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Safety, performance, and monitoring are the most important parameters for electrified powertrain components. This prompted ETAS to develop a Hardware-in-the-Loop approach that can be used to operate fuel cell ECUs in closed-loop. In addition, this approach enables the performance of comprehensive tests such as the realistic simulation of the driver, vehicle components, and environment.

ALTERNATIVE POWERTRAIN CONCEPTS

The challenging transition from traditional internal combustion engines to electrified powertrains has been on the agenda of automakers and the supply industry for many years. However, adoption of alternative technologies has remained low as a result of cooperation models optimized over many years by all the parties involved and persistently strong global sales figures for traditional powertrains. In the past, concerns about emissions associated with these powertrains have primarily led to a change of attitude in major Asian conurbations – but pressure to introduce alternative technologies is now also increasing worldwide.

Even so, research and development activities for these alternative technologies have long focused predominantly on series or parallel hybridization of the powertrain in order to maintain the benefits of fossil fuels such as the fast refueling of internal combustion engines. At the same time, battery-electric powertrain concepts continue to be stigmatized for their limited range, high weight, and comparatively long charging times.

However, huge progress is being made in this area. For example, a major intensification of research is currently under-

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Test and validation of fuel cell ECUs

way in the field of fuel cells and in the development of fuel cell-based powertrain concepts.

TEST AND VALIDATION METHODS

The fuel cell is a reliable electrochemical powertrain system component, but it, too, requires an electronic control unit (ECU). Therefore, in addition to continued improvements to the chemical, mechanical, and electrical specifications of fuel cells, it is equally important to develop high-performance ECUs and software as well as an efficient, targeted test and validation methodology for these ECUs.

As part of their efforts to develop a suitable methodology, ETAS engineers applied a Hardware-in-the-Loop (HiL) approach in order to operate fuel cell ECUs in closed-loop and, thus, enable extensive testing. The primary goal of the HiL system setup is to simulate the driver, vehicle (components), and environment as realistically as is possible and necessary. Requirements concerning the accuracy of the simulation are defined in close collaboration with the departments responsible for developing the ECU software in order to achieve coordinated quality targets.

HIL APPROACH

The HiL approach improves software development efficiency significantly and reduces both the time and cost of development. HiL systems, which can be used from the early pilot phase of software development, make a major contribution to the progress of software development. Safety-critical functions such as hydrogen leak detection, safety concepts, and the activation and pre-charge algorithms of electrical components can be tested early on at the function developer's desk or in the laboratory.

FIGURE 1 shows the front view of this kind of HiL system. The HiL system provides access to analog and digital input/output hardware boards and bus communication interfaces such as CAN and LIN, allowing users to configure these as required.

For special load functionalities, such as for the hydrogen gas injector, real or simulated electronic loads are integrated into the HiL system. The hydrogen gas injector can be simulated with high accuracy using an electronic injector load module. In this case, the similarity between the fuel cell system and the components and control strategies of a traditional internal combustion engine is exploited – both in the system design and in the simulation.

The inputs and outputs of the high-precision physical fuel cell simulation model are connected to the hardware inputs and outputs of the HiL using the software integration platform ETAS COSYM. The fuel cell model is operated on the real-time simulation computer under strict real-time conditions. Integration of the fuel cell ECU calibration interface, for example using ETAS INCA, closes the loop between simulation and fuel cell software interaction with the simulated fuel cell system.

SIMULATION MODEL OF THE FUEL CELL SYSTEM

The most important component for a HiL system is the physical simulation model of the fuel cell system, for instance ETAS LABCAR-MODEL-FC. **FIGURE 2** shows the five main parts of the fuel cell system: the fuel cell module, anode path with hydrogen supply/tank, cathode path for the air supply, cooling for system temperature control, and the electrical high-voltage path for energy storage, voltage conversion, and electrical load (electric motor). These five main parts are integrated in a complex fuel cell system and have a significant impact on efficiency.

