

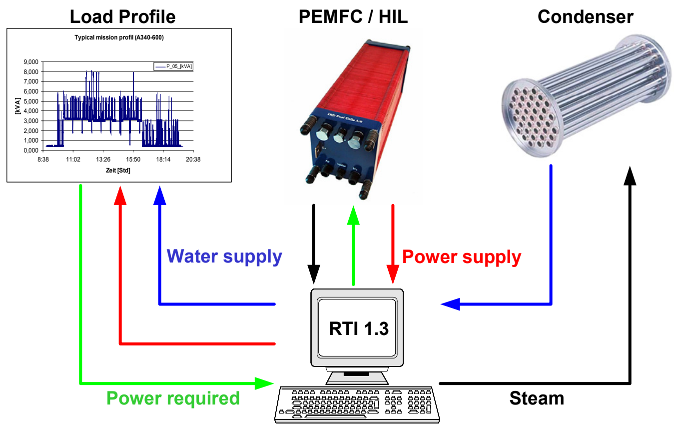

Fig. 10 HLA-Based Fuel Cell Simulation

In Fig. 10 the distributed HLA simulation for a fuel cell system is displayed. The distributed simulation consists of the condenser for the fuel cell exhaust water condensation, the fuel cell stack and a load profile. The condenser is modelled and simulated in Ottobrunn while a real fuel cell stack is integrated in Hamburg via HIL. There is no need for a central integration of the simulation participants. The expert know-how needed is present on location. This allows short iterative loops for the simulation debugging.

3.2 Fuel Cell Hardware in the Loop Simulation

As described in chapter 2.3.3 HIL can be used in the test phase, e.g. to analyse damage scenarios (see Fig. 11).

To predict the dynamic behaviour of the fuel cell system, a HIL simulation with a real fuel cell stack was established with MATLAB® SIMULINK (see Fig. 12). By means of a controlled load, a load profile can be retraced. The load profile is provided by the *From File* block. The *Wirte To Minilab* block adjusts the requested load by the resistance of the controlled load. The resistance provokes a corresponding fuel cell current, which causes a voltage change. The PEMFC power can be derived via the ohmic law.

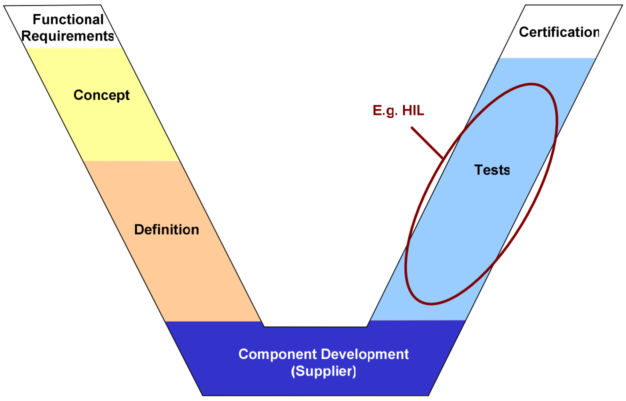

Fig. 11 HIL in the Development Process

In Fig. 13 the step response of the fuel cell power is displayed. The overshoot is clearly recognizable. The reason for this behaviour is the capacitive impedance of the fuel cell. Hence, a current change results in a delayed voltage change.

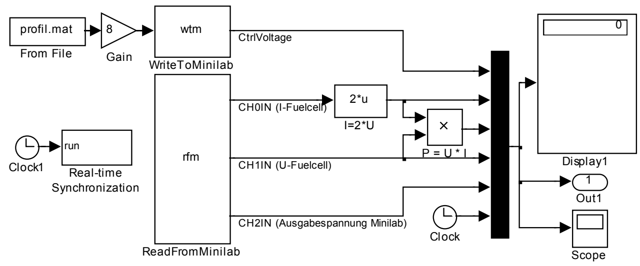

Fig. 12 Dynamical Fuel Cell System Simulation

From the fuel cell polarisation curve it is obvious that a positive current step results in a delayed decrease of voltage. At first the voltage is on a higher potential so that the product of voltage and current for a short time remains on a higher level directly after the step.

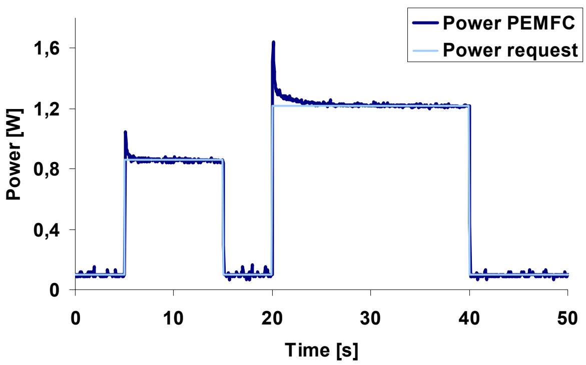

Fig. 13 Step Response of the PEMFC Power

The fuel cell power response is in the area of milliseconds. To predict negative effects of the dynamical fuel cell system behaviour for the direct current (DC) network this results are not sufficient. But assuming this perceptions the fuel cell is not the critical component regarding the dynamical system behaviour. E.g., the reformer, gas and water transports and the heat balance will have an even higher impact on the dynamic behaviour.

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