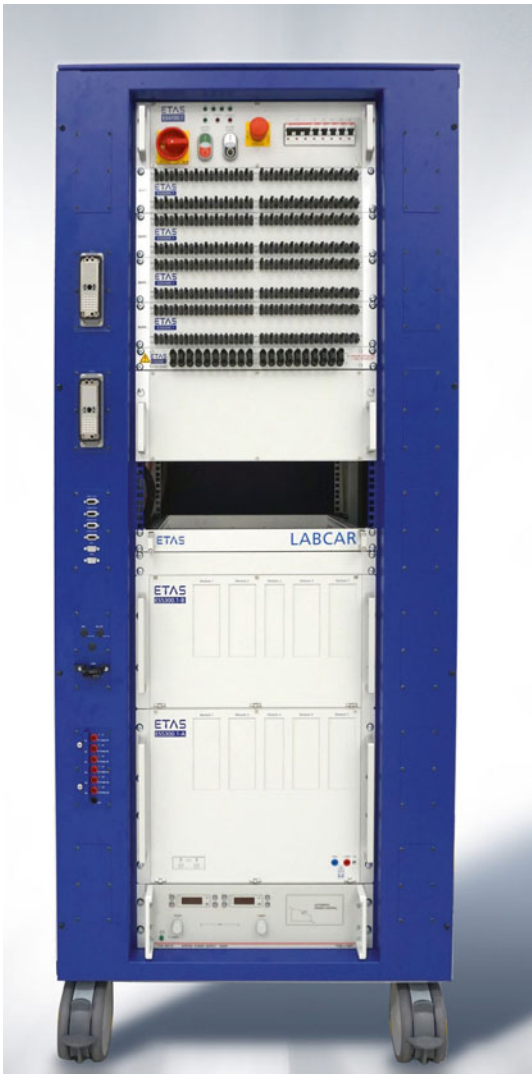

FIGURE 1 Fuel cell - LABCAR (© ETAS)

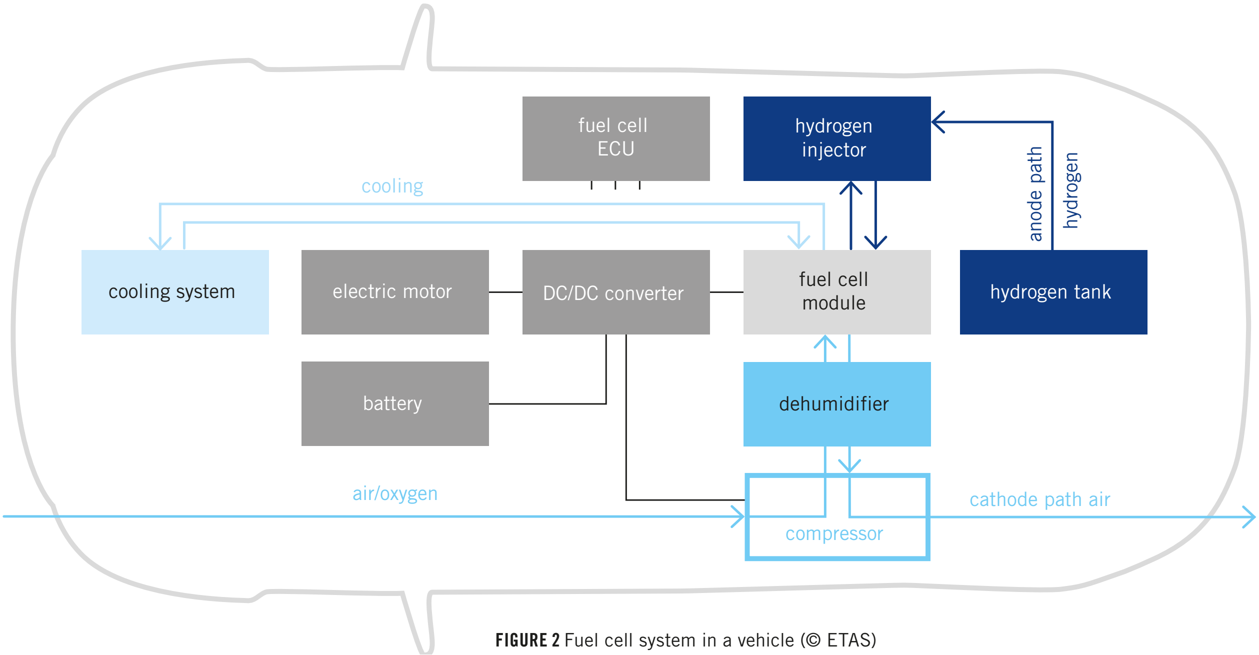

FIGURE 2 Fuel cell system in a vehicle (© ETAS)

In order to run the complete fuel cell simulation model on a HiL system, the following points must be considered:

- The model must be executable in real time.
- The single-cell fuel cell model must simulate physical laws, such as losses or effects of electric current, temperature, and electrical resistance stoichiometry as well as membrane humidity at the cellular level, precisely.
- A detailed water composition and a two-phase water model calculation are required to represent the motion and change of the states of aggregation of, for example, liquid water in the gas channel.
- A 1D multi-component gas channel model is required that enables specification of the individual gas composition of each electrode or of the simple description of pressure loss characteristics.
- Support is required for a variety of flow field designs and the detailed calculation of internal cell humidity.
- It is necessary to take into account realistic cold start behavior based on a membrane temperature model, nonlinear dynamics of the cell water composition, and temperature-dependent fluid properties.
- In order to support a variety of fuel cell architectures, a model library should be implemented.

MEMBRANE ELECTRODE ARRANGEMENT

As shown in **FIGURE 3**, an individual fuel cell in the model can be separated into multiple segments along the gas channel. While the z coordinate follows the gas flow, the x and y coordinates are arranged perpendicular to the membrane and gas channel. Each segment in this arrangement addresses all the functional layers of the fuel cell including bipolar plates, gas channels, gas diffusion, and membrane. The same system of equations can therefore be used for both an individual cell and a complete stack of many cells in series. Mass and heat flows connect the segments and layers of the cell. Exchange between model segments only takes place via heat and mass exchange in the gas channel and bipolar plates.

Due to its negligible mass, the membrane electrode arrangement (MEA) does not contribute to the energy exchange with adjacent segments. Furthermore, its expansion in the x direction is orders of magnitude smaller than in the z/y direction. Thus, spatial pressure and concentration gradients – which drive proton and water transport through the cell – occur primarily in the x direction. The main focus in modeling the spatial characteristics was therefore on the gas channel and bipolar plates. This kind of MEA model can be evaluated segment by segment and is not directly influenced by the 1D model. Its condition is determined exclusively by the general conditions of the gas channel and bipolar plate model.

The approach is rounded off with a library of multiple components. Key elements to take into account include the hydrogen gas injector (HGI), hydrogen recirculation blower (HRB), vent valve in the anode path, air compressor, humidifier in the cathode path, cooling pump, MCV valve in the cooling path, safety circuit, and DC-DC converter. The result is a complete fuel cell plant model for use in the HiL system. **FIGURE 4** shows a comparison between the results of the uncalibrated real-time HiL LABCAR simulation (red) and the vehicle test drive (blue). The same fuel cell ECU was used to obtain both results.

SYSTEM SIMULATION AND TEST DRIVE DATA

The anode (hydrogen) differential pressure in the simulation follows much the same path as that seen in the vehicle test drive. The mass flow rate (air) at the compressor also sees a largely equivalent trend between the model and test run. The electric current delivered by the fuel cell in the simulation corresponds to the vehicle data closely. And

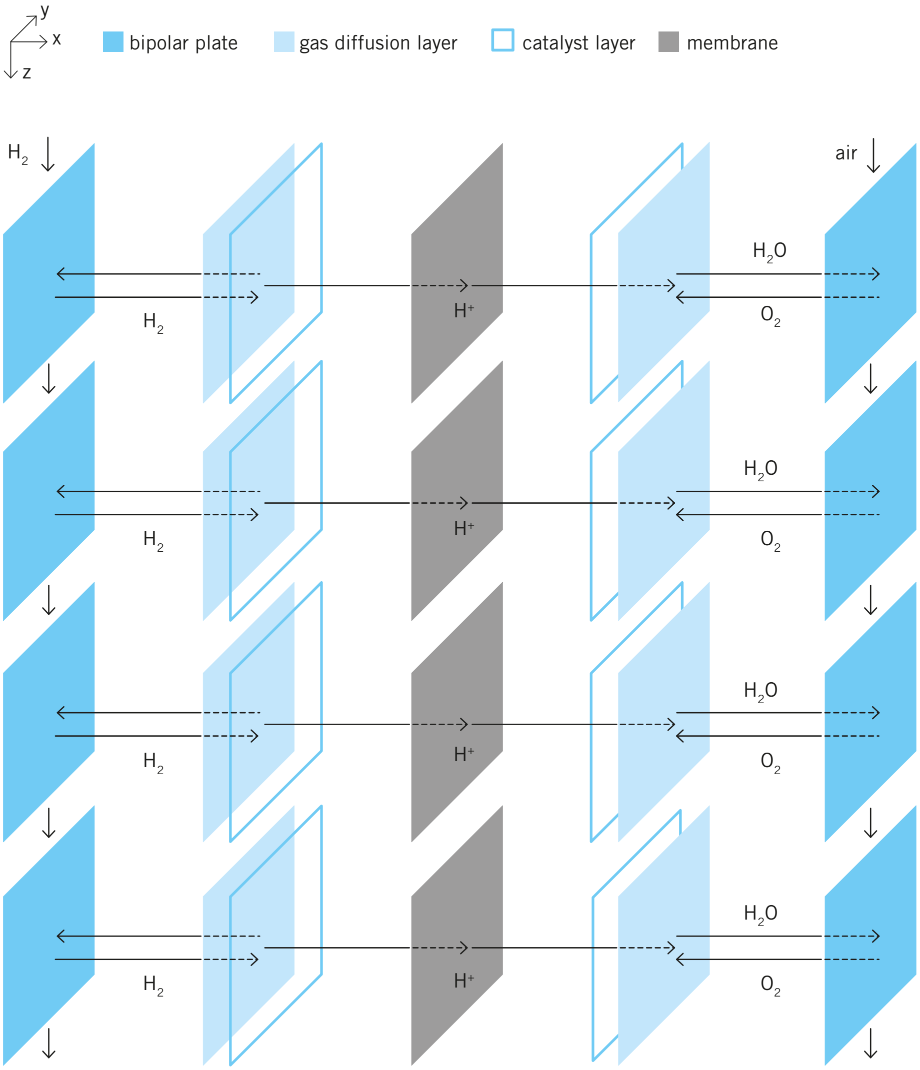

FIGURE 3 Separation of the fuel cell into individual segments (© ETAS)

the electrical voltage generated by the fuel cell module also exhibits close correspondence between the model and vehicle data.

The system simulation and test drive data can be optimized by using test bench measurements to calibrate the fuel cell model (model calibration, for example ETAS ASCMO-MOCA). The real-time fuel cell model developed and applied in this case can currently be further optimized with 350 parameters if required for ECU software development. Furthermore, simulations of the vehicle dynamics, electric motor, or battery can lead to improvements in the simulation results.

VIRTUALIZED TEST PROCESSES

Alongside the test and validation approach using HiL systems, there is an increasing need for virtualized test runs in the early phases of ECU software development. Using the fuel cell simulation model that is also employed in HiL tests, the user is able to test the functions of the fuel cell ECU by exclusively virtual means before a real ECU prototype is available. The ETAS COSYM test platform allows the software functions of the future ECU to be validated in a virtual closed-loop experiment while also enabling the simulation model to be integrated into a simulated higher-level vehicle model. By simulating all the vehicle buses – such as virtual CAN and

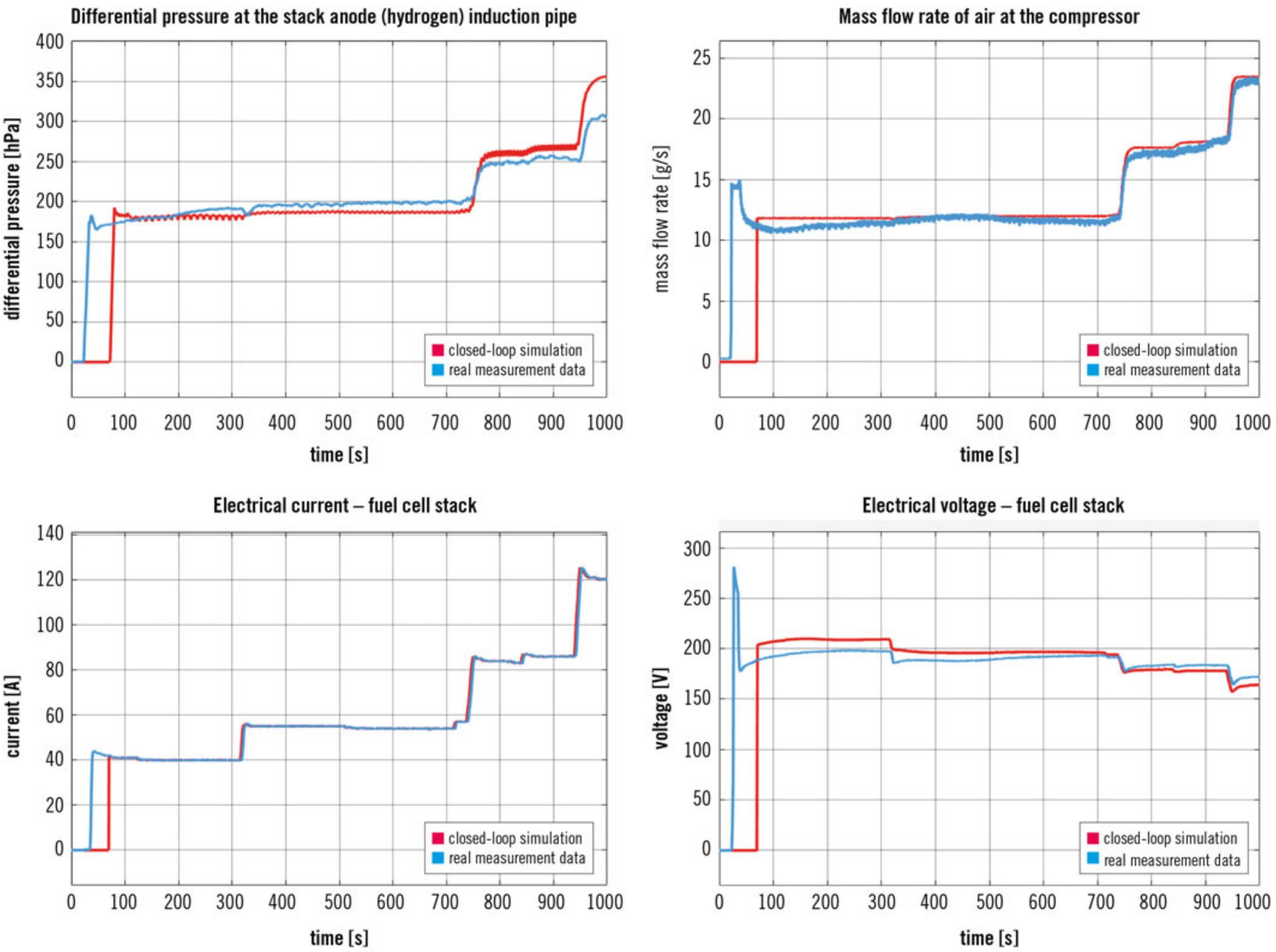

FIGURE 4 Comparison between results of LABCAR HiL simulation (red) and vehicle test drive (blue) (© ETAS)

automotive Ethernet networks – it is possible to achieve a realistic analysis of network communication even in the early stages of the development process.

SUMMARY

Safety, performance, and monitoring of powertrain components will continue to be the most important parameters for electrified powertrain components in the future. For the development and refinement of fuel cell ECUs in particular, precise, real-time simulation of the fuel cell will represent a fundamental component of validation on the HiL system in order to achieve reliable, reproducible test results. Furthermore, timely use of Software-in-the-Loop (SiL) test platforms will enable early, recursive test runs during development in a concentrated, efficient test environment. Together with the corresponding simulation models, the HiL and SiL solutions presented here provide the basis for highly efficient development of fuel cell ECUs in accordance with all safety requirements. Alongside purely battery-electric powertrain concepts, the fuel cell will therefore also soon be able to make an important contribution to make traffic more climate friendly and to meet global legislative requirements over the long term.

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